Semester Schedule and Updated Requirements
MIKE YOUNG
SYSTEMS/APM
STORYBOARD 2

WASHINGTON-1 2018
SAFETY TRL 7-9
TRL 8-9
WASHINGTON-2 2019
SME TRL 8-9
WASHINGTON-3 2020

ADAMS-1 2021
CONTAINS REL SUPPLIES
ADAMS-2 2022
TEST ISRU (TRL 7-8)
ADAMS-3 2022
ADAMS-4 2023
RETURN TO EARTH 2023

ADAMS-5, 6, 7, 8 2023
BASE ASSEMBLY DURING JEFFERSON-1
ADAMS-9 & JEFFERSON-1
2x JEFF-1 (CREWED)
SAMPLES RETURNED

H₂O³

<table>
<thead>
<tr>
<th>JEFFERSON-2, 3, 4, 5, 6, 7, 8 (2024-2025)</th>
<th>JEFFERSON-9 (2025)</th>
<th>JEFFERSON-10, 11, 12, 13 (2025-2028)</th>
</tr>
</thead>
<tbody>
<tr>
<td>* FUEL TANKS</td>
<td>REUSABLE LANDER</td>
<td>* SUPPLIES*</td>
</tr>
<tr>
<td>* REL EQUIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* SUPPLIES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* SCI EQUIP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MADISON-1 (2025-2029)</th>
<th>MADISON-2 (2030-2031)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROTATION EST.</td>
<td>REPEAT CYCLER TRIPS</td>
</tr>
<tr>
<td>POP = 8?</td>
<td></td>
</tr>
</tbody>
</table>

POP = ~8 Billion

SECOND HAB CONSTRUCTED
Deploy and test an XM module (Bigelow BA330 inflatable habitat) in orbit around the earth. Power will be provided by a solar panels and an experimental SAFE 400 nuclear reactor. Launched by a Falcon heavy, the module will achieve LEO, deploy, and inflate remotely. $12 \text{ Mg}, 16 \text{ m}^3, X \text{ kW}$

Technology goals:
Test deployment of BA330 system via remote operation
Test of custom control systems and telecoms
Raise TRL of BA330 from 7 to 8
Raise TRL of SAFE 400 from 7 to 8
<table>
<thead>
<tr>
<th>Launch</th>
<th>Launch Vehicle</th>
<th>Year</th>
<th>Description</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Falcon Heavy</td>
<td>2018</td>
<td>XM 1 (+controls), Nuclear Reactor Test 1</td>
<td>LEO</td>
</tr>
<tr>
<td>2</td>
<td>Falcon Heavy</td>
<td>2019</td>
<td>XM 2 (+controls), Orion Docking Mechanism</td>
<td>CLO</td>
</tr>
<tr>
<td>3</td>
<td>Atlas V 551</td>
<td>2020</td>
<td>1 Mg lander, Science Rover, Nuclear Reactor</td>
<td>LS</td>
</tr>
<tr>
<td>4</td>
<td>SLS</td>
<td>2021</td>
<td>2 Crewed Test to XM, docking test, and back</td>
<td>LS</td>
</tr>
<tr>
<td>5</td>
<td>SLS</td>
<td>2022</td>
<td>Hab, Modular Rover, Test ISRU</td>
<td>LS</td>
</tr>
<tr>
<td>6</td>
<td>SLS</td>
<td>2022</td>
<td>Rec Center, Pressurization/Oxygen Test Mac</td>
<td>LS</td>
</tr>
<tr>
<td>7</td>
<td>SLS</td>
<td>2022</td>
<td>ISRU, Garage, Medical Hab, 3-D Printer</td>
<td>LS</td>
</tr>
</tbody>
</table>
ISRU Technology Readiness
ISRU Requirements and Recommendations
2/11/2016
NASA’S ISRU

RESOURCE PROSPECTOR MISSION

- **RESOLVE Payload**
  - Currently TRL 4
  - Will be TRL 8 in 2020
  - Utilizes CSA’s Artemis Jr. rover
  - OVEN instrument is of interest
  - Cannot collect and process resources in desired capacity

- **Mission**
  - Tested on Mauna Kea in Hawaii
  - Planned Lunar mission in 2020
  - Planned to test in Cabeus
  - Will be tested during Lunar day

Rough Sketch of RESOLVE System
WHAT IS NEEDED

- What the ISRU needs to produce per year:
  - About 0.56 Mg of water if using HydraLOX lander
  - About 0.46 Mg of water and 24 Mg of methane if using MethaLOX lander
- Methane can also be made from hydrogen and carbon dioxide
- Electrolysis would most likely be best for separating H2 and O2
- Can produce 0.786 Mg of water, 0.004509 Mg of methane and 0.01501 Mg of carbon dioxide from one rover trip.

<table>
<thead>
<tr>
<th>Function</th>
<th>Possible Method</th>
<th>Mass (Mg)</th>
<th>Power (kW)</th>
<th>Volume (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regolith Mining</td>
<td>Rover w/ Attachment</td>
<td>25.62*</td>
<td>-</td>
<td>17.08*</td>
</tr>
<tr>
<td>Volatile Extraction</td>
<td>OVEN</td>
<td>~0.009425*</td>
<td>&lt;0.3</td>
<td>~0.006283*</td>
</tr>
<tr>
<td>Material Transport</td>
<td>Pipes/Rover?</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Numbers from relevant material collected or processed at a time

Kyle Bush
## RESOURCE PROSPECTOR SPECIFICATIONS

<table>
<thead>
<tr>
<th></th>
<th>Artemis Jr.</th>
<th>NSS</th>
<th>NIRVSS</th>
<th>DESTIN</th>
<th>OVEN</th>
<th>LAVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (Mg)</td>
<td>0.230</td>
<td>0.00185</td>
<td>0.0077</td>
<td>&lt;0.040</td>
<td>0.010</td>
<td>0.015</td>
</tr>
<tr>
<td>Volume (m^3)</td>
<td>3.644</td>
<td></td>
<td>-</td>
<td>&lt;1.013</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power Req. (W)</td>
<td>~181</td>
<td>~2.000</td>
<td>~16.31</td>
<td>&lt;150</td>
<td>&lt;300</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

**Additional Notes:**
Rover too small to mine regolith to our needs, DESTIN is also too small. NSS and NIRVSS essentially science rover’s function but less, one could be attached to mining rover for more accurate extraction. OVEN could be used to separate volatiles from regolith but needs to be scaled up. LAVA just analyzes, not processes. System also won’t be tested during lunar night but is said to operate in shadowed regions.

Video showing Resource Prospector Mission: [https://www.youtube.com/watch?v=fMXWsiaEK6Q](https://www.youtube.com/watch?v=fMXWsiaEK6Q)
**ISRU Need Numbers:**

For HydraLOX:
- 0.25 Mg (from structures)
- 0.31 Mg (for lander per launch)
*Both masses water

For MethaLOX:
- 0.25 Mg water (from structures)
- 0.21 Mg water (per launch)
- 24 Mg Methane (per launch)

*Numbers for human factors needs not included since they were unsure if ISRU water was needed

*Also assuming lander needs to be refueled once a year per the mission architecture document

**Regolith Mining Calculations:**

Avg. regolith density: $1.5 \text{ g/cm}^3 = 1500 \text{ kg/m}^3$

Rover can theoretically hold by volume:

$$1500 \text{ kg/m}^3 \times 17.08 \text{ m}^3 = 25620 \text{ kg} = 25.62 \text{ Mg}$$

So 25.62 Mg batch maximum

Water: $25.62 \text{ Mg} \times 0.03 = 0.7686 \text{ Mg}$

Methane: $25.62 \text{ Mg} \times 0.000176 = 0.004509 \text{ Mg}$

CO2: $25.62 \text{ Mg} \times 0.000586 = 0.01501 \text{ Mg}$

Note: Rover most likely won’t have capability to carry 25.62 Mg

Kyle Bush


• Most numbers for calculations from Dayle Alexander, Ariel Dimson, Caleb Engle and their previous presentations
Radiation Mitigation, Water Totals (while on mars)
February 11, 2016
The average probability of getting cancer over a lifetime is 20%.

NASA has standardized that astronauts are only allowed to increase their probability by 3%.

<table>
<thead>
<tr>
<th>Age of Career Start</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.5 Sv</td>
<td>1.0 Sv</td>
</tr>
<tr>
<td>35</td>
<td>2.5 Sv</td>
<td>1.75 Sv</td>
</tr>
<tr>
<td>45</td>
<td>3.2 Sv</td>
<td>2.5 Sv</td>
</tr>
</tbody>
</table>

Recommendation:
Limit the exposure of a crew member living on lunar surface for 4 years to 0.5 Sv.
RADIATION MITIGATION

Regolith
• ESA has a prototype of a 3D printer that uses Moon regolith

Hydrogenated Boron Nitride Nanotubes (HBNNT)
• Currently being developed for space exploration.

Electrostatic spheres
• Needs to be tested in space to increase TRL

All Technologies are TRL 5

Recommendation:
• Use all three technologies for Habs
• Use HBNNT for Rovers and Spacesuits.

This would provide back ups for our habs against radiation.

Figure 1: Example of Electrostatic Spheres

Anais Arnaiz (CAD designed by Anais Arnaiz)
The values for the maximum Sieverts allowable based upon age of career start came from a previous presentation by Kate Fowee (Human Factors group). While working with her we decided that the recommendation for the maximum allowable Sieverts for the entire 4 year stay on the lunar surface for one crew member should be 0.5 Sv. This conclusion was based upon assuming we will be using crew over the age of 35, which also meets one of the desired criteria by Professor Longuski. By limiting the exposure to 0.5 Sv crew will stay below their lifetime maximum allowable Sieverts while also being able to return to for another mission or go on to Mars.

All three forms of shielding were chosen for the habs, because it allows for redundancies in our design. This will minimize the radiation the crew is exposed to and also account for different forms of radiation.

The choice of using HBNNT for the rovers and spacesuits is due to the flexible “yarn” like material it is made of. This makes equipping the rover and spacesuits with radiation shielding and less complicated. Since they will spend minimal time in them we did not recommend more than HBNNT.

Due to some recent information that we have come across water is still a possible option for our mission. But since we do not have the ISRU developed or know certain production rates we could not make a definitive recommendation on water. Kyle Bush (Systems group) is working on the ISRU development this week and with his information, an answer on how we will use water as a shielding will be ready for next week.

Kate Fowee (Human Factors), James Millane (Mission Design), Mason Buckman (Mission Design) and Rachel Lucas (Pow/Therm) were all highly involved in collecting the data necessary to choose these options.
The Recommendation of regolith is to cover habs and not to bury them. Using this form of shielding could also enhance our partnership with ESA as an international partner.

According to ESA this robotic 3D printer can build up to 3.5m per hour and should complete construction over one of their buildings in a week.

Anais Arnaiz
These Electrostatic spheres will stand above our habs and protect them from both electrons and protons. The technology has been proven on Earth but has not been tested in space.

These spheres will also mitigate some of the issues that we may possibly run into with the magnetotail.
The Hydrogenated Boron Nitride Nanotubes are currently being developed for space radiation mitigation. Because there is a prototype its TRL is at a level 5. The product is made into "yarn" that can be used for multiple uses. Since this material is flexible the recommendation is to use these in the Rover and Spacesuits. Studies of this material and technology show many positive results.

Figure 5: Example of HBNNT [2]


February 11, 2016

Water extraction methods, determining ice sheet properties, mining techniques, moonquakes, density of regolith
**WATER EXTRACTION**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Mass at 3 m regolith depth (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>3.42 x 10⁶</td>
</tr>
<tr>
<td>CH₄</td>
<td>2.232 x 10⁴</td>
</tr>
<tr>
<td>CO₂</td>
<td>7.45 X 10⁴</td>
</tr>
</tbody>
</table>

From Project Aldrin-Purdue:
- Operate regolith furnace at 56.85°C and 10 Kpa to evaporate water
- Compress water vapor – easier to condense
- Cool water vapor through condenser

NASA Alternatives:
- **Microwave extraction of water** *(TRL 3)*
  - Selectively heating regolith
  - Lower cost/mass
- **Planetary volatiles extractor for ISRU** *(TRL 3)*
  - Can map volatile distribution
  - Determine where to extract volatiles

For Fuel Depot Only:
- Need 1.5 Mg H₂O per launch of reusable lander
- ~ 4.5 Mg H₂O for 3 landers
- **Extraction rate:** ~ 0.9 Mg H₂O per year
- * Will need to extract much more water for other launches, oxygen supply, etc.
ICE DEPOSIT DETAILS

FROM HURLEY ET AL., (2012)

- PSR ice layer will eventually be disrupted by impact gardening
  - Made thinner by removing fractions of ice

- Burial rate is 1 mm/Myr on average
  - Won’t be significantly buried in the frame of our mission

- From LCROSS impact, water ice is derived from a depth of 2-3 m

- Simulations show that the ice deposit in Cabeus is >1000 Myr old
  - Heterogeneous

- These simulations assumed the ice layer began as a 10 cm-thick layer
  - Different initial thickness = different results

- Water ice in PSR would be in the form of small grains in the regolith or a thin coating of ice on rock (Neish et al., 2011)
<table>
<thead>
<tr>
<th>Landers</th>
<th>Years</th>
<th>Water needed per lander (Mg)</th>
<th>Extraction rate (Mg H₂O/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>5</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Extraction rates assuming all landers are on the moon after 5 years.

Updated masses assuming regolith depth of 3 m. Focusing on water and methane. By Ellen Czaplinski.

From project Aldrin-Purdue (p 489): Production of 1 Kg of water = 1950 KJ

4.5 Mg of water = \(8.775 \times 10^6\) J
This shows the distribution of concentration of ice with depth and age. Hurley et al., (2012)
REFERENCES

Project Aldrin-Purdue 2015


SCIENCE GROUP
JAKE ELLIOTT

Landing Sites
LCROSS Impact Sites
Dust Accumulation Rates
Traversing Between Sites
# LANDING/IMPACT SITES

<table>
<thead>
<tr>
<th>Impact Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Crater Diameter (m)</th>
<th>Ejecta blanket diameter (m)</th>
<th>Distance to Mining Site (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centaur</td>
<td>-84.6796</td>
<td>311.2907</td>
<td>25 - 30</td>
<td>160</td>
<td>9.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Area (km²)</th>
<th>Avg. Elevation (m)</th>
<th>Avg. Slope (°)</th>
<th>Solar Insolation (W m⁻²)</th>
<th>Est. Temp Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>-84.083</td>
<td>315.567</td>
<td>0.947</td>
<td>-1178</td>
<td>1.769</td>
<td>~ 546.4</td>
</tr>
<tr>
<td>Mining</td>
<td>-84.656</td>
<td>314.558</td>
<td>1.231</td>
<td>-3672</td>
<td>1.722</td>
<td>~ 0</td>
</tr>
<tr>
<td>Mountain</td>
<td>-83.596</td>
<td>321.171</td>
<td>0.45</td>
<td>4500</td>
<td>1.645</td>
<td>~ 1092.8</td>
</tr>
</tbody>
</table>
Dust Hazards

Dust Influence Distances
- Vehicles: 20 m
- Astronauts: 8 m
- Landing: 1.5 km
  - Up to 10-15 cm objects

Dust Accumulation Rates
- From meteorite impacts: ~ 0.1 g m\(^{-2}\) yr\(^{-1}\)
- Electrostatic transport: ~ 300 g m\(^{-2}\) yr\(^{-1}\)
- Landing:
  - 1 mg cm\(^{-2}\) at a distance of 155 m

Traverse Information

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Maximum Slope (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base =&gt; Mountain</td>
<td>17.547</td>
</tr>
<tr>
<td>Base =&gt; Mining</td>
<td>23.024</td>
</tr>
</tbody>
</table>


MISSION DESIGN
PAUL WITSBERGER

Hyperbolic Rendezvous Strategy, Rendezvous Vehicle Design, and Delta V Estimates
2/10/2016
RENDZVOUS STRATEGY

Recommend four stages:

1. LEO to highly elliptical orbit
2. Elliptical to hyperbolic cycler orbit
3. Eliminate relative velocity
4. Docking

“Design the hyperbolic rendezvous to meet the 80% mission success rate and 95% crew survival rate.”

