Requirements and Capabilities of Interorbital Shuttles

W. Frank Staylor,* David R. Brooks,* and E. Brian Pritchard†
NASA Langley Research Center, Hampton, Va.

This paper examines the characteristics of unmanned and manned inter-orbital shuttle systems for missions ranging from satellite placement and repair to planetary spacecraft insertion. The velocity increment and associated propellant weight requirements are defined for the missions considered with LOX/LH_2 shown to be the most desirable propellant. On the basis of projected earth satellite and planetary spacecraft requirements for the 1975–85 time period, the need for interorbital shuttles is demonstrated. A preliminary cost analysis indicates that development costs of ~\$540 × 10^6 and \$610 × 10^6 may be expected for the unmanned shuttles, respectively. First-order total program cost estimates indicate that savings of \$0.5–\$1.5 × 10^9 may be attainable through the use of inter-orbital shuttle systems, depending on the choice of system options. Further studies of this concept should be conducted to define the systems in more detail.

Nomenclature

h = circular orbital altitude, naut mile
I_{sp} = specific impulse, sec
n = number of satellites or units
W_{BT} = basic tug weight, lb
W_{DM} = docking module weight, lb
W_P = total propellant weight, lb
W_{RM} = repair module weight, lb
W_S = satellite weight, lb
α = tankage weight fraction, tank weight/propellant weight
ΔV = one-way incremental velocity, fps
ϕ = orbital inclination angle, deg

Introduction

DURING the past decade a number of feasibility studies have indicated that aerospace technology has reached a level that would permit a low-cost Earth-to-orbit transportation system to be developed in the 70's. Joint NASA-DOD panels are evaluating various reusable concepts, and it appears that a space shuttle vehicle could become operational during the present decade. Such a vehicle could conceivably reduce low-Earth-orbit transportation costs by an order of magnitude. However, the space shuttle would be very inefficient for interorbital operations because of its large mass and low mass fraction, in comparison to a vehicle designed for inter-orbital operation only. Thus, maximum effectiveness of the total transportation system will require development of an interorbital shuttle vehicle.

The present paper discusses a versatile inter-orbital shuttle system which operates from a space station/propellant storage complex to orbital altitudes ranging from 100 naut miles to synchronous orbit. This vehicle could also be used to insert spacecraft into planetary trajectories. Both manned and unmanned systems are considered for the wide variety of space tasks foreseen for the inter-orbital shuttle, and several propulsion systems and propellants are considered for various operational modes. First-approximation cost estimates are presented which provide a basis for preliminary comparisons of total program costs for manned and unmanned inter-orbital shuttles vs current expendable launch vehicles for satellite placement and planetary spacecraft insertion missions. A necessary factor in this analysis is a projection of future Earth satellite requirements in the 1975–85 period. This projection is based on the requirements outlined by NASA planning panels, advisory groups, and industry studies dealing with future satellite requirements.[1–6]

System Requirements

It is assumed that the inter-orbital logistics vehicles, hereinafter called space tugs, will operate from base orbits in the near vicinity of manned space stations, unmanned satellite stations, and/or propellant storage facilities. A compromise between orbital lifetime, payload capability, and operational requirements for these orbiting elements indicates that the base orbit should be near-circular and at an altitude of about 270 naut mile. Figure 1 shows the propulsive ΔV required to transfer from a base orbit, h = 270 naut mile, to various orbital altitudes or planes; ~2000 fps would be required to transfer to h = 1000 naut mile while ~13,000 fps would be needed to obtain a synchronous orbit or a 30° plane change.

Propellant storage facilities will be needed in the base orbits. These space tankers would be replenished by the space shuttle. In some instances, a tanker could operate in conjunction with a manned space station which would also serve as a manned tug base and satellite repair facility. For the present analysis, it is assumed that space tankers will be available at orbital inclinations of 30° (for maximum payload from ETR), 55° (for satellite coverage of the earth's heavily populated regions), and 100° (for near-polar sun-synchronous satellites).

