A Scalable Orbital Propellant Depot Design

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This paper describes the design and features of a Scalable Orbital Propellant Depot Design tool. The purpose of the tool is to enable others to easily test the effectiveness of adding a propellant depot to an exploration architecture. Several options are available including zero boil-off technology, usable propellant and depot geometry. It is assumed that the depot is refillable with a total service life of 10 years and resides in low earth orbit. Examples of depots created with the tool are shown. Application to existing exploration architectures is also discussed.

Nomenclature

ZBO	=	zero boil-off
ADCS	=	attitude determination and control system
LOX	=	liquid oxygen
LH2	=	liquid hydrogen
H2O2	=	concentrated hydrogen peroxide (98%)
LCH4	=	liquid methane
MLI	=	multi-layer insulation
CMG	=	control moment gyros
ISRU	=	in-situ resource utilization
ESAS	=	Exploration Systems Architecture Study
L1	=	Earth-Moon Lagrange point 1

I. Introduction

Orbital propellant depots have long been considered for use in various space exploration architectures. As early as 1965 [1] there have been investigations into the idea of an on orbit gas station to save money and improve performance. All of the investigations have yet to yield an operational depot, but the idea remains alluring and continues to be worked on to this day. Current work focuses mostly on the technology surrounding the depots. Zero boil-off (ZBO) technology [2,3,4] and fluid transfer issues [5,6] get the most attention. The thought is that once the technical problems and limitations are eliminated, propellant depots will be indispensable elements for space architects.

The rationale for using propellant depots is as follows. Launching large payloads that require high reliability is expensive. Expensive spacecraft and human safety require launches to be extremely reliable. Often, a lot of the weight that is launched is propellant that is needed for mission phases beyond getting into low earth orbit. If there were a propellant depot on orbit, the needed propellant could be supplied by it. The propellant would be launched to the depot on simpler, less reliable launch vehicles, reducing the cost. In other words, space on expensive, high reliability launch vehicles would not be wasted on propellant that is relatively cheap and expendable.

Would this rationale translate into significant benefits for a given architecture? The scalable depot-sizing tool described in this paper seeks to help answer this question.

II. Scalable Depot Characteristics

The scalable depot has a cylindrical body with a planar solar array on either side (see figure 1). It has a dock and fluid transfer interface on one end. The outer shell of the depot is a debris shield to keep the tanks from being punctured. For some depot configurations, there will also be a radiator built into the debris shield. The tanks and most of the other subsystems (pumps, feed lines, avionics, etc.) reside within the debris shield.

It is assumed that the depot is refillable and has a 10-year service life. It sized for a 350 km circular orbit at 28.5 degrees inclination. The orbital characteristics have a minimal effect on the system, so really any orbit can be considered. Orbit insertion maneuvers are assumed to be performed by the launch system and are not sized for the depot. If an architecture requires the depot to perform orbit insertion burns, extra propulsion elements would need to be added to the depot.

The propellant tanks are cylindrical with hemispherical end caps. A variety of materials can be chosen for the tanks. Intertank structure and structural elements between the tanks and the debris shield are estimated to be 20% of the depot empty mass. Feed lines, harnesses, and pumps are sized in reference to the total depot length. The fluid transfer interface and dock is assumed to be similar to the international berthing and docking mechanism (with notable differences of course) and is a constant 400 kg.

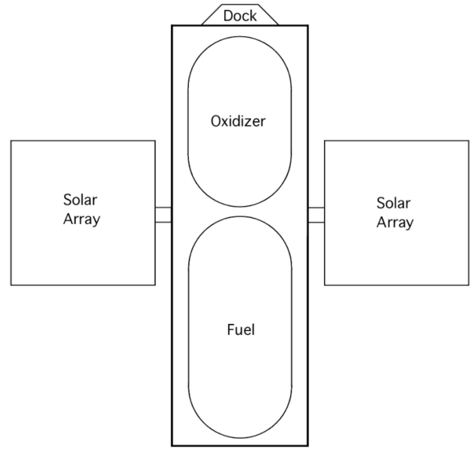

Figure 1: Simple schematic of the scalable depot

Passive insulation around the tanks is kept at a constant 50 layers of multi-layer insulation (MLI) for simplicity. Boil-off rates with passive insulation only are shown in table 1. Active insulation (ZBO) is sized in two ways. The cryocooler that removes heat from the tank is sized in reference to tank volume. The vapor shield surrounding the tank is sized in reference to tank surface area. Cryocooler power consumption is sized in relation to its mass. Boil-off rates using active insulation are assumed to be all zero (they would not be zero in reality, but it is an acceptable approximation for the purposes of this tool).

