Technical Note: Mass Driver for Lunar Transport and as a Reaction Engine

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Abstract

The mass driver is a special type of linear synchronous motor, in which small passive carrier vehicles (buckets), guided by dynamic magnetic constraint forces, are accelerated by pulsed magnetic fields. At peak velocity each bucket releases a payload, decelerates, and returns for re-use.

Theoretical work in 1974-1977 indicates that mass drivers should achieve accelerations of 100-1000 earth gravities or higher, and should operate at efficiencies (electric input to kinetic output) of 75% to 96%. A first two meter test model, built in 1977, has already demonstrated an acceleration of 33 gravities.

Parameters for two applications have been calculated, each based on the use of commercially available aluminum, capacitors, superconducting wire (needed in gram quantities for bucket coils) and silicon controlled rectifiers.

The first is the launching of materials from the lunar surface to a precise point in free space. With 3.8 kg payloads and a repetition rate of 10 launches per second, the lunar mass driver is calculated to have a mass of 232 tons exclusive of power supplies and radiators. The efficiency is calculated as 96% for a throughput of 600,000 tons per year at a launch velocity of 2400 meters/second.

A mass driver for the transfer of shuttle-lifted payloads from low Earth orbit to lunar orbit optimizes to a mass of less than 170 tons. It would have an exhaust velocity of 10,000 m/s and could lift a 700 ton payload to lunar orbit in six months, using waste external shuttle tanks, pelletized or powdered, as reaction mass. The mass driver would retain sufficient reaction mass to complete the round trip, returning in one month.

To illustrate the capability of this technique, a program is outlined in which 60 shuttle flights per year, over a seven year period, would build sufficient transport and processing capability to process in space 600,000 tons/year of lunar material, yielding 180,000 tons/year of pure metals and silicon, in addition to oxygen, for use in space manufacturing operations.

Introduction

The mass-driver concept was formulated[1] in 1974, and at that time was considered for applications both to the launching of lunar materials and to propulsion of large payloads between orbits.[2] The concept was built on the foundation of prior work on magnetic-flight transport systems.[3]

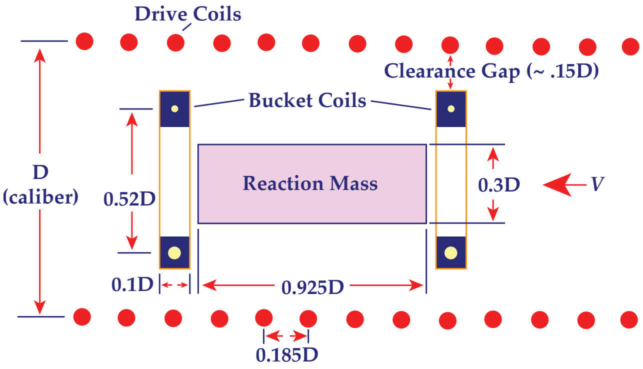


Figure 1 — Cross-Section of Carrier Vehicle (Bucket) and Surrounding Coaxial Drive Coils

Intensive theoretical work in 1976-77 yielded these conclusions:

1. For minimum mass of the accelerator, at maximum efficiency and acceleration, the optimum geometry is axial. Drive and driven coils should be circular and coaxial.
2. Efficiency increases as the number of driven (i.e. bucket) coils is reduced. For stability of the moving bucket in pitch and yaw, the minimum number of bucket coils is two, to provide restoring torques in the bucket's magnetic flight through the guideway. Therefore a two-coil bucket is optimum[4] (Figure 1).
3. Efficiency is approximately maximized[5] if each drive coil is separately controlled, and if the peak of the sinusoidal current wave-form occurs when the bucket coil is at the position where the gradient of mutual inductance dM/dx is at a maximum; x is the axial position of the bucket coil.
4. Numerically, within the constraints of available materials and components, accelerations in the

range 100-1000 gravities should be practical, for the bucket within the mass-driver accelerator. Magnetic-flight constraint forces will give to the bucket transverse oscillation frequencies in the low audio range (20-200 Hz).

