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Study 2.6 Interim Report
Programmatic Effects of Utilizing Various Space Tug Options

Prepared by ADVANCED VEHICLE SYSTEMS DIRECTORATE
Systems Planning Division

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1. INTRODUCTION

This report summarizes the results of the computerized (DORCA) analyses of a number of NASA/Non-NASA and DoD payload mission models that have been used in conjunction with studies of the Space Transportation System (STS). The first analysis performed was on the 1971 NASA/Non-NASA and DoD mission models. Subsequent to that, analyses of the June 1972 excursion to the 1971 NASA/Non-NASA mission models were performed. The mission models have two basic versions; i.e., one employing expendable payloads and another employing a "best mix" of expendable and reusable payloads. Both versions of the models have the same payload deployment schedule. However, in the "best mix" version, payloads are retrieved from orbit and, whenever possible, refurbished payloads are deployed, rather than new ones. The analyses were performed to determine the relative merits of different Tug configurations and of Tug combinations employed in several phased development schemes. The analyses considered only the Shuttle as a launch vehicle for the Tugs and the payloads.

In those cases involving reusable Tugs the analyses utilized the "best mix" version of the mission models. In this version the least expensive (overall) payload design for each mission was used in the compilation of the mission model. The mission model was, therefore, comprised of a conglomerate of the four payload designs; i.e., current expendable design, current reusable design, low cost expendable design, and low cost reusable design. In order to determine the "best mix" model, it was necessary to analyze four independent models, each comprised totally from payloads of a single design category. The four analyses were then compared, mission by mission, to determine the payload design resulting in the lowest overall cost for each mission. Fortunately, for this study the "best mix" determinations had been determined previously at Aerospace Corporation in conjunction with NASA-funded Studies 2.1 and 2.4 (FY 1972 and FY 1973 respectively). As a result, considerable savings in time and dollars were realized by Study 2.6 (FY 1973).

In those cases involving expendable upper stages, a mission model composed of current expendable payloads (one of the four used to determine the "best mix" version) was analyzed. The mission model had the same payload launch schedule as the "best mix" version; however, there were no payload retrieval missions or refurbished payload launches, as in the "best mix" case.

In the analyses utilizing versions of the 1971 mission model, five NASA MSFC defined Tugs, in addition to the current inventory of expendable upper stages, were analyzed with respect to vehicle traffic rates and total program costs. Three of the five Tugs were of current (low) technology design and two incorporated advanced technology design. Both of the advanced technology Tugs and one of the current technology Tugs included a capability to rendezvous and dock with the payloads. This capability made the concept of payload retrieval and refurbishment possible. The Tugs were employed singly and in combinations representing alternate phased development concepts. In those cases representing phased development concepts, 1985 was used as the IOC of the second Tug with one exception. The exception was a case where a current technology Tug with no rendezvous or docking provisions was initially employed and a current technology Tug with rendezvous and docking provisions phased-in in 1983. A total of 14 different analyses were performed on the 1971 NASA/Non-NASA and DoD mission models.

In the analyses of the 1972 excursion to the 1971 mission model, only three of the five NASA MSFC Tugs were investigated. Two Tugs were eliminated because of their very close similarity to two others in configuration and capability. The Tugs retained in the analysis were: (1) the current technology Tug without rendezvous and docking provisions; (2) the current technology Tug with rendezvous and docking provisions; and, (3) the baseline Tug design incorporating advanced technology structure and propulsion, and containing provisions for rendezvous/docking. As in the case of the analyses of the 1971 mission model, the Tugs were employed both singly and in combinations representing phased development schemes. Two other vehicles (not used in the analyses of the 1971 mission model) were introduced into the analysis. One vehicle was a Solar Electric Propulsion System (SEPS) with rendezvous and docking provisions. It was employed in combination with the baseline Tug on synchronous equatorial missions in one of the analyses. In this concept, the Tug delivers payloads from low earth orbit to a circular orbit at intermediate altitude where the SEPS takes over and completes the payload delivery to synchronous altitude. A reference SEPS mission time of 200 days was used in the analysis. The other vehicle was a storable propellant Tug (Model 025) that had been defined at NASA JSC. The Tug was employed singly for all of the missions for comparison with corresponding analyses utilizing the NASA MSFC Tugs.

In those cases involving phased development concepts, 1983 was used as the IOC for the second Tug, without exception. A total of 11 separate analyses were performed on the June 1972 excursion to the 1971 NASA/Non-NASA mission models.

