9. Near-Term Chemically-Propelled Space Transport Systems

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The task to be performed by near-term applications of chemical space propulsion systems has been defined by O'Neill as follows:

(a) 10,000 tons at L5 (1800 tons by 1982)

(b) 3,000 tons on the lunar surface.

This implies that 1800 tons would have to be launched by the shuttle launch vehicle, since that is presumably the only launch vehicle available in 1982. The hypothesis also requires 10,000 people at L5 and 200 people on the lunar surface. If we provide that these people must be accommodated by an equivalent of 200 pounds per person, we need to carry about 1,000 tons of human flesh and protective covering to L5 and 20 tons to the lunar surface. It is my purpose to show how this can be accomplished by means of chemical propulsion systems.

These requirements can be restated into a more specific problem: to translate these payloads into the equivalent mass requirements in low Earth orbit that would be necessary to deliver the specified tonnages to L5 and the Moon using a hydrogen-oxygen system. It would be presumptuous of me to design a future payload hauler that would do this, but I shall lay out the elements of a nearer term system, where each element can be transported to L5 by a device which can be lifted in turn by the shuttle. That, of course, will satisy the 1982 requirement. I will do the analysis in parametric form, so that if the assumed performance parameters hold, the example can serve to establish the mass ratios for all the space transport systems, and the design of a practical system for the 1989 period would be reduced merely to an engineering problem.

All of my calculations are based on the use of the hydrogen-oxygen propellant system because of its high specific impulse. I will also assume, for simplicity, that there is no long-term boil-off. Although that is a rather drastic assumption, we have postulated that power is available at both L5 and the lunar surface to refrigerate the liquid hydrogen which would otherwise escape. This would reduce propellant boil-off to that which would be lost during transport of the systems from one point to another in space; that kind of boil-off might be reduced to ½ percent of the hydrogen per day, with only a lightly insulated system to keep the mass down. Thus boiloff in space does not need to be a serious problem. However, because some of the operations will be conducted on the lunar surface where there is considerable reflection from the surface itself, storage of hydrogen there poses something more of a problem than storage of hydrogen or oxygen in space. This may make it useful to consider a combination such as liquid oxygen with amine fuels which, while it will cost 30% more in mass for the transport system, will reduce the boil-off problem very appreciably.

Table 19 lists the representative velocity increment (ΔV) requirements that have to be met for the mission of going from the low Earth orbit (LEO) to a lunar parking orbit (LPO). Low Earth orbit to the L5 position is actually slightly less, but

Table 19. Representative ΔV Requirements for Space Transport

Mission	ΔV, ft/sec
LEO → LPO	13,000
LEO → L-5	13,400
LPO → L-5	7,200
L 5 → LPO	6,100
LPO → L-5	2,250
L 5 → GSO	5,700

to first order these two missions are almost equivalent.

Going from the lunar parking orbit to the lunar surface (LS) requires a throttlable engine and a hovering maneuver before the final touchdown. Thus I have allowed 7,200 feet per second for that maneuver, whereas I have allowed only 6,100 feet per second for the ascent maneuver, which does not require hovering. Table 18 also lists the requirement for going from the lunar parking orbit to L5 and from L5 to the geosynchronous orbit (GSO). I have not examined ways of performing these missions, so there may be ways that those ΔV's can be reduced. However, such refinements will have little effect on gross propulsion system characteristics.

The hydrogen-oxygen system that I have assumed for the calculations provides an effective specific impulse of 462 pound-seconds per pound. Since there will be some losses (e.g., about 3%) in the system due to vector, attitude control and boil-off, we must have an engine whose capability is of the order of 477 seconds, which calls for an expansion ratio of the order of perhaps 450. I also assume a high mass fraction, 0.91, but since these stages are quite large, I believe this can be achieved. It has, in fact, been achieved in the second stage of the Saturn V, which also is a hydrogen-oxygen stage.

In all my calculations, I have assumed that we can't waste the equipment. That is, the hydrogen-oxygen stage has the function of delivering its payload and then returning to the starting point for reuse with a new propellant supply. For trips of the order of 13,400 feet per second, I choose to use two stages. Although it is technically feasible to do this mission in one stage, the mass fractions, and in particular the fact that there is a considerable amount of inert mass that has to be propelled both ways, penalize the payload capability rather severely. The inert mass must be given a total ΔV of the order of 27,000 feet per second.