Because, (as shown later) the launch cost of the propellant supply needed to support the space tug program is one of the primary recurring cost drivers of the system, a propulsive system should be chosen that will require a minimum number of tanker flights by the space shuttle, and yet meet the system constraints. Space-storable propellant combinations such as N_2O_4/Aerozene-50 and N_2O_4/N_2H_4 are not penalized by boil-off losses and their storage tanks can be relatively light; however, the specific impulse, I_{sp}, of storable propellants is limited to ~350 sec. On the other hand, cryogenic propellants such as LOX/LH_2 and LF_2/LH_2 (where L denotes liquid, and LOX is liquid oxygen) suffer boil-off penalties and/or must be stored in heavy insulated tanks but have I_{sp}'s ranging to ~480 sec. One measure of the relative merits of storable and cryogenic propellants is their total impulse capability after various periods of storage. The total impulse histories for three storage facilities, each with an initial propellant load of 100,000 lb, are presented in Fig. 2.[7] No significant boil-off would occur for LOX/LH_2

Presented as Paper 70-267 at the AIAA Advanced Space Transportation Meeting, Cocoa Beach, Fla., February 4–6, 1970; submitted March 13, 1970; revision received April 20, 1970.

* Aerospace Engineer, Mission Analysis Branch, Aero-Physics Division. Member AIAA.

† Head, Mission Analysis Branch, Aero-Physics Division. Member AIAA.

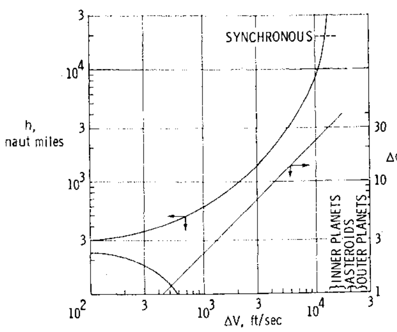

Fig. 1 Propulsive velocity requirements.

stored in a 50,000 lb propellant storage tank for 1000 days. The boil-off of the LOX/LH_2 stored in a lighter tank (10,000 lb) is more noticeable due to the lower pressure capability and less effective insulation of the lighter tank, but the total impulse capability after 1000 days is still greater than that of the storable propellant. In addition, the weight and cost differences between the cryogenic and storable facilities are negligible when compared to the total amount of propellant passing through the facility in its lifetime.

Another measure of the merit of a propellant is the ΔV capability of a space tug, considering tank weight and mission duration. In Fig. 3, tugs with hardware weights of 1000 lb, initial propellant loads of 1000 lb, and tank weights of 20 and 50 lb are compared for storable and LOX/LH_2 propellants, respectively. It is seen that the ΔV capability of the tug using LOX/LH_2 exceeds that of a similar tug using storable propellants for mission durations of ten days; a reasonable upper limit for proposed space tug missions.

It is concluded from Figs. 2 and 3 that LOX/LH_2 offers better performance than do storable propellants. Other cryogenic propellant combinations such as LF_2/LH_2 and LOF_2/LH_2 would offer even better performance than LOX/LH_2; however, these propellants are toxic, and therefore are not compatible with current operational guidelines established for the space shuttle. Another factor favoring the use of LOX/LH_2 for the space tug is that the orbital stage of the space shuttle will also use this propellant combination and under nominal conditions will orbit a considerable quantity of contingent propellant with each flight. When not needed, this propellant could be off-loaded into a storage facility and thus reduce the number of pure tanker flights required to support space tug operations.

