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# Aluminum-Fueled Rockets for the Space Transportation System

Andrew H. Cutler

## Introduction

Aluminum-fueled engines, used to propel orbital transfer vehicles (OTVs), offer benefits to the Space Transportation System (STS) if scrap aluminum can be scavenged at a reasonable cost. Aluminum scavenged from Space Shuttle external tanks (fig. 9) could replace propellants hauled from Earth, thus allowing more payloads to be sent to their final destinations at the same Shuttle launch rate.

To allow OTV use of aluminum fuel, two new items would be required: a facility to reprocess aluminum from external tanks and an engine for the OTV which could burn aluminum. Design of the orbital transfer vehicle would have to differ substantially from current concepts for it to carry and use the aluminum fuel. The aluminum reprocessing facility would probably have a mass of under 15 metric tons and would probably cost less than $200 000 000. Development of an aluminum-burning engine would no doubt be extremely expensive (1 to 2 billion dollars), but this amount would be adequately repaid by increased STS throughput. Engine production cost is difficult to estimate, but even an extremely high cost (e.g., $250 000 000 per engine) would not significantly increase orbit-raising expenses.

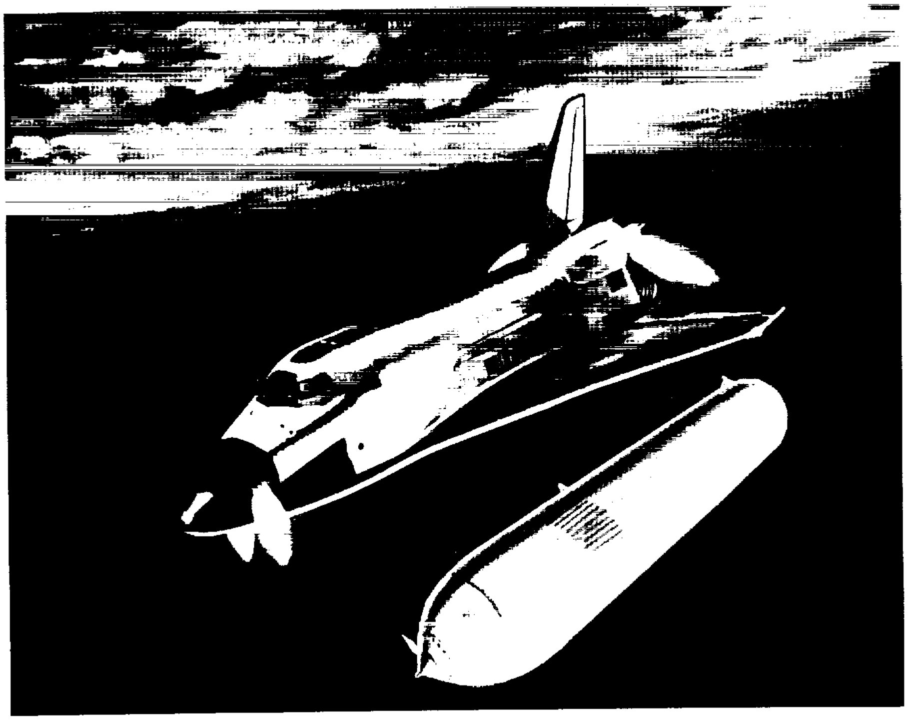

*Figure 9*

***Separation of the External Tank From the Shuttle Orbiter***

*The external tank, which carried the liquid hydrogen and liquid oxygen for the main engines of the orbiter, is 28 feet (8.5 meters) in diameter and 157 feet (47.9 meters) long. In current operations, before the Shuttle reaches orbit, the tank is released from the orbiter, follows a ballistic trajectory, and falls into a remote area of the ocean. With a slight adjustment of the orbiter's trajectory and the release point, these tanks could be carried into low Earth orbit.*

