COST-EFFECTIVENESS OF LUNAR OXYGEN AND LUNAR HYDROGEN IN FUTURE SPACE TRANSPORTATION

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Abstract

The value of lunar produced propellants in an oxygen/hydrogen earth-moon transportation is presented in this paper. A figure of merit is established that expresses the cost that lunar propellant production should not exceed if these propellants are to compete with performing missions to the moon with all-earth propellants. The conclusions of this study are 1) lunar oxygen should be used for the return from the moon and for lunar landers, 2) less than 20 to 30% of the oxygen needs in low earth orbit for trips to the moon should be hauled back from the moon, and 3) lunar hydrogen, which requires processing of enormous amounts of lunar soil, does not appear to add significant benefits to the transportation system.

Introduction

The buildup of a lunar base will require many routine flights to and from the moon with astronauts and cargo. The transportation costs for these routine flights, as with most any other space mission, will be a significant portion of the overall costs associated with the buildup and operation of the base. Transportation costs are typically dominated by the high costs associated with launching the payloads and the propellant for the corresponding transportation vehicle(s) into low earth orbit (LEO). Since propellant mass is anticipated to be a major constituent of high energy space missions such as trips to the moon, the costs of attaining propellant must be considered in determing how (or whether) to perform these missions.

Production of propellant on the moon has been suggested as a possible means of minimizing the overall transportation costs associated with building and maintaining a lunar base. Since oxygen is a major constituent of the propellant used in an oxygen/hydrogen transportation vehicle, it is natural to consider its usage since it is abundantly available on the lunar surface. Producing oxygen from the lunar regolith, as some propose, may provide substantial benefits for the earth-moon transportation system presumably by reducing the amount of propellants launched from the earth. By providing propellant on the surface of the moon, the enormous expense of launching propellants from earth can perhaps be significantly reduced. However, in order to test this suggestion it was necessary to quantify the benefits of using the moon's resources in the earth-moon transportation system.

The benefits/penalties of using lunar oxygen as propellant in the future space transportation system were documented in AIAA 89-2541 "Lunar Transportation System Optimization". This analysis has been extended to include an assessment of the benefits of using both lunar oxygen and lunar hydrogen. The implications and potential benefits of using both lunar produced oxygen and hydrogen will be discussed for an earth-moon transportation system that flies routine cargo flights to the moon. The results and conclusions of this analysis contribute relevant quantitative data for use in deciding to what extent lunar produced propellant(s) should be pursued. The analysis given here was performed under independent research and development project D-46S at Martin Marietta Astronautics.

Specifically addressed for the baseline lunar cargo delivery missions were: a) To what extent lunar produced oxygen should be utilized in optimizing the lunar transportation system, b) What portion of the lunar mission would best benefit from the use of lunar oxygen, c) How beneficial in terms of cost is the oxygen produced on the moon in the transportation system, and d) What benefit does lunar produced hydrogen provide if it can be used in the lunar landers and for the return trip to earth. This amount of hydrogen from the moon eliminates the need for the transportation vehicle from LEO to haul hydrogen to lunar orbit for the lunar lander and for the trip back to LEO.

Lunar Cargo Missions and Lunar Oxygen

Presumably, if oxygen is abundant and relatively cheap to produce on the moon, it will be advantageous to make use of it rather than launching all of the required propellant from the earth. This possiblity first implies that oxygen from the moon should be used by vehicles in the vicinity of the moon and perhaps used for the return of the lunar cargo vehicle to LEO from the moon after it has delivered its payload. The next step in speculating about potential benefits of lunar propellants deals with the idea of exporting oxygen from the moon to LEO. That is, oxygen could perhaps be transported back to LEO for subsequent flights to the moon in an attempt to lessen earth launch costs of oxygen. The unknown that needed to be determined in this analysis was "how much" oxygen should be returned. In addition, if hydrogen can also be made available on the moon for the return flights to earth and for lunar landers, it may be worthwhile to avoid hauling hydrogen from earth for these purposes. So, "How valuable is this relatively small amount of hydrogen?" also needed to be quantified.