Propellant	Boil-off Rate	
LOX	0.36	kg/hr
LH2	0.45	kg/hr
LCH4	0.33	kg/hr
Kerosene	0	kg/hr
H2O2	0	kg/hr
Liquid Xenon	0.26	kg/hr

Table 1: Propellant boil-off rates with only passive insulation

Debris shielding is sized based on the estimated outer surface area of the depot. It is a layered composite design based on the hybrid propulsion module from NASA Langley's OASIS architecture [7].

The attitude determination and control system (ADCS) consists of reaction wheels or control moment gyros (CMG) and hydrazine thrusters. The choice between reaction wheels and CMG is made based on how much control authority is needed (CMG provide more torque). Disturbances (gravity gradient, magnetic field, aerodynamic and solar radiation) are estimated and the largest one is used to size the reaction wheels or CMG. Power consumption is estimated in reference to maximum torque or momentum storage. Hydrazine thrusters are sized to be able to desaturate the reaction wheels or CMG and in addition to performing several major maneuvers when necessary (rendezvous, orbit adjustment). Avionics are kept at a constant mass of 100 kg and power consumption of 200 W.

The solar arrays are sized by estimating the power they have to produce to meet the needs of the depot. This is more than the peak power demands of the depot since the batteries have to be charged for use during eclipse. The solar arrays are made of multijunction cells (ideal efficiency of 22%). The efficiency is assumed to decrease due to stress during deployment and gradually over time. The planar solar arrays are assumed to be square for the purpose of outputting dimensions, but areas are provided as well, so they could be any shape. Batteries are lithium ion cells and are sized to store enough energy for use during eclipse. The power management and distribution unit is a constant 10 kg and consumes 10% of the total system power. Wiring and wire harnesses are sized in reference to total depot length.

III. Scalable Depot Tool Description

The following section outlines the inputs, outputs and features of the scalable depot tool.

A. Main Inputs

Propellant Type – Choice of LOX, LOX/LH2, LOX/LCH4, LOX/Kerosene, H2O2/Kerosene, Methane, or Xenon

Usable Propellant – Mass of propellant to be available after average storage time

Average Propellant Storage Time – Average time propellant will be in the tanks

Zero Boil-off – Choice of whether to use ZBO technology or not

Mixture Ratio – Oxidizer/Fuel ratio

Fuel Tank Material – Choice of aluminum, steel, titanium or composite material

Oxidizer Tank Material – Choice of aluminum, steel, titanium or composite material

Size based on…: Choice of what dimension to specify, length or radius. With volume defined by usable propellant, one more dimension is needed to size the tanks. The rest of the depot main body is sized based on tank dimensions.

Propellant types were chosen based on current popularity (storables are not included since they have ceased to be used as a main propellant) and possibilities for in-situ resource utilization (ISRU). ISRU was considered so that the possibility of using a depot for storing propellant produced on the moon or mars could be considered. Although there is no option for locating the depot outside low earth orbit, one could still use this tool as a conservative estimator for other environments, since low earth orbit is a less ideal environment for a propellant depot than other places such as Mars, the Moon, or L1.

The actual capacity will be greater than the inputted usable propellant. The tool calculates trapped propellant and boil-off over the entered average storage time and adds that to the amount of usable propellant. The inputted amount of propellant would then be available after the average storage time.

The input reference dimensions are depot radius for radius and length of cylindrical tank section(s) for length. Depot radius is simple and intuitive, but length is less so. This dimension was chosen because it is needed to size the tank and makes the calculations feasible. Using total depot length or total tank length would have required some calculations that Microsoft Excel was unable to do (it would require circular references that are hard to resolve). As it is, the tool displays the output total depot length right below the length input so it is easy to see what effects different inputs have.

B. Main Outputs

Outputs are a basic geometry and a mass breakdown of all of the depot components. Following in Table 2 and 3 is the output for an example case. The example case has the following specifications: LOX/LH2, 50,000 kg usable propellant, 60 days average storage time, no ZBO, aluminum tanks, and 10 m length of cylindrical sections. Several more examples are provided in the appendix.