Stages 1-3: Hydrolox
Stage 4: Monoprop
Analyzed 2035 launch:
- Goal was to find optimal delta V
- Iterated input values for a Lambert arc
- **Total delta V: 3.035 km/s**
- Seems low – need to verify code

### Possible Launch Dates

<table>
<thead>
<tr>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/06/2031</td>
</tr>
<tr>
<td>04/30/2033</td>
</tr>
<tr>
<td>06/14/2035</td>
</tr>
<tr>
<td>08/26/2037</td>
</tr>
<tr>
<td>10/26/2039</td>
</tr>
</tbody>
</table>

### IMLEO
- 20 Mg payload
- **40 Mg total**
- Assume hydrolox, Isp = 450 s


Plots generated while looking for optimal launch conditions.
% Paul Witsberger
% AAE450
% 02/10/2016
% Lambert Algorithm

%%%%%%%%%%%%%%%%% STEPS TO IMPLEMENT LAMBERT'S ALGORITHM %%%%%%%%%%%%%%%%%%%%
% Inputs: r1, r2, TA, TOF
% Outputs: departure delta v, arrival delta v
% anomaly, and flight path angle for the transfer arc
% 1. Distinguish angular separation between r1 and r2. Identify transfer angle as <180 or >180 degrees. Specify as type 1 or 2.
% 2. Calculate TOF_par; compare TOF_desired with TOF_par. If TOF < TOF_par, required transfer arc is hyperbolic. IF TOF > TOF_par, required transfer arc is elliptic.
% 3. Guess 'a': a = a_min is the smallest a for elliptical, a = 0 is the smallest a for hyperbolic. Guess (a_min or 0) + da, where da is small if TOF close to TOF_min and da is large is TOF >> TOF_min.
% 4a. Decide on transfer type if not already known: A or B. If elliptic:
% TOF > TOF_min -> B, TOF < TOF_min -> A.
% 4b. Calculate alpha_0, beta_0 or alpha_0', beta_0' based on the guess for a and the transfer type.
% 5. Iterate on 'a'. Use Lambert's equations plus a root-solving method
% such as fsolve or Newton's method.
% 6. Determine the parameters describing the transfer arc. There are two values of p for each value of a. Choose the appropriate value based on transfer type. Verify that the change in true anomaly is equal to the Transfer Angle (TA).

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%function [dv1, dv2, dvtot] = Lambert(r1,r2,TA,TOF,mu)% Step 1
% If transfer angle is <180, it's Type 1. If >180, it's Type 2.
if (TA < 180 && TA > 0)
   type = 1;
   fprintf('
Type 1\n')
elseif (TA > 180 && TA < 360)
   type = 2;
   fprintf('
Type 2\n')
else
   fprintf('
Invalid transfer angle.\n')
end
% Calculate the remaining space triangle geometry and find
a_min = sqrt((r1^2+r2^2-2*r1*r2*cosd(TA)));
s = 0.5*(r1+r2+c);
amin = s/2;
%% Step 2
% Calculate parabolic TOF based on the transfer type.
% TOF_par_1 < TOF_par_2
if(type == 1)
    TOF_par = 1/3*sqrt((2/mu)*(s^(3/2) -(s-c)^(3/2)));
elseif(type == 2)
    TOF_par = 1/3*sqrt((2/mu)*(s^(3/2) +(s-c)^(3/2)));
end

% If the TOF is less than that for a parabola, the transfer
% must be a hyperbola. If the TOF is greater than that for a parabola,
% the transfer must be an ellipse.
if(TOF < TOF_par)
    shape = 1; % hyperbola
    fprintf('Hyperbola\n')
elseif(TOF > TOF_par)
    shape = 2; % ellipse
    fprintf('Ellipse\n')
end

%% Step 3
% Make an initial guess for a. If hyperbolic, guess a = 0. If elliptic,
% guess a = amin. If elliptic, also calculate if it's Type A or B,
% based on comparison with TOF_min. If TOF < TOF_min -> Type A, or if
% TOF > TOF_min -> B
if(shape == 1)
    a = 0;
elseif(shape == 2)
    a = amin;
end

alpha0 = pi;
beta0 = 2*asin(sqrt((s-c)/2/a));
if(type == 1)
    TOFmin = sqrt((amin^3/mu)*((alpha0-sin(alpha0)) -(beta0-sin(beta0))));
elseif(type == 2)
    TOFmin = sqrt((amin^3/mu)*((alpha0-sin(alpha0)) +(beta0-sin(beta0))));
end

if(TOF < TOFmin)
    type_ell = 1; % A
    fprintf('Type A\n')
elseif(TOF > TOFmin)
    type_ell = 2; % B
    fprintf('Type B\n')
end

%% Steps 4 and 5
% Iterate on values of 'a' until the corresponding TOFcalc is
% within a certain user-defined tolerance of the given TOF.
done = 0;
while ~done % Read as "while not done"
    % Calculate alpha_0 and beta_0
    if(shape == 1)
        alpha0 = 2*asinh(sqrt(s/2/abs(a)));
beta0 = 2*asinh(sqrt((s-c)/2/abs(a)));
    elseif(shape == 2)
        alpha0 = 2*asin(sqrt(s/2/a));
        beta0 = 2*asin(sqrt((s-c)/2/a));
    end

    % Iterate on values of 'a' until the corresponding TOFcalc is
    % within a certain user-defined tolerance of the given TOF.
    done = 0;
    while ~done % Read as "while not done"
        % Calculate alpha_0 and beta_0
        if(shape == 1)
            alpha0 = 2*asinh(sqrt(s/2/abs(a)));
            beta0 = 2*asinh(sqrt((s-c)/2/abs(a)));
        elseif(shape == 2)
            alpha0 = 2*asin(sqrt(s/2/a));
            beta0 = 2*asin(sqrt((s-c)/2/a));
        end

        % Iterate on values of 'a' until the corresponding TOFcalc is
        % within a certain user-defined tolerance of the given TOF.
        done = 0;
        while ~done % Read as "while not done"
            % Calculate alpha_0 and beta_0
            if(shape == 1)
                alpha0 = 2*asinh(sqrt(s/2/abs(a)));
                beta0 = 2*asinh(sqrt((s-c)/2/abs(a)));
            elseif(shape == 2)
                alpha0 = 2*asin(sqrt(s/2/a));
                beta0 = 2*asin(sqrt((s-c)/2/a));
            end

            % Iterate on values of 'a' until the corresponding TOFcalc is
            % within a certain user-defined tolerance of the given TOF.
            done = 0;
            while ~done % Read as "while not done"
                % Calculate alpha_0 and beta_0
                if(shape == 1)
                    alpha0 = 2*asinh(sqrt(s/2/abs(a)));
                    beta0 = 2*asinh(sqrt((s-c)/2/abs(a)));
                elseif(shape == 2)
                    alpha0 = 2*asin(sqrt(s/2/a));
                    beta0 = 2*asin(sqrt((s-c)/2/a));
                end

            end
        end
    end
end
% Calculate TOF based on the guess for 'a'. The equation used to
% calculate TOF varies based on transfer type.

if (shape == 1)
    if (type == 1) % minus
        TOFcalc = sqrt(abs(a)^3/mu)*(sinh(alpha0) - alpha0) -
                   (sinh(beta0) - beta0));
    elseif (type == 2) % plus
        TOFcalc = sqrt(abs(a)^3/mu)*(sinh(alpha0) - alpha0) + (sinh(beta0) - beta0));
    end
elseif (shape == 2)
    if (type == 1) % minus
        TOFcalc = sqrt(a^3/mu)*(alpha0 - sin(alpha0)) -
                   (beta0 - sin(beta0)));
    elseif (type ell == 1) % 2pi minus
        TOFcalc = sqrt(a^3/mu)*(2*pi - (alpha0 - sin(alpha0)) - (beta0 - sin(beta0)));
    elseif (type ell == 2) % 2pi plus
        TOFcalc = sqrt(a^3/mu)*(2*pi - (alpha0 - sin(alpha0)) + (beta0 - sin(beta0)));
    end
elseif (shape == 2)
    if (type ell == 1) % plus
        TOFcalc = sqrt(a^3/mu)*(alpha0 - sin(alpha0)) + (beta0 - sin(beta0)));
    elseif (type ell == 2) % 2pi plus
        TOFcalc = sqrt(a^3/mu)*(2*pi - (alpha0 - sin(alpha0)) + (beta0 - sin(beta0)));
    end
end

if(abs(TOF - TOFcalc) < 10)
    done = 1; % exits the while loop if TOF is sufficiently
close
else
    if (shape == 1)
        a = a-1; % decrements 'a' if hyperbola
    elseif (shape == 2)
        a = a+1; % increments 'a' if ellipse
    end
end

% Note: For problems involving large values of a, it may be
more efficient to increase the amount that a changes by with each
% guess.

%% Step 6

% Calculate p using a. For 1H, 1A, and 2B transfers, choose the
larger % value of p. For 2H, 1B, and 2A transfers, choose the smaller
value.

if (type == 1)
    p1 = 4*abs(a)*(s-r1)*(s-r2)*sin((alpha0+beta0)/2)^2/c^2;
    p2 = 4*abs(a)*(s-r1)*(s-r2)*sin((alpha0-beta0)/2)^2/c^2;
    if (type ell == 1)
        p = max([p1 p2]);
    elseif (type ell == 2)
        p = min([p1 p2]);
    end
elseif ((type == 1 && type ell == 1) || (type == 2 && type ell == 2))
    p = max([p1 p2]);
elseif ((type == 1 && type ell == 2) || (type == 2 && type ell == 1))
    p = min([p1 p2]);
end
%% Post Processing

% Find e from p,a
if (shape == 1)
    e = sqrt(p/abs(a)+1);
elseif (shape == 2)
    e = sqrt(1-p/a);
end

% Find specific energy from a
eps = -mu/2/a;

% Find departure and arrival velocity from r1,r2,a
vd = sqrt(2*mu*(1/r1-1/2/a));
va = sqrt(2*mu*(1/r2-1/2/a));

% Find departure and arrival true anomaly from r1,r2,p,e. Check to see
% if the true anomalies add up to the transfer angle, and adjust their
% sign as necessary.
    tad = acosd((p/r1-1)/e);
taa = acosd((p/r2-1)/e);
if (abs(tad + taa - TA) < 1)
    taa = -taa;
elseif (abs(tad - taa - TA) < 1)
    taa = -taa;
elseif (abs(-tad + taa - TA) < 1)
    tad = -tad;
elseif (abs(-tad - taa - TA + 360) < 1)
    tad = -tad;
taa = -taa;
else
    fprintf('Change in true anomaly does not equal transfer angle')
end

% Calculate departure and arrival flight path angle based on p, r1, r2, % vd, and va
h = sqrt(mu*p);
gamd = acosd(h/r1/vd)*sign(tad);
gama = acosd(h/r2/va)*sign(taa);

% Calculate delta v required to rendezvous with cycler
vinf_cyc = 3.75; % km/s
hmin_cyc = 9700; % km
rmin_cyc = hmin_cyc+6378; % km
eps_cyc = vinf_cyc^2/2; % km^2/s
a_cyc = -mu/2/eps_cyc; % km
vrendez_cyc = sqrt(2*mu*(1/r2+1/2/abs(a_cyc))); % km/s

gam1 = 0;
v1 = sqrt(mu/r1);
dv1 = sqrt(v1^2+vd^2-2*v1*vd*cosd(gamd-gam1));
gam2 = atand(e*sind(taa)/(1+e*cosd(taa)));
dv2 = sqrt(va^2+vrendez_cyc^2-2*va*vrendez_cyc*cosd(gama-gam2));
dvtot = dv1 + dv2;
end
%% This script iterates through various values of r1, r2, TA, and TOF using the function Lambert.m to calculate Lambert arcs that connect to the cycler orbit.

%% Set up values
rEarth = 6378; % km
r1 = linspace(rEarth,rEarth+50000,500);
r2 = 924000;
TA = 130;
TOF = 48*60*60;
mue = 398600;

%% Iterate and collect data
a = zeros(length(r1)*length(r2)*length(TA)*length(TOF),1);
p = a;
e = a;
eps = a;
v = a;
va = a;
tad = a;
taa = a;
gamd = a;
gama = a;

parfor I = 1:length(r1)
    for J = 1:length(r2)
        for K = 1:length(TA)
            for L = 1:length(TOF)
                [dv1(I),dv2(I),dvtot(I)] = Lambert(r1(I),r2(J),TA(K),TOF(L),mue);

                if(mod(I+J+K+L,100)==0)
                    disp('Running')
                end

            end
        end
    end
end

plot(r1,dv1,r1,dv2,'r',r1,dvtot,'k')
legend('\Delta V_1','\Delta V_2','\Delta V_{tot}')
grid on
title('\Delta V vs. LEO Orbit Radius - Witsberger')
xlabel('Radius (km)')
ylabel('\Delta V (km/s)')

[minDV,index] = min(dvtot);
<table>
<thead>
<tr>
<th>Encounter</th>
<th>Date</th>
<th>Vinf (km/s)</th>
<th>Closest approach altitude (km)</th>
<th>Leg TOF (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth-1</td>
<td>10/14/07</td>
<td>5.16</td>
<td>21300</td>
<td>-</td>
</tr>
<tr>
<td>Mars-2</td>
<td>05/31/08</td>
<td>2.66</td>
<td>300</td>
<td>230</td>
</tr>
<tr>
<td>Earth-3</td>
<td>07/24/10</td>
<td>4.82</td>
<td>25900</td>
<td>784</td>
</tr>
<tr>
<td>Maneuver</td>
<td>11/04/10</td>
<td>0.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Earth-4</td>
<td>12/14/11</td>
<td>4.33</td>
<td>26200</td>
<td>508</td>
</tr>
<tr>
<td>Mars-5</td>
<td>06/16/12</td>
<td>5.86</td>
<td>7900</td>
<td>185</td>
</tr>
<tr>
<td>Earth-6</td>
<td>10/11/14</td>
<td>5.29</td>
<td>24600</td>
<td>847</td>
</tr>
<tr>
<td>Earth-7</td>
<td>03/29/16</td>
<td>5.29</td>
<td>35200</td>
<td>535</td>
</tr>
<tr>
<td>Mars-8</td>
<td>07/25/16</td>
<td>7.86</td>
<td>9900</td>
<td>118</td>
</tr>
<tr>
<td>Earth-9</td>
<td>02/04/19</td>
<td>3.97</td>
<td>22500</td>
<td>924</td>
</tr>
<tr>
<td>Earth-10</td>
<td>07/18/20</td>
<td>3.97</td>
<td>4600</td>
<td>530</td>
</tr>
<tr>
<td>Mars-11</td>
<td>12/20/20</td>
<td>4.31</td>
<td>5400</td>
<td>155</td>
</tr>
<tr>
<td>Earth-12</td>
<td>05/26/23</td>
<td>6.02</td>
<td>21000</td>
<td>887</td>
</tr>
<tr>
<td>Maneuver</td>
<td>08/02/23</td>
<td>0.11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Earth-13</td>
<td>11/12/24</td>
<td>5.85</td>
<td>29400</td>
<td>536</td>
</tr>
<tr>
<td>Mars-14</td>
<td>06/21/25</td>
<td>3.07</td>
<td>16600</td>
<td>221</td>
</tr>
<tr>
<td>Earth-15</td>
<td>08/23/27</td>
<td>5.29</td>
<td>36500</td>
<td>794</td>
</tr>
<tr>
<td>Maneuver</td>
<td>11/30/27</td>
<td>0.81</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Earth-16</td>
<td>01/11/29</td>
<td>4.61</td>
<td>31700</td>
<td>507</td>
</tr>
<tr>
<td>Mars-17</td>
<td>06/27/29</td>
<td>6.58</td>
<td>66700</td>
<td>166</td>
</tr>
<tr>
<td>Earth-18</td>
<td>11/15/31</td>
<td>4.41</td>
<td>31400</td>
<td>872</td>
</tr>
<tr>
<td>Earth-19</td>
<td>04/30/33</td>
<td>4.41</td>
<td>26700</td>
<td>531</td>
</tr>
<tr>
<td>Mars-20</td>
<td>08/20/33</td>
<td>7.34</td>
<td>10700</td>
<td>113</td>
</tr>
<tr>
<td>Earth-21</td>
<td>03/13/36</td>
<td>4.25</td>
<td>22000</td>
<td>936</td>
</tr>
<tr>
<td>Earth-22</td>
<td>08/26/37</td>
<td>4.25</td>
<td>9000</td>
<td>531</td>
</tr>
</tbody>
</table>

**Earth-1**: Maneuver 08/31/08

**Earth-1**: Maneuver 12/04/12

**Earth-3**: Maneuver 07/02/14

**Earth-4**: Maneuver 01/31/14

**Earth-5**: Maneuver 04/06/21

**Earth-6**: Maneuver 09/20/22

**Earth-7**: Maneuver 05/04/25

**Earth-8**: Maneuver 12/16/29

**Earth-9**: Maneuver 03/06/31

**Earth-10**: Maneuver 09/19/25

**Earth-11**: Maneuver 06/15/27

**Earth-12**: Maneuver 09/24/29

**Earth-13**: Maneuver 05/17/31

**Earth-14**: Maneuver 07/01/34

**Earth-15**: Maneuver 02/08/35

**Earth-16**: Maneuver 12/16/29

**Earth-17**: Maneuver 05/17/31

**Earth-18**: Maneuver 02/08/35

**Earth-19**: Maneuver 01/22/36

**Earth-20**: Maneuver 07/01/34

**Earth-21**: Maneuver 05/17/31

**Earth-22**: Maneuver 02/08/35
Sample Return Missions
Lunar Base Layout
SAMPLE RETURN MISSION

PAST AND PRESENT MISSIONS

- Luna 24 (Russia)
  - 1976
  - 170 g
  - Drilled 2 meters into surface

- Chandrayaan – 2 (India)
  - 2018
  - 6.625 tons
  - Falcon 9: Delta V = 26 km/s

- Chang’e (China)
  - Before 2020
  - Intended to collect 2.2 kg
REFERENCES

Why? - Close approximation to a human exploration mission

Sample Returns
1. Tissue missions
   - 200-300 kg (100 g/branch)
   - 200-300 kg (100 g/maintained level)

2. Sample return
   - 200-300 kg (100 g/maintained level)

3. Sample return
   - 200-300 kg (100 g/maintained level)

4. Sample return
   - 200-300 kg (100 g/maintained level)

Sample return
- 200-300 kg (100 g/maintained level)
**BACKUP SLIDES**

Michelle Madalinski

---

**Lunar Base Map/Layout**

- Distance from hab to nuclear reactor ~ 3 km
- Distance from hab to landing sites ~ 100 m - explosion?
- Distance from hab to mining site ~ 17.19 km
- Distance from hab to mountain ~ 28.13 km
- Site of hab: over or below? Close to mining site?
- ISRU placement ~ distance to landing site?
- Fuel depot placement ~ distance to landing site?
- Communication equipment placement
- Trench storage
- Fuel storage
- Solar panels for energy source (not often east maintenance occurs)

---

**Modules**

- Apollo 11
- Lunar module
- Height: 19.8 m
- Diameter: 3.4 m
- Weight: 15,500 lb
- Crew: 2

---

**Ixion (Israel)**

- Diameter: 3 m
- Height: 3 m
- Weight: 9,500 lb
- Solar panel count
Seismic Probe Mission
Soft Landing Investigation
Beginnings of Propellant Trade Study
SEISMIC ACTIVITY PROBES

Probes descend to the surface.

