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Cryogenic thermal system analysis for orbital propellant depot

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ABSTRACT

In any manned mission architecture, upwards of seventy percent of all payload delivered to orbit is propellant, and propellant mass fraction dominates almost all transportation segments of any mission requiring a heavy lift launch system like the Saturn V. To mitigate this, the use of an orbital propellant depot has been extensively studied. In this paper, a thermal model of an orbital propellant depot is used to examine the effects of passive and active thermal management strategies. Results show that an all passive thermal management strategy results in significant boil-off for both hydrogen and oxygen. At current launch vehicle prices, these boil-offs equate to millions of dollars lost per month. Zero boil-off of propellant is achievable with the use of active cryocoolers; however, the cooling power required to produce zero-boil-off is an order of magnitude higher than current state-of-the-art cryocoolers. This study shows a zero-boil-off cryocooler minimum power requirement of 80–100 W at 80 K for liquid oxygen, and 100–120 W at 20 K for liquid hydrogen for a representative Near-Earth Object mission. Research and development effort is required to improve the state-of-the-arts in-space cryogenic thermal management.

1. Introduction

In 2009, the Review of United States Human Space Flight Plans Committee, also known as the Augustine Committee, was charged by the Office of Science and Technology Policy to review the multitude of options for human spaceflight and human exploration after the planned retirement of the Space Shuttle Program. The result of the 6 months review was a 150 page report documenting various recommendations for the future of United States space policy [1]. The committee's primary finding was that achieving the ultimate goals of human space exploration to other planets would require both "physical and economic sustainabilities." The committee judged the Constellation Program [2] to be so far behind schedule and underfunded that meeting any of its objectives would be impossible. In response to the review, President Obama canceled the Constellation Program and enacted the 2010 National Space Policy of the United States of America [3].

The National Space Policy set forth new and far-reaching exploration milestones that include a crewed mission to a near Earth object (NEO) by 2025 and a crewed mission to Martian orbit by the mid-2030s. The exploration milestones follow the "Flexible Path towards Mars with alternatives to the Moon" strategy outlined by the Augustine committee. The goal of the flexible path strategy is to take incremental steps towards Mars, allowing astronauts to learn, live, and work in free space under similar conditions to those found on the way

Abbreviation: AFRL, air force research laboratory; AU, astronomical unit; CFM, cryogenic fluid management; COP, coefficient of performance; HEFT, human exploration framework team; IR, infrared; LEO, low Earth orbit; LH_2, liquid hydrogen; LO_2, liquid oxygen; MLI, multilayer insulation; NEA, near Earth asteroid; NEO, near Earth objects; SEET, space environment and effect tool; ZBO, zero-boil-off

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Nomenclature

A	propellant tank surface area, m^2
A_o	total radiating surface area, m^2
C_1	gas conduction constant
ΔV	orbital velocity change, m/s
η	cryocooler efficiency, % Carnot
β	surface absorptivity
ϵ	surface emissivity
ϵ_H	MLI hot side emissivity
ϵ_C	MLI cold side emissivity
E_{absorbed}	energy absorbed, J
E_{internal}	internally generated energy, J
$E_{\text{dissipated}}$	energy dissipated, J
f_{eclipse}	eclipse factor
γ	ratio of specific heats
K_s	solid conduction constant, W/m K
M	molecular weight, kg/kmol
M_{cooler}	cryocooler mass, kg
M_{Prop}	propellant mass, kg
M_{MLI}	multi-layer insulation mass, kg
M_{tank}	propellant tank mass, kg
$\overline{N}$	MLI density, /cm
N_s	number of layers of MLI
P	pressure of gas between MLI layers, Pa
P_{in}	power input for cryocooler, w
Q_c	cryocooler cooling power, w
Q_{er}	heat load from Earth reflected albedo, w
Q_i	spacecraft internal heat load, w
Q_{IR}	Earth infrared radiation, w
Q_m	mixer heat load, w
Q_p	penetration heat load, w
Q_{para}	parasitic heat load, w
Q_s	structural heat load, w
Q_{Sun}	solar direct radiation, w
q/A	heat load per unit area, w/m^2
R	universal gas constant, J/kg K
ρ_m	unit mass of insulation sheet, kg/m^2
ρ_s	density of spacer material, kg/m^3
σ_B	Stefan–Boltzmann constant, w/m^2 K^4
T	temperature, K
T_c	cold side temperature, K
T_h	hot side temperature, K
T_o	spacecraft equilibrium temperature, K
t_m	thickness of insulation sheet, m
t_s	thickness of spacer material, m

to Mars. Following the flexible path strategy allows humanity to gain ever-increasing operational experience in-space, growing in duration from a few weeks to several years in length, and moving from close proximity to the Earth to as far away as Martian orbit. These incremental steps involve several intermediate destinations to explore before Mars. Fig. 1, reproduced from the Augustine committee's report [1], shows a notional representation of the flexible path leading to an eventual Mars mission.

The Augustine committee also identified several technologies that it deemed critical for sustainable space exploration and thus a priority for NASA to develop. One of these technologies identified was the storage and transfer of cryogenic propellant in-space. In any exploration mission architecture, upwards of seventy percent of all payload delivered to orbit is propellant [4], and propellant mass fraction dominates every stage. Without significant breakthroughs in propulsion or materials technology [5], a more efficient and economical method to deliver and store propellant in orbit is needed. Many studies by NASA and commercial companies have examined and noted the tremendous benefits of the utilization

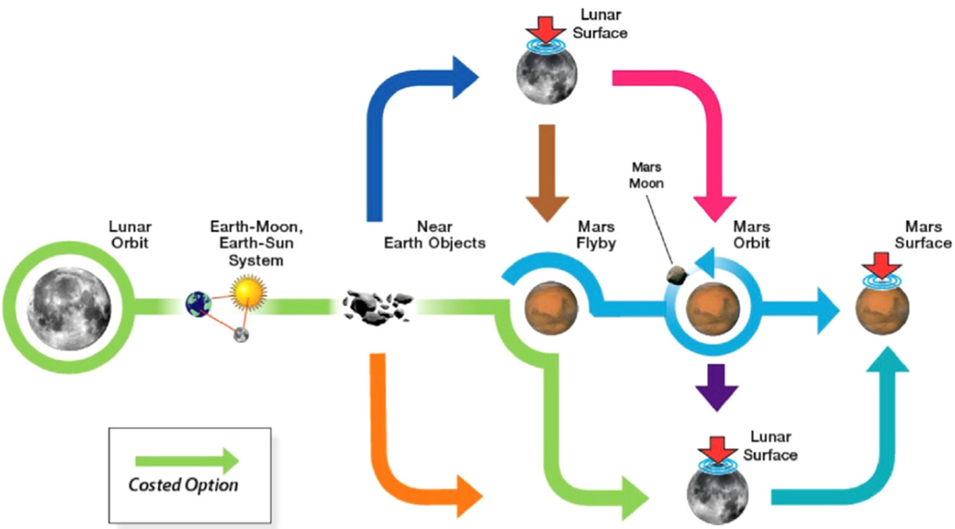

Fig. 1. Options for exploration within flexible path strategy [1].