Calculation Methods

Acceleration is most conveniently calculated by considering the energy transfer[5]

$$n_2 i_B i\left(\frac{dM}{dx}\right)\Delta X$$

from a drive coil of n_2 turns carrying instantaneous current i amperes, to a single bucket coil of i_B ampere-turns, as the bucket moves through a small distance ΔX. That energy transfer is the increase of bucket kinetic energy due to the interaction of one drive coil with one of the two bucket coils, for motion through ΔX. Summation of these energy transfers for each X-value for which the drive current is nonzero, and multiplication by two for the two bucket coils, gives the total kinetic energy increase per drive coil. With that, the peak drive current can be obtained from the required acceleration once the drive coil spacing and the mass of the (loaded) bucket are known.

Registers used in energy-transfer program

R0 $a_0 = (\Delta x) i_B / L_w n_2$

R1 Initial value of position x (meters) at which drive coil switch is closed. Zero is allowed, but constant should be chosen so that x-update subroutine never finishes with zero. R1 stores updated x.

R2 a_2 = constant used in dM/dx subroutine. For D = 5.0 cm, a_2 = 184.000138. (That is, INT = is proportional to 1/D, while FRAC is proportional to D.

R3 $a_3 = (\Delta x)R / vL_w n_2^2$. The drive winding resistance R appears only in this constant.

R4 $a_4 = (\Delta x) / vC$. The resonant capacity C appears only in this constant, and is equal to the sum of capacity on two adjacent sections of the actual mass-driver.

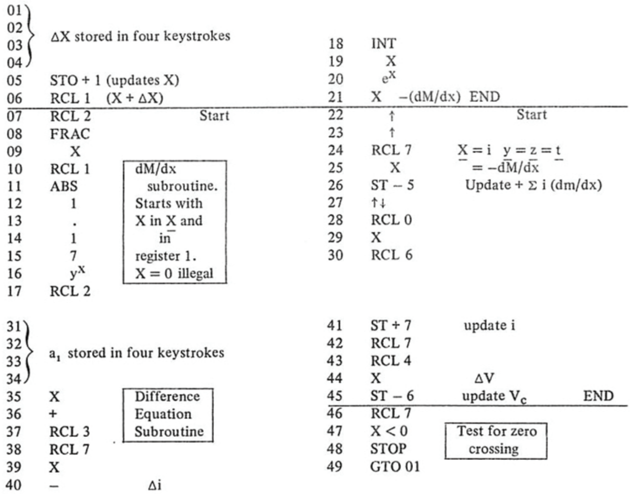
R5 Initialize to zero. Stores updated $\Sigma\, i\, (dM/dx)$.

R6 Peak voltage to which capacitor is charged before drive circuit switches on. R6 stores updated capacitor voltage V_c.

R7 Initialize to zero. Stores updated current i.

A program (Table 1) simple enough to fit on a small pocket calculator is adequate for the calculation of the total energy transfer per drive coil, and from it the peak drive current i_D.

Table 1 — Calculator Program for Energy Transfer to Moving Bucket



```
01 )
02  }  ΔX stored in four keystrokes         18   INT
03  }                                        19     X
04 )                                         20    e^X
05   STO + 1 (updates X)                     21   X    -(dM/dx)  END
06   RCL 1   (X + ΔX)
--------------------------------------------------------------------------
07   RCL 2                   Start           22    ↑                  Start
08   FRAC                                    23    ↑
09     X                                     24   RCL 7       X = i  y = z = t
10   RCL 1        | dM/dx          |         25     X           = -dM/dx
11   ABS          |  subroutine.   |         26   ST - 5      Update + Σ i (dm/dx)
12     1          | Starts with    |         27   ↑↓
13     .          | X in X and     |         28   RCL 0
14     1          |    in          |         29   X
15     7          | register 1.    |         30   RCL 6
16    y^X         | X = 0 illegal  |
17   RCL 2

31 )                                         41   ST + 7      update i
32  }  a_1 stored in four keystrokes         42   RCL 7
33  }                                        43   RCL 4
34 )                                         44   X             ΔV
35   X            | Difference |             45   ST - 6      update V_c      END
                                             ----------------------------------
36   +            | Equation   |             46   RCL 7
37   RCL 3        | Subroutine |             47   X < 0       | Test for zero |
38   RCL 7                                   48   STOP        |   crossing    |
39   X                                       49   GTO 01
40   -                  Δi
```

