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EVOLUTION OF EARTH-LUNAR TRANSPORTATION SYSTEMS

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Manned Earth-lunar transportation systems moved closer to reality with the initiation of a program to land man on the lunar surface in this decade. This will be the beginning of a transportation system connecting the Earth and the Moon, which will be improved continuously to a point where commercial traffic between these two celestial bodies becomes economically feasible. While the emphasis will be on the first manned lunar landing, it is not too early to take closer look at what might possibly follow this first landing and what refinements in the transportation system can be expected through about 1980. This is as far as one would dare to extrapolate advancement of the technology with any degree of confidence. It is quite probable that any prediction of today will be pessimistic, as new unpredictable discoveries will be made in the development of space technology.

Therefore, this study is only an attempt to develop a typical model of a lunar transportation system which will gradually be improved by incorporation of more efficient elements, such as high energy propellants, nuclear propulsion systems, and fully reusable space vehicles. Finally, it does not seem impossible to produce propellants on the surface of the Moon; this would enable space vehicles to be refueled before they return to Earth. It should be recognized, however, that this model is a hypothetical one only and has no other basis than that of imagination and a fair knowledge of the state of the art. Thus, the results of this study must be considered as very preliminary and only as describing the general trend in the evolution of Earth-lunar transportation systems.

7.1 Discussion

7.1.1 Assumptions

Modes of Operation. Seven different modes of operation will be considered which cover two decades. They can be briefly described as:

1. A large Earth launch vehicle, with two expendable chemical stages,

provides the transportation from the surface of Earth to a low-altitude orbit about it. The vehicle assumed in this example has five liquid propellant engines, each of 1,500,000 lb thrust, in the booster, and four liquid propellant engines of 200,000 lb thrust in the second stage. The orbital launch vehicle is assembled with the help of one rendezvous and docking maneuver and consists of a launch stage and a lunar landing stage, both using the hydrogen/oxygen propellant combination. The thrust levels are approximately 200,000 lb and 30,000 lb respectively. The return from the Moon is accomplished by a single stage employing conventional propellants (solid or liquid) and a direct entry into Earth's atmosphere with orbital entry velocity. This mode of operation is very close to the mission profile which probably will be employed for the first Apollo flight (stages 1, 2, 3, 4 and 5 of Table 7.1).

2. The second mode of operation is identical to the first with the exception of the lunar launch vehicle, which employs high-energy propellants instead of conventional propellants, thus reducing the take-off weight of the lunar launch vehicle by one-third. This eliminates the rendezvous requirement, as the basic launch vehicle has a direct capability within the given payload limit. It also seems advantageous to integrate the lunar landing and launch requirements into one single stage (stages 1, 2, 3 and 6 of Table 7.1).

3. The third mode of operation envisions the same ground launch vehicle to Earth orbit. The third stage, however, is now a nuclear stage that is used for the escape leg from the Earth orbit and is restarted upon arrival near the Moon for the braking maneuver into the lunar orbit. The fourth stage is a high-energy chemical propellant stage and accomplishes the lunar landing, as well as the lunar take-off, with direct entry of the manned capsule into Earth's atmosphere (stages 1, 2, 7 and 6b of Table 7.1).

4. The fourth mode of operation introduces a recoverable and reusable Earth ground launch vehicle that replaces the expendable orbital carrier vehicle used in modes 1 through 3. The thrust of this new vehicle is the same as modes 1 through 3 and, therefore, the payload capability is reduced because of the added weight for the recovery gear. This, then, requires the introduction of one rendezvous and docking maneuver as used in mode 1 (stages 8, 9, 7 and 6b of Table 7.1).

5. The fifth mode of operation uses the same reusable Earth launch vehicle as mode 4 and in addition uses a nuclear ferry vehicle capable of making a full round trip between Earth orbit and Moon orbit. It is refueled in Earth orbit by the reusable Earth launch vehicle. The local lunar transportation is provided by a single-stage chemical propellant vehicle that is refueled in lunar orbit by the lunar ferry vehicle. Its job is to transfer the cargo and crew from the lunar orbit down to the lunar surface and return the relief crew to the lunar orbit, from where

Table 7.1 Fundamental Vehicle Data

STAGE IDENTIFICATION	1	2	3	4	5	6	6a	6b		7	8	9
STAGE DESCRIPTION	Nova Jr. 1st Stage	(expendable) 2nd Stage	Orbit Launch Vehicle	Lunar Landing Vehicle	Lunar Launch Vehicle	Lunar Landing & Launch Veh.	Lunar Landing Veh. for Nuc. Ferry	Lunar Landing Vehicle	Restart for Take-off	Nuc. Orbit Launch Veh.	Nova Jr. 1st Stage	recoverable 2nd Stage
							(Cargo Only)	(Cargo and Personnel)				
F_o, thrust	7.5 x 10^6	800,000	200,000	200/215,000	30,000	30,000		30,000		70,000	7.5 x 10^6	1.0 x 10^6
W_o, initial weight	6.0 x 10^6	1,110,000	450,000	225,000	49,000	100,000	131,800	131,800	45,900	275,000	6.0	1.3 x 10^6
F_o/W_o	1.25	0.721	0.444	0.89	0.61/3.88	0.30	0.23	0.23	0.65/3.82	0.25	1.25	0.77
W_{11} useful payload	-	225,000	-	59,000	3 Men	3 Men	70,000	34,700 +	3 Men	(125, 200)	-	150,000
W_1, total payload	1,110,000	250,000	225,000	62,200	(12,500)	(13,600)	(73,700)	36,500 +	(12,500)	131,800	1.3 x 10^6	158,000
W_s, structure weight	345,000	59,300	32,000	23,000	5200	9640	8200	9200	9200	24,600	660,000	161,000
W_6, residuals	45,000	7700	2000	1400	300	760	500	24,200	700	1200	40,000	10,000
W_w, stage wet weight	390,000	67,000	34,000	24,400	5500	10,400	8700	33,400	9900	25,800	700,000	171,000
W_8, useful propellant weight	4.5 x 10^6	768,000	191,000	138,400	31,000	76,000	49,400	49,400 +-	23,500	117,400	4.0 x 10^6	971,000
W_c, cutoff weight	1.5 x 10^6	317,000	259,000	86,600	18,000	24,000	82,400	82,400	22,400	157,600	2.0 x 10^6	329,000
$\mu = \frac{W_8}{W_w + W_8}$, mass fraction	0.92	0.92	0.85	0.85	0.85	0.88	0.85	0.88		0.825	0.85	0.85
$\overline{I}_{sp}$, specific impulse	300	425	425	434	315	434	434	434		800	300	450
r, mass ratio	4.000	3.500	1.737	2.600	2.722	4.170	1.600	1.600	2.050	1.745	3.000	3.950
Δv, velocity increment	4085	5215	2310	4065	3080	6040	2000	2000	3050	4370	3240	6060
$M_{11} = \frac{W_o}{W_1}$, growth factor	24		7.23		3.920	7.35	1.79	(1.81)		2.09	3.70	
$M_1 = \frac{W_o}{W_{11}}$, eff. growth factor	26.7		7.62		-	-	1.88	-			40.0	
Reliability	1965-68: 80% -69: 85% -70: 90%		95%	90% 855%	1968:90% -69:95%	85%	1969:90% -70:95%	1969:85% -70:90%		1969:85% -70:90%	1971:83.3% -78:96%	