It is not only possible, but relatively straightforward and easy, to use a two-stage system in such a way that both stages can be recovered, as shown in Figure 60. This is a "slingshot" operation. The first stage accelerates the vehicle from a circular low Earth orbit into an elliptical orbit with an indefinite apogee, coming back to the perigee point. It imparts a velocity change of about 6,200 feet per second. The second stage then takes over and produces 4,200 feet per second, enough to reach the lunar parking orbit or L5. The second stage then refires, imparting the order of 3,000 feet per second to circularize the maneuver. It delivers its payload and has enough velocity increment left to return again to low Earth orbit, again performing the 4,2000 foot-per-second maneuver to achieve the orbit for refueling and reuse. The scheme looks more complicated on Figure 60 than, in fact, it is to execute.

The deploy/retrieve capability of the two-stage hydrogen-oxygen system is shown in Figure 61. I will now put a further stipulation on the system, which is that the two stages be identical in size. The payloads that can be deployed are shown along the abscissa as a fraction of the initial mass. The payloads that could be retrieved, if you took those stages up empty, is shown along the ordinate. Any combination of deployment and retrieval is represented by a point along the line shown. The payload that can be taken, either to L5 or to the lunar parking orbit, is about one third of what is initially in low Earth orbit, and immediately we can estimate what is required in the lunar mass orbit for inserting 10,000 tons at L5. I will use, for the sake of simplicity, the figure of one third; thus the 10,000 tons translates immediately into 30,000 tons required in low Earth orbit to accomplish the injection of that payload.

Figure 60 Method for Utilizing Two Recoverable Stages for Transport from Low Earth Orbit to Lunar Parking Orbit or L5

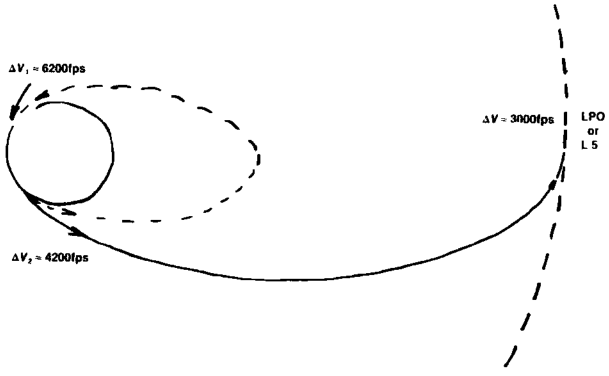
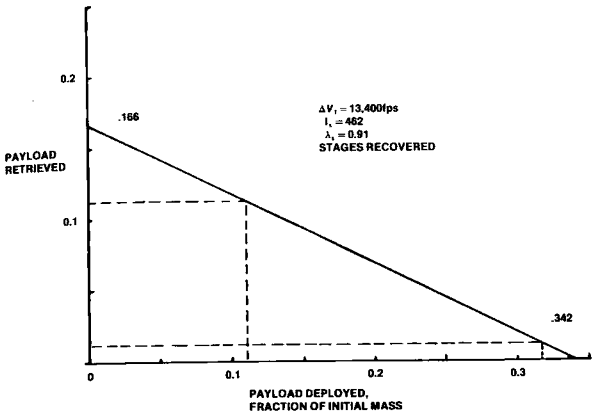


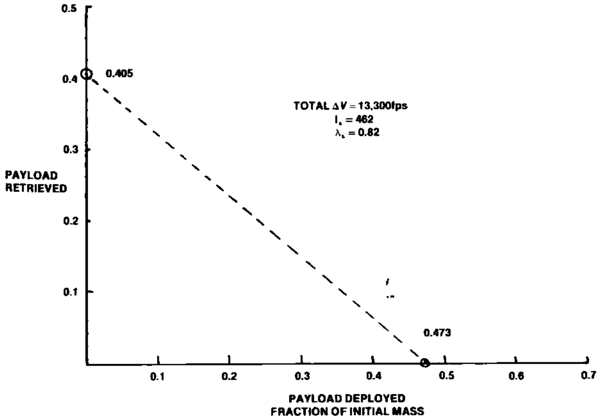
Figure 61 Deploy/Retrieve Capability for 2-Stage Hydrogen/Oxygen System



Now let's tackle the problem of 3,000 tons on the lunar surface. Here we have a more difficult situation in that we have to start from the lunar parking orbit, having gotten there by the same type of system just described, and bring whatever we have parked there down to the lunar surface. These maneuvers are to be conducted in a gravitational field, and even though this g-field is, at the surface of the Moon, only about one sixth what it is at the surface of the Earth, it prohibits the use of the loosely jointed assemblies which are possible in zero-g space.

