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Honor Capstone Lunar Logistics Study

Owen Bradley Cox

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by

Owen Bradley Cox

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Honors Capstone Director: Dr. Matthew Turner

Principal Research Engineer

Owen Cox ______________________ 04/29/2022

Student Date

Matthew W. Turner ______________________ 04/29/2022

Director Date

D. Keith Hollingsworth ______________________ 04/29/2022

Department Chair Date

William Wilkerson Digitally signed by William Wilkerson
Date: 2022.05.01 12:33:32 -05'00'
____

Honors College Dean Date

Honors College
Frank Franz Hall
+1 (256) 824-6450 (voice)
+1 (256) 824-7339
(fax) honors@uah.edu

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_ Owen Cox ________

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Date

Honors Capstone Lunar Logistics Study

MAE 490/491: Senior Design – Mission Design

Student: *Owen Cox*[1]

University of Alabama in Huntsville, Huntsville, Alabama, 35805, USA

Project Director: *Dr. Matthew Turner*[2]

University of Alabama in Huntsville, Huntsville, Alabama, 35805, USA

With NASA focusing much of its attention to returning to the moon and its wish for a long-term sustainable presence there, much will need to be done to ensure that any long-term lunar habitation receives frequent and plentiful supplies from earth. One aspect of long-term lunar habitation that may be easy to overlook is the logistical supply chain responsible for furnishing these supplies to any surface bases or space stations due to both the proximity to earth and several unique advantages of the lunar environment. There are many old and newly emerging recycling techniques that could drastically reduce the quantity of supplies that need to be delivered. This, coupled with a renewed interest in In-Situ Resource Utilization (ISRU) technologies to produce many supplies directly from the lunar environment provide a stunning amount of choice when designing a lunar logistical supply chain.

Nomenclature

ISRU	=	In-Situ Resource Utilization
CM	=	Crew Member
ISS	=	International Space Station
S&O	=	Science and Outfitting
ECLSS	=	Environmental Control and Life Support System
HLS	=	Human Lander System
SLS	=	Space Launch System

I. Introduction

NASA is currently in development of the Artemis lunar program which aims to return humans to the lunar surface. NASA also has been interested in developing lunar bases during this program. In order to establish a lunar base, it is essential to supply the crew with the essentials of life-support resources. The main issue is that these resources must be shipped to the lunar surface, which involves launching additional rockets. This leads to a question of logistics. Will NASA be able to meet the required launch rate to support a lunar base? To determine this however, the required launch rates must be known. The purpose of this Capstone is to develop the life-support and equipment consumption of a single crewmember on a lunar base and use this information to simulate the efficacy of some of the major life-support recycling and ISRU techniques. The majority of this report focuses on the life-support and equipment production per crewmember that must be modeled to answer the question of logistics. The rest of the report compares a baseline life-support model, a current ISS technology model, and an advanced ISRU model.

II. Life-support Assumptions

To begin a logistical study, the needs of an individual crew member must be determined. By defining the consumption rate of critical resources, the launch rate of materials can be calculated. This forms the core of the logistics model. NASA has produced a document entitled the "Life Support Baseline Values and Assumptions Document" with

[1] Undergraduate Student, Department of Mechanical and Aerospace Engineering

[2] Professor, Department of Mechanical and Aerospace Engineering

the stated purpose, "provide[s] analysts, modelers, and other life support researchers with a common set of values and assumptions which can be used as a baseline in their studies" [1]. This serves to ensure that all studies involving life support have a common bases of common comparison [1]. Seeing as the purpose of this project is to study the logistics of providing standard life support to a crew on a Lunar base it falls under the use case for this document perfectly. Therefore, this document is the core of the life support research in this project. Critical crew resources were defined as follows: oxygen, water, food, medical, experiments, and supplies. These products are consumed and produce the following resources that may be used for recycling purposes: carbon dioxide, waste, and wastewater. Consumption and production rates were determined and are listed in Table 1. An in-depth discussion of each resource, what it represents, and how these values were selected will follow on a resource-by-resource basis.