*A new NASA policy has been implemented which encourages use of these jettisoned external tanks. They will be made available in low Earth orbit for both commercial and nonprofit endeavors and NASA will accept proposals to use them. Between 1989 and 1994, approximately 40 external tanks will be flown. The number that would be available to private ventures will depend on a case-by-case analysis of each Space Shuttle launch and the proposed use for that particular tank.*

The combustion of aluminum delivers 22 percent more energy per unit mass of reactant than does the combustion of hydrogen. Since propellant costs on the Earth are a small part of total launch costs, the added complexity of tripropellant engines is not warranted for launch from the Earth's surface. However, if aluminum fuel were available in low Earth orbit (LEO) at a much lower cost than cryogenic fuel, the savings in propellant cost could offset the cost of developing an aluminum-fueled space engine.

## Background

Aluminum-fueled rockets are ubiquitous. Aluminum is added to the solid fuel of rockets to enhance their performance. Most ground-based solid rockets are aluminized. Solid rockets intended for launch in space are following this trend (e.g., the inertial upper stage—IUS—rockets). The Space Shuttle itself burns twice as much aluminum (in the solid rocket boosters—SRBs) as it does hydrogen (total of the elemental hydrogen in the external tank and the chemically combined hydrogen in the SRB fuel).

The aluminum oxide ($Al_2O_3$) produced by the Shuttle's combustion of aluminum quickly settles out of the atmosphere. That produced by rockets taking satellites to geosynchronous Earth orbit (GEO) does remain there. The $Al_2O_3$ would be a pollutant in cislunar space. However, the dilution is such that aluminum oxide pollution there should not be a severe problem for a long time.

Experiments have shown that aluminum additives can also enhance the performance of liquid-fueled rockets. The combined efforts of those working on solid and liquid propellant rockets might have an increased total effect if they were focused on the development of an aluminum-fueled space engine.

## Aluminum Availability in LEO

Aluminum could be made readily available as a fuel in LEO. The 1988 National Space Policy offers Shuttle external tanks (ETs) free to users in space. (The conditions include demonstrating that any reentry of the tanks can be controlled.) External tanks could be carried to orbit for little additional cost and with little adverse impact on Shuttle operations. These tanks could then be reprocessed to provide fuel aluminum.

Aluminum would probably be burned in the form of micron-sized powder. From extrapolations of current mission models, the maximum projected aluminum demand is about 14 metric tons per tank. This amount of aluminum could be recovered in the following manner (see fig. 10): All gas is vented from the tanks. A cutting machine with an electron beam cutter (demonstrated on Skylab for 2219 aluminum alloy) enters the tank. It makes circumferential cuts in the barrel sections and in the ogive (pointed arch section) immediately adjacent to the ring frames. The cuts do not cross the cable tray. These circumferential cuts are connected by longitudinal cuts along both sides of the cable tray and between the ring frames. Since the cutting is done while the thermal protection system (TPS) is still intact, all spatter and fumes will be contained inside the tank and may be trapped to prevent extensive contamination of the local area. "C"-shaped sections of the tank composed of a metal sheet coated on one side with TPS material may now be broken loose. These "C"s contain the needed 14 metric tons of 2219 aluminum alloy, so the remainder of the tank—ring frames, intertank (section between the hydrogen and oxygen tanks), slosh baffles, end domes, and cable tray—may be discarded.