As normally used, the program calculates the energy transfer for a half-cycle of oscillation. The total energy transfer for a two-coil bucket, corresponding to the passage of both bucket coils through one drive coil, is then

$$(\Delta x)\,(4 n_2 i_B)\ (\text{summation of } i\,dM/dx \text{ in register } 5)$$

Typically a step interval Δx of one millimeter is used, .001 in program steps 01-04. Each step interval requires 3.75 seconds on an HP-25, and about twice as long on an HP-67, so a half-cycle of oscillation with D = 5.0 cm takes a little over one minute. Typically the constant at is between 0.1 and 1.0.

Electrical Drive

For high efficiency, mass driver circuits should be designed so that each drive coil is excited only when its dM/dx to a bucket coil is non-zero, and so that high currents need not travel long distances. For simplicity we presently prefer a two-phase system:[4] even-numbered drive coils are connected to one phase, and odd-numbered (alternate) coils to another phase, electrically in quadrature with the first. The spacing ℓ_m between drive coils is chosen equal to the distance from dM/dx = 0 to dM/dx = maximum.

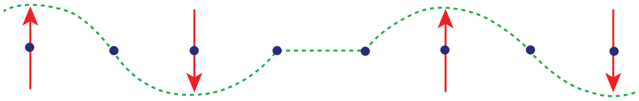


Figure 2 — Phase and Amplitude of Currents in Drive Coils Near Bucket Coil

The current in one drive coil goes through one sine wave of oscillation, during the passage of each bucket coil. The current peaks when the bucket is a distance ℓ_m away, coplanar with the adjacent drive coil, whose current is then zero. In the vicinity of each bucket coil there are then just two drive coils of one phase excited at any given time (Figure 2).

System mass is minimized by assigning a resonating capacitor to all the drive coils of one phase over a distance ℓ_s (sector length). Switching silicon-controlled rectifiers (SCR's) then connect to the sector capacitor through feeder conductors the drive coils on either side of the bucket coil (Figure 3).[6]

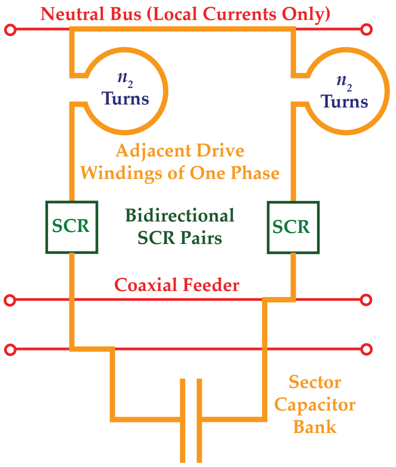


Figure 3 — Sector (Length 2) Has One Capacitor Bank Per Phase, and Typically Several Hundred Drive Windings. Heavy Lines Show Resonant Circulating Current. Capacitor Banks Are Recharged from DC Lines (not shown)

Design Choices

For simplicity a number of arbitrary choices have been made in the studies carried out up to now. Some of the most important are:

1. The ratio of bucket coil diameter to drive-coil diameter has been set equal to 0.53.
2. The cross-sectional areas A_D and A_F defined in Table 2 have been taken as increasing from the V_{MAX} point toward either end of the accelerator, so as to hold the dissipated power per meter constant along the accelerator length. In previous literature this is referred to as taper.[7]
3. A further economy in system mass can be obtained by adding SCRs to connect (bridge) adjacent feeder lines. The SCRs are switched so that at all times the sector in which the bucket is located, and the next nearest sector, are connected.[4] This reduces the capacitor masses by a factor two. Feeder mass is reduced by the same factor.
4. Use of two-phase drive, as discussed earlier.
5. Equal currents in the two bucket coils. (A further reduction of system mass could be obtained by concentrating most of the coil current (and coil mass) in one coil, at the expense of reduced restoring torques in pitch and yaw motions.)

Mass Optimization

The electrical components of a mass-driver include SCRs, drive windings, feeders, capacitors, power supplies and radiators. The equations for the minimization of system mass have been derived elsewhere, with the design choices of taper, no bridging, and three-phase drive.[7] We define:

M_s = total mass of SCR's neglecting bridging SCRs.

M_w = total mass of windings

M_F = total mass of feeders

M_c = total capacitor mass

$M_c = M_F$

Table 2 — Definition of Parameters in Mass-Driver Optimization Equations (MKS units used in all equations)

L_W	Inductance per drive winding (including mutual)
ℓ_w	Circumference of drive winding
ℓ_m	Spacing between adjacent drive windings
ℓ_p	Wavelength (= 412 m)
n_2	Number of turns per drive winding
S_{TOT}	Total length of mass-driver (accelerate + decelerate)
i_D	Peak drive current
m_1	Mass of segment carried by each bucket
V_{MAX}	Maximum velocity of bucket
m_s	SCR specific mass (Kg/peak volt-ampere)
n_c	Number of sine-wave oscillation cycles for each drive coil (= 2)
n_w	Number of drive windings simultaneously excited per phase (= 4)

f_R	Repetition rate
ℓ_s	Sector length (optimized)
ρ_R	Resistivity of drive winding
m_p	Specific mass of power supply (Kg/watt)
m_R	Specific mass of radiators (Kg/watt)
ρ_{KG}	Density of windings (Kg/m^3)
A_{DO}	Optimized winding cross-sectional area at V_{MAX} point
m_c	Specific mass of capacitors (Kg/joule)
A_{FO}	Optimized feeder cross-sectional area at V_{MAX} point

For taper, with bridging, and for two-phase drive the equations for optimization of system mass become:

$$M_S = \frac{\pi S_{TOT} i_D^2 V_{MAX} L_W m_S}{3\ell_m^2} \quad (1)$$

$$A_{DO} = \sqrt{\frac{n_C \ell_P f_R i_D^2 \rho_R \left(m_P + m_R\right)}{4 V_{MAX} \rho_{KG}}} \quad (2)$$

This formula is unchanged from that of Reference 7.

$$M_w = 8 S_{TOT} \ell_W A_{DO} \rho_{KG} / \ell_P \quad (3)$$

$$\ell_S = \left(\frac{L_W^2 i_D^2 m_C^2 n_2^2 V_{MAX}}{4 \rho_{KG} \rho_R f_R \left(m_P + m_R\right)} \right)^{1/3} \quad (4)$$

Unchanged from Reference 7.

$$A_{FO} = \frac{1}{8} \left(\frac{n_W^3 L_W i_D^4 m_C \rho_R f_R \left(m_P + m_R\right)}{2 n_2^2 \rho_{KG}^2 V_{MAX}} \right)^{1/3} \quad (5)$$

A reduction by a factor 2 from Reference 7.

$$M_F = 8 A_{FO} S_{TOT} \rho_{KG} \quad (6)$$

2/3 the value given in Reference 7.