In all of the analyses conducted, a "ground-based" operational philosophy was adopted for Tug operations. With this concept the Tug is delivered to orbit and returned after each mission is performed.
The only deviation from this general philosophy was in the SEPS operation where the SEPS itself was permitted to perform four round trip missions prior to earth return. Therefore, for 75 percent of its missions, the SEPS was essentially "space-based" rather than "ground-based."

2. BACKGROUND

The DORCA computer program was developed for NASA Headquarters, OMSF in FY 1971 and FY 1972 for use in the preliminary planning of advanced space program operations. It was designed for implementation on either the UNIVAC 1108 or the CDC 6000/7000 series machines. Utilization of the program on the UNICAL 1108 is relegated to NASA. Aerospace Corporation utilizes the program on the CDC machines. The program was designed to analyze space programs in terms of vehicle flight rates, vehicle inventories, procurement schedules, fiscal year costs and total program costs. The program "captures" (with appropriate vehicles) all payloads scheduled for delivery to, or retrieval from, orbit in a given year. Payloads are combined aboard the individual vehicle stages by a procedure that reduces the number of flights to a virtual minimum.

A number of informal analyses were performed for NASA Headquarters using the DORCA program during various stages of its development. Some of the early analyses included mission models containing manned lunar and planetary missions in addition to automated satellite programs and low earth orbit Shuttle missions. The primary event which triggered the analyses reported in this document was the definition of a number of alternate Tug configurations by NASA MSFC. At the time of their definition, a "best mix" version of the 1971 mission model (Case 403) had been synthesized and analyzed by Aerospace Corporation under FY 72 NASA Study 2.1. The task of synthesizing and analyzing the "best mix" version of the 1972 excursion to the 1971 model (Case 506), had just begun under FY 73 Study 2.4 and was not scheduled for completion for some time. Therefore, in order to initiate a trade study among the various Tug configurations, the 1971 mission model was utilized instead of waiting for the new model to be completed. The basic data used in comparing the merits of the various Tug options was, therefore, developed using the "old" 1971 mission model. Subsequent analyses using the 1972 excursion to the 1971 mission model were performed to determine if changes that had been made in the mission model would alter the conclusions

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drawn from the previous analyses. Since the analyses of the 1972 version of the model were in the nature of "check runs" they were not as broad or carried to the same depth as the previous analyses were.

The primary differences between the 1971 mission model and the 1972 excursion to that model were: (1) there was a significant increase in Shuttle sortie missions and space station operations in the 1972 excursion model; and (2) there was a reduction in payload weights and lengths in the later model. The reduction in payload weights and lengths was not general in nature but was implemented on specific payloads only.

The Study 2.1 analysis of the "best mix" version of the 1971 mission model (Case 403) used the Shuttle as the basic launch vehicle. For upper stage vehicles it made use of current expendable designs in the 1979 through 1984 time frame and a reusable Tug with rendezvous and docking provisions (Air Force OOS design) after 1984. The analyses made no investigations or assessments of alternate Tug configurations. It did however provide a reference payload mix and launch schedule to be utilized in the analysis of upper stage vehicles possessing a capability to rendezvous and dock with the mission payloads.

The Study 2.1 analysis of the "best mix" version of the 1972 excursion to the 1971 mission model (Case 506) again employed the Shuttle as the basic launch vehicle and expendable upper stages of current design prior to the Tug IOC. However, in this model, the Tug IOC was 1983 instead of 1985 and the Tug utilized was the NASA MSFC baseline Tug instead of the Air Force OOS. As in the case of the 1971 mission model analysis, the analysis of the 1972 excursion did not include an assessment of alternate Tug configurations, but it did provide a reference payload mix and launch schedule to be utilized in subsequent analyses employing reusable payloads.

These two reference analyses and their expendable payload counterparts provide the points of departure for the conduct of analyses covered in this report. The expendable payload counterpart to the "best mix" mission model retains the same launch schedule as the "best mix" model but uses only expendable payloads for missions requiring the use of an upper stage vehicle. This use of expendable payloads eliminates the retrieval and subsequent refurbishment of payloads for those missions. The expendable payload versions of the mission models were utilized in analyses employing upper stage vehicles with no rendezvous or docking capability

3. GROUND RULES AND ASSUMPTIONS

The analyses reported on in this document were based on ground rules and assumptions representing the operational philosophies and policies prevailing at the time. Since the analyses of the 1971 mission models and the analyses of the 1972 excursion were performed sequentially in time, some differences in ground rules and assumptions did exist between the two. For the most part, however, the differences were relatively small and had little significance on the outcome of the analyses. As the ground rules are discussed in the following sections, the differences will be noted.