Table 1: Life-Support Assumptions

Consumable Resource	**Consumption Rate (Kg/CM/Day)**
Oxygen	0.92
Water	24.45
Food	0.719
Medical	0.913
Experiments	4.46
Supplies	2.76
By-Product Resources	**Production Rate (Kg/CM/Day)**
Carbon Dioxide	1.17
Waste	1.96
Wastewater	24.45

The detailed description of Table 1 will begin with the oxygen resource. It is common knowledge that the human body requires sufficient levels of oxygen to function properly and even a few minutes without this precious resource can lead to serious injuries and death. Thus, oxygen has always been a key to spaceflight since its earliest inception. The value derived in Table 1 represents the weight of oxygen per crew member to sustain that crewmember for one day. This value is the result of the NASA 41-Node Man program to analyze metabolic activity. This project, known as METMAN, is a set of analysis code designed to simulate human metabolism and heat transfer. The relevant results from this research are that the oxygen consumption for a 5th, 50th, and 95th percentile crew member was determined and may be seen in Table 2 [1]. The project also calculated the standard reference crew members oxygen consumption, which was the value chosen for Table 1, however, it is noted that if a more robust life support system is desired, the 95th percentile crew member should be used [1].

Table 2: Oxygen Consumption Reference [1]

Case	**Oxygen Consumption (Kg/day)**
5th Percentile Crewmember	0.62
50th Percentile Crewmember	0.86
95th Percentile Crewmember	1.13
Reference Crewmember	0.92

The discussion of water consumption is one of the most complex in the life support model and cannot be properly evaluated without a brief discussion of wastewater generation. Water is one of the most important resources in any form of human habitation and its presence on a lunar base is required. Water is not simply used for drinking; however, in fact, most water that will be needed on the mission will be used in various hygienic and housekeeping duties. There are numerous studies performed by NASA on the water consumption of a crewmember for all these needs. The needs can change based on mission profile, however. For example, the Apollo Command Module did not contain a sophisticated commode like on the ISS, thus the level of sophistication of the facilities must be considered. For this project, the lunar base shall be considered a "Mature Planetary Base" by NASA standards [1]. This type of mission has the capabilities for not only drinking water and food rehydration water, but also for urinals, hygiene, hand washing, shaving, cleaning, showering, laundry, and dish washing [1]. This type of mission was selected as NASA is looking to establish long term lunar bases which would contain these sorts of capabilities. The research for water consumption is based on the NASA "Human Integration Design Handbook" and the Devon Island Mars Research

Station Study. This poses an issue, however, as the wastewater production section of the Baseline Life-support Assumptions Document uses information from the NASA "Human Integration Design Handbook" and the study of Ewert and Jeng in their study "Will Astronauts Wash Cloths on the Way to Mars?" [1]. This leads to discrepancies with water consumption and wastewater produced. The information from each study has been tabulated into Table 3.

Table 3: Water and Wastewater Rates Consumption/Production Reference

Source	**Water Studies (Kg/CM/Day)**	**Wastewater Studies (Kg/CM/Day)**
Drinking Water	2.0	--
Food Rehydration Water	0.5	TBD
Urinal Flush	0.5	0.5
Personal Hygiene/Oral Hygiene	0.4	0.37
Hand Wash	--	4.08
Shower	1.08	2.72
Laundry	1.8	1.8
Dish Wash	3.54	5.41
Urine	--	1.50
Latent Humidity Condensate	--	2.9
Total	**9.82**	**24.45***

** The value above is not the sum of the column. According to the Baseline Life Support Assumptions Document, "Please note that the water usage rates and wastewater generation rates sometimes differ… In some cases either the water usage or wastewater generation rates are unknown" [1]. There is likely an unseen scaling factor to account for unanticipated wastewater generation applied to the sum of the column to reach the researchers predicted total. This is not identified by the researchers, however.*

In light of the discrepancy, the value for water consumption comes into question. To resolve this issue and continue with the development of the life-support modeling, the water consumption rate was selected to be equal to the wastewater production rate. While this estimate is quite large, it does correctly model a mature planetary base and this number is a conservative estimate. Thus, the model will use a water consumption rate of 24.45 kg/CM/day.

The food resource will be discussed next. Food is the last of the typical consumables in the model. It is also simple to estimate a consumption rate due to the studies on the ISS. Crew meals have been reliably provided to the stations crew for years and this has led to an effective estimation for the quantify of food that is required for a given crew member. The food estimates are made under the assumption of dehydrated food, the same variety as shipped to the ISS. This weight includes the 16.5% upscale in mass to account for the actual packaging material. It is recognized that this is quite a small weight, however, it must be remembered that a tremendous amount of weight in food comes from the water inside it. This has been eliminated in this meal packaging technique, greatly reducing weight. The weight of the water required to rehydrate the food is accounted for, but it is done in the water and wastewater estimations, not the food estimations. This estimate also assumes the nominal consumption rate. If a more robust system is required, the upper crewmember consumption rate can be used. The resulting values can be seen in Table 4.