Locations & landmarks

Moon

N O T T O S C A L E

A C C U R A T E

L A N D I N G S I T E S

Precision lander

Surface Touchdown

Cross section/deployment

Solar panel

Seismometer &
Electric equipment

Bedrock drill
**SOFT LANDING ANALYSIS**

**RECOMMENDATIONS**

- Seismic probes need to be placed precisely on an area of bedrock
- Recommend using a Sky Crane precision landing process
- Additional options for soft landing are explored below

<table>
<thead>
<tr>
<th>Probe Name</th>
<th>Year</th>
<th>Total Mass</th>
<th>Landing System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luna 9</td>
<td>1966</td>
<td>Total: 1538 kg</td>
<td>Retro-rockets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Probe: 99 kg</td>
<td>4 outrigger engines</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nitrogen landing bag</td>
</tr>
<tr>
<td>Mars Pathfinder</td>
<td>1996</td>
<td>Probe: 463 kg</td>
<td>3 small solid boosters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 large landing bags</td>
</tr>
<tr>
<td>Phoenix Lander</td>
<td>2007</td>
<td>Science: 55 kg</td>
<td>Pulsed Propulsion System</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8 thrusters and footpads</td>
</tr>
<tr>
<td>Mars Science Lab</td>
<td>2011</td>
<td>Probe: 750 kg</td>
<td>Retro-rockets</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sky Crane</td>
</tr>
</tbody>
</table>
The design and dimensions of the seismometer probes were based off of an ocean bottom seismometer. These seismometers can handle adverse temperature and pressure environments making them an ideal candidate for off-world seismometer probes. Below is a listing of the properties of a typical ocean bottom seismometer.

**Ocean Bottom Seismometer:**
- 0.69m X 0.69m X 0.97m
- 170 kg **with** anchor and shielding weight (Not necessary on Moon)
- Seismometer itself between 10 and 20 kg, and overall probe approximately 100 kg
**Inflatable airbags coupled with outrigger engines to slow to a reasonable speed (>25 m/s)**
- Reduces amount of fuel needed for slowing down the spacecraft
- Not great for precision landings, but rather, general landing zones
- Require the use of retro-rockets or other thrusters to slow down before inflating
- Airbag technology is a very well-tested and mature technology (TRL 9)

**Pulsed propulsion system to slow down the spacecraft in small steps**
- Requires multiple thrusters
- Large amount of fuel
- Landing occurs on footpads at very low velocity
- Common method of softly landing heavy equipment

**Sky crane to slow down the spacecraft and lower to the surface via a tether**
- Sky crane portion flies away and crashes
- Perfect for a precision landing
- Similar fuel requirement as pulsed propulsion system
- System around TRL 8 or 9, has been successfully tested on Earth and Mars
- Good method of soft landing for delicate equipment
The plot to the right compares potential probe weight with the calculated propellant mass based for various rocket propellants. The plots were created assuming a necessary $dv = 2.183 \text{ km/s}$.

This plot was used in order to calculate approximate mass and volume numbers for the seismic probe mission.
The characteristics of several well-tested propellants were used in order to calculate the necessary fuel mass for the seismic probe missions. The propellant mass was then plotted against a range of possible probe masses based on the \textit{Isp} of the propellant.

Hydrozene and Dinitrogen tetroxide were the two propellants analyzed in-depth. In order to achieve a change in velocity of 2.183 km/s during descent, each probe would require 0.2926 cubic meters of Hydrozene correlating to 302 kg, and 0.0997 cubic meters of Dinitrogen tetroxide correlating to 143.60 kg of propellant. This volume and weight is all in addition to an approximate 100 kg and 0.4618 cubic meters of probe.

ΔV Requirements for Going from the Lunar Surface to CLO
**Lunar Launch Analysis**

**Constant-Thrust Takeoff and Orbit Matching**

**Goal**

Minimize ΔV for launch to CLO

**Target Circular Orbit**

- 4550 km radius
- 85° inclination

**Assumptions**

- Constant thrust/mass
- Constant acceleration due to gravity

---

Alexander Burton
### RESULTS

**Ideal Values**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>55 km</td>
</tr>
<tr>
<td>Acceleration</td>
<td>6.06 m/s²</td>
</tr>
<tr>
<td>Boost</td>
<td>2.32 km/s</td>
</tr>
<tr>
<td>Boost (total)</td>
<td>2.84 km/s</td>
</tr>
<tr>
<td>No Boost</td>
<td>2.14 km/s</td>
</tr>
<tr>
<td>No Boost (total)</td>
<td>2.65 km/s</td>
</tr>
</tbody>
</table>

**Fixed ΔVs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circularization</td>
<td>0.258 km/s</td>
</tr>
<tr>
<td>Plane Change</td>
<td>0.258 km/s</td>
</tr>
</tbody>
</table>

**Best Fit Relations**

<table>
<thead>
<tr>
<th>Boost</th>
<th>Takeoff ΔV (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost</td>
<td>((30.3a + 2072)/1000)</td>
</tr>
<tr>
<td>No Boost</td>
<td>((33.8a + 1871)/1000)</td>
</tr>
</tbody>
</table>

*a in m/s²*
% Optimal Ascent Problem with MATLAB's bvp4c
% Clear figure, command and workspace histories
% Authors: Hakusbo Chin, Alexander Burton
% Close all; clear; clc;

% Define parameters of the problem
global gm accel Vp h m0 eta f m0t
% pass these parameters to the DC and BC functions
mu = 0.004946; % km/s², Moon gravitational parameter
r = 1737; % km, Moon radius
h = 35000; % meters, final altitude (25 km perigee of elliptical orbit)
rf = 4550; % km, elliptical orbit apoapsis
rp = r + h/1000; % km, elliptical orbit perigee
g0 = 9.80466; % m/s², gravitational acceleration of Earth
accel = 1.4; % m/s², gravitational acceleration on Moon (settlement.arc.nasa.gov/leas
some/bryan/microgravity/gravbeck.html)
K = 2.166; % kN, thrust of the first stage of Titan II Rocket
f = 110w3;
h_scale = 8640; % m, atmospheric scale height
beta = h/h_scale; % [0, 1], constant used to reduce ODE equations
rhoeref = 0; % kg/m³, reference density
A = 7.0962; % m², aerodynamic reference area (cross sectional area)
diag = 10; % deg, change in right ascension of the ascending node
d1 = 10; % deg, change in inclination
accel = gm accel; % m/s², acceleration of the launch vehicle
hmount = 6000; % m, Altitude of the nearby mountain that we should clear
imp = 450; % seconds
V0 = g0 * imp; % exhaust velocity
m0t = 0;

% Variables controlling the tests
n = 100; % number of iterations
acc = linspace(1.01*accel,5.98*acc); % range of acceleration values tested
alt = linspace(100000,1000000); % range of h values tested
vo = sqrt(mu / rf); %
% store results
delav = zeros(n,5); % constant mass

% calculate velocity after launch complete
Vp = sqrt(2*mu * (1/rp - 1 / ((r+rp^2))/1000); % m/s, perigee speed

% calculate delav for change of ram and return to circular orbit
va = sqrt(2*mu * (1/rf - 1 / (rf + rp^2))); %
delav(i,4) = va - va;

delav(i,5) = 0.258; % km/s, from last week’s analysis
for i = 1:n
accel = accel(i);
eta = alt(i);
rp = r + h/1000; % km, elliptical orbit perigee
Vp = sqrt(2*mu * (1/rp - 1 / ((r+rp^2))/1000); % m/s, perigee speed
va = sqrt(2*mu * (1/rf - 1 / (rf + rp^2))); %
delav(i,4) = va - va;

% delav to get to mountain height via vertical trajectory
m0 = f / accel;
tup = sqrt(2 * hmount / (accel - g_accel));
delav(i,2) = tup * accel / 1000;

% Boundary Conditions
boundary

% initial conditions
% Launch from zero altitude with zero initial velocity
% All boundary conditions are non-dimensional
xbar0 = 0; % initial x position
ybar0 = hmount / h; % initial y position
Vbar0 = 0; % initial downrange velocity
Vbarf = [accel - acc]; % tup / Vp; % initial downrange velocity
Vbarf = [accel - acc]; % tup / Vp; % initial downrange velocity

% Solution with NO DRAG
% Solve TPBVP without drag (C_D = 0)
tend = 60000; % kg, average mass of a Titan II Rocket
end = 15000;
CD = 0;
adx = 0;

beta - a constant composed of the reference density, coefficient
for drag and the aerodynamic reference area. It is only used to simplify
the drag expressions in the ODEs.
eta = shorwref * CD * A/2;
%*******************************
%Initial Guesses
%*******************************

% Initial time
t0 = 0;

% list initial conditions in yinit, use zero if unknown
yinit = [xbar0 ybar0 Vxbar0 Vybar0 0 -1 0]; % guess for initial state and co state var

%guess for initial state and co state var

% Call bvpc to solve the TPBVVP. Point the solver to the functions
% containing the differential equations and the boundary conditions and
% provide it with the initial guess of the solution.
% Call bvpc to solve the TPBVVP. Point the solver to the functions
% containing the differential equations and the boundary conditions and
% provide it with the initial guess of the solution.
% sol = bvpc(@(exact_ode_kf, @exact_bc_kf, solinit); %

% Extract the final time from the solution:
% tf = sol.parameters(1);

% Evaluate the solution at all times in the non-dimensional time vector tau
% and store the state variables in the matrix Z.
Z = deval(sol,tau);

% Convert back to dimensional time for plotting
time = t0 + tau.*((tf-t0);
ylabel('\Delta v (km/s)', 'FontSize', 14);
figure(2)
plot(alts/1000, totalTime);
title('Burn at Takeoff vs Target Altitude', 'FontSize', 16);
xlabel('Altitude (km)', 'FontSize', 14);
ylabel('Burn Time (sec)', 'FontSize', 14);

figure(3)
plot(alts/1000, takeoffDeltaV);
title('Takeoff \Delta v vs Target Altitude', 'FontSize', 16);
xlabel('Altitude (km)', 'FontSize', 14);
ylabel('\Delta v (km/s)', 'FontSize', 14);

Published with MATLAB R2015b
• Sabatier Process for making methane
• Updated fuel depot tank sizing and comparison for hydralox/methalox tank sizes
SABATIER PROCESS

- REACTANT MATERIAL:
  - CO₂ + H₂ from electrolysis and ISRU
- PRODUCT MATERIAL:
  - CH₄ + H₂O for use as fuel for the lander, water for electrolysis or habitation
- POWER REQUIREMENTS:
  - Reaction chamber must be heated to 300-400°C
## Updated Tank Sizing Requirements

<table>
<thead>
<tr>
<th>COMPOUND</th>
<th>ENGINE</th>
<th>METHALOX ENGINE</th>
<th>HYDRALOX ENGINE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass Required</td>
<td>Tank Volume</td>
<td>Mass Required</td>
</tr>
<tr>
<td></td>
<td>[Mg]</td>
<td>[m^3]</td>
<td>[Mg]</td>
</tr>
<tr>
<td>CH4 (Methane)</td>
<td>24</td>
<td>114</td>
<td>-</td>
</tr>
<tr>
<td>H2 (Hydrogen)</td>
<td>1.2</td>
<td>-</td>
<td>17</td>
</tr>
<tr>
<td>CO2 (Carbon Dioxide)</td>
<td>2.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H20 (Water)</td>
<td>0.21</td>
<td>-</td>
<td>0.31</td>
</tr>
<tr>
<td>O2 (Oxygen)</td>
<td>182</td>
<td>160</td>
<td>187</td>
</tr>
</tbody>
</table>

**Conclusions:**

- Holding tanks for the methalox engine would be about 1/3 the size of the hydralox engine.
- Amount of required liquid oxygen is about the same for both.
- In case of methalox engine, methane can be harvested from the Moon, as well as created using the Sabatier Process and leftover hydrogen from electrolysis.
REFERENCES


% MODEL FOR FUEL DEPOT TANK SIZING METHANE ENGINE-
% AUTHOR: DAYLE ALEXANDER
% LAST UPDATED: 2/10/2016
% ASSUMPTIONS:

clear all; close all;
% KNOWN VARIABLES
raptor_mlch4=24*2;  % Mass of CH4 needed to launch
10Mg lander in Mg
raptor_of=3.8;  % O/F ratio for the Raptor engine
raptor_mlo2=raptor_mlch4*raptor_of;  % Mass of O2
needed to launch in Mg
boiloff=0.1;  % Boiloff rate for cryogens in space in %/day
rho_lox=1141;  % Density of LOX in kg/m^3
rho_ch4=421;  % Density of LCH4 in kg/m^3
rho_gox=1.35;  % Density of GOX in kg/m^3
rho_gch4=0.656;  % Density of GCH4 in kg/m^3
mm_o2=0.032;  % Molar mass of oxygen in kg/mol
mm_ch4=0.01604;  % Molar mass of methane in kg/mol
mm_h2o=0.018;  % Molar mass of H2O in kg/mol
m_ch4_daily=1000;  % Mass of GCH4 able to be made in 1
day
m_o2_daily=m_ch4_daily/mm_ch4/2*mm_o2;  % Mass of
GO2 able to be made in 1 day

% EQUATIONS
v_lox=(raptor_mlo2*1000)/rho_lox  % Min volume of LOX
v_ch4=(raptor_mlch4*1000)/rho_ch4  % Min volume of LH2
v_gox=(raptor_mlo2*1000)/rho_gox;  % Min volume of GOX
v_gch4=(raptor_mlch4*1000)/rho_gch4;  % Min volume of
GH2 needed in m^3

mol_o2=raptor_mlo2/mm_o2;  % Moles of O2 required
m_water_o2=mol_o2*2;  % Mass of
m_water_o2=(mol_water_o2*mm_h2o)/1000  % Mass of
H2O to get required O2 in Mg

% RESULTS
% VOLUME REQUIRED OF LOX TANK [m^3]
% v_lox =
% 159.8598
%
% VOLUME REQUIRED OF LCH2 TANK [m^3]
% v_ch4 =
% 114.0143
%
% MASS OF WATER REQUIRED [Mg]
% m_water_h2 =
% 0.2052
% MODEL FOR FUEL DEPOT TANK SIZING
% AUTHOR: DAYLE ALEXANDER
% LAST UPDATED: 2/10/2016
% ASSUMPTIONS: FUEL AND OXIDIZER TANKS WILL BE FILLED IN THE SAME DAY AS
% THE LAUNCH AND TANKS ARE PRE CHILLED (NO MASS LOSS)
% CRYOGENIC BURNOFF RATE IN LEO IS THE SAME AS THE SURFACE OF
% THE MOON
% IT TAKES 1 DAY TO MAKE 1000KG OF H2
% -100% EFFICIENCY

% KNOWN VARIABLES
RL10_mlh2=17*2; % Mass of H2 needed to launch 10Mg lander in Mg
RL10_of=5.5; % O/F ratio for the RL10 engine
RL10_mlo2=RL10_mlh2*RL10_of; % Mass of O2 needed to launch in Mg
boiloff=0.1; % Boiloff rate for cryogens in space in %/day
rho_lox=1141; % Density of LOX in kg/m^3
rho_lh2=71; % Density of LH2 in kg/m^3
rho_gox=1.35; % Density of GOX in kg/m^3
rho_gh2=0.085; % Density of GH2 in kg/m^3
mm_o2=0.032; % Molar mass of oxygen in kg/mol
mm_h2=0.002; % Molar mass of hydrogen in kg/mol
mm_h2o=0.018; % Molar mass of H2O in kg/mol
m_h2_daily=500; % Mass of GH2 able to be made in 1 day
m_o2_daily=m_h2_daily/mm_h2/2*mm_o2; % Mass of GO2 able to be made in 1 day