Geometry

Overall		**Solar Arrays**	
Length	21.61 m	Area	16.75 m^2
Diameter	4.56 m	Width	4.09 m
Surface Area	342 m^2	Length	4.09 m
Volume	352 m^3		
Oxidizer Tank		**Fuel Tank**	
Length	5.04 m	Length	12.24 m
Diameter	3.64 m	Diameter	3.64 m
Surface Area	57.77 m^2	Surface Area	140.22 m^2
Volume	39.96 m^3	Volume	115.09 m^3

Table 2: Geometry output for sample case

The geometry output is very basic but it is outputted for a general sense of scale and for possible use in a simple CAD model for visualization purposes.

The mass breakdown is condensed slightly in that some components that are similar or work together are grouped. Note that the propellant is greater than 50,000 kg. Again this is to account for trapped propellant and boil-off. It can be seen that for the example case, More than 2,000 kg of extra propellant is needed to account for 60 days worth of boil-off.

C. Zero Boil-off vs. Passive Comparison

Also included in the tool is a macro that performs a trade study between ZBO and passive insulation. Zero boil-off comes at a significant mass price, while passive insulation requires extra propellant to make up for boil-off. The macro produces a graph of total depot mass versus average propellant storage time. The crossover point where the added mass of the ZBO system becomes worthwhile can then be seen. The graph for the example case can be seen in figure 2. More examples are included in the appendix.

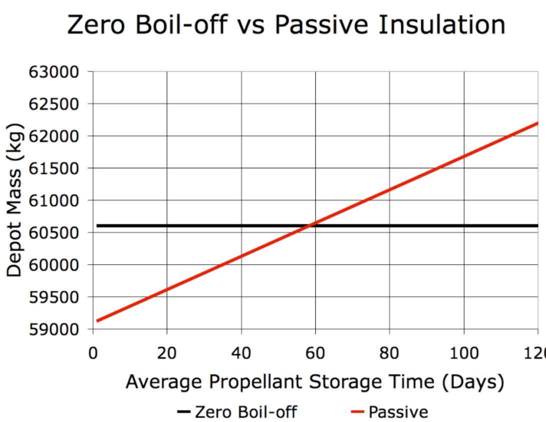

Figure 2: Trade study of ZBO vs. Passive insulation for the example case

Mass Breakdown

Structure	**6508 kg**
Tanks	2538 kg
Fuel	1797 kg
Oxidizer	741 kg
Feed Lines, pumps, etc.	324 kg
Supporting Structure	1536 kg
Debris Shield	1710 kg
Fluid Transfer Dock	400 kg
Thermal Control	**582 kg**
Heater, radiators, etc.	384 kg
Insulation	198 kg
Fuel	140 kg
Oxidizer	58 kg
Cryocooler	0 kg
Fuel	0 kg
Oxidizer	0 kg
ADCS	**248 kg**
Thrusters	100 kg
Fuel Tank	89 kg
Fly Wheels	59 kg
Power	**241 kg**
Solar arrays	123 kg
Batteries	43 kg
Distribution and Wiring	75 kg
Avionics	**100 kg**
Empty Mass	**7678 kg**
Propellant	**52966 kg**
Fuel	7934 kg
Oxidizer	44233 kg
RCS Fuel	800 kg
Total Mass	**60645 kg**

Propellant Mass Fraction	**0.860**

Table 3: Mass breakdown for example case

IV. Application to Existing Exploration Architectures

To further display output from the scalable depot tool, below is data for propellant depots sized for the Apollo architecture and the Exploration Systems Architecture Study baseline architecture.

A. Apollo

Apollo used N2O4 and hydrazine, which is not an option in the scalable depot tool. LOX/Kerosene is used instead since it has a similar Isp. Here is the configuration used for the example: LOX/Kerosene, 50,000 kg (enough for two trips to the moon), 360 days of storage, no ZBO, aluminum tanks, and10 m reference length.

The results show that a depot that could supply two Apollo missions would not be very massive (empty mass of 4,000 kg). The depot could be launched empty on any number of launch vehicles and filled up once on orbit. It could also be launched full (at 58,700 kg). Being able to launch the Apollo command, service and lunar modules empty would allow for a smaller launch vehicle to be used or an increase in performance of the architecture (more crew, lunar habitat, more science equipment, etc.). It is hard to say anything concrete with such a brief study, but the possibilities are intriguing nonetheless.