Figure 38, cited earlier, shows both the transfer vehicle and the lunar lander in transit. Figure 40, also cited earlier, shows what the landing configuration ought to look like. The core is a propulsion stage, above which is a personnel module. Strapped to the sides are equipment modules; they are carried there to reduce the center of gravity as much as possible, and could presumably be left on the surface as the payload.

Figure 62 Deploy/Retrieve Capability for Single Stage Hydrogen/Oxygen System



This system will leave the lunar parking orbit, land on the surface, deploy its payload, and then be lifted by the propulsion system through a ΔV of 6,200 feet per second back to the lunar parking orbit, there to be refueled. It is so configured that the propulsion module and the crew module can be carried in the shuttle, having a diameter of 4.4 meters. It has landing legs. It does need structural capability and strength and is an assembled unit. For the purpose of calculating what this system would require in terms of lunar parking orbit mass to land 3,000 tons on the lunar surface, I have used a stage propellant mass fraction for the entire device of .82, which might be a little on the high side. I have assumed the system total mass as it leaves the lunar parking orbit to be 180,000 pounds.

Using this system and the parameters that I have chosen, Figure 62 shows that we can land about 0.473 of the original lunar parking orbit mass on the surface of the Moon as useful payload and still get the propulsion stage back. I am going to make a rough approximation here and say that that is close to 0.5. The line is shown dotted because, with the ΔV's going and coming being different in this case, I am not sure whether it is a straight line or some sort of catenary curve. However, we are concerned only with the number .473, and if that is, in fact, close enough to one half, we can say that our 90-ton system will land 45 tons of payload. We then calculate very quickly that to put 3,000 tons of equipment on the lunar surface using this system (and also a transporter to bring the system, plus the payload, from low Earth orbit) will require 6,000 tons in the lunar parking orbit and 18,000 tons in the low Earth orbit.

Roughly, then, to accomplish the complete task of landing 3,000 tons on the Moon and bringing 10,000 tons to L5, the total mass required in low Earth orbit is about 50,000 tons.

There is an error in the way I have conducted these estimates, but that error is sufficiently small that I chose to neglect it: in calculating the masses required to be transported, I did not account for the masses that were being returned for reuse. In other words, I didn't, in making those mass estimates, fully account for the fact that I was reusing a system for the second, third, etc., time. For materials launched out of low Earth orbit to either L5 or the lunar parking orbit, this amounts to overestimating the mass requirement in low Earth orbit by about 5%, and for payloads from the lunar parking orbit to the lunar surface, the error is of the order of 10%. Because of attrition and replacement of stages and other equipment, I believe this error to be of the same order as might be expected of trips in which no payload was delivered. There are certainly going to be a number of executive, legislative, and management trips (non-productive in terms of mass transported) to account for this.

Thus, it will require 50,000 tons in low Earth orbit to do the job that we set out to do. There is nothing frightening about that number! This represents roughly 500 flights of a launch vehicle having Saturn V capability; that is, 250,000 pounds of payload capability in low Earth orbit. There is nothing about this that is remarkable. Stretched over ten years, this represents a flight a week. With a larger launch vehicle, the numbers would be shifted to require even fewer flights. I think that is well within the technological capability of this country to handle, so that in no way does it frighten me or even cause me concern.

Now let's turn to the first 1800 tons that must be delivered to L5. Because of the time frame, we will have to do this with the space shuttle. What follows is an engineering layout of a system to accomplish such a requirement.

Orbital assembly of bigger systems than can be carried in one shuttle flight certainly appears to be the right way to do the job. Although the ultimate mass of such an assembled system can be decided somewhat arbitrarily, I decided that one of the constraints would be that the modules, tanks, etc., fit the dimensions of the shuttle bay, which is 60 feet long and 15 feet in diameter and has a payload capacity of 63,000 pounds, as described by Davis in detail.