Table 4: Food Consumption Reference [1]

Estimates	**Food (Kg/CM/Day)**
Lower Estimate	0.54
Nominal Estimate	0.617
Upper Estimate	0.66
Packaging Increase	+16.5%
Nominal With Packaging	0.719

Moving away from the more traditional life-support resources, medical supplies will be discussed next. It is not feasible to assume that an astronaut will never get injured or require minor to moderate care whilst on the lunar base. To this end, medical supplies will need to be regularly provided and replaced. Medical resources are, however, unique in the concept of life-support logistics as they are only consumed when needed. Thus, it is possible to assume

that once this resource has been delivered to the lunar base, that it can safely be removed from the logistics model for the future. That is not true, however. Most medical supplies have a shelf life and most medical supplies will typically be used on a semi-regular basis, thus an estimation for the usage of these materials was undertaken. The information in Table 5 provides the estimated weight of the medical equipment needed for a lunar outpost [1]. These supplies are rated for "Level of Care Four" by the Life-support Assumptions Document. This is defined as a, "moderate level of risk for medical issues (mission length from 30 days to 210 days)" [1]. This level of care is deemed acceptable for a lunar base. With the weight of various medical supplies established, a rate of consumption needed to be calculated. This was done by assuming that one Contaminate Cleanup Kit, one Advanced Life Support/Trauma Stabilization Kit, and one Medical Procedure Kit are either used or replaced once per month. There is also a 10% increase applied to this weight to account for minor medical equipment usages. There are many additional items required to perform Level of Care Four functions, but they are single installation items and are not consumable, thus, they can be considered as part of the lunar base's construction instead of logistics.

Table 5: Medical Consumption Reference [1]

Consumable Items	**Mass (Kg)**
Contaminate Cleanup Kit	4.5
Advanced Life Support/Trauma Stabilization Kit	11.3
Medical Procedure Kit	9.1
Percent Increase	+10%
Rates	**(Kg/CM/Day)**
Total	0.913

While not required for life-support, science experiments are the primary justification for the establishment for a lunar base. Science experiments can be modeled as a consumable like the other life-support resources based on past ISS data. The reason to undertake this exercise is due to the non-negligible mass that experiments consume in typical ISS missions and how they behave as a consumable resource over the longer time spans such as in this study. This was calculation was based on the supply mission history for the ISS and the crew member count on the station. ISS resupply payload data was collected from 10/14/2017 until 2/15/2020 which accounted for 32 missions to the station [2]. The data provided in the study can be seen in Figure 1. Over the 32 missions of the study, this was the average distribution of cargo. Note that S&O stands for "Science and Outfitting" which represents the experiments resource in the life-support model.

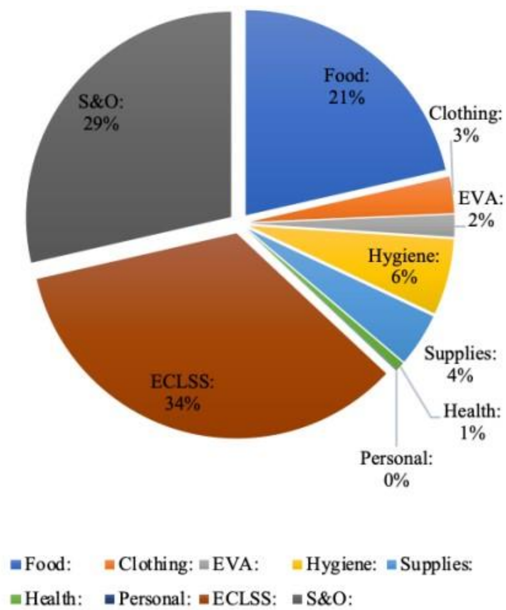

Figure 1: Average ISS Resupply Cargo Distribution [2]

The information in Figure 1 is not directly useful to the model, however. In order to determine the actual average mass, the mass for all 36 missions must be determined. To do this the payload mass for each individual vehicle must be known. This information is tabulated in Table 6.

Table 6: ISS Resupply Missions Payload Mass [3–8]

Vehicle	kg	Number of Launches in Study	Payload Mass (Kg)
Progress	2350	7	16450
*OA Payload	3513	2	7026
Dragon Resupply	6000	7	42000
Crew Demo 1	180	1	180
Souyz (2 Crew)	80	0	0
Souyz (3 Crew)	50	9	450
HTV	5900	2	11800
*Cygnus	3513	4	14052
**Boeing Starliner	--	1	--

** Standard Configuration Assumed*
*** Purposefully Excluded Due to No Delivery*

Based on the information in Table 6 and Figure 1, the mass of experiments per crew member per day based on historical ISS data can be determined. This process is recounted in Table 7.