System Definition and Missions

Both unmanned and manned tugs were considered. The unmanned tug is a combination of a basic propulsion system and modular elements (docking and repair) as required for a particular mission. It is propelled by a pump-fed, regeneratively cooled, LOX/LH_2 rocket engine which has a max thrust of about 15,000 lb with a throttling capability of at least 10:1, multiple-restart capability, and gimbal systems for thrust vector control. In general, the engine would have performance capabilities similar to that of the Pratt and Whitney RL-10.[8] The basic unmanned tug must contain

Table 1 Tug weight and cost summary

System	Weight, lb	D/D costs[a] $\times 10^{-6}$, $	Unit costs[b] $\times 10^{-6}$, $
Unmanned tug			
Propulsion module	500	150	5
Docking module	200	100	5
Repair module	400	200	10
Manned tug	4000[c]	500	25

[a] Includes 5 test units.
[b] Average of first 10 flight units.
[c] Includes two-man crew.

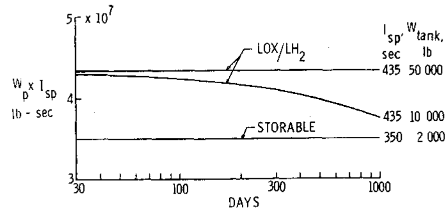

Fig. 2 Propellant impulse history comparisons.

control and guidance subsystems that would allow it to operate remotely from a base station and perform the relatively simple satellite insertion missions. The tug propellants could be contained in either integral tanks, probably requiring at least two tug configurations (low- and high-impulse missions), or in strap-on tanks attached to a basic low-impulse tug. Choice of one or the other system would depend on the traffic rates involved as well as the extravehicular activity (EVA) requirement for attachment of additional strap-on tanks.

With a docking module attached, the unmanned tug could perform satellite retrieval or relocation missions which would require a remote rendezvous and docking maneuver. Satellite repair, refurbishment, and refueling missions could constitute the major portion of the tasks, and they could be accomplished by a retrieval-repair-insertion (RRI) mode, a component-exchange mode, or by an on-location repair mode. The RRI mode would involve the retrieval of a satellite to a base orbit, repair at either an orbital facility or a ground facility (with use of the space shuttle), and return of the satellite to its original orbit. Only the basic tug and the docking module would be needed for this repair mode. The component-exchange and on-location repair modes would require both the docking module and a repair module which would have several manipulator arms capable of performing numerous tasks with near-EVA dexterity.[10,11] Tugs operating in these modes would be telemetry-controlled from either ground or orbiting stations.

A manned space tug could perform all of the missions previously mentioned for the unmanned tug plus man-ferry and rescue missions. It would be operated by a two-man crew with provisions included for several passengers (for very short trips only) and a maximum of about ten man-days operation. This tug would be capable of maneuvering independently of all other stations and would be particularly suited for satellite repair tasks which could be accomplished from inside the cabin with manual manipulators or externally by EVA. Its propulsion system would be identical to, or very similar to, that used for the unmanned tug.

The weights and the design/development (D/D) and first-unit costs are listed in Table 1 for both the manned and unmanned tugs. These estimates were based on the known weights and costs of many components, while the remainder were based on published cost estimating relationships.[15-16]

System Operations

Mission Propellant Requirements

The total propellant weight W_P required to propel an unmanned and satellite of weight W_S through ΔV and then

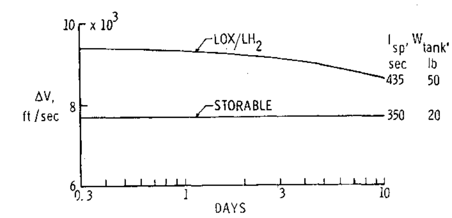

Fig. 3 ΔV history comparison for LOX/LH_2 and storable propellants, $W_{P_{initial}} = W_{BT} = 1000$ lb.

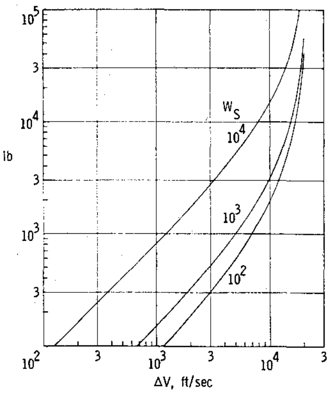

Fig. 4 Propellant requirements for insertion missions, W_{BT} = 500 lb, I_{sp} = 435 sec, α = 0.05.