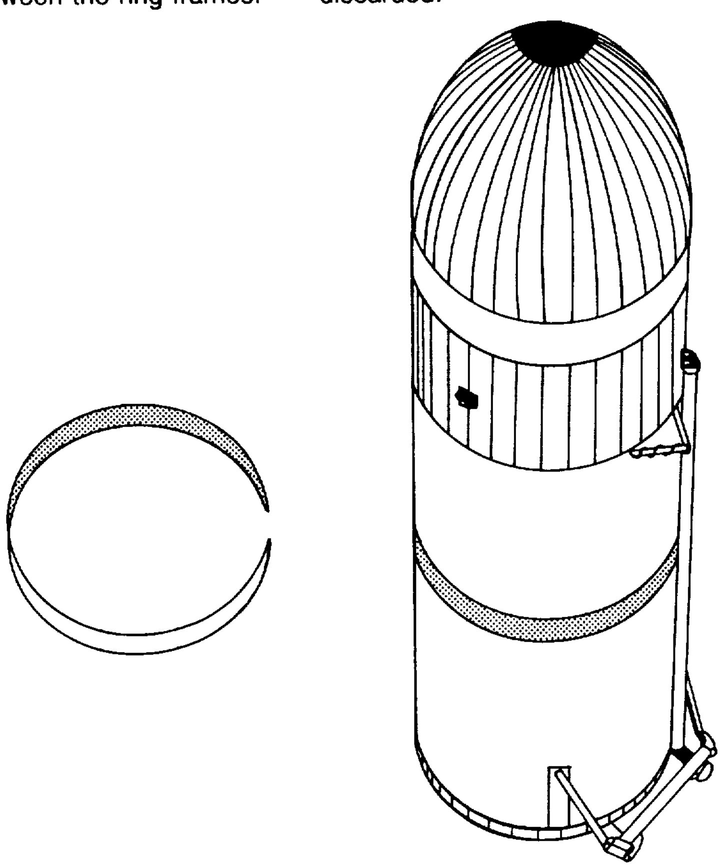

*Figure 10*

***Reprocessing of Space Shuttle External Tank***

*"C"-shaped sections could be cut from the most accessible parts of the external tank, leaving the cable tray and other complex parts to be discarded. The aluminum strips could then be rolled onto a mandrel, melted, and sprayed against a rapidly rotating wheel to produce the aluminum powder needed as fuel for a new type of engine for an orbital transfer vehicle.*

The aluminum strips may then be rolled onto a mandrel to densify them for melting. The bulk of the TPS coating will separate from the aluminum sheet while it is being rolled up. The small amount of TPS material remaining on the sheet can be removed with a rotating wire brush and discarded along with the other unprocessed materials. The rolled aluminum strip is placed in an induction furnace and melted. The liquid aluminum can be pumped from this pool and turned into powder the same way it is on Earth—by being sprayed against a rapidly rotating wheel. The vacuum of space allows efficient electron beam cutting and prevents oxidation of the aluminum powder as it is being formed.

The operation described here requires further study. Among the problems to be solved is that of disposing of the residual portions of the external tank in an environmentally acceptable way. The generation of large or small debris (e.g., pieces of insulating material) that cannot be controlled could make the aluminum scavenging concept untenable.

The amount of aluminum available in the external tanks is far larger than the amount of aluminum fuel needed. Only the most easily reprocessed part of the tanks need be worked on. These portions of the tank are composed of only one alloy, 2219, which has been extensively characterized in commercial use. These facts combined with the fact that the plant makes only one product (aluminum powder) suggest that the plant will be simple, reliable, and economical.

## Aluminum as a Propellant

The combustion of aluminum by oxygen is very energetic. Most of the energy is released as aluminum oxide condenses from the gas phase. Aluminum oxide condensation in the rocket nozzle is a rapid process. Condensation of aluminum oxide heats the gas, which expands to provide thrust. Since the aluminum oxide particles do not completely exchange momentum and energy with the gas phase, there is some impulse reduction due to two-phase flow loss. The two-phase flow loss must be controlled by including in the exhaust a gas with low molecular weight (Frisbee 1982). Hydrogen is the ideal candidate. An oxygen-hydrogen-aluminum engine with a mixture ratio of 3:1:4 is expected to have a specific impulse of over 400 seconds, and eventually it might achieve a specific impulse of over 450 seconds (Cutler 1984).