% EQUATIONS
v_lox=(RL10_mlo2*1000)/rho_lox % Min volume of LOX needed in m^3
v_lh2=(RL10_mlh2*1000)/rho_lh2 % Min volume of LH2 needed in m^3
v_gox=(RL10_mlo2*1000)/rho_gox; % Min volume of GOX needed in m^3
v_gh2=(RL10_mlh2*1000)/rho_gh2; % Min volume of GH2 needed in m^3
mol_o2=RL10_mlo2/mm_o2; % Moles of O2 required
mol_h2=RL10_mlh2/mm_h2; % Moles of H2 required
mol_water_o2=mol_o2*2; % Moles of H2o to get required O2
mol_water_h2=mol_h2; % Moles of H2O to get required H2
m_water_o2=(mol_water_o2*mm_h2o)/1000; % Mass of H2O to get required O2 in Mg
m_water_h2=(mol_water_h2*mm_h2o)/1000; % Mass of H2O to get required H2 in Mg

% MODEL FOR DAYS TO MAKE REQUIRED H2
days=linspace(1,1000,1000);
mlh2=[];
mlh2(1)=m_h2_daily;
i=1;
while(mlh2(i)<RL10_mlh2*1000)
i=i+1;
mlh2(i)=mlh2(i-1)+m_h2_daily-mlh2(i-1)*(boiloff/100);
end
days_h2=i

% MODEL FOR DAYS TO MAKE REQUIRED O2
mlo2=[];
mlo2(1)=m_o2_daily;
i=1;
while(mlo2(i)<RL10_mlo2*1000)
i=i+1;
mlo2(i)=mlo2(i-1)+m_o2_daily-mlo2(i-1)*(boiloff/100);
end
days_o2=i

% RESULTS
% VOLUME REQUIRED OF LOX TANK [m^3]
v_lox = % 163.8913
% VOLUME REQUIRED OF LH2 TANK [m^3]
v_lh2 = % 478.8732
% MASS OF WATER REQUIRED [Mg]
ml_water_h2 = % 0.3060
% DAYS IT TAKES TO MAKE REQUIRED LH2
days_h2 = % 71
% DAYS IT TAKES TO MAKE REQUIRED LOX
days_o2 = % 48
% CODE FOR MASS REQUIREMENTS OF SABATIER PROCESS

% MODEL FOR SABATIER PROCESS
% AUTHOR: DAYLE ALEXANDER
% LAST UPDATED: 2/10/2016
% ASSUMPTIONS:
% - POWER REQUIRED TO HEAT THE REACTANTS TO 350C
% - CAN MAKE 1KG OF CH4 PER DAY
% - CAN HARVEST 5KG OF CH4 PER DAY

clear all; close all;

% CONSTANTS
p_h2=0.0899;  % Density of H2 at 350C [kg/m^3]
p_h2o=575;  % Density of H2O at 350C [kg/m^3]
p_co2=1.977;  % Density of CO2 at 350C [kg/m^3]
p_ch4=0.7165;  % Density of CH4 at 350C [kg/m^3]
m_ch4_daily=6;  % Amount of CH4 produced daily [kg]

mm_h2=0.002;  % Molar mass of hydrogen [kg/mol]
mm_h2o=0.018;  % Molar mass of H2O [kg/mol]
mm_co2=0.044;  % Molar mass of CO2 [kg/mol]
mm_ch4=0.016;  % Molar mass of CH4 [kg/mol]

m_ch4=1;  % Mass of CH4 required [Mg]
mol_ch4=m_ch4*1000/mm_ch4;  % Mols of CH4 required [mols]
mol_h2o=mol_ch4*2;  % Mols of H2O required [mols]
mol_h2=mol_ch4*4;  % Mols of H2 required [mols]
mol_co2=mol_ch4;  % Mols of CO2 required [mols]

m_co2=mol_co2*mm_co2  % Mass of H2O required [kg]
m_h2o=mol_h2o*mm_h2o  % Mass of H2O required [kg]
m_h2=mol_h2*mm_h2  % Mass of H2 required [kg]

% MODEL FOR DAYS TO MAKE REQUIRED CH4

days=linspace(1,1000,1000);
mch4=[];
mch4(1)=m_ch4_daily;
i=1;

while(mch4(i)<m_ch4*1000)
    i=i+1;
    mch4(i)=mch4(i-1)+m_ch4_daily;
end

days_ch4=

% MASS OF WATER CREATED [kg]
% m_h2o =
%   5.4000e+04
%
% MASS OF HYDROGEN REQUIRED [kg]
% m_h2 =
%   1200
%
% MASS OF CARBON DIOXIDE REQUIRED [kg]
% m_co2 =
%   2750
%
% DAYS REQUIRED TO MAKE NEEDED CH4
% days_ch4 =
%   167
POSSIBLE SCHEMATIC FOR FUEL DEPOT INCLUDING SABATIER PROCESS AND ELECTROLYSIS IN CASE OF METHALOX ENGINE
10Mg and 20Mg Cargo Lander Mass and Propellant Volume Specifications
10Mg and 20Mg Cargo Lander Fuel Selection
FUEL/OXIDIZER MASS AND VOLUME

For the Hydrolox engine, the RL10B-2 is being used (Isp = 464 seconds, O/F = 5.88)
For the Methalox engine, Andrew’s initial engine specifications are being used (Ispvac = 389 seconds, O/F = 4.0)

For the RL10B-2, the lander is launched from a Falcon Heavy
For the Methalox, the lander is launched from an SLSB1B

<table>
<thead>
<tr>
<th>10Mg Cargo Landers</th>
<th>Total Propellant Mass (Mg)</th>
<th>Mass of Fuel (Mg)</th>
<th>Mass of LOX (Mg)</th>
<th>Volume of Fuel (m^3)</th>
<th>Volume of LOX (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL10B-2</td>
<td>47.01</td>
<td>6.833</td>
<td>40.179</td>
<td>96.24</td>
<td>35.21</td>
</tr>
<tr>
<td>Methalox</td>
<td>94.95</td>
<td>18.99</td>
<td>75.96</td>
<td>45.11</td>
<td>66.57</td>
</tr>
</tbody>
</table>

For the RL10B-2, the lander is launched from a Falcon Heavy
For the Methalox, the lander is launched from an SLSB1B

<table>
<thead>
<tr>
<th>20Mg Cargo Landers</th>
<th>Total Propellant Mass (Mg)</th>
<th>Mass of Fuel (Mg)</th>
<th>Mass of LOX (Mg)</th>
<th>Volume of Fuel (m^3)</th>
<th>Volume of LOX (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL10B-2</td>
<td>93.22</td>
<td>13.55</td>
<td>79.672</td>
<td>190.84</td>
<td>69.83</td>
</tr>
<tr>
<td>Methalox</td>
<td>121.38</td>
<td>24.28</td>
<td>97.1</td>
<td>57.66</td>
<td>85.1</td>
</tr>
</tbody>
</table>

- For the 20Mg Lander, the Methalox engine is unable to reach the Moon’s surface with the SLSB1B

Brock Miller
### Trade Study between Hydrolox and Methalox

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Startability</th>
<th>Refuelling</th>
<th>Efficiency</th>
<th>Storage</th>
<th>TRL</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrolox</td>
<td>2.5</td>
<td>2.5</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>3.75</td>
</tr>
<tr>
<td>Methalox</td>
<td>2.5</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>1.5</td>
<td>2.975</td>
</tr>
<tr>
<td>Weighting</td>
<td>0.15</td>
<td>0.05</td>
<td>0.35</td>
<td>0.25</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Startability – Both Require ignition systems
Refueling – For now, the cargo landers are not planned to be refueled
Efficiency – Hydrolox have Isp values of about 450 s, Methalox is about 390 s
Storage – More volume will be needed for Hydrolox (less dense fuel)
TRL – Hydrolox is highly proven, having flown many missions as opposed to Methalox which has a TLR of 3-4
REFERENCES


clear all; close all; clc

g0 = 9.80665; %m/s
rho_ox = 1141; %kg/m^3
Delta_V1 = 4750; %m/s
Delta_V2 = 2656; %m/s

mpaymg = input('What is the Payload Mass in Mg from Tug? ');
mpay = mpaymg * 1e6;
Isp = input('What is the Isp of your LRE in seconds? ');
OF = input('What is the O/F of your LRE? ');
menuvar = menu('What Launch Vehicle will be used?','Falcon Heavy','SLSB1A','SLSB1B');
if menuvar == 1
    mini = 53e6; %g
elseif menuvar == 2
    mini = 77e6; %g
else
    mini = 105e6; %g
end

menuvar2 = menu('What Fuel will be used?','Hydrogen','Methane');
if menuvar2 == 1
    rho_fuel = 71; %kg/m^3
else
    rho_fuel = 421; %kg/m^3
end

LEO to CLO
MR1 = exp(Delta_V1/(g0*Isp)); %Initial Mass over Final Mass
mfinal1 = (mini/MR1);
imert1 = mini/11;
mprop1 = (mini - mfinal1);

CLO to Surface With Payload
mprop2 = mfinal1 - minert1;
mini2 = mfinal1+mpay;

if menuvar == 1
    mini = 53e6; %g
elseif menuvar == 2
    mini = 77e6; %g
else
    mini = 105e6; %g
end

Vol_ox = mass_ox/(1000*rho_ox);
Vol_fuel = mass_fuel/(1000*rho_fuel);

fprintf('----Cargo Lander Specs----

----LEO to CLO----

Initial Mass %4.2f Mg\n,mini/1e6
Final Mass %4.2f Mg\n,mfinal1/1e6
Inert Mass %4.2f Mg\n,minert1/1e6
Propellant Mass Used %4.2f Mg\n,mprop1/1e6
Propellant Mass Remaining %4.2f Mg\n,mprop2/1e6

----CLO to Surface----

Initial Mass %4.2f Mg\n,mini2/1e6
Final Mass %4.2f Mg\n,mfinal2/1e6
Inert Mass %4.2f Mg\n,minert1/1e6
Total Propellant Used %4.2f Mg\n,mtotprop/1e6
Excess Mass %4.2f Mg\n,mexcess/1e6
Fuel Mass %4.2f Mg\n,mass_fuel/1e6
Oxidizer Mass %4.2f Mg\n,mass_ox/1e6
Fuel Tank Volume %4.2f m^3\n,Vol_fuel
Oxidizer Tank Volume %4.2f m^3\n,Vol_ox

Brock Miller
Previous calculations were re-done for $g = 9.80665 \, \text{m/s}^2$

10 Myr Lander: 47.01 Mg - RL10B-2 Hydrelx Falcon Heavy

20 Myr Lander: 93.22 Mg - RL10B-2 Hydrelx SLSB16

\[ \text{RL10B-2} \quad \text{V}_1 = 5.89 \quad \Rightarrow \quad \text{MassL/Prop} \quad \text{ratio} \]

\[ \text{mass prop} / (\%L) = \text{mass LH} \]

\[ \text{mass prop} = \text{mass LH} \times \text{mass prop} \]

\[ \text{Prop} = 11.42 \quad \text{kg} \text{/ kg} \]

\[ \text{Meth} = 71 \quad \text{kg} \text{/ kg} \]

10 Myr

\[ \text{V}_{\text{helium}} = 75.21 \text{m}^3 \]

\[ \text{M}_{\text{helium}} = 6.513 \text{ Mg} \]

\[ \text{V}_{\text{helium}} = 90.24 \text{ m}^3 \]

\[ \text{M}_{\text{helium}} = 40.179 \text{ Mg} \]

20 Myr

\[ \text{V}_{\text{helium}} = 69.83 \text{ m}^3 \]

\[ \text{M}_{\text{helium}} = 13.540 \text{ Mg} \]

\[ \text{V}_{\text{helium}} = 190.84 \text{ m}^3 \]

\[ \text{M}_{\text{helium}} = 39.467 \text{ Mg} \]

For a methane-LOX engine

\[ \text{Mass prop}_{\text{methane}} \]

\[ \text{10 Myr Lander: 116.76 Mg - Initial Specifications} \quad \text{For our Methane-LOX} \]

\[ \text{20 Myr Lander: 130 Mg - our Methane-LOX engine} \]

\[ \text{Methane-LOX:} \quad \%L = 4.0 \]

\[ \text{I}_{\text{sp}} = \text{sec} \quad \text{From Andrews's} \quad \text{CEA runs} \]

\[ \text{Prop} = 1141 \text{ kg} \text{ / kg} \]

\[ \text{Meth} = 99.2 \text{ kg} \text{ / kg} \]

\[ \text{10 Myr} \quad \text{V}_{\text{helium}} = 55.28 \text{ m}^3 \]

\[ \text{V}_{\text{helium}} = 81.58 \text{ m}^3 \]

\[ \text{20 Myr} \quad \text{V}_{\text{helium}} = 57.66 \text{ m}^3 \]

\[ \text{V}_{\text{helium}} = 85.10 \text{ m}^3 \]

---

**Trade Study**

<table>
<thead>
<tr>
<th>Stability</th>
<th>Rebinding</th>
<th>Efficiency</th>
<th>Storage</th>
<th>TRL</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrelx</td>
<td>2.5</td>
<td>2.0</td>
<td>9.0</td>
<td>6.0</td>
<td>2.75</td>
</tr>
<tr>
<td>Methane</td>
<td>2.5</td>
<td>5.0</td>
<td>3.0</td>
<td>5.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Weighting</td>
<td>0.15</td>
<td>0.05</td>
<td>0.35</td>
<td>0.25</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Justifications -

  - **Stability**: Stability is important for precise landings and maneuvers, however both Hydrelx and methane-LOX require ignition systems to start.

  - **Rebinding**: Rebinding capability is not important for the rovers, but is required for the overall mission. For this reason, a LOX system would be used.

  - **Efficiency**: The engine picked for this mission will need to power the craft from LE to CLO, meaning high Iorestation is needed. Hydrelx engines are known to be extremely efficient with Isp's of 4500. Methane-LOX engines, however, are estimated at 350.

  - **Storage**: Both fuels are cryogenic, requiring special storage units. Liquid hydrogen, however, must be stored at a much lower temperature, meaning more insulation is needed for the tanks. Also, since hydrogen has a lower density, more tank volume is needed.

  - **TRL**: Using something that is already proven saves development costs and the spacecraft would require more power. Hydrelx engines have been proven, whereas methane-LOX engines are just now starting to be tested on Earth and in environmental trials (TRL 3-5).

Brock Miller
- Utilizing the NSTAR engine, the optimal vehicle for a 1 year transfer with a 20T payload would be (Assuming 6 km/s DV)
  - 5.4 N of thrust from 59 NSTAR engines
  - Initial Mass: 28,481 kg
  - Propellant Mass: 5,104 kg Xenon
- Optimum vehicle for a 5T payload (with 1 year transfer)
  - 1.6 N of thrust from 18 NSTAR engines
  - Initial Mass: 8,168 kg
  - Propellant Mass: 1464 kg of Xenon
- The absolute maximum electric can do, by vehicle:

<table>
<thead>
<tr>
<th>Max Engines, Max Payload Case:</th>
<th>SLS 1A</th>
<th>SLS 1B</th>
<th>FH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max #Engine</td>
<td>231.00</td>
<td>675.00</td>
<td>121.00</td>
</tr>
<tr>
<td>Max Thrust(N)</td>
<td>21.25</td>
<td>62.10</td>
<td>11.13</td>
</tr>
<tr>
<td>Max kW usage</td>
<td>531.30</td>
<td>1552.50</td>
<td>278.30</td>
</tr>
<tr>
<td>Engine Mass Total(kg)</td>
<td>6699.00</td>
<td>19575.00</td>
<td>3509.00</td>
</tr>
<tr>
<td>Solar Panel Mass(kg)</td>
<td>2656.50</td>
<td>7762.50</td>
<td>1391.50</td>
</tr>
<tr>
<td>Total Inert Mass:</td>
<td>10355.50</td>
<td>28337.50</td>
<td>5900.50</td>
</tr>
<tr>
<td>Propellant Mass Fraction</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>m0(kg)</td>
<td>70000.00</td>
<td>105000.00</td>
<td>53000.00</td>
</tr>
<tr>
<td>mf(kg)</td>
<td>57454.70</td>
<td>86182.06</td>
<td>43501.42</td>
</tr>
<tr>
<td>mp (kg)</td>
<td>12545.30</td>
<td>18817.94</td>
<td>9498.58</td>
</tr>
<tr>
<td>Mpayload</td>
<td>47099.20</td>
<td>57844.56</td>
<td>37600.92</td>
</tr>
<tr>
<td>TOF (years)</td>
<td>0.57</td>
<td>0.29</td>
<td>0.82</td>
</tr>
</tbody>
</table>
## Performance Data

<table>
<thead>
<tr>
<th>Propellant</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix Thrust (N)</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Engine</td>
<td></td>
</tr>
<tr>
<td>2.17</td>
<td>4.35</td>
</tr>
<tr>
<td>Power Required (KW)</td>
<td>5.00</td>
</tr>
<tr>
<td>Total Engine Mass (kg)</td>
<td>63.04</td>
</tr>
<tr>
<td>Solar Panel Mass (kg)</td>
<td>25.00</td>
</tr>
<tr>
<td>Total Inert Mass</td>
<td>1088.04</td>
</tr>
<tr>
<td>Propellant Mass Fraction</td>
<td>0.18</td>
</tr>
<tr>
<td>m/f(kg)</td>
<td>6010.04</td>
</tr>
<tr>
<td>m/pe(kg)</td>
<td>7417.37</td>
</tr>
<tr>
<td>prop(kg)</td>
<td>3299.51</td>
</tr>
<tr>
<td>T/L Years</td>
<td>7.06</td>
</tr>
</tbody>
</table>