In order to determine the benefits of using lunar oxygen in the transportation system for delivering cargo to the moon, the performance of these missions had to be modelled. This meant establishing a set of requirements and framework assumptions that correspond to the situation being modelled. The requirements and framework groundrules used in this analysis are as follows:

- delivery of 20 metric tons (44000 lbm) to the lunar surface in each mission from low earth orbit
- reusable, aeroassisted lunar cargo vehicle based in low earth orbit (LEO) and a reusable cargo lander based on the lunar surface (for the mission scenario that uses lunar orbit as a node)
- lunar oxygen returned to LEO in main propellant tanks

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- oxygen for lunar cargo vehicle return to LEO is from the moon
- all oxygen for the lunar cargo lander is from the moon
- vehicle subsystem scaling relationships and mission plan from Orbital Transfer Vehicle (OTV) Phase A Study for NASA Marshall Space Flight Center (MSFC NAS8-36108) performed by Martin Marietta Astronautics Group
- all hydrogen is from the earth (unless stated otherwise)

The first mission scenario considered during the study uses low lunar orbit (LLO) as a transportation node. Figure 1 depicts the delivery of cargo (and hydrogen for the lunar lander) from LEO to LLO with a lunar cargo vehicle (LCV). This handoff of payload and hydrogen to the lunar cargo lander (LCL) is depicted in Figure 2. During the same mating, the LCL transfers lunar liquid oxygen (LLOX) of the amount desired into the oxygen tanks of the LCV. The amount transferred from the LCL to the LCV is at least enough for the LCV t(get back to LEO from LLO. The LCV then returns to LEO where it will refuel with earth hydrogen, top-off with earth oxygen, and pick up another payload to be delivered to the moon.

The payload is then delivered to the surface of the moon with the lunar cargo lander. After the cargo is delivered to the lunar surface, the LCL fills up with oxygen needed for the next round-trip to LLO. This amount of oxygen includes not only that necessary for its own propulsion, but for the LCV return to LEO in addition to the amount of LLOX the LCV is hauling back to LEO.

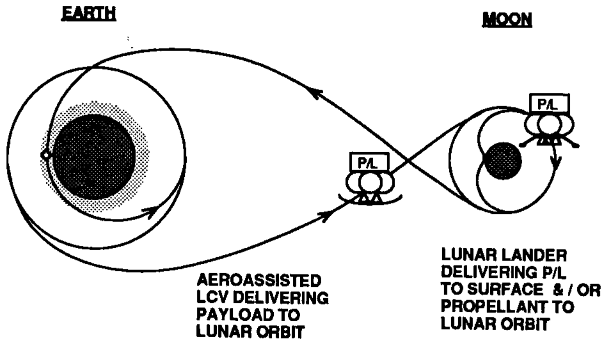

Figure 1 Lunar Orbit Node Mission Profile

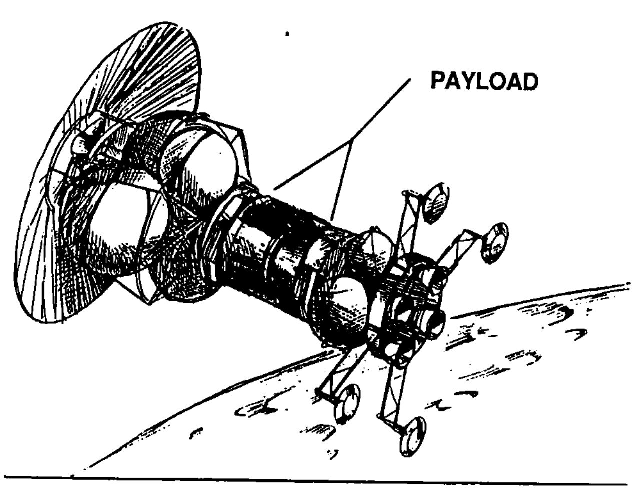

Figure 2 Cargo Handoff and Propellant Transfer In LLO

Figure 3 depicts a similar scenario except the LCV delivers the cargo directly to the surface of the moon instead of rendezvousing with an LCL in lunar orbit for the handoff of the payload and propellants. This requires the LCV to have landing legs. The LCV picks up LLOX at the lunar surface (instead of in LLO as in the previously described case) for return to LEO and for delivery of LLOX back to LEO for the next trans-lunar injection (TLI). After picking up LLOX the LCV performs a direct ascent and returns to LEO following aerocapture.