3.1 1971 Mission Model

The basic 1971 mission model was adapted from the April 1971 NASA Payload List. This original listing covered a period from the early 1970's through the year 1990. The listing was expanded to include the years 1991 through 1997 by duplicating, in those years, the payload schedule from 1981 through 1987. The "best mix" version of the 1971 mission model (Case 403) was derived using the payload launch schedule contained in the original listing. The determination of the "best mix" version of the mission model required that the basic mission be analyzed four different times. Each analysis was conducted with one of the four payload configurations (i.e., current expendable, current reusable, low cost expendable, and low cost reusable) used throughout the model. For each of these individual analyses the vehicles employed remained constant; in this case, they were the Shuttle and the reusable Tug with payload retrieval provisions. After the results of the four analyses were obtained, the payload configuration resulting in the lowest cost to a mission was selected as the mission's entry into the "best mix" version of the model. Each mission was studied and its "best" payload configuration selected on an individual basis. The "best mix" version of the model was utilized in analyses conducted using the space Shuttle and upper stage vehicles possessing rendezvous and docking capability. The upper stage vehicles were not available at the beginning of the program but were phased in at a later date.

A modified "best mix" version of the mission model was utilized in those analyses that employed the Shuttle and upper stage vehicles (with payload retrieval provisions) that were available at the beginning of the program (1979). In this modified version the payload mix was identical to that in the "best mix" version. However, because of the early availability of the Tug, payload retrieval and the deployment of refurbished payloads was initiated earlier than in the "best mix" version.

The expendable payload version of the 1971 model was derived from the "best mix" version of the model instead of starting from scratch with the original payload listing. This was done basically for two reasons: (1) so that reusable payloads (as determined in the "best mix" selection) could be used for missions capable of being serviced by the Shuttle alone, thereby taking advantage of the economic benefits resulting from reusability; and, (2) so that low cost versions of the expendable payloads could be used (instead of their current design counterparts) for those missions where it proved more economical in the "best mix" version of the model. The expendable payload version of the model therefore did not consist exclusively of current expendable payloads as might be expected. This expendable version of the model was used in analyses employing the Shuttle and expendable upper stage vehicles or reusable upper stage vehicles without rendezvous and docking provisions.

3.2 1972 Excursion to 1971 Mission Model

The 1972 excursion to the 1971 mission model was obtained from a memorandum to NASA Associate Administrators from the AAD/Deputy Associate Administrator of NASA. The excursion to the 1971 model introduced an increased number of Shuttle sortie missions in the program and, in some cases, reduced the weight of payloads requiring upper stage vehicles (Tugs) for delivery. Despite these differences, the excursion and the model itself were very similar with respect to the analytical techniques that were applied to them. The program duration of the excursion was 1979 through 1997 as it was in the 1971 model. Also, the payload schedule in the years 1991 through 1997 was a duplicate of the 1981 through 1987 schedule. A "best mix" version of the 1972 excursion was derived in the same manner as was the best mix version of the 1971 model and was applied in basically the same manner; i.e., for analyses utilizing the Shuttle and a phased-in Tug possessing capability for rendezvous and docking.

The expendable payload version of the 1972 excursion was synthesized and utilized basically in the same manner as was its 1971 model counterpart. The major difference was that no low cost expendable payloads were included in this version. Experience with the expendable payload version of the 1971 model had shown that even though the low-cost version of the payload resulted in the least cost for a mission in the "best mix" version of the model, it did not necessarily remain the least cost payload type when significant changes were made to the types of payloads comprising the model. The basic reason for this is that payloads combined (for transport) differently in the revised model than in the original one; therefore, the cost to the missions were different than before. Because of the uncertainties involved it was decided to use all current expendable payloads rather than carry over their low cost counterparts from the "best mix" version as was done with the 1971 mission model.