Table 7.1 Fundamental Vehicle Data (continued)

STAGE IDENTIFICATION	10		10a		6c		11		8a	12	
STAGE DESCRIPTION	Nuclear Round-Trip Ferry		Nuclear Ferry with Lunar Refueling		Lunar Shuttle (Orbit Fueled)		Lunar Shuttle (Lunar Surface Fueled)		Chemical Booster	Nuclear Ship	Nuclear Return
					From Orbit	To Orbit	To Orbit	From Orbit			
F_o, thrust	200,000		200,000		30,000	30,000	230,000	230,000	7.5×10^6	3×10^6	
W_o, initial weight	300,000	78,800	300,000	78,800	110,000	30,400	198,500	251,000	6×10^6	3,175,000	3,045,000
F_o/W_o	0.67	2.54	0.67	2.54	0.273	0.99	1.16	0.92	1.25	0.94	0.99
W_{11}, useful payload	88,500	3 Men	120,000	3 Men	36,400	3 Men	-	120,000	-	30,000 150,000	-
W_1, total payload	93,200	10,000	127,000	10,000	38,300	10,000	10,000	127,000	3,175,000	30,000 160,000	30,000
W_s, structure weight	33,400	33,400	33,400	33,400	8500	8500	18,300	18,300	400,000	490,000	490,000
W_6, residuals	35,400	1600	1600	1600	11,900	500	1700	1700	25,000	25,000	25,000
W_w	68,800	35,000	35,000	35,000	20,400	9000	114,000	20,000	425,000	515,000	515,000
W_8, useful propellant weight	128,000	33,800	128,000	33,800	41,800	11,400	74,500	94,000	2,400,000	2,500,000	2,500,000
W_c, cutoff weight	172,000	45,000	172,000	45,000	68,700	19,000	124,000	157,000	3,600,000	675,000	545,000
$\mu = \frac{W_8}{W_w + W_8}$, mass fraction	0.82		0.82		0.855		0.894		0.85	0.84	
$\bar{I}_{sp}$, specific impulse	800		800		434		434		400	900	
r, mass ratio	1.745	1.745	1.745	1.745	1.600	1.600	1.600	1.600	1.663	4.700	5.580
Δv, velocity increment	4350	4350	4350	4350	2000	2000	2000	2000	2000	13,670	15,200
$M_{11} = \frac{W_o}{W_1}$, growth factor	2.19	-	2.19	7.88	1.87	3.04	1.91	1.97	1.89	17.5	101
$M_1 = \frac{W_o}{W_{11}}$, eff. growth factor	-	-	2.31	-	-	-	-	2.09	-	-	-
Reliability	1972: 75% 1978: 91%		1972: 75% 1978: 91%		1972: 75% 1974: 86%		1975: 85% 1978: 91%				

*Individual columns are arranged according to vehicles rather than stages.

they are taken back to Earth orbit by the nuclear orbit ferry vehicle. In this mode, all vehicles are reusable several times. Obviously the efficiency of the operation will improve with time as the number of re-uses is increased by the learning factor and improved reliability (stages 8, 9, 10 and 6c of Table 7.1).

6. The sixth mode of operation is of interest only if it becomes possible to produce propellants on the Moon. Under conditions yet to be determined, it might be more economical to refuel with propellants produced on the Moon; thus, the lunar shuttle vehicle could be refueled on the lunar surface instead of in Earth orbit. The lunar shuttle vehicle has to double in size to carry the increased payload of the ferry, if the rendezvous mode in Earth orbit is employed; or the rendezvous can be eliminated if the size of the lunar shuttle remains the same. The first of these two options is used in this calculation (stages 8, 9, 10a and 11 of Table 7.1).

7. The seventh and last mode of operation is entirely different and might be of interest if large amounts of liquid hydrogen become available on the Moon. The total space transportation system may then be reduced to two vehicles - a chemical, reusable booster that transports the second stage, a nuclear spaceship, beyond the atmosphere and returns to Earth. The nuclear stage then makes the entire trip to the lunar surface, eliminating lunar orbital operations entirely, and is refueled on the Moon. The return trip is performed in one sweep; the nuclear engine is restarted upon entry into Earth's atmosphere to reduce the peak deceleration loads to a tolerable level of perhaps not more than 1.5 G. The landing can then take place under power or with the assistance of a flex wing deployed in the subsonic range at an altitude of about 10 km. The nuclear ship can be overhauled and reused for a new trip (stages 8a and 12 of Table 7.1).

8. An arbitrarily selected schedule for the development and operational cycle of these seven modes of operation is shown in Fig. 7.1.