Geometry

Overall		Solar Arrays	
Length	18.24 m	Area	10.38 m^2
Diameter	2.87 m	Width	3.22 m
Surface Area	178 m^2	Length	3.22 m
Volume	118 m^3		
Oxidizer Tank		**Fuel Tank**	
Length	9.44 m	Length	5.16 m
Diameter	2.30 m	Diameter	2.30 m
Surface Area	68.11 m^2	Surface Area	37.24 m^2
Volume	35.95 m^3	Volume	18.22 m^3

Table 4: Geometry output for the Apollo example

Mass Breakdown

Structure	**3213 kg**
Tanks	851 kg
Fuel	301 kg
Oxidizer	550 kg
Feed Lines, pumps, etc.	274 kg
Supporting Structure	800 kg
Debris Shield	888 kg
Fluid Transfer Dock	400 kg
Thermal Control	**305 kg**
Heater, radiators, etc.	200 kg
Insulation	105 kg
Fuel	37 kg
Oxidizer	68 kg
Cryocooler	0 kg
Fuel	0 kg
Oxidizer	0 kg
ADCS	**207 kg**
Thrusters	100 kg
Fuel Tank	65 kg
Fly Wheels	42 kg
Power	**175 kg**
Solar arrays	76 kg
Batteries	34 kg
Distribution and Wiring	65 kg
Avionics	**100 kg**
Empty Mass	**4000 kg**
Propellant	**54691 kg**
Fuel	14326 kg
Oxidizer	39785 kg
RCS Fuel	581 kg
Total Mass	**58691 kg**

Propellant Mass Fraction	**0.922**

Table 5: Mass breakdown for the Apollo example

B. Exploration Systems Architecture Study Baseline

The addition of a propellant depot to the ESAS baseline architecture will be explored in more depth soon, but here a quick glance at what the depot might look like. The configuration: LOX/LH2, 100,000 kg propellant (enough for one lunar mission), 360 days storage time, ZBO, aluminum tanks, and 15 m reference length.

Geometry

Overall		**Solar Arrays**	
Length	29.33 m	Area	120.90 m^2
Diameter	5.29 m	Width	11.00 m
Surface Area	531 m^2	Length	11.00 m
Volume	645 m^3		
Oxidizer Tank		**Fuel Tank**	
Length	7.03 m	Length	16.44 m
Diameter	4.23 m	Diameter	4.23 m
Surface Area	93.42 m^2	Surface Area	218.55 m^2
Volume	78.99 m^3	Volume	211.39 m^3

Table 6: Geometry output for ESAS baseline example

Mass Breakdown

Structure	**11212 kg**
Tanks	4643 kg
Fuel	3253 kg
Oxidizer	1390 kg
Feed Lines, pumps, etc.	440 kg
Supporting Structure	3072 kg
Debris Shield	2657 kg
Fluid Transfer Dock	400 kg
Thermal Control	**2236 kg**
Heater, radiators, etc.	768 kg
Insulation	312 kg
Fuel	219 kg
Oxidizer	93 kg
Cryocooler	1156 kg
Fuel	863 kg
Oxidizer	293 kg
ADCS	**641 kg**
Thrusters	100 kg
Fuel Tank	322 kg
Fly Wheels	219 kg
Power	**1170 kg**
Solar arrays	885 kg
Batteries	187 kg
Distribution and Wiring	98 kg
Avionics	**100 kg**
Empty Mass	**15359 kg**
Propellant	**104894 kg**
Fuel	14571 kg
Oxidizer	87429 kg
RCS Fuel	2894 kg
Total Mass	**120253 kg**

Propellant Mass Fraction	**0.848**

Table 7: Mass breakdown for ESAS baseline example

At 15,000 kg, this depot could be launched by a number of commercial launch vehicles or certainly the NASA cargo launch vehicle. Again, being able to launch the other mission elements empty would provide increased flexibility. Launch vehicle sizes could be reduced or performance could be enhanced. Whether this added flexibility is worth the investment into a propellant depot has yet to be seen.

