Engineering Notes

Parametric Analysis of Single-Stage Earth-Departure-Stage In-Orbit Refueling

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Nomenclature

A	=	total mass stage gear ratio
A_1	=	propellant mass stage gear ratio
I_{sp}	=	stage specific impulse, s
m_{EDS}	=	total Earth-departure-stage stage mass (reference case is overlined), kg
m_d	=	stage inert mass (reference case is overlined), kg
m_p	=	Earth-departure-stage propellant mass (reference case is overlined), kg
m_{pl}	=	cargo launch-vehicle payload mass (reference case is overlined), kg
m_{p0}	=	Earth-departure-stage payload mass (reference case is overlined), kg
$m_{p\,tank}$	=	tanker launch vehicle propellant payload mass (reference case is overlined), kg
m_{tot}	=	cargo launch-vehicle total mass (reference case is overlined), kg
α	=	propellant fill ratio coefficient
β	=	payload growth rate
Γ	=	packaging efficiency
ΔV_0	=	design delta V (reference case is overlined), m/s
λ	=	tare overhead fraction
μ	=	stage inert mass fraction

I. Introduction

AN EARTH departure stage (EDS) is one of the required developments toward the establishment of a future launch infrastructure for human space exploration beyond low Earth orbit (LEO). Because orbital maneuvers required in human spaceflight missions to the Moon and Mars imply demanding delta V budgets compared to LEO missions, an in-orbit propulsion stage will likely be required to efficiently meet overall mission requirements in conjunction with a new generation of man-rated transportation infrastructure [1] such as NASA's Space Launch System [2]. Traditionally, conceptual studies considered "all-up" launch architectures, where the EDS was launched fully fueled and ignited once the EDS and payload combination was already injected in LEO [3–6]. Nevertheless, previous studies considered on-orbit refueling of the upper stages of the launch vehicle stack, including refueling of the EDS, as a technology of interest to enhance payload capacity [7]. On-orbit refueling options have also been considered as means to allow the use of smaller launch vehicles (LVs) with respect to heavy-lift and super-heavy-lift LVs that are typically required in all-up architectures of human space exploration missions beyond LEO [7]. Previous studies have also considered reference designs of high-specific-impulse electrical tugs for refueling chemical orbital transfer vehicles for geostationary transfers [8] and on-orbit refueling of satellites in orbit [9,10]. However, there has been little systematic effort in the literature in characterizing fundamental tradeoffs associated with on-orbit refueling from a systems architecture perspective.

The goal of this Note is to fill this gap in the literature and explore possibilities associated with different on-orbit refueling strategies while evaluating associated performance benefits. This goal is achieved through a first-order parametric analysis of on-orbit refueling of single-stage Earth departure stages. The analysis derives nondimensional parameters for payload growth rates and packaging ratios, which make the framework suitable to be used to any reference payload mass size of interest and allow consideration of a variety of classes of launch vehicles.

II. Parametric Approach

This section describes the parametric approach that has been developed for the analysis, documenting assumptions, and sizing processes followed for two different on-orbit refueling strategies considered in the study. The Note considers in-orbit refueling scenarios where a single-stage EDS is carried by a cargo LV to LEO and is later refueled by a tanker LV. The goal of the analysis is to quantify the performance benefits associated with on-orbit refueling operations, as measured by payload capability growth for an EDS operating from LEO, and the packaging efficiency associated, as measured by the ability of enabling refueling using a tanker LV of similar class of the cargo LV. The analysis is performed through a parametric model that compares a reference case to other scenarios where two different on-orbit refueling strategies are considered.