Space Vehicles. The space vehicles required for these seven basic modes of operations are listed in Table 7.1. There are essentially twelve basic component units (stages) and a few modifications thereof. The essential weight data of these stages are compiled. The first two columns represent the two stages of the first generation, expendable, Earth launch vehicle. The third and fourth columns represent the chemical propellant, orbital launch, and the lunar landing stages, respectively, used in the first mode of operation. Vehicle 5 is the conventional lunar launch stage and 6 is the integrated lunar landing and launch stage used in the second mode of operation. A modification of the last is needed, as soon as the nuclear orbit launch stage is introduced, to adjust to the increased payload capability. Two versions are listed, one for cargo transportation only (6a) and one for mixed cargo and personnel transportation (6b). The

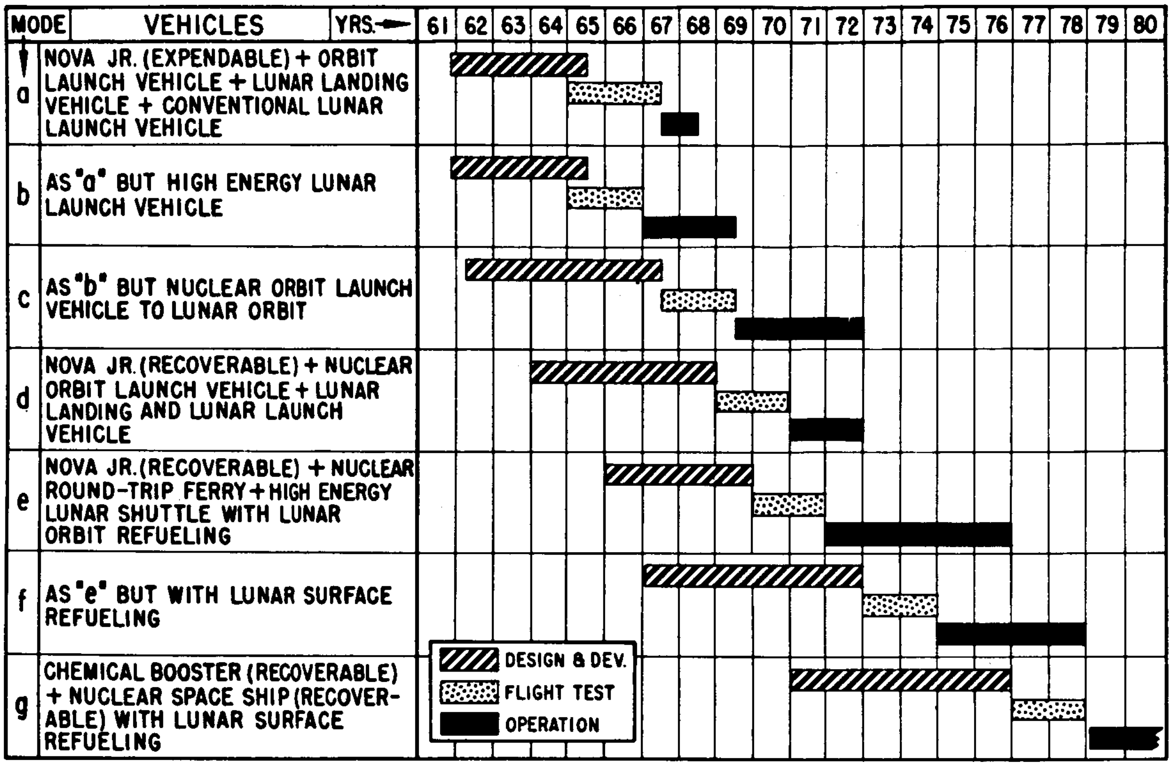

Fig. 7.1 Assumed time table for individual modes of operation.

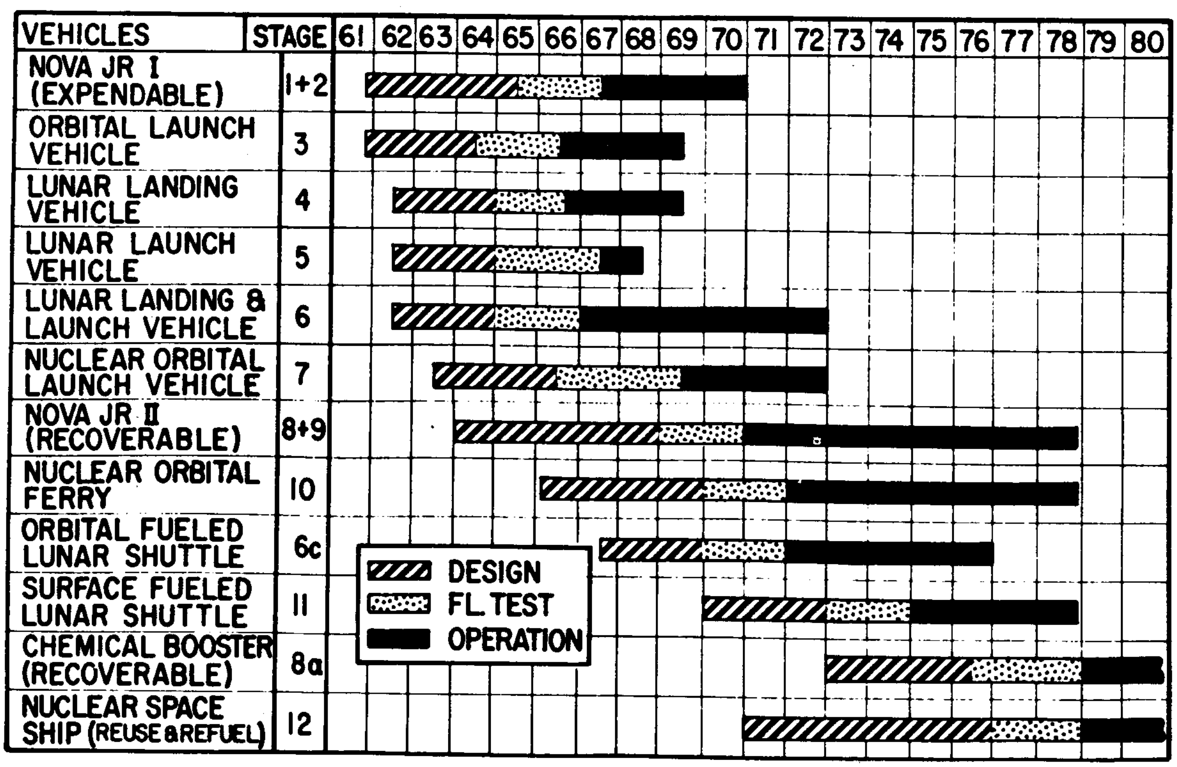

Fig. 7.2 Assumed time tables for individual hardware units.

nuclear orbit launch vehicle, which is reusable, appears in columns 8 and 9, first and second stages, respectively. Column 10 shows some of the data of the nuclear ferry vehicle capable of making a full round trip. A modification of this vehicle, resulting from the introduction of refueling in the lunar orbit, is listed in column 10a. The lunar shuttle vehicle, when refueled in the lunar orbit, is a modification of the original lunar landing and launch vehicle 6 and is listed in column 6c. With the introduction of refueling on the lunar surface, this vehicle grows in size and requires a more powerful engine. Except for this change, it is similar to 6 but is listed separately in column 11. A modification of the reusable booster (8) is used for launching the nuclear spaceship, column 12. The basic change is a reduction in propellant volume; its weights are listed in column 8a. Column 12 represents the nuclear spaceship for the outbound and return legs of the lunar trip.