The extent of LLOX delivered back to LEO with the LCV was varied in order to understand if there might be an optimum or a feasibility limit for LLOX exportation. The presumption in previous lunar propellant utilization studies has been that it would be advantageous to return LLOX to LEO for subsequent trips to the moon. Therefore, the mission scenario in this study considered the delivery of the cargo to lunar orbit with the LCV, and then the LCV acquires LLOX for the trip back to LEO as well as returning LLOX to LEO. The range of returned LLOX studied extended from zero to 100 percent of LCV oxygen needs (when the LCV begins a mission in LEO) being of lunar origin. As mentioned earlier, LLOX was also assumed to be used for all the LCL oxygen needs.

The amounts of propellant used in the lunar cargo delivery mission are given in Figure 4. The propellant that is launched from the earth and transferred to the LCV in LEO is termed as "LEOPROP". Notice that the total amount of propellant required increases as more and more of the LCV oxygen is obtained from the moon. Thus, in attempting to deliver LLOX from the moon back to earth orbit for subsequent cargo delivery flights to the moon, the total propellant needed for the transportation system actually increases. LEOPROP does decrease slightly, however. That is, the amount that needs to be launched from the earth does decrease by a small amount. Nonetheless, one conclusion from this figure is that if total propellant consumption increases as more and more

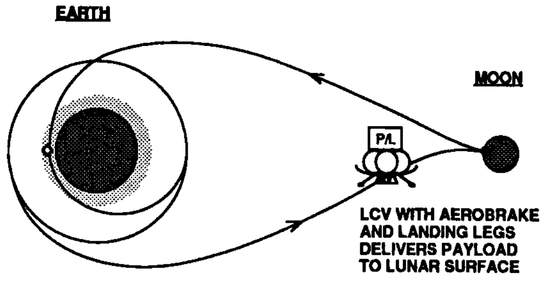

Figure 3 Direct-to-Surface Mission Profile

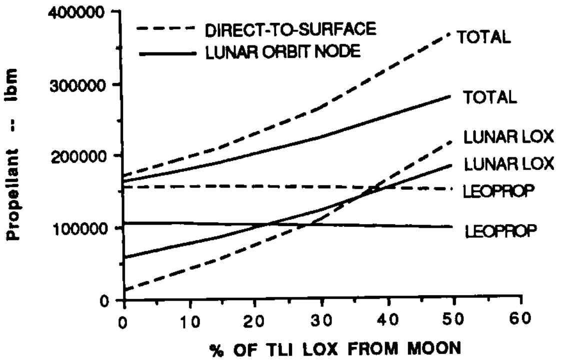

Figure 4 Propellant Usage--No Lunar H2

LLOX is used, then the cost of producing LLOX would need to become cheaper as more of it was used.

Figure of Merit for Lunar Propellant

A major problem in assessing the potential benefits of lunar produced oxygen (LLOX) was in expressing an appropriate figure of merit for measuring these benefits or drawbacks. Obviously, if a space transportation system using lunar oxygen is deemed to be less expensive than a system using propellants launched from earth, there exists a basis for selecting that system of operation.

Extensive life cycle costing was avoided during this study because typically the extreme effort spent in quantifying the details of life cycle cost of space missions only adds to the confusion rather than reducing it. Instead, a relatively simple figure of merit was derived and quantified that gives the "breakeven" conditions for the use of lunar oxygen compared to exclusively using propellants launched to LEO from the earth. Specifically, of interest was the cost of lunar oxygen production for which the use of lunar oxygen in the earth-moon transportation system would break even with the case where only earth propellants are used.

In order to keep actual dollar figures out of the study, a ratio of the per-pound cost of oxygen produced on the lunar surface to the per-pound cost of providing propellant in LEO was calculated as the figure of merit. The value of this ratio was calculated by setting the overall propellant cost when using LLOX equal to the propellant (launch) costs of the all-earth-propellant case. This "breakeven" cost ratio was quantified over the range of LCV LLOX usage mentioned earlier. This figure of merit was developed in order to show the conditions (i.e. the per-pound cost of lunar oxygen) for which lunar produced oxygen will break even with using only earth launched propellant. If all this seems confusing, an example illustrating this figure of merit follows in the next few paragraphs.