Table 7: Experiments Consumption Reference

Item	Value	Units
Average Mass Per Resupply	2873.69	Kg/Mission
Science and Operations (29%)	833.36938	Kg/Mission
Average Crew of 7		
Average Mass Per Resupply	410.53	Kg/Mission/CM
Science and Operations (29%)	119.05	Kg/Mission/CM
Elapsed Time for Analyzed Missions of 854 Days		
Average Mass Per Resupply	15.38	Kg/Day/CM
Science and Operations (29%)	4.46	Kg/Day/CM
Experiments	**4.46**	**Kg/CM/Day**

The last resource considered is more abstract than the others. This resource has been termed “supplies”. The intention of this designation originates from a desire to include air quality control equipment and spare parts for life-support equipment. During research, however, these two are often combined. There was also a discovery that a nonnegligible portion of mass sent to the ISS includes office supplies. Thus, the concept of the “supplies” resource was born. In the life-support model, supplies represent life-support mass that is not water, oxygen, or food while still being historically ECLSS resources. Supplies also includes consumable office supplies as can be seen in Figure 2. Figure 2 is the breakdown of the supplies category of Figure 1. The breakdown of ECLSS category from Figure 1 is also displayed in Figure 2. Please note that these are based on the 36 historical ISS resupply missions.

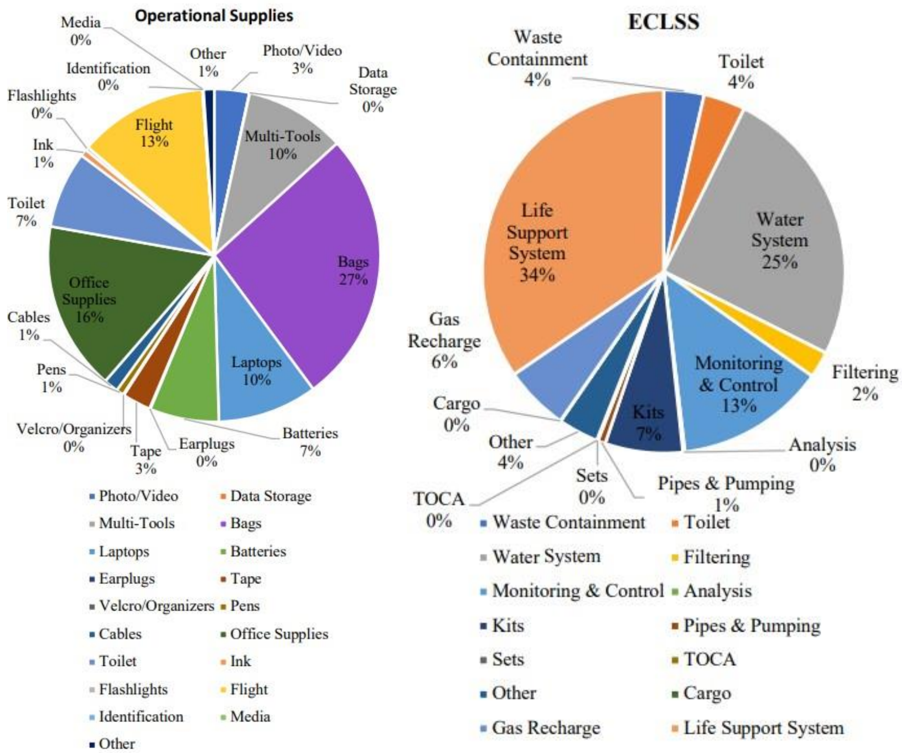

Figure 2: Supplies and ECLSS Breakdown [2]

In order to correctly determine the supplies category for the life-support model, an analysis of the data in Figure 2 is required. Recall that the supplies category for the life-support model will include the operational supplies category and will not include water, food, and oxygen since they are already accounted for. Thus, the ECLSS category should only include the following: waste containment, toilet, gas recharge, other, cargo, TOCA, sets, pipes & plumbing, monitoring and control, and filtering. This is due to the Life Support System and Water System already being accounted for. The calculations for the sum of the appropriate ECLSS considerations and the office supplies are located in Table 8.