The horizontal lines represent the initial thrust, several weights, propellant mass fraction μ, the specific impulse, mass ratio, velocity increment and growth factors. An assumption of mission reliability in a particular year is listed in the last line of Table 7.1.

Typical schedules and time periods, where the various stages and space vehicle will be in operational use, are shown in Fig. 7.2.

Cost and Mission Reliability. Table 7.2 summarizes the cost of individual stages, spare parts, and launch operations as a function of time for all seven modes of operation. The second part indicates the assumptions made for the individual mission reliability of single stages, as well as the total mode of transportation of each system under consideration. Dividing the cost by reliability and payload (or number of personnel) weight yields the specific transportation cost per pound payload or per round trip. These figures can also be used to determine the direct operating cost for Earth-to-orbit transportation resulting from these examples.

7.1.2 Results

Specific Transportation Cost for Personnel. If the results of Table 7.2, with consideration of the schedules given in Fig. 7.1, are plotted versus time, the curves shown in Fig. 7.3 results. It is interesting to note that the round-trip cost for the first astronauts (excluding the development cost) should be close to $40,000,000/man. It is obvious that the introduction of high-energy propellants for the return trip pays off nicely, and the trip costs are reduced to about 50 per cent in mode 2. Therefore, it seems that mode 1 will have only very temporary importance and should not be pursued unless a higher probability of success can be expected. Fig. 7.3 further shows that a nuclear propulsion system should be used as early as possible, since it promises an additional reduction of the round-trip cost by 50 per cent in mode 3. This mode is the best that can be expected with expendable systems. The introduction of a reusable Earth-to-orbit carrier vehicle will not pay off before 1972 (mode 4) because of

Table 7.2 Cost and Reliability Estimates for Lunar Mission

MODE OF OPERATION	a				b			c			d		e			f				g		
YEAR	1967 Pers.	1967 Cargo	1968 Pers.	1968 Cargo	1967 Personnel	1968	1969	1969	1970	1971	1971	1972	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
Vehicle cost per launch:																						
Stage I	35.0	35.0	34.0	34.0	17.5	17.0	16.5	16.5	16.3	16.0												
Stage II	8.3	8.3	8.0	8.0	4.2	4.1	4.0	4.0	3.9	3.8	26.6	18.6	18.6	15.5	14.0	6.5	5.9	5.4	5.0	2.6	2.4	2.1
Stage III	3.5	3.5	3.5	3.5	3.5	3.4	3.3	5.4	5.2	5.0	5.0	4.8	4.6	4.3	3.8	3.5	3.2	3.0	2.8	21	11.5	10
Stage IV	3.8	3.8	3.8	3.8	6.2	6.1	6.0	4.3	4.2	4.1	4.1	4.0	1.0	0.6	0.4							
Stage V	5.8	-	5.8	-	-	-	-	-	-	- -	-	-	-	-	-	-	-	-	-			
Spare parts	10	-	9.0	-	10.0	9.0	8.8	8.8	8.6	8.4	8.2	8.0	1.8	0.9	0.6	0.6	0.5	0.4	0.3	2	2	2
Launch operations	8	8	7.9	7	-	-	-	-	-	-	4.5	4.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1	1	1
$\$10^6$	74.4	58.6	72	57.2	41.4	39.6	38.6	39.0	38.2	37.3	48.4	37.9	26.6	21.9	19.4	11.2	10.2	9.4	8.7	26.6	16.9	15.1
Stage I Reliability	.86	.86	.90	.90	.86	.90	.92	.93	.94	.95		-	-							.95	.96	.97
Stage II	.85	.85	.88	.88	.85	.88	.90	.91	.92	.93	.833	.909	.909	.937	.947	.952	.957	.959	.960	.90	.93	.94
Stage III	.95	.95	.96	.96	.95	.96	.97	.97	.98	.98	.98	.98	.80	.833	.856	.875	.889	.90	.91	.90	.93	.94
Stage IV	.90	.90	.91	.91	.95	.96	.97	.97	.98	.98	.98	.98	.86	.91	.933	.947	.954	.958	.960	-	-	-
Stage V	.95	-	.96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mission Reliability	.60	.63	.664	.692	.66	.73	.78	.796	.831	.850	.80	.873	.626	.71	.756	.789	.815	.826	.840	.77	.83	.86
Payload weight		59,000		59,000				34,7[illegible]	34,700	34,700	34,700	34,700	36,400	36,400	36,400	120 K	120 K	120 K	120 K	150 K	150 K	150 K
Crew number	3				3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	10	10	10
\$/lb		1576		1400				677	636	607	837	600	583	424	352	95	83	76	69	150	88	76
10^6 \$/man	41.3		36.1		20.9	18.1	16.5	8.5	7.96	7.60	10.5	7.5	7.1	5.15	4.28	0.95	0.83	0.76	0.69	1.20	0.7	0.61