A. Reference Case

The reference case consists of a fully fueled single-stage EDS of mass $\bar{m}_{EDS}$ delivered in LEO by a cargo LV. It is assumed that the EDS and its payload $\bar{m}_{p0}$ have a nominal total mass equal to $\bar{m}_{pl}$, that is,

$$\bar{m}_{pl} = \bar{m}_{EDS} + \bar{m}_{p0} \tag{1}$$

Once in LEO, the EDS accelerates the nominal payload $\bar{m}_{p0}$ for a change in orbital velocity $\Delta\bar{V}_0$. Using the rocket equation [11], the reference EDS mass can be calculated as

$$\bar{m}_{EDS} + \bar{m}_{p0} = \bar{m}_p + \bar{m}_d + \bar{m}_{p0} = \left\lfloor \left(\frac{\mu}{1-\mu} + 1\right) A_1 + 1 \right\rfloor \bar{m}_{p0} = A \cdot \bar{m}_{p0} \tag{2}$$

$$A_1 = \frac{(1-\mu)(1-R)}{\mu R - 1} \tag{3}$$

where R is the EDS gear ratio defined as a function of $\Delta\bar{V}_0$ and stage specific impulse I_{sp}:

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Table 1 Survey of existing and proposed U.S. cryogenic upper stages (public-domain data)

Name	Gross mass, t	Dry mass, t	Dry mass fraction	I_{sp}, s
Centaur B–X	19.1	2.4	0.11	470
Centaur C	15.6	2.0	0.11	425
Centaur C–X	19.1	2.4	0.11	450
Centaur D/E	16.3	2.6	0.14	444
Centaur I	15.6	1.7	0.10	444
Centaur-2A	19.1	2.3	0.11	449
Centaur-3A	18.7	1.9	0.09	451
Centaur-V1	22.8	2.0	0.08	451
Centaur-V2	23	2.2	0.09	451
Delta 4-2	24.2	2.8	0.10	462
Delta 4H-2	30.7	3.5	0.10	462
Average	— —	— —	0.10	451

$$R = \exp\left(\frac{\Delta \bar{V}_0}{g I_{sp}}\right) \tag{4}$$

μ is the dry mass fraction of the EDS stage, which relates the stage dry mass $\bar{m}_d$ and propellant mass $\bar{m}_p$ as follows:

$$\bar{m}_d = \mu(\bar{m}_d + \bar{m}_p) = \frac{\mu}{1-\mu}\bar{m}_p \tag{5}$$

The reference case considered in this Note assumes $I_{sp} = 451$ s and $\mu = 0.10$ as performance values for the analysis. These assumptions represent average performance values of cryogenic upper stages, as derived by a survey on public domain data of existing and proposed cryogenic upper stages (that are close analogs to Earth departure stages). The survey is shown in Table 1.

B. Refueling Scenarios Modeling Approach

In the refueling scenarios considered, the EDS initially carries $\alpha \cdot m_p$ propellant, where m_p is propellant mass at full load, and α is the fill ratio coefficient (varying from 0 to 1). Therefore, tanker LVs carry a propellant mass of $(1-\alpha)m_p$ as their payload. A tare overhead fraction λ is added to account for refueling equipment (worst-case reference value considered $\lambda = 0.30$), making the total payload propellant for tanker LVs equal to

$$m_{p\,\mathrm{tank}} = (1-\alpha)m_p(1+\lambda) \tag{6}$$

The goal is to estimate the increased payload capacity on the cargo LV achieved by means of on-orbit refueling, as measured by payload growth rate β:

$$m_{p0} = \bar{m}_{p0}(1+\beta) \tag{7}$$

Payload growth rate achieved is a function of the chosen refueling strategy. In both refueling strategies considered, a constraint is set so that all EDS configurations are such that the total mass of the EDS stage plus carried payload equals the total EDS mass plus payload mass of the reference case:

$$\begin{aligned} m_{\mathrm{tot}} &= m_{\mathrm{EDS}} + m_{p0} \\ \bar{m}_{\mathrm{tot}} &= \bar{m}_{\mathrm{EDS}} + \bar{m}_{p0} \\ m_{\mathrm{tot}} &= \bar{m}_{\mathrm{tot}} \rightarrow m_{\mathrm{EDS}} + m_{p0} = \bar{m}_{EDS} + \bar{m}_{p0} \end{aligned} \tag{8}$$

The isomass constraint shown in Eq. (8) enables comparison of payload growth rates between different refueling strategies. The following sections describe those strategies and derive associated closed form expressions of payload growth rates.