As previously derived[7] and illustrated,[8] the winding mass equals the total mass of power supplies and radiators associated with winding losses; similarly, the feeder mass equals the mass of power supplies and radiators associated with feeder losses. The power supply mass required for the "Kinetic power,"

$$P_K \equiv \frac{1}{2} m_1 f_R V_{MAX}^2 \quad (7)$$

is $m_p P_K$, so the total electrical component mass of the mass-driver, including all power supplies and radiators, is:

$$M_S + 2M_W + 3M_F + m_P P_K \quad (7a)$$

Component Requirements

For launch of materials from the lunar surface, V_{MAX} is slightly less than 2400 m/s, and a mass-driver could be constructed on the basis of values of m_s and m_c corresponding to presently available shelf-times. For all mass-driver designs studied so far, the values of ρ_{KG} and ρ_{KG} corresponding to aluminum at room-temperature have been used.

A mass-driver reaction engine (MDRE) optimized for lifting accumulated shuttle payloads to lunar orbit, using waste external tankage as reaction mass, would have V_{MAX} near 10,000 m/s, more than twice the exhaust velocity of the best chemical rockets.[8] The SCR's of such a machine would operate in short pulses of only a few microseconds duration, at repetition rates of a few per second. We expect that in that service SCRs could have much higher current ratings (lower values of m_s) than in conventional powerline service, and recommend developmental research on high-current, short-pulse, low-mass SCRs and alternative competing solid-state switches as usefully contributing to the evolution of high-performance MDRE's. The uncertainties in SCR mass for high V_{MAX} mass-drivers are sufficiently great at present that in this paper we do not list values for m_s.

Design Examples

The optimized parameters for a mass-driver to be located on the lunar surface are given in Table 3.

Table 3 — Lunar Mass-Driver

Mission: Accelerate and guide lunar materials to precise point in space.

Capability: 30,000 tons/year initial, to 600,000 tons/year with added power supply.

Parameters	
Geometry	Axial
Drive coil diameter	26 cm

Parameters	
Peak drive voltage	674 volts
Acceleration	1000 m/s^2
Total length (acceleration & deceleration)	4320 m
Bucket mass (empty)	3.8 kg
Payload mass	3.8 kg
Cycle rate (during lunar day)	0.5 —> 10 Hz
Winding mass	152 tons
Feeder mass (= capacitor mass)	38 tons
Efficiency (DC —> Kinetic power)	96%
Photovoltaic power supply (at lunar surface)	15 tons/MW
Waste-heat radiators	20 ton/MW

For an MORE to operate as an inter-orbital tug, parameters are summarized in Table IV.

Table 4 — Parameters for Mass-Driver Reaction Engine (MORE)

Exhaust Velocity V_{MAX}	10,000 m/s
Specific Impulse	1,020 seconds
Exhaust rate	.07 Kg/sec
Thrust	700 newtons
Electric components (excluding SCR's)	140 tons

Economics

The economic payoff potential of an MDRE can be estimated roughly by noting that its initial establishment in orbit would be at the expense of some half-dozen Shuttle flights, and that it could then lift to geosynchronous or higher orbit about 17,000 tons of payloads over a ten-year period, from a low orbit reachable by the Shuttle. If MDRE components cost $1,100/Kg, and Shuttle flights $20 million each, the amortized cost of MDRE freight transfer over a ten-year period, excluding development and maintenance, is therefore roughly $18/Kg. That is approximately 1/40 of the cost per kilogram of Shuttle lift from the Earth to low orbit, and less than 1% of the cost for Earth to geosynchronous transport by Shuttle and chemical upper-stage. The potential advantage of an MDRE is therefore such that its value is relatively insensitive to details of design and development costs.

Test Model

A working model mass-driver (Figure 4) was built during early 1977 as a student volunteer project.[9,10] Its performance measured during a demonstration at a Conference[11] is given in Table 5. Guidance was mechanical rather than by magnetic flight.