a K signifies x 10^3

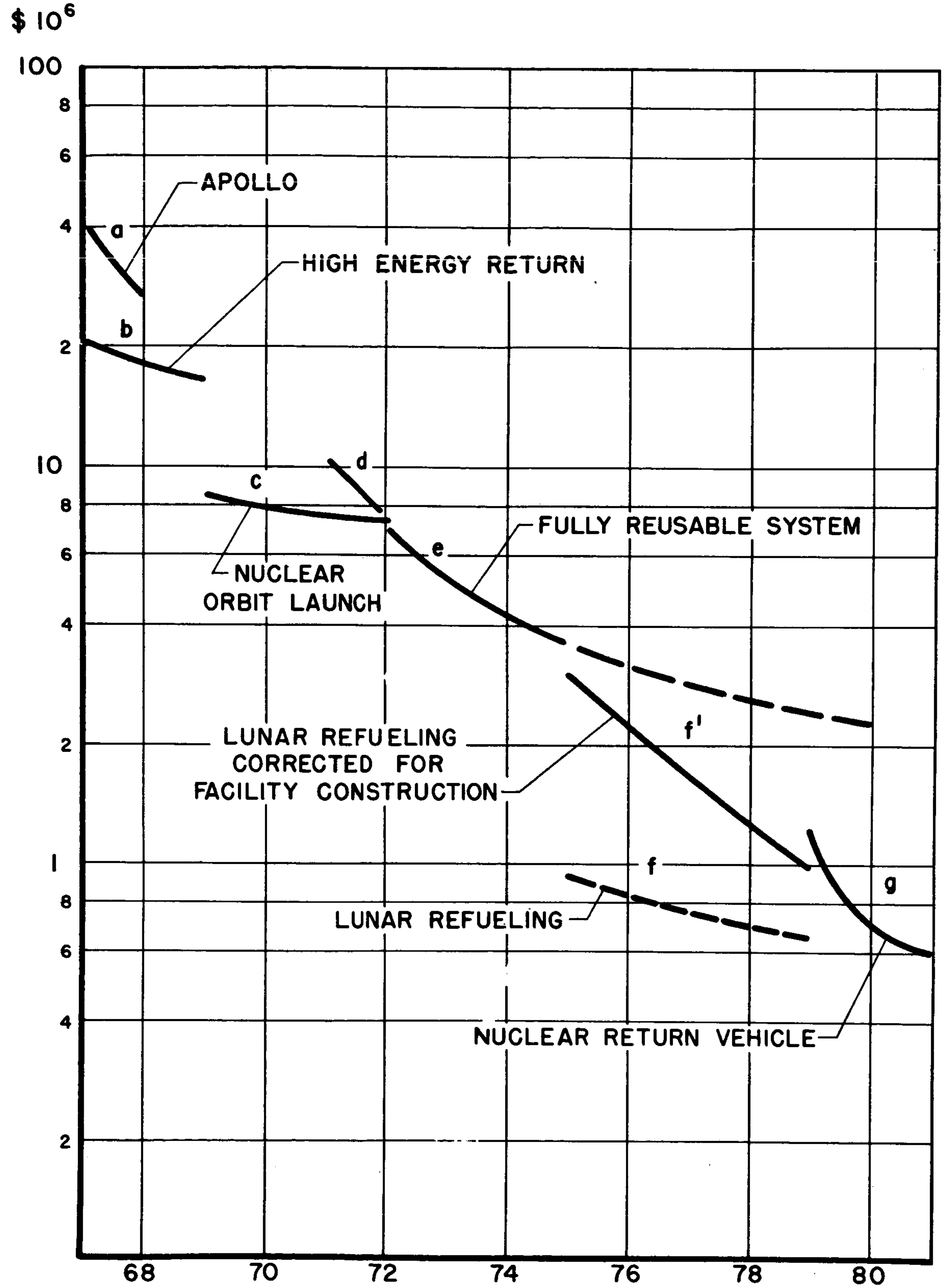

Fig. 7.3 Lunar round-trip cost trends.

the small reuse rates and low reliability.

Later, however, especially in connection with reusable nuclear ferry and lunar shuttle vehicles (mode 5), the reusable launch vehicle should reduce substantially the round-trip cost to less than $40,000,000/man by about 1975, and less than $2,000,000/man by 1980. This cost is as low as we can hope to go, unless a way can be found to produce propellants on the Moon. The lower line indicated for mode 6 is of a hypothetical nature. It would be valid only if propellant production facilities can be erected on the Moon at no cost. The upper line for mode 6 is arbitrarily drawn to indicate the trend desired. The difference between these two lines is the equivalent of the funding available for the establishment and operation of lunar propellant production facilities. Should these expenses be much larger, mode 5 would do as well. Finally, mode 7 indicates what can be expected by the introduction of first-class transportation, represented by a chemically boosted, all-nuclear spaceship for the round trip. This would, however, require the production of huge amounts of liquid hydrogen on the Moon, which at this time does not appear feasible. From Fig. 7.3, it is seen that three phases of manned lunar transportation systems will be of particular interest in the next 15 years:

1. 1967 - 69: All-chemical expendable systems with direct hyperbolic entry (mode 2)
2. 1970 - 72: Expendable systems with a nuclear orbit-to-orbit stage and direct hyperbolic entry (mode 3)
3. 1973 - 75: All-chemical, reusable, orbital carrier vehicle with nuclear ferry vehicle from orbit-to-orbit and return, and chemical, lunar round-trip shuttle vehicle, with return through Earth orbit at orbital entry velocity (mode 5)

Specific Transportation Cost for Cargo. A similar picture emerges for cargo transportation, and is shown in Fig. 7.4. The second mode of operation (2) does not apply because high-energy propellants are introduced in the return stage only. Thus, a drop from about $1600/lb of payload to about $650/lb can be expected by the introduction of a nuclear propulsion system in the orbit-to-orbit leg. The next big improvement comes with the fully reusable system (mode 5), which reduces the cost to $300/lb during the 1975-'76 period. The only known way to reduce it further is by propellant production and refueling on the lunar surface. If this is at all feasible, a cost of $100/lb can be achieved. The same three phases shown above as desirable for personnel transportation are equally suitable for cargo transportation.

Also of interest for general comparison is the specific transportation cost for the Earth-to-orbit phase resulting from these assumptions. The trend of this cost is shown in Fig. 7.5. Starting with a $132/lb cost in 1967 for expendable systems, there is a cross-over point in 1971 at