**Prohibitive for ALL VEHICLES**

Kind of Arbitrary/Realism Cutoffs at:
- Do-able on Falcon Heavy
- Do-able on SLS Block 1A
- Do-able on SLS Block 1B

- Power Req > 200 KW
- T/L > 1.5 years

### Graphs

- **Transfer Time vs. Initial Mass**
- **Transfer Time vs. Thrust**
- **Thrust vs. Initial Mass**

---

**Footer:**

**Purdue University**
Interestingly, Thrust and Initial Mass scale linearly. This result can be inferred from the travel time equation for electric vehicles, $\text{TOF} = \Delta V \times \text{Initial Mass} / \text{Thrust}$.
### NSTAR 3rd Stage

<table>
<thead>
<tr>
<th>Specifications (per Engine)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DeltaV Assumption</td>
<td>6000 m/s</td>
<td></td>
</tr>
<tr>
<td>Thrust (N)</td>
<td>0.092</td>
<td>0.019</td>
</tr>
<tr>
<td>Isp (s)</td>
<td>3100</td>
<td>1900</td>
</tr>
<tr>
<td>kW</td>
<td>2.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Fuel</td>
<td>Xenon</td>
<td></td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

**Solar Panel Specific Mass:** 5 kg/kW

**SLS Block 1A Payload to LEO:** 70000 kg
**SLS Block 1B Payload to LEO:** 105000 kg
**Falcon Heavy Payload to LEO:** 53000 kg

### Max Engines, Max Payload Case:

<table>
<thead>
<tr>
<th></th>
<th>SLS 1A</th>
<th>SLS 1B</th>
<th>FH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max # Engine</td>
<td>231.00</td>
<td>675.00</td>
<td>121.00</td>
</tr>
<tr>
<td>Max Thrust (N)</td>
<td>21.25</td>
<td>62.10</td>
<td>11.13</td>
</tr>
<tr>
<td>Max kW usage</td>
<td>531.30</td>
<td>1552.50</td>
<td>278.30</td>
</tr>
<tr>
<td>Engine Mass Total (kg)</td>
<td>6695.00</td>
<td>19575.00</td>
<td>3509.00</td>
</tr>
<tr>
<td>Solar Panel Mass (kg)</td>
<td>2656.50</td>
<td>7792.50</td>
<td>1391.50</td>
</tr>
<tr>
<td>Total Inert Mass</td>
<td>10355.50</td>
<td>28337.50</td>
<td>5900.50</td>
</tr>
<tr>
<td>Propellant Mass Fraction</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>m0 (kg)</td>
<td>70000.00</td>
<td>105000.00</td>
<td>53000.00</td>
</tr>
<tr>
<td>mf (kg)</td>
<td>57454.70</td>
<td>86182.60</td>
<td>43501.42</td>
</tr>
<tr>
<td>mp (kg)</td>
<td>12545.30</td>
<td>18817.94</td>
<td>9498.58</td>
</tr>
<tr>
<td>Mpayload</td>
<td>47099.20</td>
<td>57844.56</td>
<td>37600.92</td>
</tr>
<tr>
<td>TOF (years)</td>
<td>0.57</td>
<td>0.29</td>
<td>0.82</td>
</tr>
</tbody>
</table>

(Found using Circle packing calculator @ http://www.packomania.com/)
NTR trade study
Preliminary methane engine sizing
NUCLEAR THERMAL ROCKET

NERVA PROGRAM

NERVA program total cost: $2.7 billion in 1973
~$15 billion in 2016
Engine’s test ended at TRL 6

ISP $\approx 850$ s
Dry Mass = 34 Mg
Thrust$_{\text{vac}}$ = 334 kN
$V_{\text{prop}} = 2030$ m$^3$
$t_b = 1200$ s

<table>
<thead>
<tr>
<th>Proposed Timeline</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 – 2018</td>
<td>Fabricate NERVA engine and have ground testing finished</td>
</tr>
<tr>
<td>2018</td>
<td>Attach NERVA engine to XM1 and test in space</td>
</tr>
<tr>
<td>2019 – 2025</td>
<td>Redesign based off flight performance and remanufacture</td>
</tr>
<tr>
<td>2025</td>
<td>Retest NERVA with XM3</td>
</tr>
<tr>
<td>2026 - ?</td>
<td>Make design tweaks and integrate with vehicle to go to Mars</td>
</tr>
</tbody>
</table>
O/F = 4
ISP = 389 s
Pc* = 1410 psi
Ae/At = 165
Pump-fed
60/80% Bell Nozzle
Closed Cycle

*Based on MERLIN 1-D
For NERVA rocket, they used 144 Mg of LH2 fuel
Using Density of LH2 = 70.8 kg/m³
We will have a volume of 2030 m³

NERVA program development cost includes research and development, manufacturing of 3 engines, nuclear fuel, and testing costs.
Dry mass is 34 Mg
Full mass is 178 Mg
Propellant Mass is 144 Mg
Using rocket equation the Delta V this setup will produce is ~13,400 km/s

The ISP difference between conventional bipropellant chemical rockets and the NERVA design greatly reduces fuel costs to get to the Moon and then to Mars eventually.
Methane O/F ratio optimization for chamber pressure = 1410 psi and Ae/At = 165

O/F is optimum around 4 as this is the highest value of ISP.

<table>
<thead>
<tr>
<th>O/F</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isp,Vac [m/s]</td>
<td>2907.5</td>
<td>3400.8</td>
<td>3778.2</td>
<td>3822.3</td>
<td>3467.6</td>
<td>3389.3</td>
<td>3207.4</td>
</tr>
<tr>
<td>Mach,e #</td>
<td>4.633</td>
<td>5.280</td>
<td>5.211</td>
<td>4.494</td>
<td>4.711</td>
<td>4.949</td>
<td>5.149</td>
</tr>
<tr>
<td>CF</td>
<td>2.016</td>
<td>1.8746</td>
<td>1.9607</td>
<td>2.0428</td>
<td>2.0295</td>
<td>2.0042</td>
<td>1.9775</td>
</tr>
<tr>
<td>C* [m/s]</td>
<td>1385.2</td>
<td>1757.3</td>
<td>1870.1</td>
<td>1793.4</td>
<td>1708.6</td>
<td>1636.6</td>
<td>1574.4</td>
</tr>
<tr>
<td>Pe [bar]</td>
<td>.04896</td>
<td>.03573</td>
<td>.03511</td>
<td>.05212</td>
<td>.04479</td>
<td>.03931</td>
<td>.03526</td>
</tr>
</tbody>
</table>

Action Items for Engine
- Refine optimum O/F ratio
- Define how much thrust is required and maximize thrust to weight ratio
- Size nozzle for # of motors
- Select how many motors will be used for upper stage


90 ANDREW CULL
FOOD GROWTH OPTIONS

COMPARISON OF TWO OPTIONS – FEED 8 PEOPLE

• Option 1: All food grown on moon
  • Mass: 95 Mg
  • Power: 13 kW
  • Volume: 520 m³
  • Water Needed: 1050 L
  • Total Crops Needed:
    – Broccoli – 896
    – Carrot – 2016
    – Green Beans – 672
    – Leaf Lettuce – 560
    – Potato – 235
    – Soybeans – 2016
    – Sweet Corn – 1176

• Option 2: Supplement 1 meal a day with prepackaged food
  • Mass: 14 Mg
  • Power: 5.4 kW
  • Grow room volume: 265 m³
  • Storage Volume: 250 m³
  • Water Needed: 570 L
  • Total Crops Needed:
    – Broccoli – 448
    – Carrot – 1344
    – Green Beans – 168
    – Leaf Lettuce – 140
    – Potato – 157
    – Soybeans – 1456
    – Sweet Corn – 392

Recommendation: Option 2

Rachael Hess
DAILY MEAL PLAN & ADDITIONAL INFORMATION

• Breakfast:
  • 1 cup of Broccoli
  • ¾ cup of soybeans
  • 1 cup of potatoes
  • 2 cups of carrots
  • 1 cup of green beans

• Lunch:
  • ¾ cup of soybeans
  • 1 cup of potatoes
  • 2 cups of carrots
  • 2 cups of lettuce
  • 1 cup of corn
  • 1 cup of green beans

• Dinner:
  • Prepackaged Dinner (MRE)

• Two story upright cylinder
• 3.75 m radius
• Each floor with height 3 m
• 57 growing systems per floor
• Water required for set-up: 570 L
  • Will need to replenish entire water supply 4 to 6 times a year
• Current TRL: 7
### Plants Only

<table>
<thead>
<tr>
<th># of Crops</th>
<th>Calories</th>
<th>Fat</th>
<th>Sodium</th>
<th>Carbohydrates</th>
<th>Dietary Fiber</th>
<th>Sugars (g)</th>
<th>Protein (g)</th>
<th>GOALS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>124</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>36</td>
<td>8</td>
<td>12</td>
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<tr>
<td></td>
<td>312</td>
<td>0</td>
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<td>84</td>
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<td>6</td>
<td></td>
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<tr>
<td></td>
<td>68</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>30</td>
<td>4</td>
<td>0</td>
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<td></td>
<td>144</td>
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<td>0</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td></td>
<td>330</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>27</td>
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<td>0</td>
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<tr>
<td></td>
<td>1660</td>
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<td>0</td>
<td>0</td>
<td>24</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>270</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>138</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2908</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>24</td>
<td>3</td>
<td>15</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>0</td>
<td>0</td>
<td>121</td>
<td>96</td>
<td></td>
<td>3000</td>
</tr>
</tbody>
</table>

### One Week, 4 People

<table>
<thead>
<tr>
<th></th>
<th>Broccoli</th>
<th>Carrot</th>
<th>Green Beans</th>
<th>Leaf Lettuce</th>
<th>Potato</th>
<th>Soybeans</th>
<th>Sweet Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Week, 4 People</td>
<td>112</td>
<td>336</td>
<td>2240</td>
<td>2240</td>
<td>168</td>
<td>10080</td>
<td>168</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Number of Crops per plant</th>
<th>Number of Plants Needed per week</th>
<th>Harvest Time (Weeks)</th>
<th>Harvest Time (Weeks In Space)</th>
<th>TOTAL CROPS NEEDED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>10</td>
<td>8</td>
<td>8</td>
<td>896</td>
</tr>
<tr>
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<td>0</td>
<td>6</td>
<td>6</td>
<td>2016</td>
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<td></td>
<td>20</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>672</td>
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<td>20</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>560</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>7</td>
<td>235.2</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>12</td>
<td>6</td>
<td>10</td>
<td>2016</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17</td>
<td>6</td>
<td>14</td>
<td>1176</td>
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</tbody>
</table>

Rachael Hess
### Power:

<table>
<thead>
<tr>
<th>Description</th>
<th>Power</th>
<th>Weight of lights</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 light</td>
<td>30 W</td>
<td>0.82 kg</td>
</tr>
<tr>
<td>Total light power</td>
<td>6330 W</td>
<td>All lights</td>
</tr>
<tr>
<td>1 system</td>
<td>32 W</td>
<td>90.72 kg</td>
</tr>
<tr>
<td>All systems</td>
<td>6720 W</td>
<td>All system</td>
</tr>
</tbody>
</table>

**TOTAL POWER** 13050 W  
**Total Weight** 94784.55819 kg
# of Crops | 1 | 1 | 4 | 10 | 10 | 2 | 130 | 1 | TOTALS | GOALS
---|---|---|---|---|---|---|---|---|---|---
Calories | 1250 | 62 | 208 | 17 | 36 | 220 | 1199 | 90 | 3081.888889 | 3000
Fat | 100 | 2 | 0 | 0 | 0 | 0 | 82 | 4 | 188.333333 | 100
Sodium | 51 | 2 | 16 | 0 | 0 | 0 | 0 | 0 | 69 | 100
Carbohydrates | 55 | 4 | 16 | 1.5 | 0 | 18 | 27 | 6 | 127.944444 | 100
Dietary Fiber | 60 | 18 | 56 | 7.5 | 2 | 16 | 100 | 8 | 267.1666667 | 100
Sugars (g) | 69 | 4 | 24 | 1 | 0 | 2 | 22 | 5 | 126.6666667 | 125
Protein (g) | 70 | 6 | 4 | 1 | 0 | 6 | 98 | 4 | 189.2222222 | 56
Vitamin A | 10 | 22 | 1712 | 7.5 | 53 | 0 | 1 | 2 | 1807.944444 | 100
Vitamin C | 35 | 270 | 52 | 15 | 11 | 90 | 27 | 10 | 510.4444444 | 100
Calcium | 70 | 8 | 16 | 2 | 1 | 4 | 75 | 0 | 176.1111111 | 100
Iron | 35 | 8 | 8 | 3 | 2 | 12 | 234 | 2 | 304 | 100

| | Broccoli | Carrot | Green Beans | Leaf Lettuce | Potato | Soybeans | Sweet Corn |
---|---|---|---|---|---|---|---|
One Week, 4 People | 56 | 224 | 560 | 560 | 112 | 7280 | 56 |
Number of Crops per plant | 1 | 1 | 20 | 20 | 5 | 50 | 2 |
Number of Plants Needed per week | 56 | 224 | 28 | 28 | 22.4 | 145.6 | 28 |
Harvest Time (Weeks) | 10 | 7 | 7 | 6 | 8 | 12 | 17 |
Harvest Time (Weeks In Space) | 8 | 6 | 6 | 5 | 7 | 10 | 14 |
TOTAL CROPS NEEDED | 448 | 1344 | 168 | 140 | 156.8 | 1456 | 392 |

Rachael Hess
<table>
<thead>
<tr>
<th>Description</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of lights</td>
<td>0.82 kg</td>
</tr>
<tr>
<td>All lights</td>
<td>93.48 kg</td>
</tr>
<tr>
<td>1 system</td>
<td>90.72 kg</td>
</tr>
<tr>
<td>All system</td>
<td>10342.08 kg</td>
</tr>
<tr>
<td><strong>Total Weight</strong></td>
<td><strong>14231.56 kg</strong></td>
</tr>
</tbody>
</table>

**Power:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 light</td>
<td>30 W</td>
</tr>
<tr>
<td>Total light power</td>
<td>1610 W</td>
</tr>
<tr>
<td>1 system</td>
<td>32 W</td>
</tr>
<tr>
<td>All systems</td>
<td>3648 W</td>
</tr>
<tr>
<td><strong>TOTAL POWER</strong></td>
<td><strong>5258</strong></td>
</tr>
</tbody>
</table>
February 11, 2016
Medical tests/supplies
Physical and mental health tests/supplies
Water requirements
Hab design
## Equipment/System Mass and Power

### Physical Fitness

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass [kg]</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treadmill Ladder&lt;sup&gt;1&lt;/sup&gt;</td>
<td>174.4</td>
<td>Self-powered</td>
</tr>
<tr>
<td>Force Treadmill&lt;sup&gt;1&lt;/sup&gt; (x2)</td>
<td>459</td>
<td>Self-powered</td>
</tr>
<tr>
<td>Advanced Resistive Exercise Device (ARED)&lt;sup&gt;1&lt;/sup&gt;</td>
<td>800</td>
<td>100W cont., 200W peak</td>
</tr>
<tr>
<td>Cycle Ergometer&lt;sup&gt;1&lt;/sup&gt; (x2)</td>
<td>53.6</td>
<td>Self-powered</td>
</tr>
<tr>
<td>VO2 Max Equipment&lt;sup&gt;2&lt;/sup&gt;</td>
<td>3.5</td>
<td>60W max</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1491</strong></td>
<td><strong>260W max</strong></td>
</tr>
</tbody>
</table>

### Radiation

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass [kg]</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tissue Equivalent Proportional Counter&lt;sup&gt;1*&lt;/sup&gt;</td>
<td>0.9</td>
<td>Battery</td>
</tr>
<tr>
<td>Charged Particle Directional Spectrometer&lt;sup&gt;1*&lt;/sup&gt;</td>
<td>3.6</td>
<td>Battery</td>
</tr>
<tr>
<td>Radiation Area Monitor&lt;sup&gt;1*&lt;/sup&gt; (x4)</td>
<td>0.548</td>
<td>Battery</td>
</tr>
<tr>
<td>Crew Passive Dosimeter&lt;sup&gt;1*&lt;/sup&gt; (x8)</td>
<td>0.168</td>
<td>Battery</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.216</strong></td>
<td><strong>TBD</strong></td>
</tr>
</tbody>
</table>