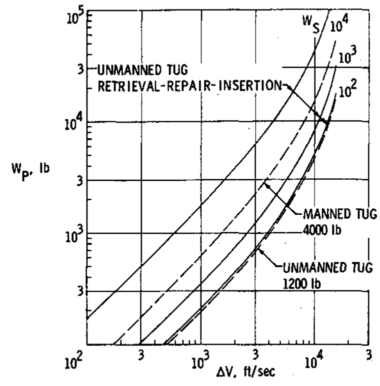

Fig. 6 Propellant comparisons for three satellite repair modes.

return the tug to its original orbit is presented in Fig. 4. It is assumed that the basic tug weight W_{BT} is 500 lb; the integral tanks weigh 5% of their propellant load (α = 0.05)[7] and are optimized for each ΔV, and that the I_{sp} of the LOX/LH_2 propulsion system is 435 sec. Less than 1000 lb of propellant would be required for many low-orbit missions, while about 30,000 lb would be needed to place a 10,000 lb satellite into a synchronous orbit (Fig. 1).

Nuclear engines similar to the NERVA[9] may become operational at about the same time as the space shuttle, and they could be used to propel space elements such as a tug. In Fig. 5 the propellant weights required for nuclear tugs (LH_2, α = 0.10, Ref. 12) with various I_{sp} capabilities and system weights are compared to the conventionally propelled LOX/LH_2 tug for W_S = 10^4 lb. The nuclear shuttle does not become competitive with the tug on a propellant weight basis until one-way mission ΔV requirements reach ~14,000 fps. Nuclear shuttles are superior to the LOX/LH_2 tugs, however, for lunar cargo shuttle and deep space insertion missions for which $\Delta V > 20{,}000$ fps.

The manned and unmanned tugs considered here can also be compared in terms of propellant weights required to perform a given mission. These requirements are shown in Fig. 6 for three satellite repair modes. The RRI mode could be conducted by the unmanned tug weighing 700 lb ($W_{BT} + W_{DM}$) on the retrieval run and 500 lb on the insertion run (W_{BT}, only). Both the component-exchange and on-location repair modes could be conducted by the unmanned tug weighing 1200 lb ($W_{BT} + W_{DM} + W_{RM}$) or the manned tug system weighing 4000 lb (W_P's for these modes are independent of W_S if the weights of exchanged components or repair materials are negligible). The unmanned repair tug mode would require the least propellant and is equivalent to the RRI mode for W_S = 0. The manned tug mode is equivalent to the RRI mode for W_S = 2800 lb.

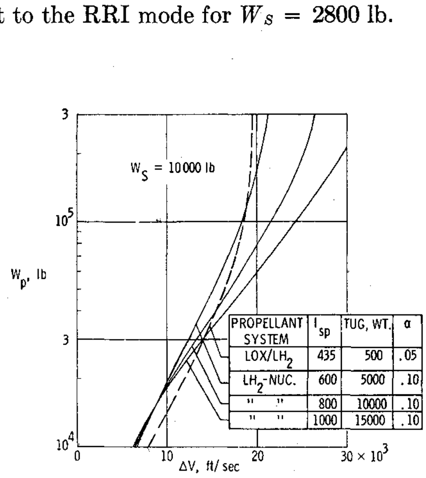

Fig. 5 Propellant comparisons for LOX/LH_2 and LH_2-nuclear space tugs, W_S = 10,000 lb.

Satellite Maintenance Schedule

Minimum propellant requirements would not always dictate the tug mode used to repair a satellite. For instance many satellite malfunctions would require manual repairs and, therefore, more propellant. The RRI mode would represent the most conservative approach, while the unmanned mode would represent the least conservative approach. To estimate total program costs for the tug systems, it is necessary to allocate a certain percentage of the repair missions to each of the three modes considered in the previous section. These allocations are shown in Fig. 7 as a function of satellite weight. It is believed that most heavy satellites (W_S = 3000–10,000 lb) would have many experiments and redundant systems and, hence, would be amenable to on-location maintenance and component exchange. Most of the lighter satellites (W_S = 100 to 1000 lb), however, would be more amenable to the RRI mode.