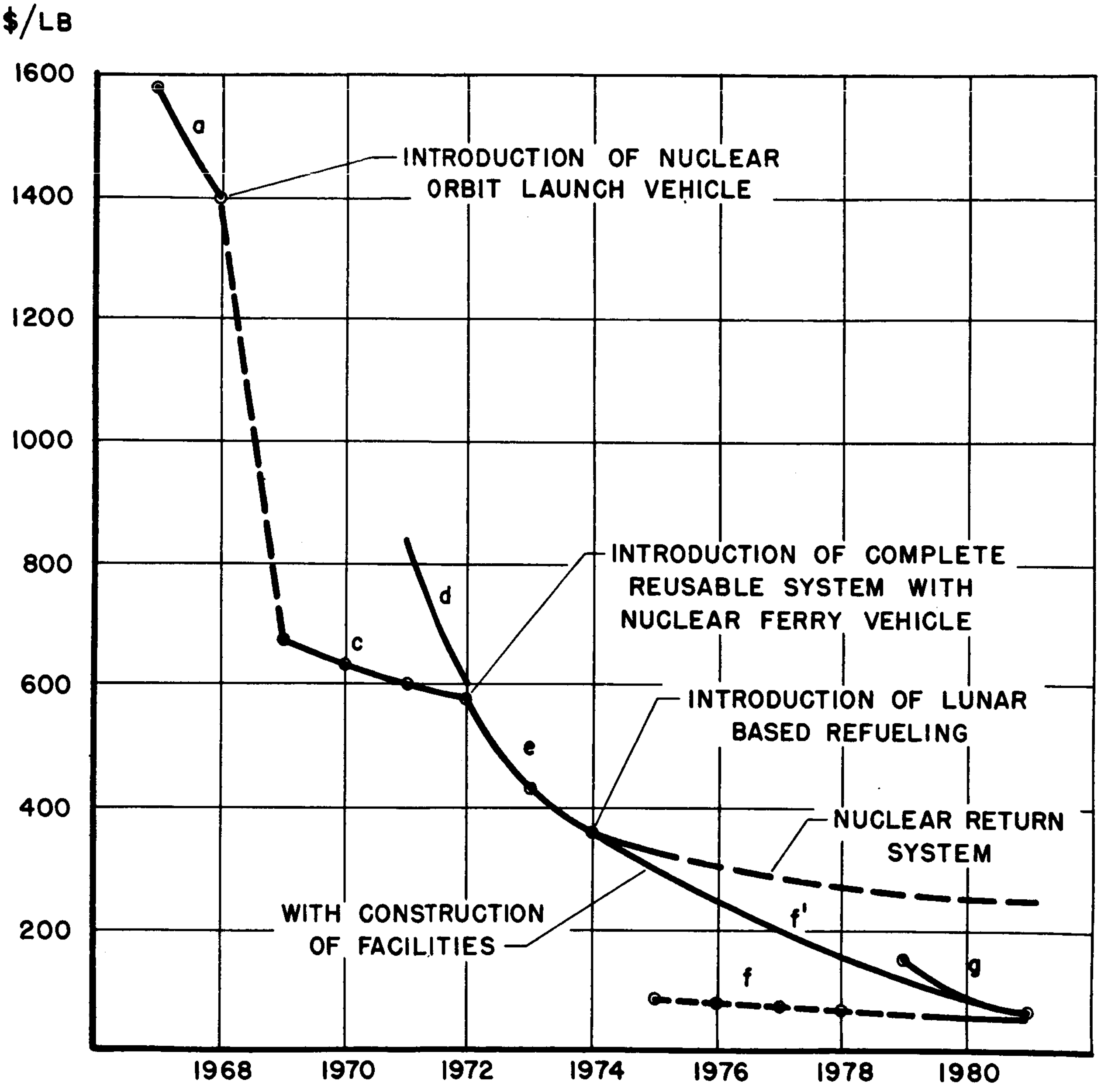

Fig. 7.4 Trends of cargo transportation cost to the Moon.

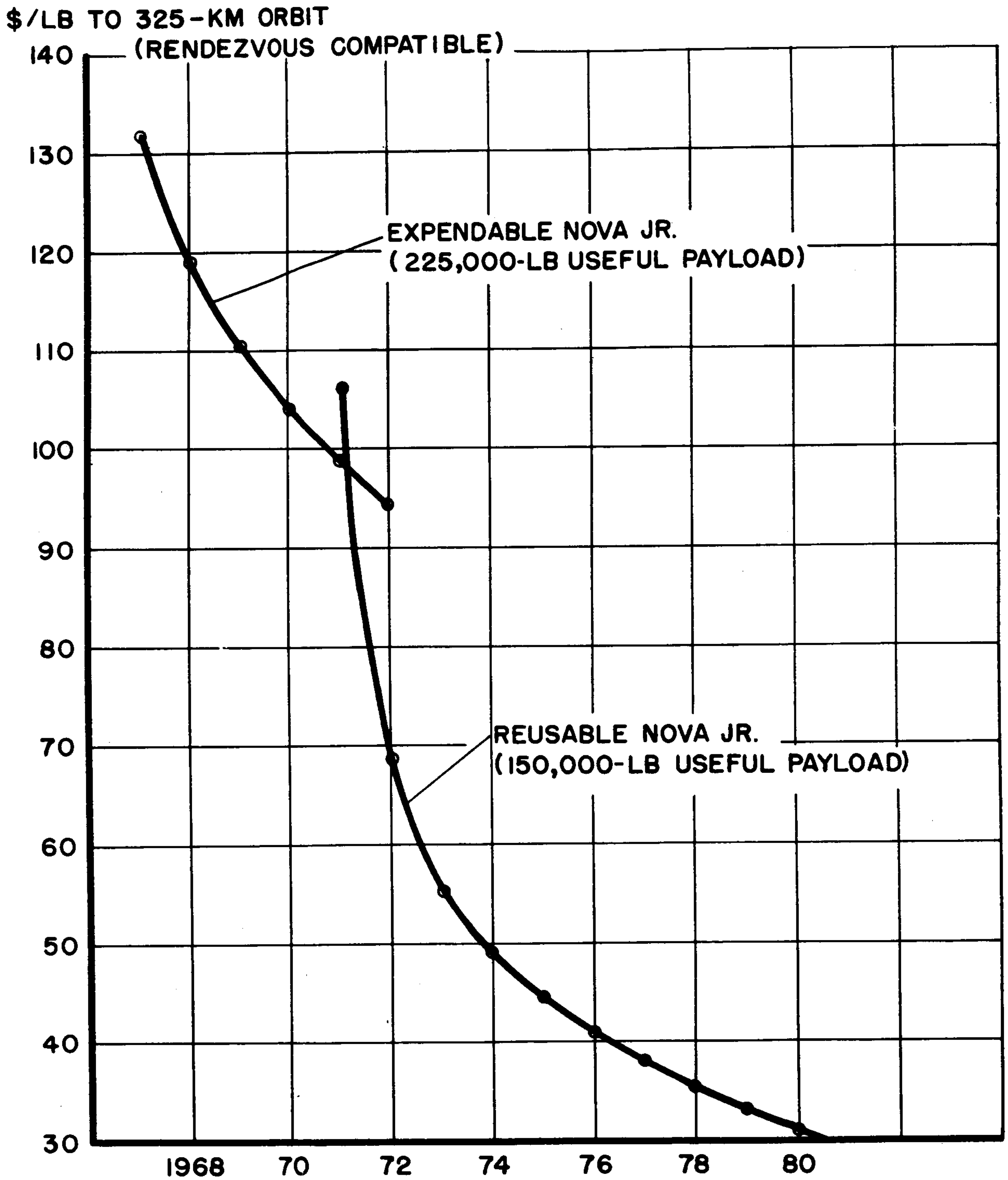

Fig. 7.5 Earth-to-orbit cost trends.

about $100/lb with the reusable orbital carrier vehicle. As the effeciency of the reusable vehicle improves, the specific transportation cost comes down to about $30/lb by 1980. It should be kept in mind, however, that this is only the direct operating cost and does not include development cost and other fixed costs.