V. Future Work

The foundation of the depot model is all here. Most of the components are sized with well-established mass estimating relationships and techniques. A few parts of the model could be improved though.

The ZBO system sizing estimates in particular could use a higher fidelity model. A full thermodynamic model that adjusted to the model inputs (type of propellant, depot location, etc.) would be ideal. Heat transfer varies depending on the vehicle configuration [2]. If there were a more specific structural model, structural effects on heat transfer could also be taken into account. There are many more components that could be modeled as well, radiators, heaters for other elements, propellants like H2O2 freezing, etc. Boil-off modeling with just passive insulation would also improve with a better thermal model. The thermodynamics of a propellant depot are very complex, something which the current model does not fully reflect.

The possibility of propellant depots at locations other than low earth orbit (Moon, Mars, L1) would also be a valuable addition. This would require proper modeling of each location's environment (albedo, solar flux, etc.). It would also require the more complex thermodynamic model mentioned above to use those additional inputs.

The current geometry outputs are sufficient for a sketch or simple CAD model, but aren't as streamlined as they could be. One option would be a VBA script that drew a sketch within the output sheet based on the specific configuration. This would give a general sense of dimensions and scale quickly and easily. Another option would be to have the tool output a file specific to a CAD program. A CAD drawing of any depot could then be quickly produced.

It is also the authors hope that tool will be used, in this or an advanced form, to study the viability of using a propellant depot in future exploration endeavors.

Appendix

Appendix I: Zero Boil-off vs. Passive Insulation Comparisons

All of these trade studies have the following inputs in common: 50,000 kg propellant, aluminum tanks, and 10 m reference length.