As shown in Table 20, it would take 11 flights of the shuttle to do the job, that is to transport to low Earth orbit 633,000 pounds of system, propellants and payload. Stage One carries with it all of the liquid oxygen necessary for Stage One, and weighs 63,000 pounds; no strange coincidence. Stage Two is exactly the same kind of stage, because I elected to use the same size stage in both instances. Now, we need to take up liquid oxygen to put into each of these tanks, so the next four flights are engaged in carrying up sufficient oxygen to fill the two tanks already up there (I defer the liquid hydrogen to reduce boil-off). The 7th, 8th, and 9th shuttle flights each carry up 63,000 pounds of payload, for a total of 189,000 pounds. Finally, the liquid hydrogen is carried up in two flights. Because the liquid hydrogen is low in density, we only need to carry 33,000 pounds per stage, but in order to keep the stages symmetrical, I elected to carry the same quantity in two tanks for each stage.

Table 20. Modular Delivery to Low-Earth Orbit (LEO)

Shuttle Flight No.	Mission	Mass in LEO (pounds)
1	Stage 1, L 0_2	13K, 50K
2	Stage 2, L 0_2	13K, 50K
3	L 0_2 Tanker	63K
4	"	63K
5	"	63K
6	"	63K
7	Payload	63K
8	Payload	63K
9	Payload	63K
10	L H_2 Tank	33K
11	"	33K

Table 21. Modular Tank Sizing, O/F = 6.0

	Liquid Oxygen Tank	Liquid Hydrogen Tank
Ullage, %	6	14
Propellant mass, lb.	183K	30.5K
Volume, cu. ft.	2,700	7,800
Diameter, ft.	14	14
Length, ft.	21	54, or 2 at 29 each

Table 21 shows the volume of the tanks using an oxygen/hydrogen ratio of six. One tank to carry almost 31,000 pounds of liquid hydrogen has a length of about 54 feet, if the diameter is confined to 14 feet. For the sake of propulsion stage symmetry, and at the cost of stage mass fraction, I prefer to carry the same quantity of propellant in two tanks, each 29 feet in length. The oxygen tank has a length of 21 feet if its diameter is 14 feet, and this is readily accommodated in the shuttle. Allowing for the ullages shown, the total mass required for the oxygen is 183,000 pounds, and the toal mass required for the first stage of the hydrogen is 30,500 pounds.

Figure 63 shows the system when assembled. Only liquid oxygen is transferred from tanker to stage. The liquid hydrogen tanks are simply attached to the stage and become the stage system tanks. Stage One is on the right with two hydrogen tanks, which have been carried up separately and attached to the stage. The oxygen tank is carried up with the stage and is refueled by tanker operation. Stage Two is exactly the same. The payloads are on the left. The space transportation vehicle ignition mass, the mass in low Earth orbit, is 444,000 pounds. The payload mass is about 189,000 pounds at launch and 180,000 pounds when it reaches the lunar parking orbit or L5.

Figure 63 Modular Space Transport Vehicle

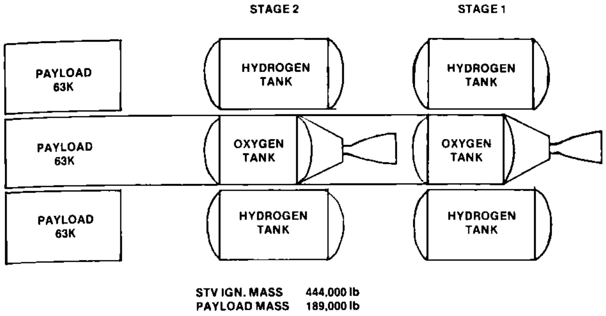
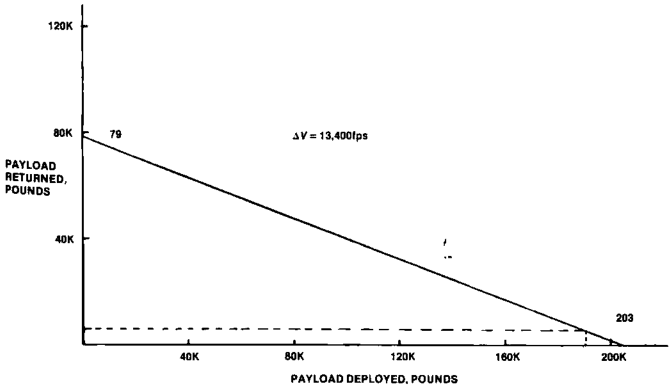


Figure 39, cited previously, shows on the right the Modular Space Transport Vehicle just described. What is shown is the lunar landing system; one of the stages is shown, one is already gone. The payload is on the left.