Expected Transport Volume. In this chapter it is necessary to make an assumption of the total amount of traffic or transport volume, for this influences the cost assumptions. For this purpose a model of a typical Earth-lunar transport volume is developed.

The basic assumption is that from 1967 to 1980 a constant share of the gross national product (GNP) will be used for the development and operation of the Earth-lunar transportation system and a lunar base. This was assumed to be 0.25 per cent of the total GNP. Assuming further that the growth of the GNP is 3.5 per cent per year, and that half of the lunar operation funds (e.g., 0.125 per cent) is used for research and development plus the operation of the lunar base itself; the other half is available for the procurement and operation of the space vehicles needed to operate the transportation system between Earth and Moon. This results in the amounts given in column 2 of Table 7.3, starting with $790,000,000 in 1967 and growing to $1,280,000,000 in 1981. Using the preferred mode of operation in each particular year, and the specific transportation cost shown in Figs. 7.3 and 7.4, the number of annual flights as shown in column 3 of Table 7.3 results. From this, the total number of personnel transported to and from the Moon can be derived (column 4) as well as the total weight of the cargo actually delivered to the Moon. Only the successful flights are listed here.

There is a big increase in transport volume (personnel and cargo) in 1975 with the introduction of lunar refueling. Whether this is feasible or desirable remains to be seen. It can be assumed, however, that this additional capacity is available for the assembly and operation of the lunar propellant production site. These figures are used to determine the amount of facility weight that can be afforded to make this scheme pay off. It was found that the propellant production facility (roughly) should not exceed 1 lb if facility weight for each pound of propellant produced each year, to make this economically attractive. If this figure should be larger, it might be preferable to retain the fully reusable mode with refueling in Earth orbit. To show the available manpower and cargo for the lunar production facility a little more clearly, Figs. 7.6 and 7.7 have been included.

7.2 Conclusions

From the results of this study, the following three phases of development in Earth-lunar transportation systems can be foreseen clearly:

Table 7.3 Expected Transport Volume of Lunar Transportation Systems

1	2	3	4	5
Year	Lunar Transport. Funds Per Year	No. Flights Per Year (successful)	No. of Passenger Round Trips Per Year	Annual Cargo Delivered
	[10^6 $]			10^6 lb
1967	790	6	12	0.342
1968	818	8	12	0.429
1969	845	14	42	0.472
1970	875	19	56	0.674
1971	905	21	62	0.712
1972	937	22	68	0.778
1973	972	32	96	1.136
1974	1005	39	118	1.421
1975	1040	73	220	8.750
1976	1078	86	260	10.380
1977	1115	97	297	11.700
1978	1155	112	335	13.380
1979	1195	60	390	7.930
1980	1235	88	572	11.890
1981	1280	73	730	11.210

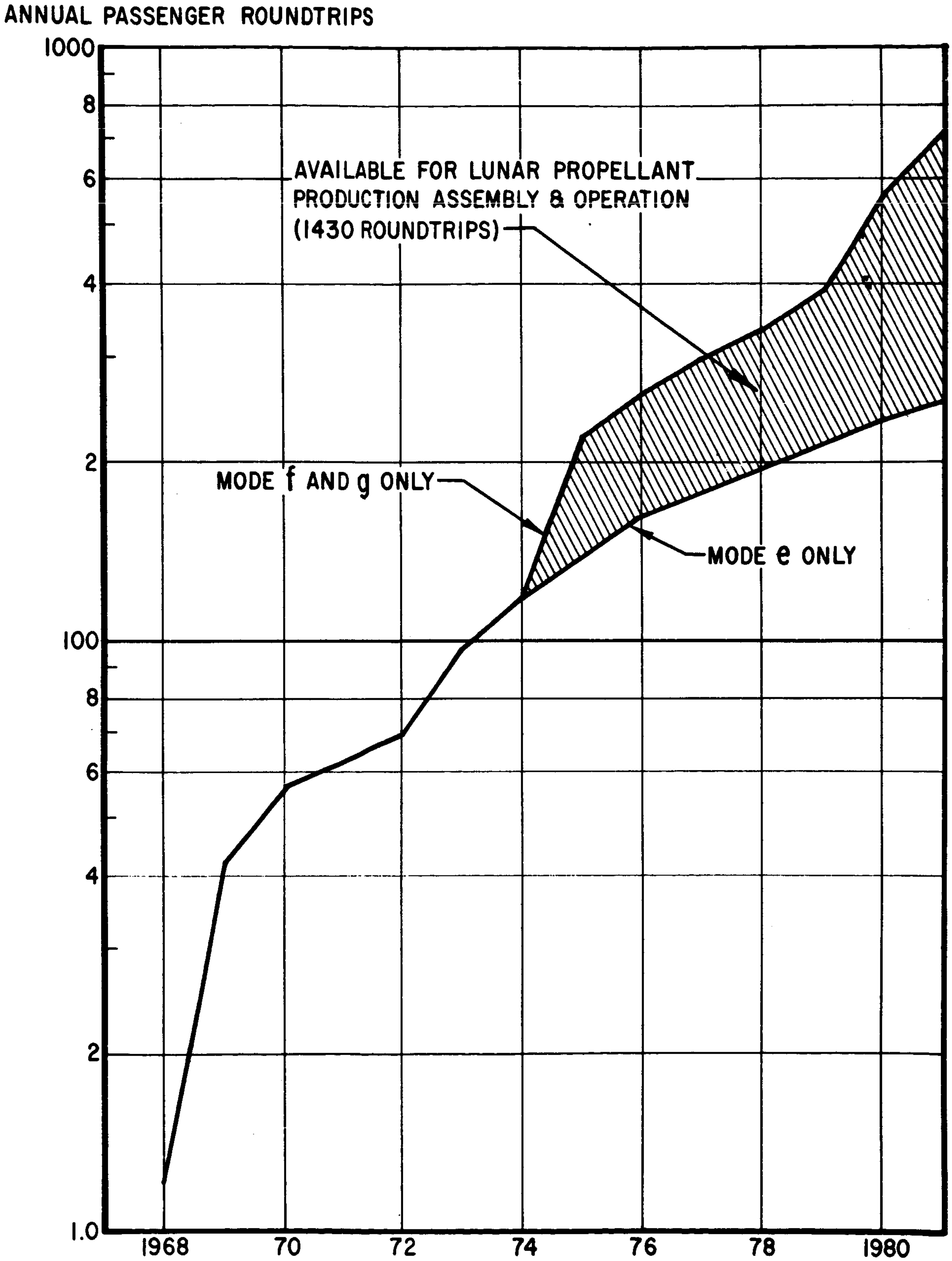

Fig. 7.6 Earth-Moon annual transport volume vs. time (0.125 per cent of GNP).