The operational life expectancy of many current satellites is often limited by the lifetime of the electrical power or ACSs, or by the station-keeping capability of the satellite.[13,14] Current research in the areas of improved solar-cell, radioisotope and nuclear power sources, and low-thrust devices may enable these systems to outlast the usefulness of most satellites. Although research and development also continue to extend the operational lifetime of ACSs, it is believed that ACSs will be the pacing items for satellite longevity.

Projected estimates of operational lifetimes of ACSs with and without maintenance are presented in Fig. 8. It is assumed that the upper curve can be obtained by a single maintenance mission with the mode determined from Fig. 7 (i.e., one-time maintenance will approximately double the system lifetime) and it is expected that both lifetimes will be increased between 1975 and 1985 by experience and development. With extensive maintenance and/or replacement of major components, it can be reasoned that the lifetime of an ACS could be extended almost indefinitely. However, new experiments and instrumentation demanding more electrical power and telemetry, for instance, would require an improved spacecraft as well. Therefore, a spacecraft obsolescence lifetime exists which would preclude maintenance beyond that period.

Traffic Models

Any suggested satellite traffic schedule for the 1975–1985 period must be considered as a tentative proposal, particu-

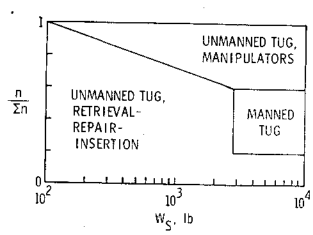

Fig. 7 Satellite repair mode allocations.

Table 2 Orbital traffic schedule

Satellite type	n 1975[a]	n 1985[b]	Weight class, 10^3 lb	$\langle W_S \Delta V\rangle$, 10^6 ft-lb/sec	$\langle \Delta V\rangle$, 10^3 fps
Communications	5	8	0.1– 0.3	0.6	3.0
	6	10	0.3– 0.6	4	8.0
	10	16	0.6– 1.0	9	11.0
	3	5	1.0– 3.0	25	12.4
	1	2	3.0– 6.0	55	12.4
	0	2	6.0–10.0	100	12.4
Meteorological/ weather	5	7	0.3– 0.6	1.5	3.0
	7	10	0.6– 1.0	7	9.0
	2	3	1.0– 3.0	25	12.4
Earth resources	2	5	0.1– 0.3	0.4	2.0
	9	15	0.3– 0.6	3	7.0
	5	9	0.6– 1.0	6	9.0
	2	3	1.0– 3.0	25	12.4
Navigation/ aircraft	5	12	0.1– 0.3	1.5	7.0
	5	8	0.3– 0.6	4	9.0
	2	3	0.6– 1.0	10	12.4
Scientific	3	5	0.1– 0.3	1	5.0
	5	9	0.3– 0.6	3	7.0
	2	3	0.6– 1.0	4	5.0
	2	3	1.0– 3.0	12	6.0
	2	4	3.0– 6.0	25	5.0
	1	3	6.0–10.0	100	12.4
Research/ development	1	2	0.1– 0.3	0.02	0.1
	3	5	0.3– 0.6	1	2.0
	1	2	1.0– 3.0	8	4.0
	1	1	6.0–10.0	15	2.0

[a] Total 90.
[b] Total 155.

larly if one assumes that the space shuttle will be phased in as the primary transport vehicle during that period. The expected order-of-magnitude reduction in orbital transportation costs and increased capabilities of various space systems will undoubtedly have a significant effect upon space programs in the 80's. For instance, programs that are marginal with current methods may become feasible, and the use of costly materials and miniaturization techniques could be relaxed, resulting in satellites that weigh more yet cost less.[17]