C. Refueling Strategy 1: Transfer Some Fuel, No Payload

The first refueling strategy being considered, named "transfer some fuel, no payload", is illustrated in Fig. 1. This strategy involves launching a partially fueled EDS carrying the nominal reference case payload $\bar{m}_{p0}$. The EDS is then refueled in orbit by one or more tanker LVs. In this strategy, the limit case $\alpha = 1$ reproduces the EDS of the reference case. As α is reduced, both the payload and the EDS grow in size as space is made available by propellant instead being delivered by tanker LVs. As a result, the limit case of $\alpha = 0$ is the case in which both the EDS and EDS payload are maximum.

Payload growth rate is derived by applying the constraint described in Eq. (8):

$$\bar{m}_{\mathrm{tot}} = A\bar{m}_{\mathrm{pl}}(1+\beta) - m_p(1-\alpha) \tag{9}$$

Substituting terms using the parameterization shown in Table 1 leads to the following expression for β:

$$\beta = \frac{A}{A-(1-\alpha)A_1} - 1 \tag{10}$$

Packaging efficiency Γ is defined as the ratio between propellant mass to be delivered by the tanker LV (including tare overhead) and cargo LV payload mass:

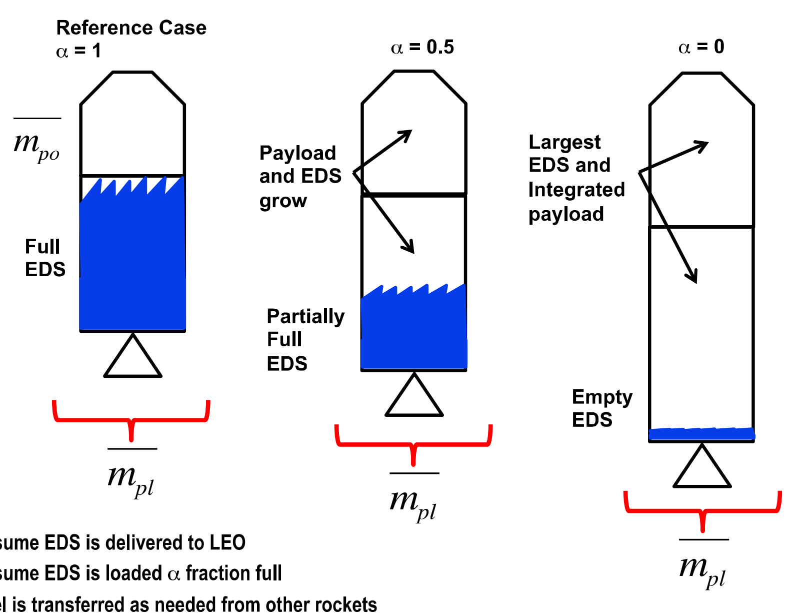

Fig. 1 Refueling strategy 1: transfer some fuel, no payload.

$$\Gamma = \frac{m_{p\,\mathrm{tank}}}{m_{p0}} \tag{11}$$

Section III will compare payload growth rate and packaging efficiency shown in Eqs. (10) and (11) with the payload growth rate and packaging efficiency of refueling strategy 2, which is now discussed.

D. Refueling Strategy 2: Transfer Some Fuel, All Payload

The second refueling strategy being considered, named "transfer some fuel, all payload", is illustrated in Fig. 2. In this strategy, the initial cargo LV delivers to LEO a partially filled EDS but does not carry any payload. Differing from the first strategy, both propellant and payload are transferred to the EDS by means of tanker LVs. While propellant is transferred to the cargo LV as required, refueling strategy 2 does not consider cases of partial payload transfer between tanker and cargo LVs because it is assumed that payload is assembled and integrated on the ground to minimize operational risk. Note that, in this strategy, $\alpha = 1$ does not reproduce the reference case because the payload is carried by tanker LVs in this scenario, whereas payload is carried by the cargo LV in the reference case.