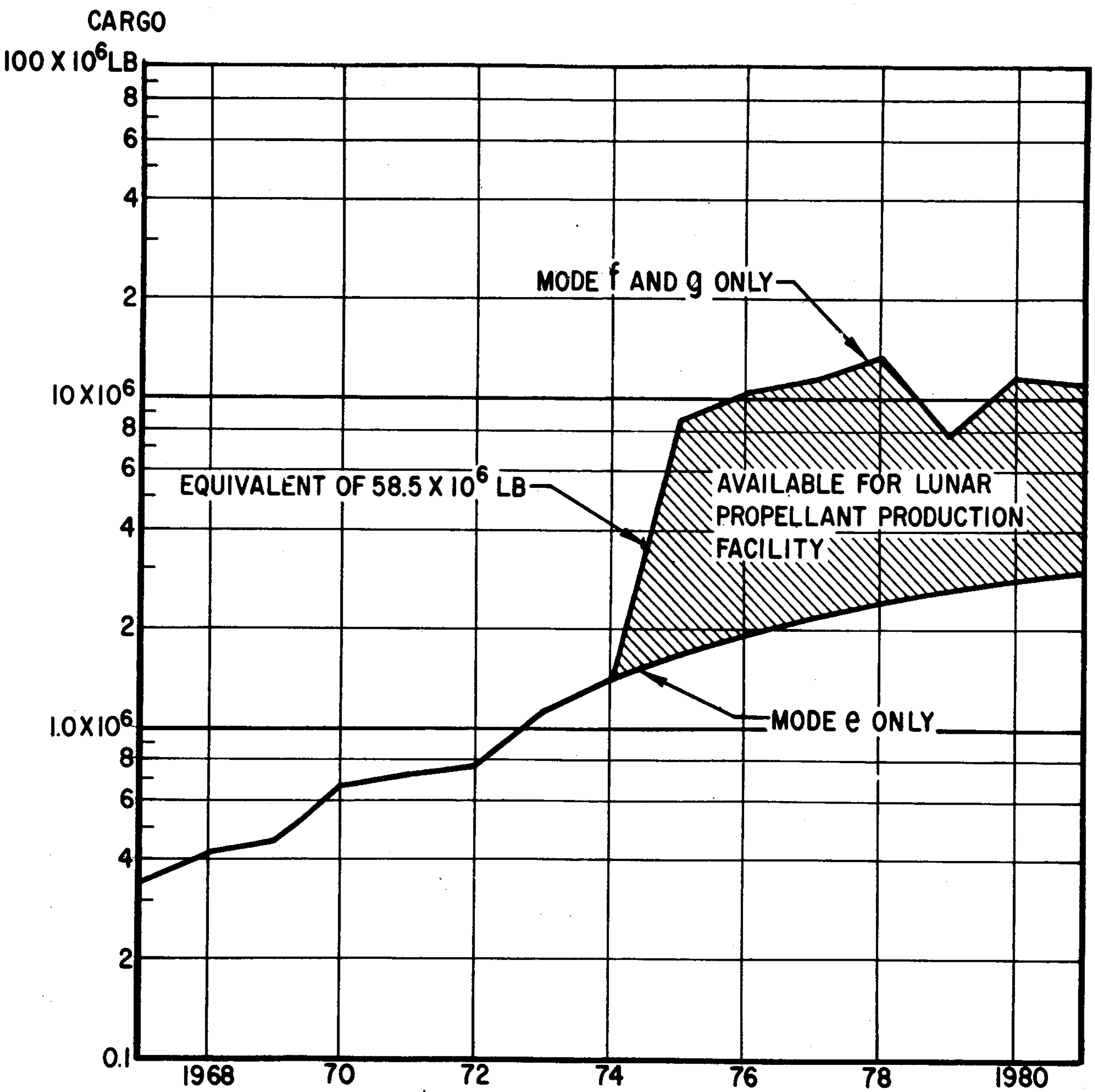

Fig. 7.7 Earth-Moon annual cargo transport volume vs. time (0.125 per cent of GNP).

1. 1967 - 69: All-chemical, expendable, rocket vehicles with direct hyperbolic entry into Earth's atmosphere
2. 1969 - 72: Expendable space vehicles with a nuclear, orbit-to-orbit stage and direct entry into Earth's atmosphere
3. 1972 - 75: All-chemical, reusable, orbital carrier vehicle with reusable, nuclear, ferry vehicle from orbit-to-orbit (and return) and chemical, reusable, lunar-round-trip (shuttle) vehicle. This mode of operation requires Earth and lunar orbital operations and eliminates the hazardous hyperbolic entry into Earth's atmosphere. Return of the personnel is accomplished with orbital velocity with moderate deceleration and good control at the landing site

Additional conclusions are as follows:

1. The round-trip cost is expected to drop by one order of magnitude from $40,000,000/man to $4,000,000/man between 1968 and 1975.
2. The specific transportation cost (direct operating cost only) for cargo to the lunar surface is expected to drop from $1600/lb in 1967 to about $300/lb in 1976.
3. The production of propellants on the Moon and refueling on the lunar surface, if feasible, would reduce the cost of personnel transportation to less than $1,000,000/man and the specific cargo transportation cost to less than $100/lb.
4. A propellant accumulator in Earth orbit (Profac) does not seem to offer any economical advantages over a nuclear ferry vehicle if it is limited in its applications to chemical rockets only.
5. It appears that transport volumes of approximately 150 round trips per year to the lunar surface and cargo at the rate of about 1,500,000 lb/yr will be economically feasible by the middle of 1970.