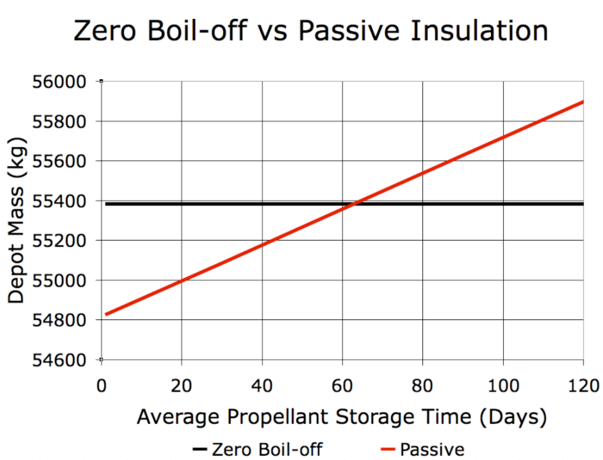

Figure 3: LOX only

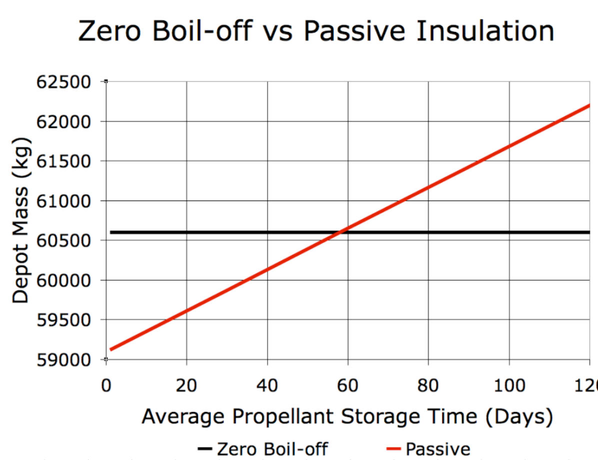

Figure 4: LOX/LH2

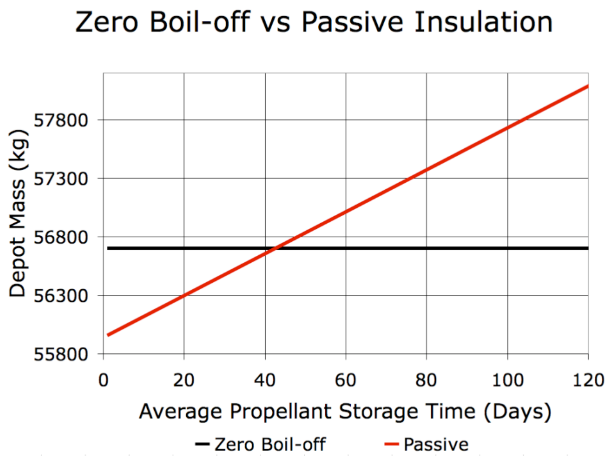

Figure 5: LOX/LCH4

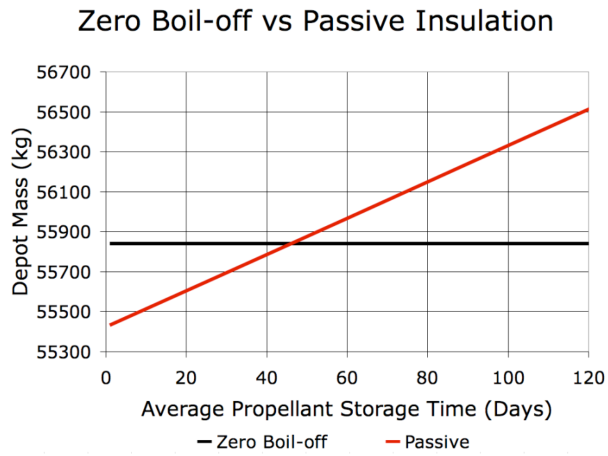

Figure 6: LOX/Kerosene

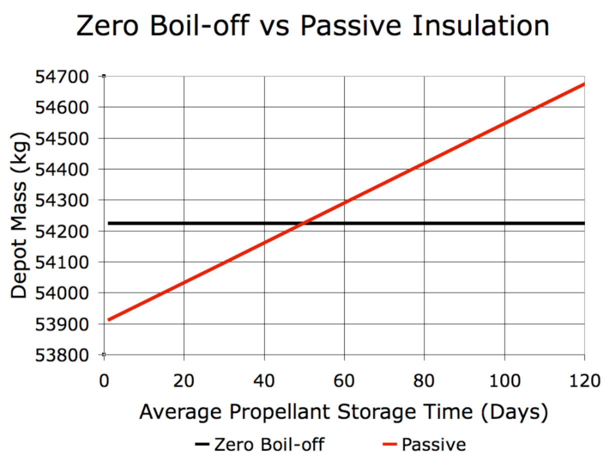

Figure 7: Liquid Xenon

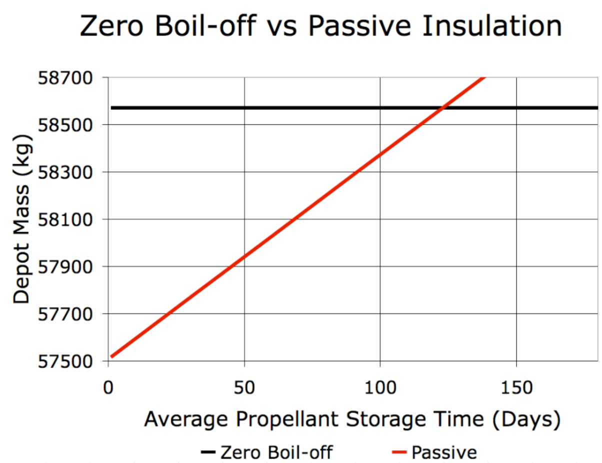

Figure 8: Methane

Appendix II: Additional Depot Examples

Example 1: LOX/Methane, 50,000 kg usable, 90 days storage, no ZBO, aluminum tanks, and 10 m ref. length.

Geometry

Overall		**Solar Arrays**	
Length	18.78 m	Area	11.22 m^2
Diameter	3.14 m	Width	3.35 m
Surface Area	201 m^2	Length	3.35 m
Volume	145 m^3		
Oxidizer Tank		**Fuel Tank**	
Length	8.17 m	Length	6.86 m
Diameter	2.51 m	Diameter	2.51 m
Surface Area	64.43 m^2	Surface Area	54.10 m^2
Volume	36.31 m^3	Volume	29.82 m^3