Table 8: Supplies Consumption Reference

Item	Value	Total
Average Mass Per Resupply	2873.69	Kg/mission
Office Supplies (4%)	114.9475	Kg/mission
ECLSS (34%)	977.05375	Kg/mission
ECLSS Parts, Kits, (Non water, oxygen items) * Estimation (41%)	400.59204	Kg/mission
Average Crew of 7		
Operational Supplies (4%)	16.42	Kg/Mission/CM
ECLSS (34%)	139.58	Kg/Mission/CM
ECLSS Parts, Kits, (Non water, oxygen items) * Estimation (41%)	57.23	Kg/Mission/CM
Elapsed Time for Analyzed Missions of 854 days		
Operational Supplies (4%)	0.62	Kg/Day/CM
ECLSS (34%)	5.23	Kg/Day/CM
ECLSS Parts, Kits, (Non water, oxygen items) * Estimation (41%)	2.14	Kg/Day/CM
Supplies Total	**2.76**	**Kg/Day/CM**

With this, the consumption rates for all resources have been established for a crew member. Next, a brief overlook as to the byproducts of this consumption is explored. The three output resources are Carbon Dioxide, Waste,

and wastewater. The generation of carbon dioxide is based on the same METMAN study for the oxygen consumption. The wastewater has been discussed in the water section. However, it should be noted here that wastewater in the life-support model includes both urine and greywater. The waste category only tracks waste that can potentially reclaimed. For the purposes of this study, only feces are in this category due to the water that could theoretically be reclaimed. Other waste products such as food wrappers, uneaten food, general rubbish, broken equipment, unused consumables, etc. are not feasibly reclaimable and are thus not kept track of by the model. The byproduct resources are shown in Table 9. The life support model does not include the disposal of these other waste elements. It is assumed that they are either returned to earth or stored/vented on the lunar surface.

Table 9: Byproduct Production Reference [1]

Resource	Production (Kg/CM/Day)
CO2	1.17
Wastewater	29.35
Waste	0.123

This concludes the life-support requirements for a single crew member per day. This information was used to create the baseline model that is discussed in the next section.

III. Baseline Model

With the life-support information described in Table 1 established, a discussion of the computational model used to assess the lunar logistics can begin. The model centers on using the rates defined in Table 1 to step through a definable timeframe and determining when a resupply mission or crew exchange mission is required. To accurately function the model requires information on the proposed mission architecture. This is primarily represented by the lunar throw mass of the mission architecture. This is simply the mass that the defined resupply vehicle can place on the lunar surface per launch. The crew vehicle in the proposed architecture also needs to be defined. The model can determine crew exchange missions as well if the crew per launch and required lunar base crew are defined. The model also considers several features that would typically be expected in a real mission environment. For example, the number of extra resources over what is strictly required can be input as a percentile increase. There is also a system to determine what the minimum number of supplies on base are. This system is based on the number of resupply failures that are allowed before the crew run out of resources. The final input is the number of supplies that must be present when the first crew arrives. This value is then multiplied by the minimum number of resources to determine the starting resource allocations of the lunar base. The basic inputs can be seen in Table 10 for the baseline model.

Table 10: Baseline Model Inputs

Input	Value
Extra Supply Scale Factor	10%
Total Simulation Time	10 years
Lunar Base Crew Complement	14 CM
Crew per Vehicle	7 CM
Crew Stay Time	0.5 years
Minimum Time Between Resupply Missions	1 month
Maximum Delivery Failures Allowed	2
Initial Supply Multiplier	3
Lunar Throw Mass	90718.5 kg

The baseline model is constructed using the NASA Artemis 3 mission architecture. The baseline model includes no life-support recycling of any variety. This is to construct a baseline from which the effectiveness of recycling and ISRU techniques to ease logistics can be assessed. The baseline model uses a launch architecture based on the Artemis 3 mission profile. This is a multi-vehicle approach. The HLS is therefore of the starship proposal variety. Current estimates involving the refueling of this vessel in low earth orbit before its trip to the lunar surface require one starship tanker and four starship refuelers. A crew mission functions the same but with one additional vehicle launching, the SLS. The results for this baseline Artemis 3 mission architecture are shown in Figure 3. Note that the launch schedule is the date by which the mission must be accomplished, it may be accomplished before the

required date, but the schedule shows when each mission is scheduled to complete at maximum. The launch summary is included in Table 11.