## Propellant Demand in LEO

Much of the mass currently lifted to LEO is propellant for orbit raising and maneuvering. According to OTV transportation models (table 8), 45-180 metric tons of payload mass per year will be lifted to geosynchronous Earth orbit as soon as an OTV is available or expendable rockets can be fueled at the space station. To lift these payloads from LEO to GEO, 90-360 metric tons of propellants will be required in LEO. The specific propellant requirement depends on the design and performance of the OTV used, including whether or not it is reusable. In this paper, I have assumed a propellant-to-payload ratio of 2:1. Some of this (130-325 metric tons per year) can be scavenged from the Space Shuttle's external tank in the form of unused hydrogen and oxygen (see table 9).

TABLE 8. *Models for Orbital Transfer Vehicle Traffic*

| Model | Payload size, metric tons | Mass to GEO per year, metric tons |
|---|---|---|
| Cooper[a] | 6.82 | 122.9 |
| Current comsats | 1.14 | 45.5 |
| Advanced comsats | 4.55 | 182 |
| General Dynamics[b] | 4.55 | 54.6 |
| Eagle Engineering[c] | 15.3 | Not specified |

[a]Lawrence P. Cooper, 1984, Propulsion Issues for Advanced Orbital Transfer Vehicles, NASA TM-83624.
[b]Michael C. Simon, personal communication.
[c]Hubert P. Davis, 1983, Lunar Base Space Transportation System, Eagle Engineering report EEI 83-78.

## Aluminum-Fueled Engines for OTV Propulsion

Table 9 shows the amounts of O-H and O-H-Al propellant usable under different conditions. If the traffic model requires more propellant than can be scavenged, additional propellant must be carried in place of payloads of greater intrinsic value or new technology must be introduced to improve performance.

Marginal improvements can be made in OTV performance by incorporating advanced cryogenic engines. Improving engine performance from the current $I_{sp}$ of 460 seconds to an $I_{sp}$ of 480-490 seconds would allow 7-11 percent more payload to be carried to GEO with the same cryogenic propellant supply.

If oxygen-hydrogen-aluminum engines were available (and relatively small amounts of hydrogen

TABLE 9. *Usable Propellant Available in LEO Yearly*
[In metric tons]

| Model parameters | Cryogens for use in 6:1 O-H engine | Aluminum for use in 3:1:4 O-H-Al engine | With additional hydrogen[a] | Total propellants usable in 3:1:4 O-H-Al engine |
|---|---|---|---|---|
| 24 flt./yr, loaded at 75% of maximum mass | 325 | 372 | 46 | 743 |
| 24 flt./yr, loaded at 100% of maximum mass | 129 | 148 | 18 | 295 |
| Martin Marietta study,[b] standard ET | 196 | 224 | 28 | 448 |
| Martin Marietta study,[b] ET with aft cargo carrier | 130 | 148 | 19 | 297 |

[a]Because the ratio of hydrogen to oxygen is twice as high in the O-H-Al engine as it is in the O-H engines (OTV and Shuttle), additional hydrogen from Earth would be needed in order to use all the scavengeable oxygen.

[b]Martin Marietta, Michoud Division, 1984, STS Propellant Scavenging Systems Study, Addendum to Performance Review, performed under contract NAS8-35614, Jan. The Martin Marietta mission model has been normalized to 24 flights to the space station per year, a slightly higher rate than that used in the study.

could be added), the amount of scavengeable propellants would double (table 9). Besides the aluminum to match the scavenged hydrogen and oxygen, there would be excess aluminum to match hydrogen and oxygen transported from Earth, thus doubling its effectiveness.

A simplified cost model is shown in figure 11.

If the assumptions used here are shown to be valid, the model indicates that significant cost savings can be made, even at low traffic levels, by scavenging cryogens from the Space Shuttle and, at higher traffic levels (above 90 metric tons per year), significant cost savings could also be made by scavenging aluminum from the external tank.