Figure 64 is essentially the plot we discussed before, but reduced to practical mass terms. It shows what payloads the stages can take to L5 or the lunar parking orbit, using the masses that I used. It comes out to 203,000 pounds, but its real capability is better represented as 3 shuttle trips, or 189,000 pounds. The system capabilities then allow a return to low Earth orbit of 6,000 pounds for every flight to L5. These figures provide a mass at L5 of 30% of the low Earth orbit mass, somewhat less than the one-third I assumed in earlier calculations. The capability of bringing 6,000 pounds back with each flight just might turn out to be useful, so it seems to me that system makes pretty good sense.

This specific case illustrates that even cursory attention to the pragmatic engineering details of the capability per stage, matching with the launch vehicle, etc., will modify the academic solution, but not really terribly much. All of the answers in this brief space propulsion analysis indicate solutions that are technologically reasonable, even in the optimistic time frames given for implementing the entire system of power generation in space.

Figure 64 Payload Capability for Modular 2-Stage Hydrogen/Oxygen Space Transportation Vehicle



One matter I haven't discussed, and I have avoided it rather deliberately, is the matter of costs for developing and producing this equipment. Such cost estimates can be made readily by anyone who is expert in the propulsion field.

DISCUSSION

Q. *It is a good thing to see people dreaming again. We used to do things like this all the time a few years back. Why not spend a million dollars to bring NERVA (Nuclear Engine for Rocket Vehicle Applications) to operational status and use it?*

A. That argument has to be examined. The assumptions that I was presumed to work on did not include it. Addressing the question, though, I think there are some problems that should not be overlooked in operating a nuclear system in space. One of them is what you need to do to shield the personnel involved in the operation from the radiation that you generate. I also would bring up the question, since I ended on the point of cost, of reminding you that this operation is just a matter of delivering a payload, and one has to look at the cost to see whether the chemical approach isn't, in fact, the cheaper way to do it rather than using a nuclear system.

There is also a psychological point: a lot of people, particularly younger people, have a hatred of nuclear power. One of the reasons for doing the job without invoking nuclear power is that you avoid raising all these emotional issues. Further, I have been told by NASA that anytime professional NASA cost estimators hear the word "nuclear rocket," the price of any piece of equipment, even if it's got nothing nuclear in it but is just labeled as part of that system, goes up by a factor of about six.

Q. *Aside from the development costs, could you give an estimate on the dollars per pound based only on the system payload?*

A. There are two factors involved in the cost. One is the development cost, the so-called non-recurring cost, and the other is the recurring cost. I am not sure which would dominate. The fact is, I don't think the systems or the operations in space begin to approach the operational costs of getting everything into Earth orbit, because the masses are reduced at every step of the process. You can translate the whole problem back into what it costs you to put the mass up into low Earth orbit, and I don't think you have to multiply it even by two to encompass all the rest of the systems.

Q. *If that's 50,000 tons, or roughly a hundred million pounds, and we use O'Neill's figure of four hundred dollars a pound, it's forty billion dollars.*

A. That's not an incredible number.

Q. *Would you say that the cost of putting mass in Earth orbit would be substantially less if they were started from the upper Earth atmosphere? For example, a lighter-than-air craft might be used as a launching platform.*

A. That point comes up again and again. It is true that you can reduce the mass of the launch vehicle by some amount – I'm not sure how big it is, but I'm sure it's under five percent. I don't think that kind of operation would ever be justified in terms of cost.

Q. *The advertised figures, as I understand, for the shuttle are ten or eleven million dollars per launch. If we up that to, say, 15 million per launch just to be on the safe side, it would cost a total of about twenty five billion dollars to lift your 50,000 tons to low Earth orbit.*

A. A previous comment estimated that forty billion dollars would encompass the whole transportation system. That may be about right.