It requires about 220,000 pounds of propellant for an LCV to deliver a 20 metric ton payload to the surface of the moon when using propellant from earth only. That is, the vehicle starts out with the payload and 220,000 pounds of loaded propellant in LEO. This amount of propellant also allows the vehicle to not only deliver the payload to the moon, but also return itself to LEO in order to perform the next mission.

Now let's take a case where the LCV starts out in LEO on a cargo delivery mission to the moon using some lunar oxygen that it brought back from the moon on the previous mission. Let's assume that 15% of the oxygen that the vehicle needs to begin its mission in LEO has been obtained from the moon. Let's also assume the LCV will receive enough lunar oxygen to get back to LEO after delivering its cargo to the moon. For this particular case, the LCV and a LCL use a total propellant of 80,000 pounds of lunar oxygen and 105,000 pounds of propellant obtained in LEO--185,000 pounds total. This is a reduction from the baseline all-earth propellant case where 220,000 pounds were needed.

So, if propellant costs $3000 a pound to launch into LEO, the propellant for the baseline case would cost 220,000 times $3000 or $660 million. Now, for the 15% LLOX case: LEO propellant costs would be 105,000 times the same $3000 per pound or $315 million. So, how much can we afford to spend on LLOX and break even with the baseline case? The answer is $660 million (that we would have spent on the baseline case) minus $315 million (for the LEO propellant in the 15% case) which amounts to $345 million that can be spent on LLOX production (at the surface of the moon) of the 80,000 pounds of LLOX used. This converts to $4312 a pound that can be spent on LLOX for this case and breakeven with the case where no LLOX is used.

A non-dimensional method of expressing our figure of merit in order to avoid presenting actual dollar values was to take the $4312 a pound for LLOX and divide it by the $3000 a pound for LEO propellant cost. This equals 1.44. In other words, for this 15% LLOX case, lunar oxygen can cost 1.44 times as much as propellant costs in LEO and the mission propellant costs will break even with the baseline case where no LLOX is used.

A non-dimensional expression (equalling 1.44 for this particular case) was derived using only propellant amounts in order to express the "breakeven" cost of LLOX relative to the cost of providing oxygen in LEO. This value was calculated over the entire range of LLOX usage investigated by this study. Let's call this non-dimensional cost ratio "R". This eliminated the speculation of what earth-to-orbit launch costs are.

Figure 5 shows the R (breakeven) values for LLOX use as a function of the percentage of LCV LOX that is of lunar origin. For example, for the LLO case LLOX can cost about two times as much as LOX in LEO and still break even with the case of using all-LEO propellants. However, this is only for the condition where no LLOX is returned to LEO for LCV use in the next mission (at 0.0 on the X-axis). At this point LLOX is only used by the lander (LCL) and for returning the cargo vehicle (LCV) from lunar orbit back to LEO.

By bringing LLOX back to LEO (that is for values greater than 0.0), the breakeven cost ratio of LLOX decreases; i.e. LLOX must get less and less expensive to produce in order to break even with all-LEO propellants. It is apparent, therefore, that using LLOX

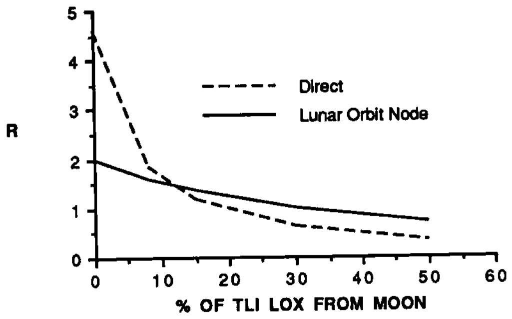

Figure 5 R Values When Using No Lunar H2

for only LCV return to LEO after payload delivery (no LLOX returned to LEO) is the most advantageous usage of LLOX on a cost per pound basis. This is based on the maximum R value occurring at the point where no LLOX is returned to LEO for the next trip to lunar orbit.