As in the previously considered refueling strategy, enforcing Eq. (8) leads to the following expression:

$$\bar{m}_{\mathrm{tot}} = (A - 1)\bar{m}_{\mathrm{pl}}(1 + \beta) - m_p(1 - \alpha) \tag{12}$$

Solving for β, the following expression is obtained:

$$B = \frac{A}{(A - 1) - (1 - \alpha)A_1} - 1 \tag{13}$$

Packaging efficiency Γ is measured as the ratio between propellant mass to be delivered by the tanker LV (including tare overhead) plus cargo LV payload mass and the cargo LV payload mass itself:

$$\Gamma = \frac{m_{p\,\mathrm{tank}} + m_{p0}}{m_{p0}} \tag{14}$$

As expressions for payload growth rates and packaging efficiencies have been derived for both refueling strategies, Sec. III will now develop a comparative analysis leading toward the development of insights on the aforementioned refueling scenarios.

III. Results

This section develops comparative analysis between the two on-orbit refueling strategies discussed in this Note and derives general insights on single-stage EDS refueling. Figure 3 shows the payload growth rate as a function of delta V achieved by the EDS for three different EDS fill ratios. These results shows that payload growth rate ranges between 1.5 and 25, with the range depending on the reference delta V required by the EDS and the fill ratio coefficient being considered. Figure 4 shows said range for a delta V of $\Delta V = 3000\ \mathrm{m/s}$, which is the reference case being considered. A delta V of $3000\ \mathrm{m/s}$ is, in fact, approximately the delta V required to transition from LEO to a parabolic Earth escape orbit, which is considered a reference case for human space exploration missions beyond LEO. In this scenario, a cargo LV carrying 25 tons of payload

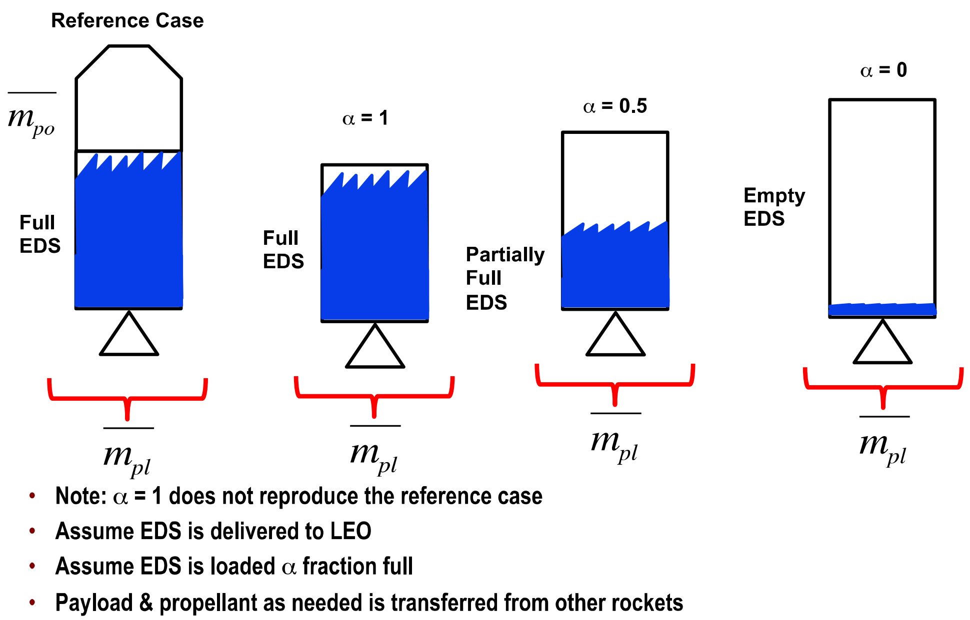

Fig. 2 Refueling strategy 2: transfer some fuel, all payload.