### Miscellaneous

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass [kg]</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam Mats (x4)</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>6, 10, 20 lb weight set</td>
<td>97.98</td>
<td>N/A</td>
</tr>
<tr>
<td>Baslet-M Cuff set (x8)</td>
<td>8</td>
<td>N/A</td>
</tr>
<tr>
<td>Heart Rate Monitors (x8)</td>
<td>0.392</td>
<td>Battery</td>
</tr>
<tr>
<td>Actiwatches (x8)</td>
<td>0.24</td>
<td>Battery</td>
</tr>
<tr>
<td>Interferometer</td>
<td>36</td>
<td>TBD</td>
</tr>
<tr>
<td>IBM ThinkPad A31p Laptop</td>
<td>3.5</td>
<td>60W max</td>
</tr>
<tr>
<td>MELFI (-80 deg. C freezer)</td>
<td>800</td>
<td>550W, 900W max</td>
</tr>
<tr>
<td>Spacesuit</td>
<td>140</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1380</strong></td>
<td><strong>~960W max</strong></td>
</tr>
</tbody>
</table>

Working on getting power requirements to charge radiation devices

Notes:
1. Used on ISS or adapted/very similar to ISS technology
2. Used for pre-/post-flight examinations
3. Recommended to be tested before crewed mission

Very important – cannot eliminate

Power consumption constant (always on)

---

Kelly Kramer
<table>
<thead>
<tr>
<th>MEDICAL</th>
<th>Mass [kg]</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasound¹ (x2)</td>
<td>8</td>
<td>50W max</td>
</tr>
<tr>
<td>Surface Electromyography²</td>
<td>2.3</td>
<td>5.8W</td>
</tr>
<tr>
<td>OCT Eye Scan²</td>
<td>34.1</td>
<td>70W max</td>
</tr>
<tr>
<td>Pulmonary Function System¹</td>
<td>84</td>
<td>205W avg, 252W max</td>
</tr>
<tr>
<td>Holter Monitor¹ (x4)</td>
<td>0.224</td>
<td>Battery</td>
</tr>
<tr>
<td>Air Sampler SWAB¹ (x2)</td>
<td>6</td>
<td>Battery</td>
</tr>
<tr>
<td>Refrigerated Centrifuge²</td>
<td>80</td>
<td>900W max</td>
</tr>
<tr>
<td>Centrifuge²</td>
<td>17</td>
<td>500W max</td>
</tr>
<tr>
<td>Exam Table</td>
<td>200</td>
<td>60W</td>
</tr>
<tr>
<td>Dynamic Posturography²</td>
<td>352</td>
<td>1200W</td>
</tr>
<tr>
<td>Bone Densitometry²</td>
<td>360</td>
<td>40W idle, 750W max</td>
</tr>
<tr>
<td>IVGEN¹</td>
<td>Included in ECLSS</td>
<td>Included in ECLSS</td>
</tr>
<tr>
<td>Total</td>
<td>1143</td>
<td>3787W max</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MENTAL HEALTH</th>
<th>Mass [kg]</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>iPads²</td>
<td>3.552</td>
<td>12W charging</td>
</tr>
<tr>
<td>LED Goodnight Bulb³</td>
<td>0.09</td>
<td>9.5W</td>
</tr>
<tr>
<td>LED Awake and Alert Bulb³</td>
<td>0.363</td>
<td>13.5W</td>
</tr>
<tr>
<td>Solid State Lighting Module¹*</td>
<td>51</td>
<td>450W</td>
</tr>
<tr>
<td>Computer with Oculus Rift</td>
<td>8.79</td>
<td>62W idle, 300W</td>
</tr>
<tr>
<td>LED Monitor</td>
<td>2.81</td>
<td>22W</td>
</tr>
<tr>
<td>LED TVs</td>
<td>11.79</td>
<td>0.3W idle, 90W average</td>
</tr>
<tr>
<td>Camera¹</td>
<td>1</td>
<td>Battery (rechargeable or disposable)</td>
</tr>
</tbody>
</table>

Notes:
1 Used on ISS or adapted/very similar to ISS technology
2 Used for pre-/post-flight examinations
* Recommended to be tested before crewed mission
Very important – cannot eliminate
Power consumption constant (always on)
### Medications and Water for Medical Use

<table>
<thead>
<tr>
<th>Water</th>
<th>kg/person/day</th>
<th>gal/person/day</th>
<th>kg/person/day</th>
<th>gal/person/day</th>
<th>75 kg/person/day</th>
<th>g/person/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>0.84</td>
<td>0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>drinking water</td>
<td>10</td>
<td>2.64</td>
<td>1.62</td>
<td>0.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dried food</td>
<td>1.77</td>
<td>1.77</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water for food</td>
<td>4</td>
<td>1.06</td>
<td>0.8</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>exercise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2925</td>
<td></td>
</tr>
<tr>
<td>shower/clean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10 L</td>
<td></td>
</tr>
<tr>
<td>IV water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.5298948 L/person/day</td>
<td>0.2925 L/person/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3113.4116 L/person/year</td>
<td>0.2925 L/person/year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 L extra</td>
<td>8.5298948 L/person/day</td>
<td>0.2925 L/person/day</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>72 ears</td>
<td>3113.4116 L/person/year</td>
<td>0.2925 L/person/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>at least 3L</td>
<td>12453.646 L/person/4 years</td>
<td>0.2925 L/person/4 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>of IV to return</td>
<td></td>
<td></td>
<td>49814.585 L/4crew/4y</td>
<td>0.2925 L/person/month</td>
</tr>
<tr>
<td></td>
<td></td>
<td>44 years</td>
<td></td>
<td></td>
<td>49814.585 L/4crew/4y</td>
<td>0.2925 L/person/month</td>
</tr>
<tr>
<td></td>
<td></td>
<td>weight [kg]</td>
<td></td>
<td></td>
<td>49814.585 L/78 ears</td>
<td>0.2925 L/person/year</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>49.814585 m3</td>
<td>0.2925 L/person/year</td>
</tr>
</tbody>
</table>

### Medicines, etc

- syringes
- sterile swab devices
- biophosphonates
- salivettes
- epinephrine
- gloves
- melatonin
- HRF supply kit
- zolpidem (ambien)
- USP grade crystalline salt
- Ramelteon
- bandages
- antihistamines
- ace bandages
- Amofistine
- plaster/strip/s
- Bio 300
- (5)-Androstene Steroids
- Granulocyte-macrophage colony-stimulating Factor
- ibuprofen
- 13.056
- Heat shock proteins
- tylenol
- 15.36
- Heat shock proteins
- aspirin
- 9.984
- Inositol Hexaphosphate (IP6)
- caffeine
- 23.04
- Inositol Signaling Molecule (ISM)
- peptobismal
- Nanotube Anti-Radiation Pill
- blood pressure
- Radiation vaccine
- vitamin D
- 0.3212
- laxatives
- vitamin K
- 1.4016
- immodium
- Potassium
- 116.8
- Chemicals for blood, urine, saliva, stool
- forteo injections
- 8760
- 1152
- anaylation
<table>
<thead>
<tr>
<th>Physical Fitness</th>
<th>mass [kg]</th>
<th>power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>foam mats x4 (prana)</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>6,10,20 lb weight sets (any)</td>
<td>97.98</td>
<td>N/A</td>
</tr>
<tr>
<td>PrimusRS</td>
<td>438</td>
<td>2400</td>
</tr>
<tr>
<td>treadmill ladder x1 (original Jacobs ladder)</td>
<td>147.4</td>
<td>self powered</td>
</tr>
<tr>
<td>force plate x1 (innervations)</td>
<td>17</td>
<td>USB powered</td>
</tr>
<tr>
<td>O2/CO tanks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>braslet, braslet-m cuff set x8</td>
<td>8</td>
<td>N/A</td>
</tr>
<tr>
<td>woodway force treadmill x2</td>
<td>459</td>
<td>none</td>
</tr>
<tr>
<td>inclined leg press</td>
<td>ARED</td>
<td></td>
</tr>
<tr>
<td>bench press</td>
<td>ARED</td>
<td></td>
</tr>
<tr>
<td>cycle ergometer x2 (danish aerospace)</td>
<td>53.6</td>
<td></td>
</tr>
<tr>
<td>Colbert system (150,000 miles) x2 (nasa)</td>
<td>1994</td>
<td></td>
</tr>
<tr>
<td>heart rate monitors x8 (garmin)</td>
<td>0.392</td>
<td>N/A</td>
</tr>
<tr>
<td>advanced resistive exercise device</td>
<td>100 cont, 200 peak</td>
<td></td>
</tr>
<tr>
<td>other equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>curve treadmill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>spin bikes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| note: Colbert uses woodway treadmill which is self powered and has added resistance |

<table>
<thead>
<tr>
<th>Medical Equipment</th>
<th>mass[kg]</th>
<th>power[W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ultrasound x2 (GE)</td>
<td>8</td>
<td>max 50W, but varies (conservative)</td>
</tr>
<tr>
<td>surface electromyography (delsys)</td>
<td>2.3</td>
<td>5.8</td>
</tr>
<tr>
<td>MRI</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>CDP</td>
<td>no info</td>
<td></td>
</tr>
<tr>
<td>OCT (heidelberg)</td>
<td>34.1</td>
<td>70 max</td>
</tr>
<tr>
<td>other eye scan</td>
<td>no info</td>
<td></td>
</tr>
<tr>
<td>echocardiograph</td>
<td>use ultrasound</td>
<td></td>
</tr>
<tr>
<td>blood pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vo2 max equipment (korr)</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>photoacoustic analyzer</td>
<td>PFS</td>
<td></td>
</tr>
<tr>
<td>gas delivery system</td>
<td>PFS</td>
<td></td>
</tr>
<tr>
<td>pulmonary function system</td>
<td>84</td>
<td>205 avg (252 max)</td>
</tr>
<tr>
<td>CBPD system</td>
<td>PFS</td>
<td></td>
</tr>
<tr>
<td>holter monitor x4 (braemarinc)</td>
<td>0.224</td>
<td>battery</td>
</tr>
<tr>
<td>urine analyzer</td>
<td>chemicals</td>
<td></td>
</tr>
<tr>
<td>blood analyzer</td>
<td>chemicals</td>
<td></td>
</tr>
<tr>
<td>saliva analyzer</td>
<td>chemicals</td>
<td></td>
</tr>
<tr>
<td>stool analyzer</td>
<td>chemicals</td>
<td></td>
</tr>
<tr>
<td>air sampler SWAB x2</td>
<td>6</td>
<td>battery</td>
</tr>
<tr>
<td>refrigerated centrifuge (nuwind)</td>
<td>80</td>
<td>900</td>
</tr>
<tr>
<td>regular centrifuge hitachi</td>
<td>17</td>
<td>AC 240 V, 10A</td>
</tr>
<tr>
<td>measure white blood cell count</td>
<td></td>
<td></td>
</tr>
<tr>
<td>measure stress hormones</td>
<td></td>
<td></td>
</tr>
<tr>
<td>stir bars</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV bags</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IVGEN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>exam table (brewer)</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>ambulatory echocardiogram</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bone densitometry</td>
<td>360</td>
<td>40 - 750 max</td>
</tr>
</tbody>
</table>
REFERENCES


REFERENCES


Specifications Pages – Don’t lend themselves well to AIAA format


REFERENCES


[41] http://www.capcomespace.net/dossiers/ISS/europe/columbus/Nouvea

Solar cell manufacturer comparison, solar array location study
SOLAR CELL COMPARISONS

- Spectrolab produces the best solar cell for our purposes

<table>
<thead>
<tr>
<th></th>
<th>AzurSpace 3G30C</th>
<th>SpectroLab NeXt</th>
<th>Sol Aero ZTJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power on Mt. (kW/m²)</td>
<td>3.66</td>
<td>3.74</td>
<td>3.83</td>
</tr>
<tr>
<td>Max Power at Base Loc. (kW/m²)</td>
<td>3.11</td>
<td>3.33</td>
<td>3.21</td>
</tr>
<tr>
<td>Efficiency</td>
<td>29.5%</td>
<td>29.5%</td>
<td>29.5%</td>
</tr>
</tbody>
</table>
**SOLAR ARRAY PLACEMENT**

- At the Mountain
  - Need to use AC power
  - Need to insulate cables
  - More complex, more problems

- Near the Base
  - DC power
  - No transformers
  - Easier to monitor
  - Less mass

---

**Power Loss vs Wire Diameter**

**Wire mass to Mountain vs Diameter**

Nick Ramser
% Nick Ramser AAE450 2nd Presentation

T_base = 220;
T_mt = 285;
dT_base = (28+273.15 - T_base);
dT_mt = (28+273.12 - T_mt);

% Azur Space Solar Cell Properties (at 28 deg C)
as_area = 40 * 80 / 100; % (cm^2)
as_mass = 86;
as_Voc = 2.7; % Open circuit voltage (V)
as_dVocdT = -6.2 * 1000; % (V/deg C)
as_Vmp = 2.411; % (V)
as_dVmpdT = -6.7 / 1000; % (V/degC)
as_Isc = 520.2 / as_area; % (mA/cm^2)
as_dIscdT = .36 / as_area; % (mA/cm^2.degC)
as_Imp = 504.4 / as_area; % (mA/cm^2)
as_dImpdT = .24 / as_area; % (mA/cm^2.degC)
as_eff = .295;
as_Isc_base = as_Isc + as_dIscdT * dT_base;
as_Imp_base = as_Imp + as_dImpdT * dT_base;
as_Voc_base = as_Voc + as_dVocdT * dT_base;
as_Vmp_base = as_Vmp + as_dVmpdT * dT_base;
as_FF_base = FF(as_Isc_base, as_Imp_base, as_Voc_base, as_Vmp_base);
as_Pmax_base = Pmax(as_Voc_base, as_Isc_base, as_FF_base) / 10

% Sol Aero
sa_mass = 84; % (mg/cm^2)
sa_eff = .295;
sa_Voc = 2.726;
sa_dVocdT = -6.3 / 1000;
sa_Isc = 17.4;
sa_dIscdT = 11.7 / 1000;
sa_Vmp = 2.41;
sa_dVmpdT = -6.7 / 1000;
sa_Imp = 16.5;
sa_dImpdT = 9.1 / 1000;
sa_Isc_base = sa_Isc + sa_dIscdT * dT_base;
sa_Imp_base = sa_Imp + sa_dImpdT * dT_base;
sa_Voc_base = sa_Voc + sa_dVocdT * dT_base;
sa_Vmp_base = sa_Vmp + sa_dVmpdT * dT_base;
sa_FF_base = FF(sa_Isc_base, sa_Imp_base, sa_Voc_base, sa_Vmp_base);
sa_Pmax_base = Pmax(sa_Voc_base, sa_Isc_base, sa_FF_base) / 10
sa_Isc_mt = sa_Isc + sa_dIscdT * dT_mt;
sa_Imp_mt = sa_Imp + sa_dImpdT * dT_mt;
sa_Voc_mt = sa_Voc + sa_dVocdT * dT_mt;
sa_Vmp_mt = sa_Vmp + sa_dVmpdT * dT_mt;
sa_FF_mt = FF(sa_Isc_mt, sa_Imp_mt, sa_Voc_mt, sa_Vmp_mt);

sa_Pmax_mt = Pmax(sa_Voc_mt, sa_Isc_mt, sa_FF_mt) / 10

% Spectro lab
sl_mass = 84;
sl_eff = .295;
sl_Voc = 2.633;
sl_dVocdT = -5.8 / 1000;
sl_Isc = 17.176;
sl_dIscdT = 11.6 / 1000;
sl_FF = .85;

sl_Isc_base = sl_Isc + sl_dIscdT * dT_base;
sl_Voc_base = sl_Voc + sl_dVocdT * dT_base;
sl_Pmax_base = Pmax(sl_Voc_base, sl_Isc_base, sl_FF) / 10

sl_Isc_mt = sl_Isc + sl_dIscdT * dT_mt;
sl_Voc_mt = sl_Voc + sl_dVocdT * dT_mt;
sl_Pmax_mt = Pmax(sl_Voc_mt, sl_Isc_mt, sl_FF) / 10

% Power Loss
V = 360;
density = 8960;
P_dem = 300 * 1000; % (W)
mt_dist = 45 * 1000; % (m)

P_base_m = (2 * P_dem)^2 .* R_base ./ (V^2);
P_loss_base = (2 * P_dem)^2 .* R_base ./ (V^2);
P_loss_mt = (1 / .8 * P_dem)^2 .* R_mt ./ (V^2);

figure(1)
pplot(D_wire, P_loss_mt / 1000 / 1000);
title('Power Loss vs Wire Diameter');
xlabel('Diameter (m)');
ylabel('Power Loss (W/m)');

wire_mass_mt = density / 1000 * pi * mt_dist .* (D_wire / 2).^2;
wire_mass_base = density * pi * base_dist .* (D_wire / 2).^2;

figure(2)
pplot(D_wire, wire_mass_mt / 1000);
title('Wire mass to Mountain vs Diameter');
xlabel('Diameter (m)');
ylabel('Wire Mass (Mg)');
P_base_m = (2 * P_dem - P_loss_base(21)) / (wire_mass_mt(21) + as_area ... 
* as_mass)
P_mt_m = (1 / .8 * P_dem - P_loss_mt(21)) / (wire_mass_mt(21) + as_area ... 
* as_mass)


February 11, 2016
Power Estimates for Charged Spheres - Radiation Shield
Safe Distance for Nuclear Reactor
Power Estimates for Charged Spheres