It should be noted that the curves in Figure 5 by themselves cannot be used to determine the optimum extent of LLOX use. The curves only represent the conditions for which LLOX breaks even with the all-earth propellant case. Estimates for the per-pound costs of LEOPROP and LLOX should be multiplied by the respective amounts of propellant used from each location in order to get a total cost comparison. These propellant amounts were given in Figure 4. With these propellant amounts, one can speculate on the cost of producing oxygen on the moon and then determine its benefits (or penalties) for any extent of its use. However, based upon the breakeven "R" values given in Figure 5, a broad conclusion can be stated that the production of lunar oxygen will have to be less than the price of LEOPROP for LCV LLOX usage of greater than about 20% to be cost-effective (for the LLO node case).

In addition to the costs associated with launching propellant into space or producing it on the moon for use in the space transportation system, there are other costs that are of interest. The propellant amounts in Figure 4 are examined here in order to assess other transportation cost items that are related to propellant quantity. The propellant requirements grow significantly with increasing amounts of LLOX usage as shown in the figure. Additional servicing operations would be required corresponding to increased amounts of propellant to be transferred, either in earth orbit, lunar orbit, or on the moon. Also, greater vehicle costs would result if larger vehicles that carry more propellant need to be developed rather than smaller ones. Or if the same size vehicles were to be used, greater flight operations costs would result because more missions would have to be flown using the same size vehicles. Therefore, quantifying the costs mentioned here would provide further rationale for not returning large amounts (say, greater than 20%) of LCV LOX from the moon.

The results of the analysis presented above show that it is not advantageous to use large amounts of lunar produced oxygen as a propellant in the earth-moon transportation system. This was shown not only by the increasing amounts of propellants required when more and more LLOX is used, but the non-dimensional cost analysis (with R value calculations) demonstrates that LLOX must become increasingly cheaper to produce as more of it is used in the transportation system. The other costs of operating the vehicles in the transportation system dependent upon the quantities of propellant used did not need to be quantified due to the indications that doing so would only confirm the conclusions based upon the quantified results presented.

Benefits of Using Lunar Hydrogen

In addition to containing oxygen, the lunar regolith is a potential source of hydrogen. Hydrogen implanted by the solar wind is present in the bulk surface regolith in concentrations of 20-100 ppm, and may be released by heating to temperatures on the order of 600 deg C. Therefore, this study considered the utilization of relatively small amounts of lunar hydrogen (compared to the amounts of lunar oxygen considered) for the portions of the mission deemed to benefit most from it.

Suppose that hydrogen is available from the moon for lander usage and for return of the LCV to LEO from the moon. This results in a total propellant reduction as seen by comparing Figure 6 with Figure 4. Due to this reduction of total propellant usage, it would seem that lunar produced propellants would be more cost-effective by using lunar hydrogen in this manner. Figures 7 and 8, for LLO node and direct-to-surface scenarios respectively, show this to be true since the R values for the cases utilizing lunar hydrogen are increased from the cases that used no lunar hydrogen. The increase in R values is most noticeable when returning substantial amounts of lunar oxygen to LEO since having hydrogen available at the moon for hauling large cargo back to LEO reduces the initial TLI significantly.

Since it is unreasonable to assume that the cost of providing hydrogen on the moon will be equal to the cost of providing oxygen, Figure 9 is provided in order to attain the relative amounts of each propellant when utilizing lunar hydrogen. This information combined with the propellant amounts from Figure 6 will provide all the information necessary for one to make their own comparisons of total propellant costs depending upon speculations of each propellant's cost.

As an example, let's consider a mission case where a total of 100,000 lbm of lunar propellants (both oxygen and hydrogen) are used. This corresponds roughly to a case where 20% of TLI oxygen is being returned to LEO in addition to delivering a 20 tonne payload to the moon. Since the fraction of the total that is hydrogen is dependent upon mission profile, let's use a representative value from Figure 9 of 10% of the total being lunar hydrogen. This gives us 10,000 lbm of lunar hydrogen. Assuming an availability of hydrogen