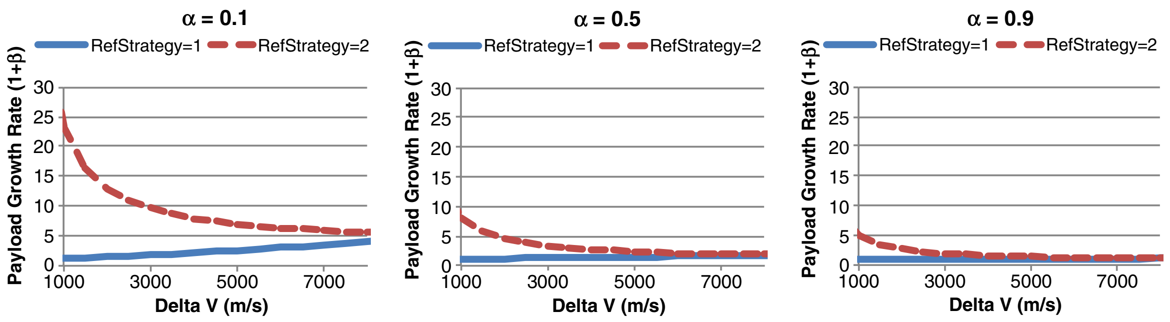

Fig. 3 Payload growth rate as a function of EDS design delta V for 0.1 (left), 0.5 (middle), and 0.9 (right) propellant fill ratio values.

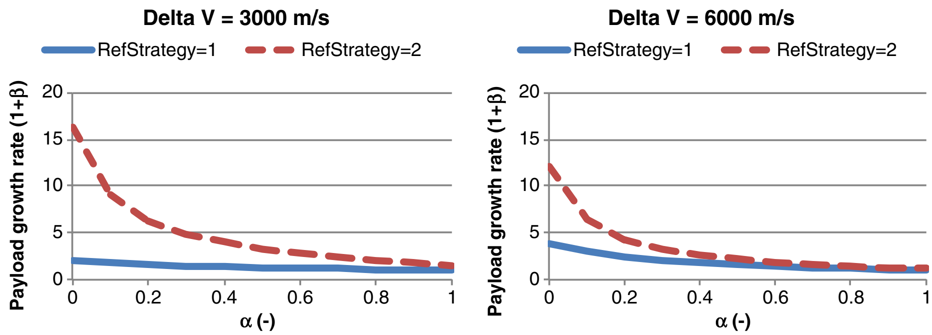

Fig. 4 Payload growth rate as a function of propellant fill ratio for EDS design delta *V* cases of 3000 m/s (left) and 6000 m/s.

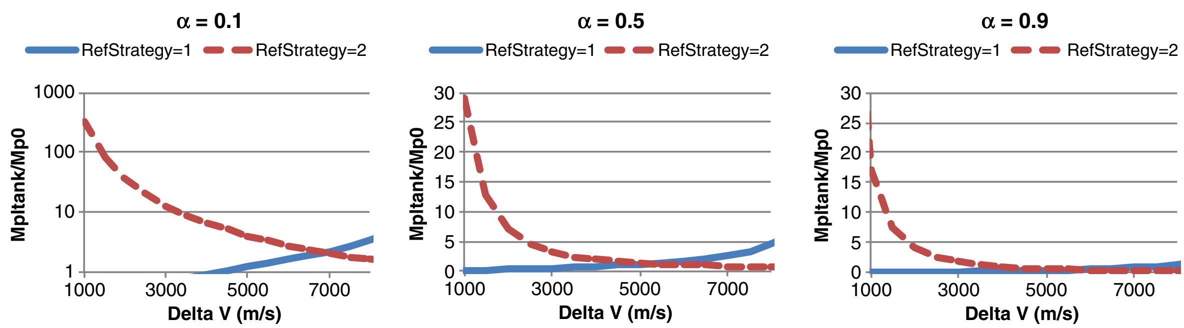

Fig. 5 Packaging efficiency as a function of EDS design delta *V* for 0.1 (left), 0.5 (middle), and 0.9 (right) propellant fill ratio values.