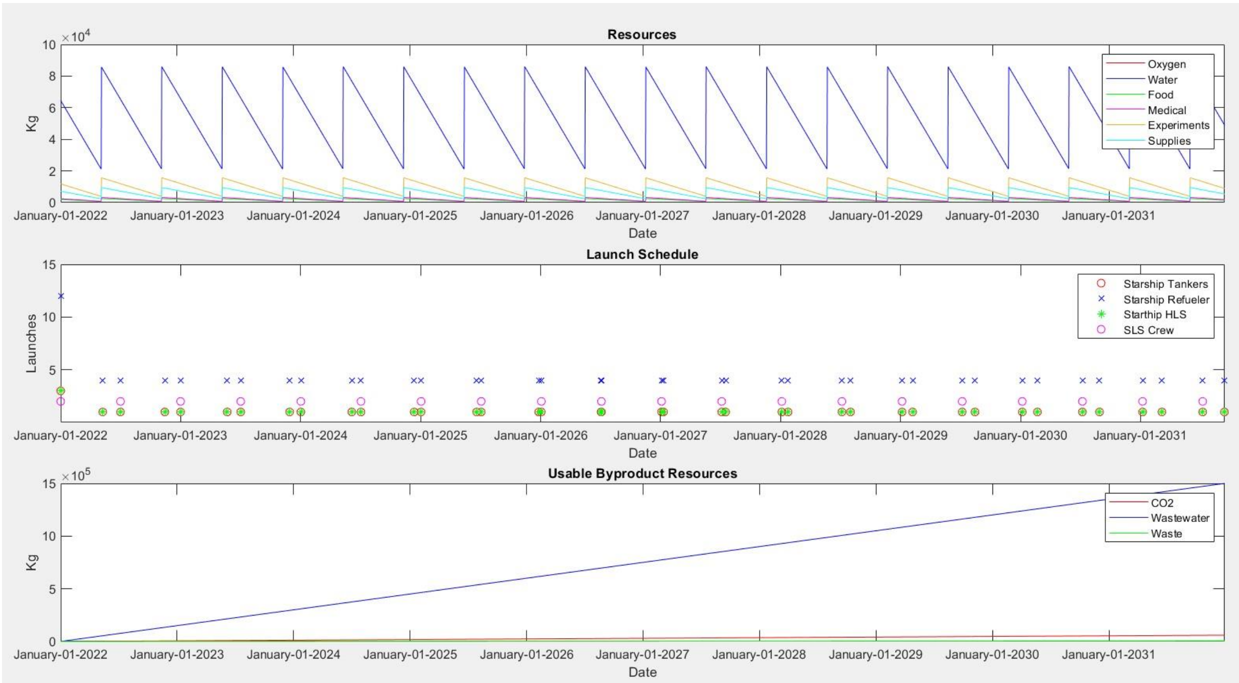

Figure 3: Baseline Model

Table 11: Baseline Model Launch Summary

Vehicle	Total Launches
Starship Tankers	41
Starship Refueler	164
Starship HLS	41
SLS	40
Total	286

The results of Figure 3 are quite intriguing. Notice how the Starship HLS has the payload capacity to deliver all of the necessary resources for the first crew to arrive in a single launch. The second launch of HLS on ay zero is the crew launch. Also note how water is by far the most mass intensive resource to transport. This is why much hope has been placed in finding water ice on the moon for ISRU production to reduce this enormous logistical consumer.

IV. ISS Comparable Recycling Technology

With the development of the life-support model and the baseline model, the effectiveness of different life-support technologies can now be assessed. To begin, the first investigation will use the same techniques currently in use on the ISS. The ISS currently relies on a sophisticated water recovery system. This is useful because, as the baseline model effectively illustrates, water is the most intensive resource to ship to the lunar outpost. The water recovery system is split into two modules, the Urine Processor Assembly, and the Water Processor Assembly. The Water Processor Assembly focuses on retrieving moisture from the air inside the station [9]. The Urine Processor Assembly focuses on recovering water from urine; however, it is likely that this system is also capable or processing greywater. Reading the study "Status of the Regenerative ECLSS Water Recovery System" and gaining an understanding of how this system works provides reason to believe that greywater recycling can also work within this system [9]. The ISS does not produce much of the greywater that will be present in the lunar base of the "Mature Planetary Base" category thus the ISS does not incorporate greywater treatment with this system. Assuming that the system can recycle greywater however, water can be reclaimed at an 85% capacity. The ISS also includes a Sabatier reaction system. This reaction could theoretically produce oxygen from carbon dioxide and hydrogen, but its primary purpose is to act as a carbon dioxide remover. The hydrogen for the reaction comes from the electrolysis of water to create the stations

breathable oxygen. Since this system would require input hydrogen and is focused on reducing carbon dioxide instead of being a primary source of oxygen, it is not included in this model. Thus, the recycling techniques for the ISS Comparable Recycling Technology can be seen in Table 12 with the inputs to the simulation being the same as in Table 10. The results from the simulation can be seen in Figure 4. The launch schedule is summarized in Table 13.