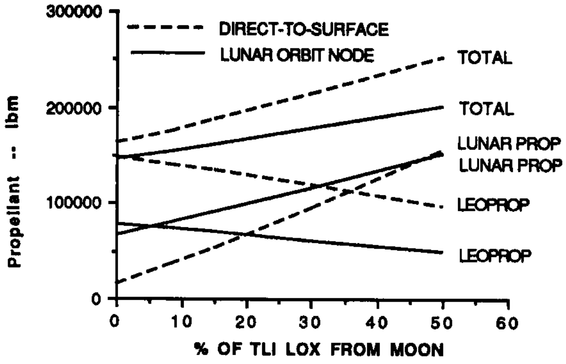

Figure 6 Propellant Usage--With Lunar H2

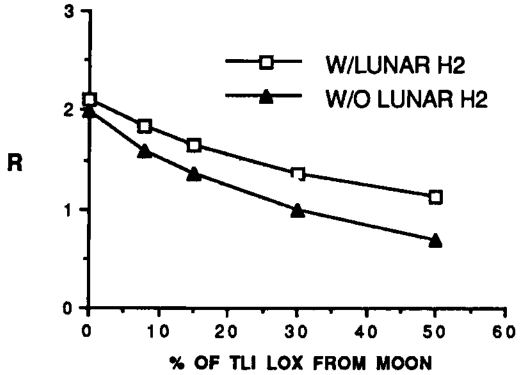

Figure 7 Lunar Orbit Node Option--R Values

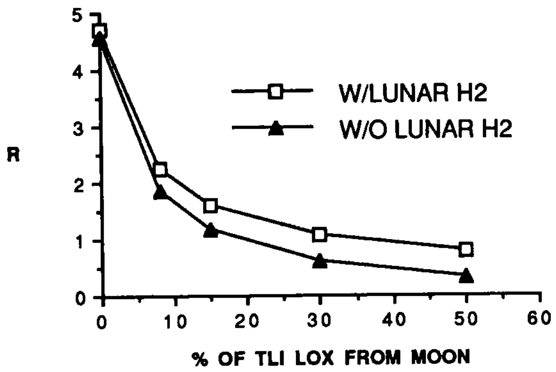

Figure 8--Direct-to-Surface R Values

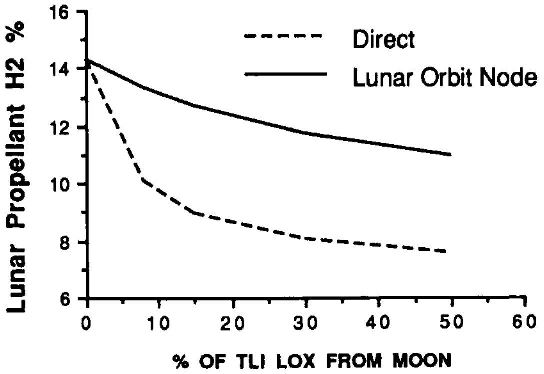

Figure 9 Hydrogen % of Lunar Propellant

on the order of 50 ppm by weight, about 90,000 tonnes of lunar regolith must be processed to obtain 10,000 lbm of hydrogen for propellant. This does not appear to be very feasible. In addition, the benefits in terms of the "R" value when using lunar hydrogen only occur for large values of TLI LLOX exportation where the value of "R" has already fallen off.

Lunar Propellant Analysis Conclusions

The extent of lunar oxygen usage recommended by this study (if lunar oxygen is used in the earth-moon transportation system) is to provide all the LOX needs of a lunar lander (for the mission profile that uses lunar orbit as a node). For the direct-to-surface scenario, lunar LOX usage for the moon-LEO leg of the trip is recommended. For both mission profiles it is not recommended to return to LEO a large percentage (greater than about 20 to 30%) of LOX needed for subsequent trips to the moon.

Utilizing lunar hydrogen does not appear to provide significant benefits to the earth-moon transportation system in terms of cost-effectiveness of using lunar propellants. Since enormous amounts of soil processing would be required for the relatively small amounts examined in this study, its production cost on the moon would most likely be substantially greater than the cost of providing lunar oxygen. However, cost estimates (of one's own choosing) for propellant in LEO and on the surface of the moon should be multiplied by the propellant amounts provided in this analysis in order to provide an absolute total propellant cost comparison. These costs per pound should consist of the total amortized cost of the lunar produced propellant, since the costs associated with the production plant must be included.