A traffic model (Table 2) was developed based on studies of future satellite needs by NASA planning panels, advisory groups, and industry (a partial listing of these studies is included in Refs. 1–6). Table 2 lists the satellite types, numbers, and weights projected for the 1975–1985 period, plus the mean insertion momentum, $\langle W_S\Delta V\rangle = (\Sigma n W_S \Delta V/\Sigma n)$ and the mean incremental velocity, $\langle \Delta V\rangle = (\Sigma n W_S \Delta V/\Sigma n W_S)$. A linear increase in total satellite traffic is assumed between the years 1975 (90) and 1985 (155).

In Table 3 a proposed balanced-base planetary program schedule is presented which gives the various planetary objectives, numbers of spacecraft, and years of launch.[6] Also listed are the insertion weights, velocities, and vehicles. With the exception of the outer planet missions, a high-impulse space tug could insert the mission payloads into their planetary trajectories and return to its base orbit. For the outer planet missions the tug could be used as an expendable upper stage, or it could boost the payload atop an Agena D to a ΔV of about 15,000 fps and allow the expendable Agena D stage to complete the ΔV requirement. The latter method will be assumed in subsequent calculations.

Total propellant requirements for the programs listed in Tables 2 and 3 may be defined from the information in Figs. 6–8. An average of about 240,000 lb/yr of LOX/LH_2 are required over the ten-year program. This rate would require a minimum of five space-shuttle flights (50,000 lb payload) per year to support the space tug operations in satellite placement and maintenance, and planetary spacecraft insertion.

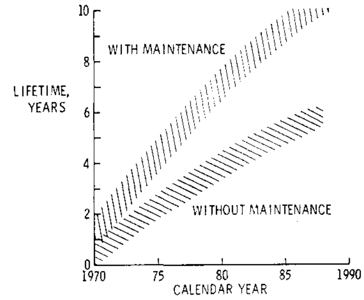

Fig. 8 Operational lifetimes of attitude control systems.

Cost Analysis

Nonrecurring costs for the space tug system include design/development and procurement of the initial operational system which would include such items as manned and unmanned tugs, propellant storage facilities, orbital base and ground support facilities, and the initial costs to launch the orbital elements. The total D/D costs and the costs for procurement of four flight units would be about $\$540 \times 10^6$ for the unmanned tugs and $\$610 \times 10^6$ for the manned tugs (see Table 2) which includes orbital transportation costs of $\$10 \times 10^6$ for each system. The D/D, orbital transportation and procurement costs for three propellant storage facilities would be about $\$100 \times 10^6$. Therefore, the total nonrecurring costs for an operational system would be about $\$640 \times 10^6$ for the unmanned tug system, $\$710 \times 10^6$ for the manned tug system, and $\$1250 \times 10^6$ for both tug systems (no additional propellant storage facilities).

A mean orbital transportation cost ($\phi = 20°$ to $100°$) of \$100/lb is assumed and the bulk LOX/LH_2 propellant cost, which should be less than \$1/lb in 1975, is neglected. Tug replacement costs (or amortization) should be proportional to their usage which is, in turn, assumed to be a function of the propellant consumed. These costs, based on the fifth through tenth flight units, would be about \$15 and \$25 per pound of propellant consumed by the unmanned and manned tugs, respectively. Satellite replacement and annual maintenance costs for those satellites serviced by the tugs are