- Chose a sphere radius of 1 m
- To charge 35 spheres we need **0.0131 kWh** of energy
- 35 spheres would then take up a volume of **146.6077 m³**
- Spheres must be 50 MV each
**SPHERE MASS AND NUCLEAR TECH**

**MASS OF CHARGED SPHERES**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Mass for 1 m Radius Spheres (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>7.5766</td>
</tr>
<tr>
<td>Aluminum</td>
<td>11.7569</td>
</tr>
<tr>
<td>Iron</td>
<td>34.2691</td>
</tr>
<tr>
<td>Copper</td>
<td>39.0154</td>
</tr>
</tbody>
</table>

**NUCLEAR REACTOR**

<table>
<thead>
<tr>
<th>Reactor</th>
<th>SAFE-400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Fluid</td>
<td>Sodium</td>
</tr>
<tr>
<td>Distance from Base</td>
<td>1.1265 km</td>
</tr>
</tbody>
</table>
%Energy to Charge a Sphere by Induction
%Power/Thermo
%Rachel Lucas

% contact email: lucas27@purdue.edu

epsilon = 8.854187817 * 10^(-12); % vacuum permittivity in F/m
Q = 0.0005; % Electric charge in C
ko = 1/(4*pi*epsilon);
R = linspace(0.1,5,2^12);
U = ((3*ko)/5)*((Q^2)./R); % Electrostatic energy in J
U = U/(3.6*10^6); % Electrostatic energy in kWh
figure;
plot(R,U*35); % 35 spheres total
xlabel('Sphere Radius (m)');
ylabel('Electrostatic Energy (kWh)');
title('Electrostatic Energy to Charge Spheres');

V = (4/3)*pi*(R.^2); % Volume of a sphere in m
figure;
plot(R,V*35); % 35 spheres total
xlabel('Sphere Radius (m)');
ylabel('Volume (m^3)');
title('Volume of Spheres');
V = (4/3)*pi*(R.^3 - (R-0.01).^3);
M_Al = (V*35)*1000000*2.7*(1/1000000);
M_Fe = (V*35)*1000000*7.87*(1/1000000);
M_Cu = (V*35)*1000000*8.96*(1/1000000);
M_Mg = (V*35)*1740*(1/1000);
figure;
plot(R,M_Al);
hold on;
plot(R,M_Fe);
plot(R,M_Cu);
plot(R,M_Mg);
legend('Al','Fe','Cu','Mg');
xlabel('Sphere Radius (m)');
ylabel('Mass (Mg)');
title('Mass of Spheres');
R = 1;
eV = Q./(4*pi*epsilon*R); % Electric potential in V
References
INSULATION OPTIONS

- MLI
  - Thin
  - Delicate
  - Low heat transfer
- Lunar Regolith
  - Thick
  - Durable
  - High heat transfer
- MLI + Lunar Regolith
  - Very low heat transfer
  - Durable

Weronika Juszczak
### Thickness and Heat Transfer

<table>
<thead>
<tr>
<th>Thickness [m]</th>
<th>q'' (Watts/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLI</td>
<td>0.06</td>
</tr>
<tr>
<td>Regolith</td>
<td>1.00</td>
</tr>
<tr>
<td>MLI + Regolith</td>
<td>1.06</td>
</tr>
</tbody>
</table>

- Greatest heat transfer (coldest temperature)
- 30 layers of Regolith with a distance of 0.002 m between sheets
- Efficiency of number of layers
- Safety range between $0.015 < \varepsilon_{\text{eff}} < 0.005$ for 15 or more layers

Weronika Juszczak
%% Heat Transfer Analysis for Insulating Habs
%% Weronika Juszczak

\begin{verbatim}
\% Angle of Sun Above Lunar Horizon [deg]
b = [1:1:179]; % Angle of Sun Above Lunar Horizon [deg]
\% Latitude [deg]
a = 82; % Latitude \[deg\]
\% Temperature based on angle of the sun above the lunar horizon [K]
Tm = 373.9*(cosd(a)^.25).*((sind(b).^1.67); % Temperature based on angle of the sun above the lunar horizon \[K\]
\% number of layers of lunar regolith
n = [0:1:50]; % number of layers of lunar regolith
\% Thermal conductivity of MLI spencer [W/m*K]
ks = 0.00004; \% Thermal conductivity of MLI spencer \[W/m*K\]
\% Temperature of Inside Wall [K]
Tw1 = 293; % Temperature of Inside Wall \[K\]
\% Temperature of Outside Wall [K]
Tw2 = 120; % Temperature of Outside Wall \[K\]
\% length between layers of MLI \[m\]
L = .002; % length between layers of MLI \[m\]

%% Heat Transfer Across MLI with Varying n
\% Conduction Heat Transfer of Spacer
qc = ks*(Tw1-Tw2)./(n*L);
\% Radiation Heat Transfer
e = 0.04; % emissivity
boltz = 5.67e-8; % Boltzman constant \[W/m^2*K^\-4\]
qr = (e./(n+1)).*(2-e)).*boltz.*(Tw1.^4-Tw2.^4); % heat transfer per unit area for radiation heat transfer \[Watts/m^2\]
qtot = qr+qc;

figure
plot(n, qtot,n,qr,n,qc)
legend('total','radiation','convection')
title('Heat Transfer per Unit Area','FontSize',20)
xlabel('Number of MLI layers (n)')
ylabel('Heat Flux [Watts/m^2]')

figure
plot(L.*n,qtot)
title('Heat Transfer vs. Thickness of MLI','FontSize',20)
xlabel('Thickness [m]')
ylabel('Heat Flux [Watts/m^2]')
\end{verbatim}

%% Heat Transfer Through Regolith of Varying Thickness
kr = .015; % Thermal conductivity of Lunar Regolith 1 M thick \[W/m*K\]
x = [.5:.1:4]; % Thickness of Regolith \[m\]
qc_r = kr*(Tw1-Tw2)./(x); % Heat flux of regolish of varying thickness

figure
plot(x,qc_r)
title('Heat Transfer vs. Thickness of Regolith','FontSize',20)
xlabel('Thickness [m]')
ylabel('Heat Flux [Watts/m^2]')

%% Heat Transfer Regolith of Thickness X_R
X_R = 1; % Thickness of Regolith \[m\]
qc_r_tot = kr*(Tw1-Tw2)/X_R;

% Effective Emittance
em = 0.3; % emissivity of mylar
e1 = e;
e2 = .85;
eff = (((2.*n)./em)-n-1+(1/e1)+(1/e2)).^\-1
effs = eff(31);

plot(n,eff)
title('Effective Emittance of MLI','FontSize',20)
xlabel('Number of Layers')
ylabel('Eff')

Weronika Juszczak
%% Heat through MLI of thickness t_M
N_M = 30;
t_M = L*N_M;
qc_M = ks*(Tw1-Tw2)/(N_M*L);
qr_M = (e/((N_M+1)*(2-e)))*boltz.*(Tw1^4-Tw2^4);
q_M_tot = qc_M + qr_M;

%% Heat Transfer of Regolith and MLI of Specified Thickness
N = 30;
X = 1;
R1 = L*N/ks; % Thermal resistance of MLI
R2 = X/kr; % Thermal resistance of Regolith
q_comb = (Tw1-Tw2)/(R1+R2);
t_comb = X + L*N;

%% Heat Transfer Varying T
Tw2 = Tm;
qc_tot_T = (Tw1-Tw2)/(R1+R2);
qc_M_T = ks*(Tw1-Tw2)/(N_M*L);
qr_M_T = (e/((N_M+1)*(2-e)))*boltz.*(Tw1^4-Tw2^4);
q_M_tot_T = qc_M_T + qr_M_T;
qc_r_tot_T = kr*(Tw1-Tw2)/X_R;

figure
plot(Tw2,qc_tot_T,Tw2,q_M_tot_T,Tw2,qc_r_tot_T)
legend('MLI+Regolith','MLI','Regolith')
title('Heat Transfer vs. Moon Temperature','FontSize',20)
xlabel('Temperature (K)')
ylabel('Heat Flux [Watts/m^2]')
• MLI Material: Aluminized Mylar with heavy polyethylene terapthalate
• Calculations made at steady state
• Lunar Regolith properties at a depth of 1 meter
  \[ \rho = \rho_0 + \kappa \cdot \ln(z + 1) \]
• Temperature of solar flux a function of angle of sun above horizon and latitude
  \[ T_{\text{moon}}(K) = 373.9(\cos\phi)^{25}(\sin\theta)^{167} \]
• Through Layers of MLI considered radiation between layers, conduction between layers
• Through lunar regolith considered conduction
• Things to consider in the future: conduction between gas molecules, radiation between outside surface and sun/atmosphere
http://lss.fnal.gov/archive/other/ssc/sscl-526.pdf

http://uspas.fnal.gov/materials/10MIT/Lecture_5.1.pdf


http://elib.dlr.de/85680/1/Thomas_Ballatre_Diplomarbeit_2013.pdf

http://www.thermalengineer.com/library/effective_emittance.htm
Ferrying Lander
- Control Scheme Comparison
- Actuators and Astrionics (instrumentation/sensors)
CONTROL SCHEME COMPARISON

Stabilization Techniques

Gravity Gradient Stabilization
- Low use of power
- Low use of resources and instruments
- Difficult to dock with

Spin Stabilization
- Little power needed compared to 3-axis
- Continuous Process
- Simple
- Instruments only take measurements in one direction every rotation

Three-Axis Stabilization
- No need to de-spin instruments
- Better docking capabilities
- More control/accuracy
- Higher power costs

<table>
<thead>
<tr>
<th>Type of Forces Effecting Ferrying Lander</th>
<th>Torque (Nm)</th>
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<tbody>
<tr>
<td>Gravitational</td>
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<tr>
<td>Solar Radiation Pressure</td>
<td>8.0379e-04</td>
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<tr>
<td>Reflected Solar Radiation</td>
<td>7.3757e-10</td>
</tr>
<tr>
<td>Gravity Gradient</td>
<td>5.9847e-12</td>
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</tbody>
</table>

Author: Zarin Bari
Landing Mechanism
- Autonomous Precision Landing and Hazard Avoidance Technology (*ALHAT*)
  - Can be used in any lighting condition
  - Used for crewed, cargo and robotic vehicles
  - TRL 6

<table>
<thead>
<tr>
<th>Astrionics</th>
<th>Mass [Mg]</th>
<th>Power [W]</th>
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<tbody>
<tr>
<td>3-D Flash Lidar</td>
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<tr>
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<td>Doppler Lidar</td>
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<td>Laser Altimeter</td>
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<tr>
<td>Star Sensors*</td>
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<td>Sun Sensors*</td>
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<td></td>
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<td>1.872e-5</td>
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<tr>
<td>Magnetometers</td>
<td>0.0001</td>
<td>0.85</td>
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<td></td>
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<td>9.365e-5</td>
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* Redundancy

Actuators & Control Scheme

<table>
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<tr>
<th>Control Scheme</th>
<th>Mass [Mg]</th>
<th>Power [W]</th>
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<tbody>
<tr>
<td>Control Moment Gyroscope (CMG)</td>
<td>0.2720</td>
<td>276</td>
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<tr>
<td></td>
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<td>1.620</td>
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<tr>
<td>Reaction Wheels (4)</td>
<td>0.0200</td>
<td>80</td>
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<tr>
<td></td>
<td></td>
<td>0.006719</td>
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</tbody>
</table>
REFERENCES


Author: Zarin Bari
Calculating forces on the Ferrying Lander

clear all; close all; clc;

% Dimensions of the Ferrying Lander
% --> for now the lander dimensions are based off the Apollo Lunar Lander
% These values will change!!!
% --> also currently assuming the ferrying lander to be cylindrical
h = 6.985; % height in m
d = 9.4488; % diameter in m
r = d/2;

% moment of inertia values based on apollo lunar lander for now
% https://www.hq.nasa.gov/alsj/a14/a14mr-a.htm
Ixx = 3347 * 1.35581795; %kg-m^2
Iyy = 2878 * 1.35581795; %kg-m^2
Izz = 2055 * 1.35581795; %kg-m^2

% Solar Radiation Pressure
solar_cons = 1367; %ave solar constant in W/m^2
c = 3e8; % speed of light in m/s^2
As = (2*pi*r^2*h) + (2*pi*r^2); %surface area in m^2
q = 0; % assume perfect absorption
cps = 4; % assume the centers are close to each other
cm = 3.4925;
i = 0; %angle of incidence of the sun in degrees
Ts = (solar_cons/c)*As*(1+q)*(cps-cm)*cosd(i) %in Nm

% Reflected Solar Radiation
a = 0.11; % Bond albedo for the moon
k_elm = 1.5;
Rp = 1736482; % radius of the moon in m
r = 147000000 * 1000; %shortest distance from moon to sun in m
rps = 363104 * 1000; %perigee of the moon in m
Frsr = 2*k_elm*As*a*Rp^2*solar_cons / (3*c*r^2*rps^2); %force
Trsr = Frsr*rarm %in Nm

% Gravity Gradient
mu = 4.9048695e12; % gravitational parameter of the moon in m^3/s^2
theta = 1; %degrees
R = rps; % should be Rp + location of mass -- distance from center of moon to the s/c in m
Tg = ((3*mu)/(2*R^3))*abs(Izz - Iyy)*sind(2*theta) %in Nm
Projected Landing Scenario using ALHAT

Source: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100025705.pdf
Communication Satellites
  • Communication method
Requirement
- Continuous 2-way HD video link
  - Need 10-15 Mbps

Laser compared to radio-frequency
- Smaller wavelength = smaller receivers
- 10-100 times faster than RF
- Increased signal strength

Laser Communications Limitations
- Must have a ground station in view
  - Multiple satellites
- Requires great accuracy
- Weather on Earth can affect signal
COMMUNICATION SYSTEM
LUNAR LASER SPACE TERMINAL (LLST)

- Has 3 dedicated ground stations built already
- Flew aboard Lunar Atmosphere and Dust Environment Explorer (LADEE)
  - 9/7/13 – 4/18/14
- Estimated TRL 7
- To be tested again in 2017 on the Laser Communications Relay Demonstration (LCRD) mission

<table>
<thead>
<tr>
<th>LLST Specification</th>
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<tbody>
<tr>
<td>Data rate downlink</td>
<td>622 Mbps</td>
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<tr>
<td>Data rate uplink</td>
<td>20 Mbps</td>
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<tr>
<td>Power</td>
<td>137 W</td>
</tr>
<tr>
<td>Mass</td>
<td>30 Kg</td>
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### Specification

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<th>LLST</th>
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<tr>
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<td>Data rate downlink</td>
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<td>100 Mbps</td>
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<tr>
<td>Data rate uplink</td>
<td>20 Mbps</td>
<td>-</td>
</tr>
<tr>
<td>Mass</td>
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<td>21 kg</td>
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<td>Volume</td>
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<td>0.029 m^3</td>
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<tr>
<td>Power</td>
<td>137 W</td>
<td>95 W</td>
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</table>

**LADEE**

Mass: 0.4 Mg
Power: 295 W

**References**


Fuel Depot Sizing and Material Selection
### HYDROLOX

<table>
<thead>
<tr>
<th>Material</th>
<th>LH2</th>
<th>LOX</th>
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</thead>
<tbody>
<tr>
<td>Mass [Mg]</td>
<td>103.5276</td>
<td>374.7526</td>
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<tr>
<td>Volume [m$^3$]</td>
<td>480</td>
<td>165</td>
</tr>
<tr>
<td>Wall Thickness [m]</td>
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<td>0.275</td>
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<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>SS</th>
<th>Ti</th>
<th>Al</th>
<th>SS</th>
<th>Ti</th>
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<tbody>
<tr>
<td>Wall Thickness [m]</td>
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<td>0.06</td>
<td>0.07</td>
<td>0.015</td>
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</table>

### METHALOX

<table>
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<tr>
<th>Material</th>
<th>Methane</th>
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<tbody>
<tr>
<td>Mass [Mg]</td>
<td>117.6805</td>
<td>437.8208</td>
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<tr>
<td>Volume [m$^3$]</td>
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<td>165</td>
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<tr>
<td>Wall Thickness [m]</td>
<td>0.25</td>
<td>0.32</td>
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</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>SS</th>
<th>Ti</th>
<th>Al</th>
<th>SS</th>
<th>Ti</th>
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</thead>
<tbody>
<tr>
<td>Wall Thickness [m]</td>
<td>0.0775</td>
<td>0.06</td>
<td>0.07</td>
<td>0.015</td>
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**PURDUE UNIVERSITY**
CRYOGENIC CONSIDERATIONS

ASSUMPTIONS MADE

Calculations performed considering conductive heat transfer only

Fuel storage values required for one assent to XM3 and decent back to lunar surface

Found cylinder dimensions using optimal radius and height to minimize surface area

MLI data acquired from Power/Thermo group

Fuel volume, storage temperature, and properties provided by Propulsion group

Assumed fuel depot would stand in PSR (average temp approx. 40K)