3.3 Tug Operations/Performance

In the analyses of both the 1971 mission model and the 1972 excursion to it, the reusable Tugs were operated in the "ground-based" mode. In this mode the Tug is returned to earth after each mission that it flies and is refurbished for its next flight. It was assumed that the Tug could be turned around in a five-week period, thereby making it capable of performing ten flights per year. Tug lifetimes, for purposes of these analyses, were assumed to be 20 flights or five years whichever occurred first. The above ground rules and assumptions are the only common ones between the two sets of analyses in the area of Tug operations and performance. Differences in this area between the two sets of analyses are as follows:

3.3.1 Scar Weight

In the analysis of the 1972 excursion a scar weight, chargeable to the Tug, was used in connection with the Shuttle payload deployment/retrieval capability. This scar weight results from the operational interface hardware required between the Tug and the Shuttle. This effectively reduces the combined Tug/payload weight that can be delivered to orbit by the Shuttle (where the Shuttle is not constrained by Tug/payload length) and could eliminate a payload that would otherwise have gone on the flight. In the 1971 mission model analyses no scar weight was used.

3.3.2 Constraints on Tug

In the analyses of the 1972 excursion a ground rule limiting operations to the "ground-based" mode was imposed. The "ground-based" mode limits Tug-payload assembly operations to the ground except in the few cases where the Tug-payload assembly cannot be flown by the Shuttle. In those few cases, the docking of Tug to payload in orbit was allowed. As a consequence, Tug performance in the deployment mode was constrained to conform to the Shuttle's payload capability to specific orbits of interest. Tug performance was computed restricting the combined weight of the Tug, payload, propellant, and interface equipment (scar weight) to a value equal to the Shuttle payload capability to the parking orbit from which the Tug mission was to originate.

In the 1971 mission model analyses, Tug performance was computed on the basis of fully loaded Tugs without regard to weight constraints.

3.3.3 Propellant Loading

In the analysis of the 1972 excursion the Tugs were propellant off-loaded in those cases where the payload weight to be transported by the Tug was less than its computed capability. The payload loading procedure is done using the maximum payload capability (both weight and length) of the Tug. Since the payloads are discrete items having finite weights and lengths, it is virtually impossible to load the Tug exactly to its maximum capability. In order to eliminate carrying excess weight (propellant) aboard the Tug the excess propellant was off-loaded.

In the 1971 mission model analyses the Tugs were flown fully loaded with propellant whether or not it was actually required.

3.4 Tug Configuration/Characteristics

The Tug mass properties, configuration, and costing parameters utilized in the 1971 mission model analyses are presented in Tables 3-1 and 3-2. Similar data on the vehicles used in the analyses of the 1972 excursion to the 1971 model are shown in Tables 3-3 and 3-4. All five of the Tugs utilized in the analysis of the 1971 model were conceived and defined by NASA MSFC. Three of the five Tugs used in the 1972 excursion analyses were repeats from the 1971 mission model analyses, whereas the other two configurations were unique to the 1972 excursion analyses. The two unique Tug configurations were (1) the storable propellant Tug (Model 025) defined by NASA JSC; and, (2) the combination of the NASA MSFC baseline Tug and a solar electric propulsion system (SEPS) defined jointly by Rockwell International and the NASA MSFC SEPS project office.

A number of the analyses performed on both the 1971 model and the 1972 excursion included phased Tug operations. In the phased Tug operation the model under analysis uses a Tug with reduced capability initially but phases in a Tug with higher performance later in the program. Unlike the analyses employing a single Tug, the RDT&E costs of two Tugs must be factored into the analysis. The total cost for the phased development of two Tugs is less than the sum of their individual RDT&E costs but greater than the RDT&E cost of the most expensive one. The "equivalent" RDT&E cost for various phased Tug schemes (which are not shown in Tables 2 and 4) used in the analyses are as follows:

Initial Tug	Final Tug	Two Tug RDT&E Cost
LTND	BL	$885 million
LTRD	BL	990 million
LBND	BL	890 million
LTND	LTRD	414 million
LTND	LTFX	780 million
LTRD	LTFX	800 million

The Tugs were assumed to be 35-ft in length.