Table 12: ISS Comparable Recycling Technology Summary

Method	Usage Reduction
ISS Water Recovery System	85%

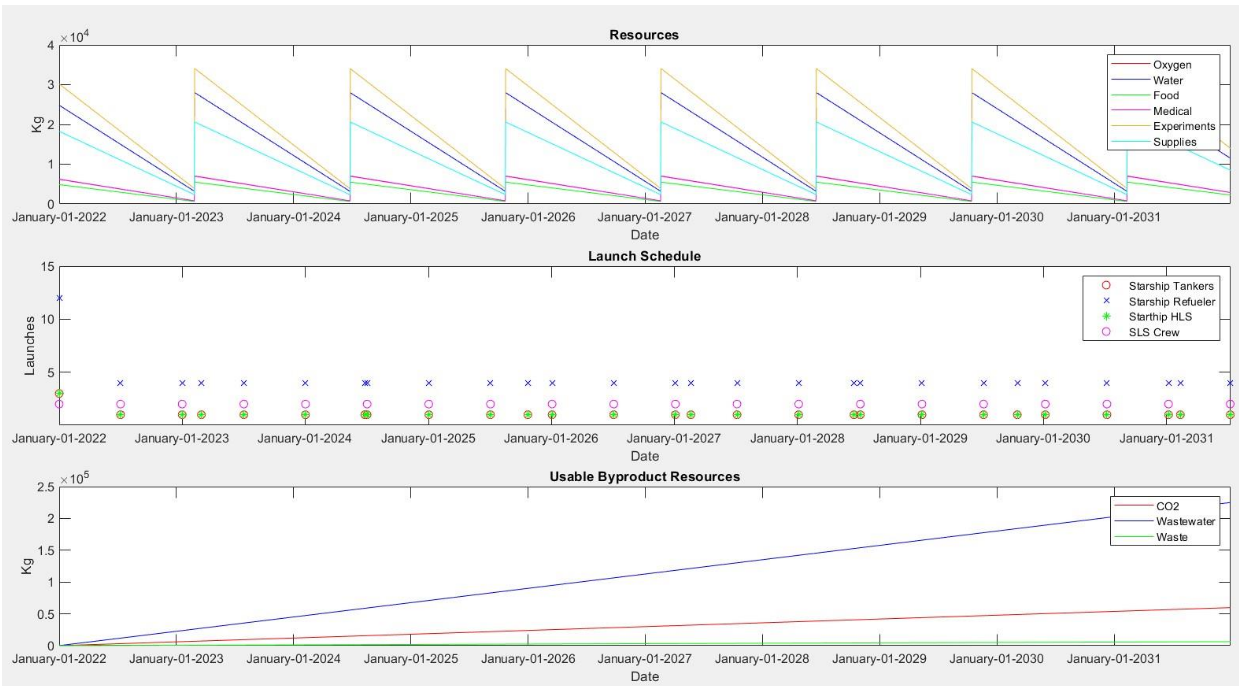

Figure 4: ISS Comparable Recycling Technology Simulation

Table 13: ISS Comparable Recycling Technology Launch Summary

Vehicle	Total Launches
Starship Tankers	29
Starship Refueler	116
Starship HLS	29
SLS	40
Total	214

By simply incorporating existing water reclamation technology, 72 launches are saved. This also allows for the primary cargo of the lunar base to be scientific experiments rather than water. With a basic understanding of how simple recycling can affect the logistical supply chain of the lunar base, a discussion of future advancements and their effects will follow.

V. Advanced ISRU

Advanced ISRU on the lunar surface mostly consist of finding and extracting water ice from permanently shadowed lunar craters. Advanced ISRU and recycling techniques should be able to drastically reduce the resupply missions required. For this study, it is assumed that the 85% wastewater recycling capabilities can be improved based on the recoverable moisture from the waste resource which is estimated to 41.9% water by mass. Along with this, ice extraction from the surface is also considered. This should entirely remove the need for water shipments to the lunar base. Along with this, electrolysis of the water from the ISRU system can be converted to oxygen through the electrolysis system. Thus, the needs of oxygen and water are satisfied with no shipments from earth. There is also

potential for farming to reduce the food need. For this study a 33% reduction in the food need from on-base farming is assumed. Farming is an incredibly complex process in space as can be seen in the Baseline Life Support Assumptions document. Accurately modeling a full farming system is beyond the scope of this report so an estimation of 33% will be used. Based on all of this, the model can be seen in Tables 14 and 15 along with Figure 5. The inputs are the same as Table 10.