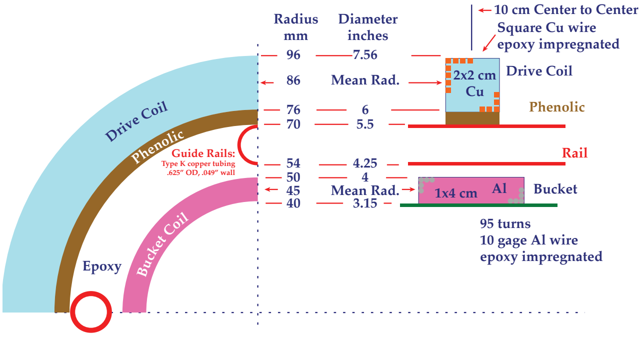


Figure 4 — Working Model Mass-Driver. After Two Meters of Acceleration, the Bucket Is Slowed to a Halt by 8 Meters of Frictional Braking

Applications

Mass-drivers would play major roles in a near-term, minimum-cost program for the utilization of non-terrestrial materials in space manufacturing.[12,13] One such program has been studied in some detail;[13] it would proceed in several steps, at each of which progress could be evaluated and a decision made on whether to proceed:

1. Development of an inter-orbital MDRE, of a small chemical tug for crew transport, and of a crew module for the Shuttle and tug.
2. Assembly in low orbit of a MDRE.
3. Use of MDRE, with Shuttle tankage in pelletized or powdered form as reaction mass, to assist in all large-scale operations in geosynchronous or higher orbit. These operations could include satellite power prototype tests, deployment of large communications satellites, and possibly an unmanned materials-recovery mission to high orbit from an Apollo/ Amor asteroid with particularly favorable orbital elements.

4. Development of a lunar-based mass driver for the transport of lunar materials into space, and of a chemically-propelled lander. A decision to proceed by that route would be made either as an alternative to, or as complementary to, a decision to utilize asteroidal materials.
5. Transport to lunar surface of approximately 1,100 tons of equipment and supplies, including a lunar mass-driver, sized for 600,000 tons/year but powered for only 30,000, a crew habitat, power plant, necessary supporting equipment and supplies, and an equal mass of chemicals for soft-landing that cargo.
6. Establishment of the transport of lunar materials at the rate of 30,000 tons/year. Once available in space, in advance of any chemical processing capability, those materials would be usable as reaction mass for large MDREs, and also as cosmic-ray shielding for all crew-habitats required in geosynchronous or higher orbit.
7. Development of chemical processing and fabrication facilities, sized for 30,000 tons/year of throughput, and development of small, modular crew habitats to support these facilities.
8. Deployment of that equipment via SDLV (Shuttle-derived lift vehicle) and MDRE to a high-orbital location.
9. Use of the high-orbital lunar-coils processing facility to produce approximately 2,000 tons/year of photovoltaic arrays, 7,000 tons/year of workforce habitat modules, and several thousand tons/year of liquid oxygen, to be used as propellant for chemical rockets, as breathing oxygen, as the weightiest component of water, and as environmentally benign reaction mass for MDRE's.
10. Over a four-year period, on the basis of about 15 Shuttle and 45 SDLV flights per year, the expansion of processing and lunar transport to a throughput of 600,000 tons/year. During that period all complex components (processing and fabrication plants, additional MDRE's, and certain habitat equipment) would continue to come from the Earth. The original space processing facilities would be relied on only for the simple and repetitive production of photovoltaic arrays and habitat modules.

A program of that kind, based on minimizing investment and maximizing return at each step, appears capable of reaching the level of 600,000 tons/year of lunar-materials throughput without ever exceeding the lift requirements of the space-Shuttle era. About 300 flights in all, 150 Shuttle and 150 SDLV, would be needed. At a rate of 50-60 flights/year, the 600,000 ton/year rate would be reached in about seven years (Figure 5) and would include 100 SDLV flights to deliver a stock of food and other organic materials to the orbital manufacturing site to provide reserve supplies for emergencies.