Average PSR temperature below freezing point of LOX, Methan, above LH2
% Austin Black/Brian O'Neill/Weronika Juszczak

clear;clc;close all;

t_fuel = [17 65 100]; % Storage Temp of Fuels [LH2 LOX Methane] [K]
t3 = 41.15; % Ambient Temperature (avg. temp of PSR) [K]
tf = t3.*(9/5)-459.67; % Temp Kelvin to Farenheit
delta_t = t_fuel-t3; % Temp Difference across container wall
l = [0.01:.0025:1]; % Container thickness array
V = 160; % Fuel Volume [m^3]

ri = nthroot((2*V)/(4*pi),3); % Optimal inner radius to minimize surface area
h = V/(pi*(ri^2)); % Optimal inner height to minimize surface area

ISA = 2*pi*(ri^2)+2*pi*ri*h; % Inner Surface area [m^2]
OSA = 2.*pi.*((ri+l).^2)+2.*pi.*(ri+l).*h;
A = ISA+(OSA./2);
A_end = pi*(ri^2);

rho_fuel = [70.8 1141 438.89]; % [LH2 LOX Methane] kg/m^3
rho_con = [2700 8000 4430]; % [Al SS Ti] kg/m^3
M_fuel = [2.02 31.2 16.043]; % [LH2 LOX Methane] kg/kmol
R = 8314; % J/kmol.K

n = 1;
while n<= 3;
    P_fuel(n) = rho_fuel(n)*(R/M_fuel(n))*t_fuel(n);
    n=n+1;
end

hoop_LOX = ((P_fuel(1)*(2*ri))./(2.*l))/1000000;
hoop_LH2 = ((P_fuel(2)*(2*ri))./(2.*l))/1000000;
hoop_meth = ((P_fuel(3)*(2*ri))./(2.*l))/1000000;
long_LOX = ((P_fuel(1)*(2*ri))./(4.*l))/1000000;
long_LH2 = ((P_fuel(2)*(2*ri))./(4.*l))/1000000;
long_meth = ((P_fuel(3)*(2*ri))./(4.*l))/1000000;

yield = [276 215 880]; % Tensile Yield Strength [Al SS Ti] [MPa]
length_LOX = [0.06 0.07 0.015]; % Min thickness [Al SS Ti] [m]
length_LH2 = [0.22 0.275 0.067]; % Min thickness [Al SS Ti] [m]
length_meth = [0.25 0.32 0.0775]; % Min thickness [Al SS Ti] [m]

ro_LOX = []; 
ro_LH2 = []; 
ro_meth = []; 
n = 1;
while n<= 3;
    ro_LOX(n) = ri+length_LOX(n);
    ro_LH2(n) = ri+length_LH2(n);
    ro_meth(n) = ri+length_meth(n);
    n = n+1;
end

rho_MLI = 95;
k_MLI = 0.0001;
ADDITIONAL SLIDES

MATLAB CODE

rho_MLI = 95;
k_MLI = 0.0001;

% Aluminum
al = [0.07918 1.09570 -0.07277 0.08084 0.02803 -0.09464 0.04179...
     -0.00571 0]; % Constants for thermal conductivity calc
rho_al = 2700; % density

% 304 Stainless Steel
ss = [-1.04087 1.3982 0.2543 -0.6260 0.2334 0.4256 -0.4658 0.1650...
     -0.0199];
rho_ss = 8000; % density

% Ti-6Al-4V Titanium
ti = [-5107.8774 19240.422 -30789.064 27134.756 -14226.379 4438.2154...
     -763.07767 55.796592 0];
rho_ti = 4430; % density

% Heat Transfer Coefficients
k_al = 10.^(al(1)+al(2)*log10(t3)+(al(3)*log10(t3).^2)+(al(4)*log10(t3).^3)...
   +(al(5)*log10(t3).^4)+(al(6)*log10(t3).^5)+(al(7)*log10(t3).^6)+...
   +(al(8)*log10(t3).^7)+(al(9)*log10(t3).^8));
k_ss = 10.^(ss(1)+ss(2)*log10(t3)+(ss(3)*log10(t3).^2)+(ss(4)*log10(t3).^3)...
   +(ss(5)*log10(t3).^4)+(ss(6)*log10(t3).^5)+(ss(7)*log10(t3).^6)+...
   +(ss(8)*log10(t3).^7)+(ss(9)*log10(t3).^8));
k_ti = 10.^(ti(1)+ti(2)*log10(t3)+(ti(3)*log10(t3).^2)+(ti(4)*log10(t3).^3)...
   +(ti(5)*log10(t3).^4)+(ti(6)*log10(t3).^5)+(ti(7)*log10(t3).^6)+...
   +(ti(8)*log10(t3).^7)+(ti(9)*log10(t3).^8));

% Heat Transfer Calculations [Al SS Ti]
R_innerLOX = [ ];
R_innerLOX(1) = (log(ro_LOX(1)/ri))/(2*pi*k_MLI*length_LOX(1));
R_innerLOX(2) = (log(ro_LOX(2)/ri))/(2*pi*k_MLI*length_LOX(2));
R_innerLOX(3) = (log(ro_LOX(3)/ri))/(2*pi*k_MLI*length_LOX(3));
R_innerLH2 = [ ];
R_innerLH2(1) = (log(ro_LH2(1)/ri))/(2*pi*k_MLI*length_LH2(1));
R_innerLH2(2) = (log(ro_LH2(2)/ri))/(2*pi*k_MLI*length_LH2(2));
R_innerLH2(3) = (log(ro_LH2(3)/ri))/(2*pi*k_MLI*length_LH2(3));
R_innermeth = [ ];
R_innermeth(1) = (log(ro_meth(1)/ri))/(2*pi*k_MLI*length_meth(1));
R_innermeth(2) = (log(ro_meth(2)/ri))/(2*pi*k_MLI*length_meth(2));
R_innermeth(3) = (log(ro_meth(3)/ri))/(2*pi*k_MLI*length_meth(3));

% Heat Transfer Coefficients
R_totalLOXal(n) = R_innerLOX(1)+log((ro_LOX(1)+l_MLI(n))/(ro_LOX(1)))/(2*pi*k_MLI*l_MLI(n));
R_totalSS(n) = R_innerSS(1)+log((ro_LOX(1)+l_MLI(n))/(ro_LOX(1)))/(2*pi*k_MLI*l_MLI(n));
R_totalLH2al(n) = R_innerLH2(1)+log((ro_LH2(1)+l_MLI(n))/(ro_LH2(1)))/(2*pi*k_MLI*l_MLI(n));
R_totalmethal(n) = R_innermeth(1)+log((ro_meth(1)+l_MLI(n))/(ro_meth(1)))/(2*pi*k_MLI*l_MLI(n));

% Heat Transfer Coefficients
Q_LOX_al(n) = delta_t/R_totalLOXal(n);
Q_LOX_ss(n) = delta_t/R_totalSS(n);
Q_LOX_ti(n) = delta_t/R_totalti(n);
R_totalH2al(n) = R_innerH2(1)+log((ro_LH2(1)+l_MLI(n))/(ro_LH2(1)))/(2*pi*k_MLI*l_MLI(n));
R_totalH2ss(n) = R_innerH2(2)+log((ro_LH2(2)+l_MLI(n))/(ro_LH2(2)))/(2*pi*k_MLI*l_MLI(n));
R_totalH2ti(n) = R_innerH2(3)+log((ro_LH2(3)+l_MLI(n))/(ro_LH2(3)))/(2*pi*k_MLI*l_MLI(n));
Q_LH2_al(n) = delta_t/R_totalH2al(n);
Q_LH2_ss(n) = delta_t/R_totalH2ss(n);
Q_LH2_ti(n) = delta_t/R_totalH2ti(n);
R_totalmethal(n) = R_innermeth(1)+log((ro_meth(1)+l_MLI(n))/(ro_meth(1)))/(2*pi*k_MLI*l_MLI(n));
R_totalmethss(n) = R_innermeth(2)+log((ro_meth(2)+l_MLI(n))/(ro_meth(2)))/(2*pi*k_MLI*l_MLI(n));
R_totalmethti(n) = R_innermeth(3)+log((ro_meth(3)+l_MLI(n))/(ro_meth(3)))/(2*pi*k_MLI*l_MLI(n));
Q_meth_al(n) = delta_t/R_totalmethal(n);
Q_meth_ss(n) = delta_t/R_totalmethss(n);
Q_meth_ti(n) = delta_t/R_totalmethti(n);

MATLAB CODE
```matlab
figure(2);
subplot(3,1,1);
plot(l_MLI./0.0127,Q_LOX_al);
hold on;grid on;
plot(l_MLI./0.0127,Q_LOX_ss);
plot(l_MLI./0.0127,Q_LOX_ti);
title('Conductive Heat Transfer vs. MLI Layers - LOX');
xlabel('MLI Layers');
ylabel('Conductive Heat Transfer [W]');
legend('Aluminum','Stainless Steel','Titanium');
subplot(3,1,2);
plot(l_MLI./0.0127,Q_LH2_al);
hold on;grid on;
plot(l_MLI./0.0127,Q_LH2_ss);
plot(l_MLI./0.0127,Q_LH2_ti);
title('Conductive Heat Transfer vs. MLI Layers - LH2');
xlabel('MLI Layers');
ylabel('Conductive Heat Transfer [W]');
legend('Aluminum','Stainless Steel','Titanium');
subplot(3,1,3);
plot(l_MLI./0.0127,Q_meth_al);
hold on;grid on;
plot(l_MLI./0.0127,Q_meth_ss);
plot(l_MLI./0.0127,Q_meth_ti);
title('Conductive Heat Transfer vs. MLI Layers - Methane');
xlabel('MLI Layers');
ylabel('Conductive Heat Transfer [W]');
legend('Aluminum','Stainless Steel','Titanium');
```

```matlab
n = 1;
while n<=3;
    m_LOX(n) = (((pi*(ro_LOX(n)^2)*h)-pi*(ri^2)*h-2*length_LOX(n))*rho_con(n))/1000;
    m_LH2(n) = (((pi*(ro_LH2(n)^2)*h)-pi*(ri^2)*h-2*length_LH2(n))*rho_con(n))/1000;
    m_meth(n) = (((pi*(ro_meth(n)^2)*h)-pi*(ri^2)*h-2*length_meth(n))*rho_con(n))/1000;
    m_MLI_LOX(n) = (((pi*((ro_LOX(n)+0.25)^2)*h)-pi*((ro_LOX(n)^2)*h-2*length_LOX(n)))*rho_MLI)/1000;
    m_MLI_LH2(n) = (((pi*(ro_LH2(n)+0.25)^2)*h)-pi*(ro_LH2(n)^2)*h-2*length_LH2(n)))*rho_MLI)/1000;
    m_MLI_meth(n) = (((pi*(ro_meth(n)+0.25)^2)*h)-pi*(ro_meth(n)^2)*h-2*length_meth(n)))*rho_MLI)/1000;
    n = n+1;
end
```
http://www.math-prof.com/Calculus_1/Calc_Ch_17.asp
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100034929.pdf
http://www.sfu.ca/~mbahrami/ENSC%20388/Notes/Staedy%20Conduction%20Heat%20Transfer.pdf
Lander Structural Analysis
LANDING GEAR
BUCKLING ANALYSIS

• Determine acceptable range of values for strut thickness

• Find critical loads for different materials

• Determine whether buckling or yielding drives design

![Critical Force vs. Thickness](image)

**Figure 1**: Buckling Analysis for Carbon Fiber Composite – Adrian Pansini
- Aluminum alloys and carbon fiber composites have similar mechanical properties
- Aluminum alloys proven through use in Apollo program
- Best option so far is carbon fiber composites
  - Lightest material
  - Similar properties to proven materials

Figure 1: Material comparison – Adrian Pansini

Adrian Pansini
%% Critical Load Calculator for Buckling

clear all
close all
clc

promptr2 = 'Enter the outer radius of the cylinder [m]: ';
promptr1 = 'Enter the inner radius of the cylinder [m]: ';
promptE = 'Enter the Elastic modulus of the material [Pa]: ';
promptK = 'Enter the effective length of the cylinder: ';
promptL = 'Enter the length of the cylinder [m]: ';
fprintf('

');

r2 = input(promptr2);
r1 = input(promptr1);
E = input(promptE);
I = (pi/4)*(r2^4 - r1^4);
K = input(promptK);
L = input(promptL);

Fcr = ((pi^2)*E*I) ./ ((K*L).^2);

fprintf('The critical load for buckling is %.3f N

', Fcr);

%% Trends for Buckling + Yield

% Plotting Fcr vs. Cylinder Thickness

figure(1);
E = 70*10^9; % Pa
K = 1;
L = 3; % m
t = 0.005:0.0001899:0.1; % m
I = (pi/4)*((r2.^4 - (r2-t).^4));
Fcr = ((pi^2)*E*I) ./ ((K*L).^2); % N
area = pi*(r2.^2 - (r2-t).^2); % m^2
sigmay = 600*10^6; % Pa
Fcry = sigmay * area; % N

plot(t,Fcr,'b');
title('Critical Force vs. Thickness');
xlabel('Thickness [m]');
ylabel('Fcr [N]');
hold on;
plot(t,Fcry,'g');
legend('Critical Buckling','Critical Yield');
MATLAB SCRIPT

%% Material Comparison

figure(2);
E = 70*10^9; % Pa
K = 1;
L = 1:0.01:6; % m
t = 0.1;
I = (pi/4).*((r2.^4 - (r2-t).^4));
Fcr = ((pi^2)*E*I) ./ ((K*L).^2);
area = pi*((r2.^2 - (r2-t).^2)); % m^2
sigmay = 600*10^6; % Pa
Fcry = sigmay * area; % N
plot(L,Fcry,'b');
title('Critical Force vs. Length');
xlabel('Length [m]');
ylabel('Fcr [N]');
hold on;
plot(L,Fcry,'g');

%% Plotting Fcr vs. Cylinder Thickness

E = [70*10^9, 50*10^9, 40*10^9, 30*10^9];
sigmay = [600*10^6, 420*10^6, 300*10^6, 200*10^6];
K = 1;
L = 3; % m
t = linspace(0.005, 0.1, 501); % m
Fcr = zeros(length(t));
I = (pi/4).*((r2.^4 - (r2-t).^4));
area = pi*((r2.^2 - (r2-t).^2)); % m^2
Fcr1 = ((pi^2)*E*(1)*I) ./ ((K*L).^2); % N
Fcry1 = sigmay(1) .* area; % N
Fcr2 = ((pi^2)*E*(2)*I) ./ ((K*L).^2); % N
Fcry2 = sigmay(2) .* area; % N
Fcr3 = ((pi^2)*E*(3)*I) ./ ((K*L).^2); % N
Fcry3 = sigmay(3) .* area; % N
Fcr4 = ((pi^2)*E*(4)*I) ./ ((K*L).^2); % N
Fcry4 = sigmay(4) .* area; % N

%% Plotting Fcr vs Cylinder Length

L = 1:0.01:6; % m
t = 0.1; % m
I = (pi/4).*((r2.^4 - (r2-t).^4));
Fcr1 = ((pi^2)*E*(1)*I) ./ ((K*L).^2); % N
Fcry1 = sigmay(1) .* area; % N
Fcr2 = ((pi^2)*E*(2)*I) ./ ((K*L).^2); % N
Fcry2 = sigmay(2) .* area; % N
Fcr3 = ((pi^2)*E*(3)*I) ./ ((K*L).^2); % N
Fcry3 = sigmay(3) .* area; % N
Fcr4 = ((pi^2)*E*(4)*I) ./ ((K*L).^2); % N
Fcry4 = sigmay(4) .* area; % N
REFERENCES

• [1] Carbon Steel mechanical properties
  • http://www.ezlok.com/TechnicallInfo/MPCarbonSteel.html

• [2] Carbon Fiber mechanical properties

• [3] Aluminum 7075 mechanical properties
  • http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA7075T6

• [4] Aluminum 2024 mechanical properties
  • http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA2024T4
XM-2 Design and Structural Analysis
SLS Payload Fairing for Reference
XM-2 DESIGN
BASED ON BIGELOW 330

- Dimensions based on BA330
- Deployed Volume: \( \approx 338 \, m^3 \)
- Deployed Mass: TBD
- Power: TBD
- Items Left to Determine
  - Need material definition.
  - Need to finalize XM shell.
  - Need to work with Power/Thermal and Human Factors to define power requirements.

* SolidWorks model by Amit Soni
• Major structural concern is the multi-layer inflatable shell.
• Loading conditions
  • Interior pressurization
  • Launch load
  • Orbital Maneuvers
  • Docking/undocking
  • Solar radiation, etc.
• Need to determine shell layer composition.
• Systems Request: Payload Fairing Envelope
  • 7.5m dia
  • 14.03m length
  • Usable volume : 620m³

* SolidWorks models by Amit Soni
* SolidWorks drawing by Amit Soni. All dimensions in meters.
• Internal Pressure Model: 101.325 kPa
• Gravity Load: 6 G’s
• Proof of concept modeled with 30 pllys of Kevlar 29, oriented at 0°, 45°, 90°, -45° for isotropic properties.
• Only outer shell analyzed.

* SolidWorks FEA model by Amit Soni
• Material properties still to be researched
• Shell compositions provided in Simosen, et. al (2000)
• BA330 shell very similar.
• Kevlar could be replaced by Vectran
• Layers to be modeled in Solidworks FEA

* Inflatable Layup created from information provided in Simosen, et. Al (2000)