Table 14: Advanced ISRU Summary

Method	Usage Reduction
Water Recovery System and ISRU Water Extraction from Lunar Surface	100%
Oxygen Produced Through Electrolysis from ISRU Water Extraction	100%
Farming Increasing Food Capacity	33%

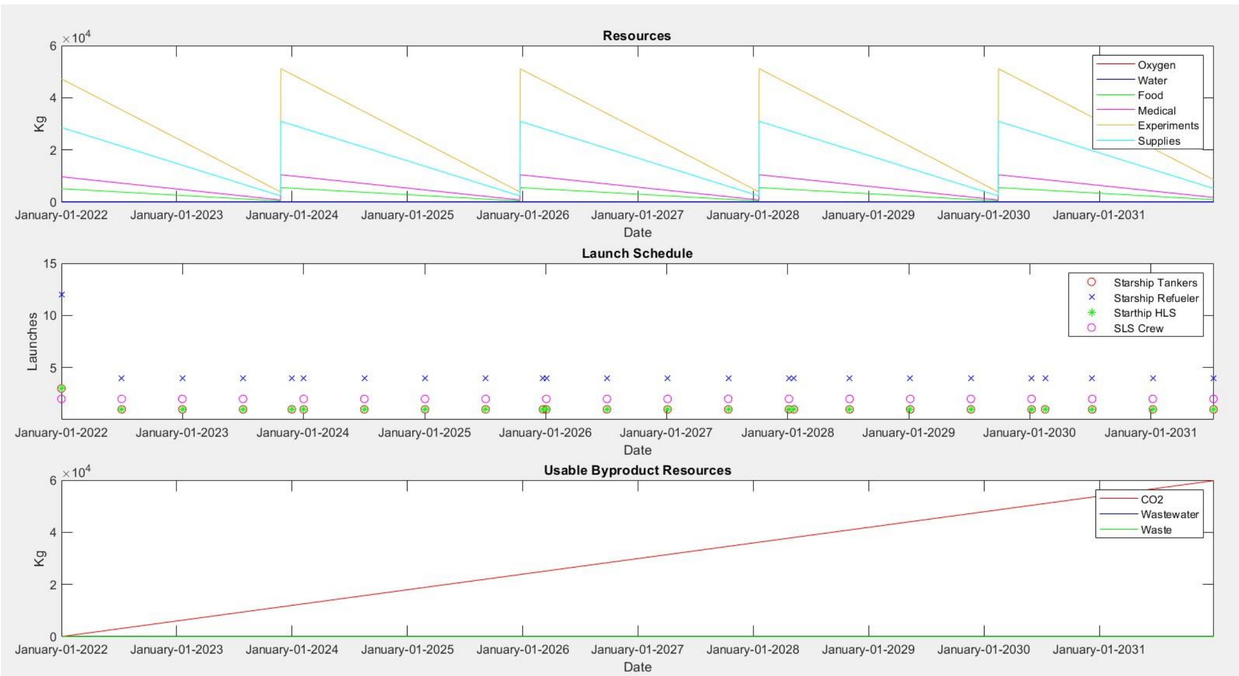

Figure 4: Advanced ISRU Simulation

Table 15: Advanced ISRU Technology Launch Summary

Vehicle	Total Launches
Starship Tankers	26
Starship Refueler	104
Starship HLS	26
SLS	40
Total	196

When compared to the ISS Comparable Recycling Technology, advanced ISRU saves an additional 18 launches. This appears to have reached a point of diminishing return, where additional ISRU and life-support recycling technology will have less impact on reducing the overall logistical supply chain of a lunar base.

VI. Conclusion

In conclusion, the development of a life-support model and its usage in calculating the launch vehicles required to support a lunar base have been developed. Life-support modeling was based on official NASA handbooks and the quality and expectations of these life-support requirements were tailored to match NASA's near-term Artemis

mission goals. The mission architecture analyzed was also the same type as the Artemis mission architecture. A baseline model of a lunar outpost using no life-support recycling or ISRU methods was modeled to compare technologies and strategies against. A model of current life support recycling techniques, modeled after those on the ISS, show that simply reclaiming water can drastically decrease the number of supply missions that need to be launched to the lunar outpost. What is more interesting however, is how an advanced lunar outpost, one capable of using sophisticated life-support recycling equipment and entirely eliminate the need to send water and oxygen to the lunar base through advanced ISRU will only slightly decrease the logistical load on the supply chain. The conclusion to be drawn is that life-support recycling and ISRU systems reach a point of diminishing return where great effort must be placed into developing these systems with only minimal easing of the launch schedule. It is likely that current life-support recycling technology is therefore more than adequate to establish such a lunar outpost. Life-support resources are not the limiting factor in the establishment of this lunar base. A sufficient vehicle launch rate will always be required under the Artemis mission architecture and improving life-support recycling and ISRU technology is only going to be able to reduce that launch rate by a finite amount before NASA is going to have to establish the robust supply lines to the lunar base.

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