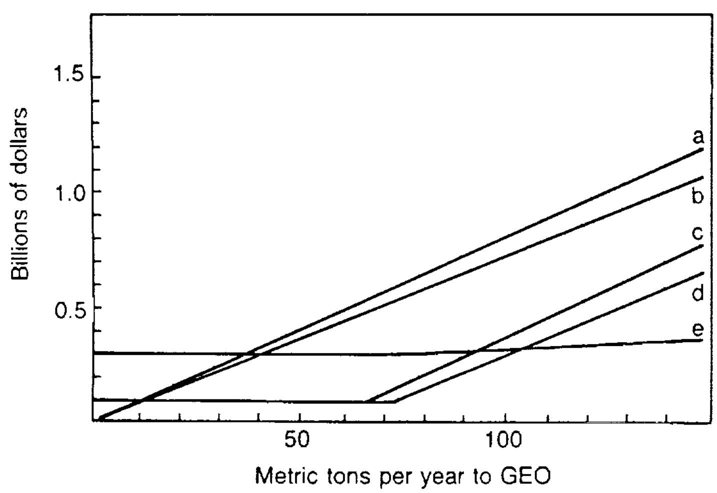


*Figure 11*

***Relative Propellant Costs for Orbital Transfer***

*This figure shows the relative propellant costs for lifting payloads from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO) using* (a) *all propellant from Earth at $4000/kg,* (b) *all propellant from Earth and an advanced cryogenic engine,* (c) *scavenged cryogenic propellants,* (d) *scavenged cryogenic propellants and the advanced cryogenic engine, and* (e) *scavenged aluminum as well as scavenged oxygen and hydrogen.*

*The weight of the orbital transfer vehicle (OTV) is ignored, and the propellant-to-payload ratio is assumed to be 2:1 Cryogen scavenging is assumed to cost $100 000 000 per year, and aluminum scavenging is assumed to cost an additional $200 000 000 per year. Cryogens in excess of scavenging availability are taken to cost $4000 per kg delivered to LEO. The amounts of scavengeable materials available are those presented in the second model in table 9.*

*Line* a *represents the current practice, in which an oxygen-hydrogen engine boosts a payload using twice its weight in propellant which was brought to LEO at a cost of $4000 per kg. Line* b *represents a similar practice but with an advanced engine that is 10% more efficient. Line* c, *representing the use of the current engine with scavenged cryogens, stays at the cost of scavenging the cryogenic propellants until they are used up [when the payload equals 1/2 the scavengeable amount (129 metric tons in the second model in table 9)], and then goes up with the same slope as that of line* a. *Line* d *represents the use of the advanced engine with scavenged cryogens, and thus it starts going up at about 72 metric tons (the amount of payload that can be carried with the 129 metric tons of scavenged cryogens with an engine that is 10% more efficient) and then parallels line* b. *Line* e *represents the practice the author is advocating--the use of an oxygen-hydrogen-aluminum engine. It stays at the combined cost of scavenging both cryogens and aluminum until all the scavenged hydrogen, about half the scavenged oxygen, and an equal amount of aluminum is used up (at about 74 metric tons of payload). Then this line rises very slowly to cover the cost of bringing to LEO from Earth the additional hydrogen needed to match up with the remaining half of the scavenged oxygen and an equal amount of the abundant scavengeable aluminum. Cryogen scavenging can be a very cost-effective strategy even at low traffic levels. Aluminum scavenging could be effective above 90 metric tons per year of traffic (where line* e *crosses line* c*).*

## Conclusion

Aluminum-fueled space engines may be more economical than advanced cryogenic engines in the regimes where advanced engines can offer significant savings over current technology (that is, where there is enough traffic that the benefits from improved performance exceed the cost of developing a new engine). Thus, assuming that all programs for the development of new engines have about the same cost, any argument which justifies developing advanced oxygen-hydrogen engines justifies investigating the development of an aluminum-fueled space engine. The most economical way to run an OTV program may be to rely on an OTV with a current RL-10 engine until propellant demand is near the scavenged supply and then change over to an OTV propelled by an oxygen-hydrogen-aluminum engine.

## References

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Frisbee, Robert H. 1982. Ultra High Performance Propulsion for Planetary Spacecraft. JPL Report D-1097. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.