Table 5 — Measured Performance of Mass-Driver Model Built in 1977

Length	2 meters
Drive coil diameter	0.15 meters
Bucket mass	0.5 Kg
Acceleration	33 gravities
V_{MAX}	36 m/s
Acceleration time	0.11 second

Table 6 — Mass Budget for Lunar Surface

Item	Mass (tons)
Axial mass-driver electrical components	232
Foundations	100
Maintenance enclosure	100
Photovoltaic power supply (for 30,000 tons/year)	93
Downrange course-correction stations	50
Habitat (temporary for 50, long-tour for 10)	300
Life support resupply (50 people, 1 year, 10 Kg/day)	180
Silicon & glass-fiber plant for materials encapsulation	30
Total lunar	1,085
Resupply for operations personnel	37 tons/year

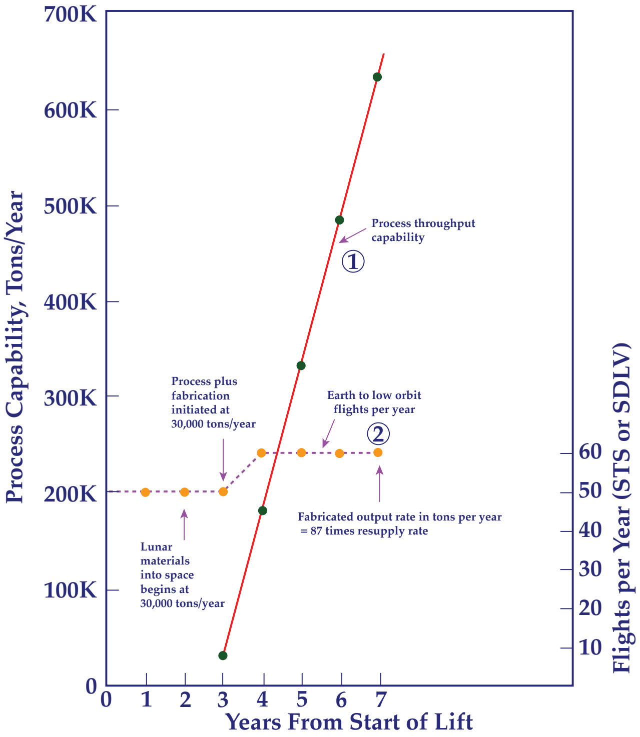


Figure 5 — Development of Space-Manufacturing Within the Limits of the Shuttle. Over a Seven-Year Period, 50 to 60 Shuttle or Shuttle-Derived Freight Rocket Launches Per Year Are Adequate to Install All Equipment Necessary for the Transport and Processing of 600,000 Tons/Year of Lunar Material

Economic Payback

The most recent studies suggest that 600,000 tons of lunar materials would yield about 180,000 tons of finished products, made of lunar metals and silicon.[14] A minimum value for these products is set by noting the lift costs saved by obtaining these materials from a non-terrestrial source rather than from the Earth's surface.

The Boeing Aerospace Company, in a NASA-funded contractor's report,[15] concludes that on the basis of advanced (Class IV) lift vehicles to low orbit, plus arcjet-thruster transfer between orbits, powered from a satellite power station payload assembled in low orbit, a recurring cost of $100/Kg for lift to geosynchronous orbit may eventually be met. On that basis, a space manufacturing facility established over a seven-year period for $1.2 B/year of lift costs (Shuttle and SDLV) would then produce more than $18 B/year in value (180,000 tons/year x $100/kg).

As of 1977, three Conferences,[16,17] and three NASA-funded summer studies,[13,18,19] on space manufacturing have been held. Although no scheduled program yet exists in this field, funded research activity is now going on in the areas of mass-driver development, the chemical processing of lunar materials, and the optimization of satellite power station design for the use of non-terrestrial materials.

For a number of reasons it seems wise to encourage that space manufacturing be carried out as an international program, for the benefit of all humankind. A first step in such a development is to insure that such internationally-shared benefits not be prevented by treaty agreements unduly restricting the use of non-terrestrial materials.

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