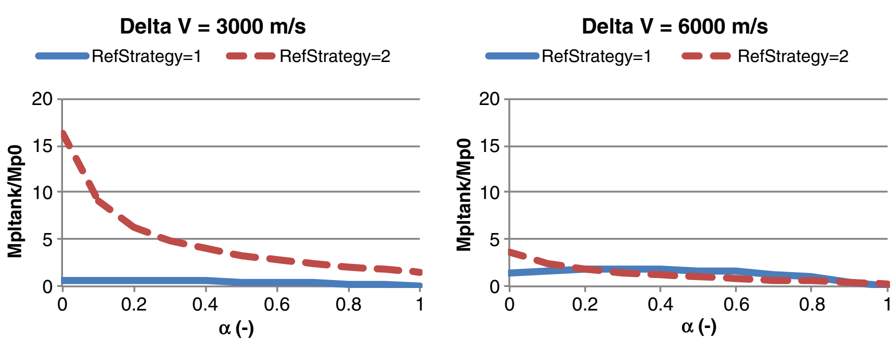

Fig. 6 Packaging efficiency as a function of propellant fill ratio for EDS design delta *V* cases of 3000 m/s (left) and 6000 m/s.

(Shuttle-class or Ariane 5-class LV) is capable of launching an EDS with throw capacity ranging between 37.5 and 400 tons to LEO. However, high payload growth rates lead to dissimilar, and larger, tanker LVs compared to their corresponding reference cargo LVs. Figure 5 shows the ratio of tanker payload mass and cargo payload mass, here referred to as packaging efficiency, a significant proxy for dissimilarity in size between the tanker LV and the cargo LV. Figure 6 shows packaging efficiency as a function of propellant fill ratio for the reference scenario with an EDS design delta *V* of 3000 m/s, compared to a design delta *V* scenario of 6000 m/s. As it can be seen from the figures, tanker vehicle size and dissimilarity with cargo vehicle size is of particular concern with refueling strategy 2 (transfer some fuel, all payload), which allows for larger EDS sizes due to mass made available by payload transfer. Packaging efficiency therefore suggests two different launch vehicle family development strategies. A first strategy is to design tanker LVs and the cargo LV of similar size. In this case, refueling strategy 1 displays higher packaging efficiencies with a payload growth rate of up to 2.5, that is, a 150% payload growth capability with respect to the reference scenario. A second strategy is to design launch vehicles that are very dissimilar in size, with a smaller cargo LV carrying the EDS and a larger tanker LV carrying propellant. In this scenario, refueling strategy 2 seems the most promising because it delivers very large payload growth rates as shown by the analysis. This strategy leads to a payload growth rate of up to 18 times the reference case payload for an EDS design delta *V* of 3000 m/s. Furthermore, this result suggests a hybrid refueling strategy where crew and a crew capsule are launched along with a small man-rated cargo LV with an unfueled (or partially fueled) EDS, while propellant is delivered to LEO by a larger unmanned tanker LV. This strategy likely delivers significant reduction in overall lifecycle cost because it removes the need for man-rated super-heavy lift launch vehicles.

IV. Conclusions

This Note set out a parametric model to study on-orbit refueling of single-stage Earth departure stages. The model is of general use because it employs nondimensional parameters than can then be scaled to any reference case of interest. The model has been used to evaluate two different on-orbit refueling strategies: one where partial refueling occurs with no payload transfer, and one where partial refueling occurs along with payload transfer. The main tradeoff that has been identified in the analysis occurs between payload growth rate, as measured by the ratio of payload mass compared to payload mass of a reference sizing case with no on-orbit refueling, and associated packaging efficiency, as measured by the ratio in size between the cargo and tanker launch vehicles. Higher payload growth gains lead to higher dissimilarities in cargo/tanker launch vehicle sizes, hence leading to different on-orbit refueling approaches. A first on-orbit refueling approach is tailored to lead to similar size tanker and cargo launch vehicles with modest payload growth rates compared to a reference nonrefueling scenario. A second approach is instead tailored to lead to very dissimilar tanker and cargo launch vehicle sizes. Dissimilarity allows to design smaller man-rated cargo launch vehicles and larger unmanned tanker launch vehicles, leading to likely reduction of overall lifecycle costs for a human spaceflight mission.

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