Table 3 Planetary program schedule

Mission	Calendar year	Weight, lb	ΔV, 10^3 fps
Mercury			
Venus-Mariner flyby	1978	800	15.4
Solar electric orbiter	1982	8000	14.6
Venus			
Explorer orbiter	1975, 80, 83	650	13.5
Flyby/probes	1975 (2)	3000	13.5
Buoyant station	1980	3500	13.5
Mariner orbiter/rough lander	1983 (2)	6000	13.5
Mars			
Explorer orbiter	1975, 77, 81	650	13.5
Viking orbiter/soft lander	1975, 77	9700	14.4
High data orbiter	1979, 84	7000	13.5
Soft lander/orbiter	1984	6000	12.8
Outer planets[a]			
J-S-P swingby	1972 (2)	1500	26.0
Jupiter orbiter	1978	2200	24.0
J-U-N swingby	1970 (2)	1500	26.0
Jupiter flyby probes	1980, 84	2400	23.5
Saturn orbiter/probes	1981	2600	23.5
Comets			
Kopff rendezvous	1983	8500	14.0
Halley flyby	1985	1200	13.5
Asteroids			
Solar electric belt survey	1975	1500	13.5
Eros flyby	1981	1000	12.4

[a] These missions require the tug + Agena D.

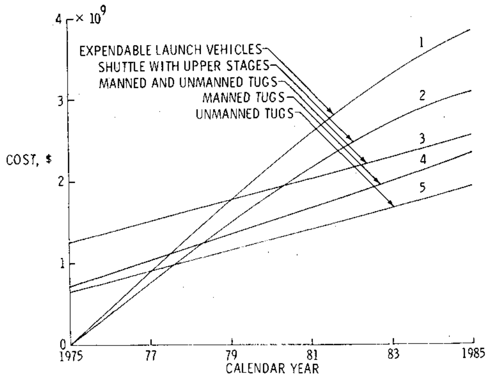

Fig. 9 Total Earth-satellite program costs.

assumed to be $40,000 \times W_S^{0.7}$ and $1600 \times W_S^{0.7}$, respectively.

Total Earth-Satellite Program Costs

Total program costs are shown in Fig. 9 for the earth satellite program projected for the 1975–1985 time period using the traffic model illustrated in Table 2 and the following five methods of approach: 1) ground-launched with expendable vehicles ranging from the Scout to the Saturn I (no satellite maintenance); 2) launched into base orbits with the space shuttle and then inserted into a mission orbit by an expendable upper stage (no maintenance); 3) launched into base orbit with the space shuttle (both manned and unmanned tug systems available for final insertion and maintenance tasks); 4) launched into base orbit with the space shuttle (only manned tug available for insertion and maintenance); and 5) launched into base orbit with the space shuttle (only unmanned tug available for insertion and maintenance). It can be seen that the conventional method 1 would cost about 4×10^9 and about 800×10^6 could be saved in recurring costs with the development of the space shuttle. Nonrecurring costs of the shuttle and tug system (method 5), would be recovered after two years of operation (see intersection of curves 1 and 5), and the system will yield a saving of about 2×10^9 during the first ten years. Even the most conservative tug approach, (method 3), could be amortized in four years.

Planetary Program Insertion Costs

Payload insertion costs for the balanced-base planetary program are given in Fig. 10 for the 1975–1985 time period. Expendable launch vehicles, expendable upper stages with the space shuttle, and the unmanned tugs with the space shuttle are considered as the modes of insertion. Development of the space shuttle would allow a cost saving of about 300×10^6, which would be matched by additional savings of about 300×10^6 with the development of an unmanned insertion tug. Since it is assumed that the unmanned tug nonrecurring costs are paid for in the earth-satellite program, as opposed to the planetary exploration program, only recurring costs are shown in Fig. 9.

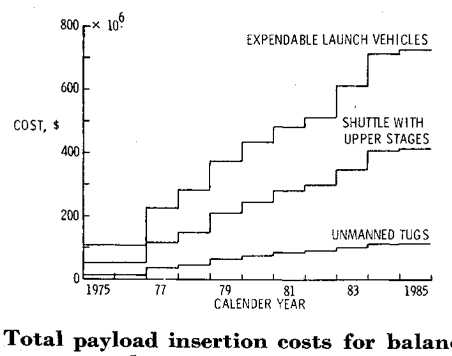

Fig. 10 Total payload insertion costs for balanced-base planetary program.