Table 8: Example 1 geometry output

Mass Breakdown

Structure	**3624 kg**
Tanks	1047 kg
Fuel	478 kg
Oxidizer	569 kg
Feed Lines, pumps, etc.	282 kg
Supporting Structure	892 kg
Debris Shield	1003 kg
Fluid Transfer Dock	400 kg
Thermal Control	**342 kg**
Heater, radiators, etc.	223 kg
Insulation	119 kg
Fuel	54 kg
Oxidizer	64 kg
Cryocooler	0 kg
Fuel	0 kg
Oxidizer	0 kg
ADCS	**210 kg**
Thrusters	100 kg
Fuel Tank	66 kg
Fly Wheels	44 kg
Power	**184 kg**
Solar arrays	82 kg
Batteries	35 kg
Distribution and Wiring	66 kg
Avionics	**100 kg**
Empty Mass	**4459 kg**
Propellant	**53088 kg**
Fuel	12304 kg
Oxidizer	40187 kg
RCS Fuel	598 kg
Total Mass	**57548 kg**

Propellant Mass Fraction	**0.912**

Table 9: Example 1 mass breakdown

Example 2: H_2O_2/Kerosene, 100,000 kg usable, 365 days storage time, no ZBO, aluminum tanks, 12 m ref. length.

Geometry

Overall		Solar Arrays	
Length	21.44 m	Area	15.84 m^2
Diameter	3.22 m	Width	3.98 m
Surface Area	233 m^2	Length	3.98 m
Volume	175 m^3		
Oxidizer Tank		**Fuel Tank**	
Length	13.22 m	Length	3.93 m
Diameter	2.58 m	Diameter	2.58 m
Surface Area	106.96 m^2	Surface Area	31.82 m^2
Volume	64.40 m^3	Volume	16.01 m^3

Table 10: Example 2 geometry output

Mass Breakdown

Structure	**4207 kg**
Tanks	1257 kg
Fuel	288 kg
Oxidizer	969 kg
Feed Lines, pumps, etc.	322 kg
Supporting Structure	1063 kg
Debris Shield	1166 kg
Fluid Transfer Dock	400 kg
Thermal Control	**404 kg**
Heater, radiators, etc.	266 kg
Insulation	139 kg
Fuel	32 kg
Oxidizer	107 kg
Cryocooler	0 kg
Fuel	0 kg
Oxidizer	0 kg
ADCS	**371 kg**
Thrusters	100 kg
Fuel Tank	163 kg
Fly Wheels	108 kg
Power	**232 kg**
Solar arrays	116 kg
Batteries	42 kg
Distribution and Wiring	74 kg
Avionics	**100 kg**
Empty Mass	**5314 kg**
Propellant	**103463 kg**
Fuel	12593 kg
Oxidizer	89407 kg
RCS Fuel	1463 kg
Total Mass	**108777 kg**

Propellant Mass Fraction	**0.938**

Table 11: Example 2 mass breakdown

Example 3: Liquid Xenon, 30,000 kg usable, 365 days storage, ZBO, aluminum tanks, 8 m ref. length.

Geometry

Overall		**Solar Arrays**	
Length	8.13 m	Area	10.77 m^2
Diameter	1.88 m	Width	3.28 m
Surface Area	54 m^2	Length	3.28 m
Volume	23 m^3		
Oxidizer Tank		**Fuel Tank**	
Length	0.00 m	Length	6.50 m
Diameter	0.00 m	Diameter	1.50 m
Surface Area	0.00 m^2	Surface Area	30.75 m^2
Volume	0.00 m^3	Volume	10.67 m^3

Table 12: Example 3 geometry output

Mass Breakdown

Structure	**1470 kg**
Tanks	271 kg
Fuel	271 kg
Oxidizer	0 kg
Feed Lines, pumps, etc.	122 kg
Supporting Structure	410 kg
Debris Shield	268 kg
Fluid Transfer Dock	400 kg
Thermal Control	**218 kg**
Heater, radiators, etc.	102 kg
Insulation	31 kg
Fuel	31 kg
Oxidizer	0 kg
Cryocooler	85 kg
Fuel	85 kg
Oxidizer	0 kg
ADCS	**113 kg**
Thrusters	100 kg
Fuel Tank	8 kg
Fly Wheels	5 kg
Power	**148 kg**
Solar arrays	79 kg
Batteries	35 kg
Distribution and Wiring	34 kg
Avionics	**100 kg**
Empty Mass	**2049 kg**
Propellant	**30673 kg**
Fuel	30600 kg
Oxidizer	0 kg
RCS Fuel	73 kg
Total Mass	**32722 kg**

Propellant Mass Fraction	**0.935**

Table 13: Example 3 mass breakdown

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