Concluding Remarks

The present analysis indicates that propellant loads up to 50,000 lb are required for interorbital shuttles (space tugs) capable of accommodating both earth-satellite and planetary probe injection missions. The preferred propellant combination is LOX/LH_2.

The large number of satellite and planetary probe missions projected for the 1975–85 time period coupled with the efficiency and reusability of space tugs indicate that such systems would be desirable for the post 1975 period. Both manned and unmanned tugs appear to be desirable for a viable program of earth-orbital operations in conjunction with manned space stations. First-order total program cost estimates indicate that savings of $0.5 to $1.5 $\times 10^9$ may be attainable through the use of interorbital shuttle systems, depending on the choice of system options.

References

[1] Carver, K. R., ed., *TRIAD (Tellurian Resources Inventory and Development)—Preliminary Design of an Operational Earth Resources Survey System,* NASA Contract NSR 47-003-010, NASA Langley Research Center and Old Dominion University, 1969.

[2] Doyle, R. O., ed., "A Long-Range Program in Space Astronomy—Position Paper of the Astronomy Missions Board," SP-213, July 1969, NASA.

[3] Nordbery, W., "Development of Meteorological Satellites in the United States," TM X-63313, Aug. 1968, NASA.

[4] Spence, R. E., "Future Role of Satellites in Air Traffic Control," AIAA Paper 66-259, Washington, D.C., May 1966.

[5] "Communications and Navigation/Traffic Control," ORL Experiment Program, Vol. B, Part VI, NASA CR-70346, Contract NASw-1215, Feb. 1966, IBM Federal Systems Division, Rockville, Md.

[6] "America's Next Decade in Space—A Report for the Space Task Group," Sept. 1969, NASA.

[7] Benton, W. et al., "Propellant Storability in Space," Technical Documentary Rept. RPL-TDR-64-75, Contract AF04-(611)-9078, June 1964, General Electric Co., Spacecraft Department, Philadelphia, Pa.

[8] Iacobellis, S. F., Larson, V. R., and Burry, R. V., "Liquid-Propellant Rocket Engines: Their Status and Future," *Journal of Spacecraft and Rockets,* Vol. 4, No. 12, Dec. 1967, pp. 1569–1580.

[9] Corrington, L. C., "The Nuclear Rocket Program—Its Status and Plans," *Journal of Spacecraft and Rockets,* Vol. 6, No. 4, April 1969, pp. 465–470.

[10] Interion, A. and Kugath, D., "Remote Manipulators in Space," *Astronautics & Aeronautics,* Vol. 7, No. 5, May 1969, pp. 40–51.

[11] Interion, A. and Kugath, D., "Manipulator Technology—Ready for Space Now," *Astronautics & Aeronautics,* Vol. 7, No. 9, Sept. 1969, pp. 24–32.

[12] McArthur, G. L. and Tarter, J. H., "Integration of Cryogenic Dynamic Power System with Vehicle Cooling System," *Journal of Spacecraft and Rockets,* Vol. 1, No. 2, March–April 1964, pp. 149–154.

[13] Timmins, A. R., "The Effectiveness of Systems Tests in Attaining Reliable Earth Satellite Performance," TN D-3713, Nov. 1966, NASA.

[14] Mercy, K. R., "Environmental Test Contribution to Spacecraft Reliability," TN D-4181, Nov. 1967, NASA.

[15] Hoffman, F. E., Johnson, G. W. S., and Simonsen, L. H., "Development of Cost Estimating Techniques and Relationships for Unmanned Space Exploration Missions," PRC R-870, Oct. 1966, Planning Research Corporation, Los Angeles, Calif.

[16] Campbell, H. G. and Dreyfus, D. J., "Manned Spacecraft Cost-Estimating Relationships," Memorandum RM-5317-NASA, June 1967, Rand Corporation, Santa Monica, Calif.

[17] Tischler, A. O., "A Commentary on Low-Cost Space Transportation," *Astronautics & Aeronautics,* Vol. 7, No. 8, Aug. 1969, pp. 50–64.