Table 3-1. Definition of Tug Options, 1971 Mission Model

Tug \ Characteristics	Rend & Dock Cap		Structure/Tanks		Engine		
	Yes	No	Low Tech	Adv Tech	Mod RL-10 6/1 MR	Ext Cycle RL-10	High P_C LOX/LH_2
Full Capability (BL)	X			X			X
Low Technology (LTND)		X	X		X		
Low Technology (LBND)		X		X	X		
Low Technology (LTRD)	X		X		X		
Full Capability (LTFX)	X		X			X	

Table 3-2. Characteristics of Tug Options, 1971 Mission Model

	Full Capability Tug	Low Technology Tugs			Full Capability Tug
PARAMETER	BL	LTND	LBND	LTRD	LTFX
Burnout Wt (W_{BO}), Kg (lb)	2800 (6,170)	5770 (6,109)	2550 (5,618)	2810 (6,545)	3160 (6,974)
Dry Struc Wt (W_{SD}), Kg (lb)	2370 (5,223)	2370 (5,224)	2145 (4,733)	2595 (5,725)	2730 (6,024)
Non-Usable Prop Wt (W_{NUP}), Kg (lb)	431 (950)	401 (885)	401 (885)	372 (820)	431 (950)
Main Engine Prop Wt, Kg (lb)	26950 (56,000)	26950 (56,000)	26950 (56,000)	26950 (56,000)	26950 (56,000)
RCS Prop Wt (W_{ACP}), Kg (lb)	225 (497)	288 (636)	288 (636)	304 (671)	225 (497)
In-Flt Prop Losses (W_{NIE}), Kg (lb)	128 (283)	112 (247)	112 (247)	166 (367)	186 (410)
Scar Weight, Kg (lb)	663 (1,462)	819 (1,806)	663 (1,462)	819 (1,806)	663 (1,462)
RDT&E Cost, $ millions	700	295	325	375	620
First Unit Cost	24.0	11.5	11.7	13.5	23.0
Main Engine Thrust, Kb (lb)	4540 (10,000)	6800 (15,000)	6800 (15,000)	6800 (15,000)	9070 (20,000)
Main Engine I_{SP}	470	440	440	440	466

Table 3-3. Definitions of Tug Options, 1972 Excursion

Characteristics / Tug	Rend Dock Cap.		Structure/Tanks		Engine
	Yes	No	Low Tech	Adv Tech	
Full Capability (BL)	X			X	High P_C LOX/LH_2
Low Technology (LTND)		X	X		Mod RL-10, 6/1 MR
Low Technology (LTRD)	X		X		Mod RL-10, 6/1 MR
Storable Prop (ST)	X		X		8000 Lb Thrust, GG Cycle
Full Cap + SEPS (BL-SEP)	X			X	Solar Electric Propulsion

Table 3-4. Characteristics of Tug Options, 1972 Excursion

PARAMETER	JSC Model 025	MSFC BL	MSFC LTND	MSFC LTRD	SEP
Propellant Capacity, Kg (Lb)	27500 (60624)	26000 (56000)	26000 (56000)	26000 (56000)	1450 (3200)
Nonusable Prop, Kg (Lb)	274 (605)	431 (950)	401 (885)	372 (820)	
**Nonimpulsive Prop, Kg (Lb)	248 (546)	354 (780)	400 (883)	470 (1038)	
Dry Struct. Wt, Kg (Lb)	1305 (2876)	2370 (5223)	2370 (5224)	2595 (5725)	1090 (2400)
Supt Struct Wt Pen, Kg (Lb)	680 (1500)	664 (1806)	819 (1806)	819 (1806)	
I_{SP} (Sec)	339	470	470	470	3000
Power Level (KW)	NA	NA	NA	NA	21
Length, M (Ft)	7.50 (24.6)	10.68 (35.0)	10.68 (35.0)	10.68 (35.0)	2.90 (9.5)
Diameter, M (Ft)	3.05 (10.0)	4.57 (15.0)	4.57 (15.0)	4.57 (15.0)	
Flight Lifetime (Flights)	20	20	20	20	***4/20
RDT&E Costs ($M)	215.4	700	295	375	147.5
First Unit Cost ($M)	4.53	24	11.5	13.5	25.59
Flight (Ops) Cost ($M)	0.98	1.83	1.26	1.36	2.34
Refurbish Cost ($M)	NA	NA	NA	NA	*4.76

* MERCURY PROPELLANT

** INCLUDES ACS PROPELLANT

*** ASSUMED FOUR FLIGHT LIFETIME PRIOR TO REFURB PLUS FOUR REFURB CYCLES

3.5 Shuttle Operations/Performance

During the initial phases of the Shuttle operations the ground and flight operations and post-flight analyses will be conducted in such a manner that the yearly flight rate will be much lower than the ultimate rate. Therefore, in the early years of the operational period it would seem reasonable to restrict the number of flights permitted on the Shuttle. In the analyses of the 1971 mission model no restrictions on flight rate were imposed since the nature of the analyses (Tug tradeoffs) did not seem to warrant additional complications in the analysis. However, in the analyses of the 1972 excursion a schedule of permissible Shuttle flights in the early years was adhered to. The phase-in flight schedule restrictions used were:

Year	Max. No. of Flights
1979	15
1980	24
1981	32
1982	40
1983	60

The Shuttle performance data utilized in the analyses of the 1971 mission model were the current data (as developed by NASA contractors and in-house studies) at the time the analyses were conducted. Payload capabilities of the Shuttle that were utilized in the analyses are as follows:

ORBIT					PAYLOAD	
h_a		h_p		i		
KM	NMI	KM	NMI	DEG	KG	LB
185	100	185	100	28.5	29,484	65,000
370	200	370	200	28.5	28,350	62,500
648	350	648	350	28.5	23,133	51,000
185	100	185	100	90	18,144	40,000
740	400	740	400	90	8,165	18,000
185	100	185	100	100	15,876	35,000
926	500	926	500	100	4,491	9,900

As can be seen from the above data, some differences (other than Shuttle performance) exist in the assumed parking and/or operational orbits.

The Shuttle performance data used in the 1972 excursion to the 1971 mission model analysis, were in conformance with the Shuttle RFP, the Level I Requirements, and the NASA JSC Payload Accommodations Document. The payload capability of the Shuttle to various orbits of interest (and those utilized in the analyses) are as follows:

ORBIT					PAYLOAD	
h_a		h_p		i		
KM	NMI	KM	NMI	DEG	KG	LB
296	160	296	160	28.5	29,484	65,000
463	250	463	250	28.5	26,989	59,500
556	300	556	300	28.5	24,585	54,200
740	400	740	400	28.5	19,368	42,700
500	270	500	270	55	20,865	46,000
296	160	296	160	90	17,917	39,500
500	270	500	270	90	12,610	27,800
926	500	926	500	90	2,812	6,200
296	160	296	160	100	15,422	34,000
926	500	926	500	100	1,633	3,600

As can be seen from the above data, some differences (other than Shuttle performance) exist in the assumptions utilized for parking and/or operational orbital altitudes. The primary differences are the changes in altitude of the basic parking orbits at the various inclinations; i.e., 185 km (100 nmi) in the 1971 mission model versus 296 km (160 nmi) in the 1972 excursion.

3.6 Solar Electric Propulsion System (SEPS) Operations/Performance

An analysis of the "best mix" version of the 1972 excursion to the 1971 mission model was conducted utilizing the baseline Tug for all missions except the synchronous equatorial missions, which were serviced instead by a combined Tug-SEPS operation. In the combined operation, the Tug (operated in a ground-based mode) would deliver the payload from the parking orbit to some intermediate orbit where the SEPS (operated in a space-based mode) would take over and complete the delivery to synchronous equatorial orbit. For payload retrieval missions the operation was reversed; i.e., the payload was delivered from synchronous equatorial orbit to an intermediate orbit by the SEPS. There a waiting Tug would take over and complete the delivery to the parking orbit for ultimate retrieval by the Shuttle.

In the space-based mode the SEPS was presumed to be stationed in an intermediate orbit and remain there until it had completed four round-trip missions to synchronous equatorial orbit. Upon completing four round-trips the SEPS was returned to earth for refurbishment and a new (or refurbished) SEPS delivered to orbit as its replacement. Sufficient propellant to perform the SEPS round trip mission was presumed to be delivered to orbit with each SEPS payload. In effect, then, the SEPS was propellant off-loaded for each mission since its tankage was capable of holding enough propellant to accommodate all four round trip missions. In this manner a little extra performance was squeezed from the vehicle.

The basic definition of the vehicle was taken from Reference 2. Performance computations of the Tug-SEPS combination were performed in-house at Aerospace Corporation utilizing an existing performance program. The program, while not rigidly exact, closely approximates the Tug-SEPS operation and is based on the following assumptions:

a. Only circular changeover orbits are considered in the optimization process.

b. Tug characteristic velocity between the Shuttle orbit and the changeover orbit is calculated by a two-impulse optional split plane change program and then multiplied by 1.023 to allow for the effects of finite burning and gravity losses.

c. SEPS characteristic velocity between the changeover orbit and synchronous orbit is calculated from Reference 3 as:

$$V_{ch} = \sqrt{V_{co}^2 + V_{sync}^2 - 2V_{sync}V_{co}\ \cos\left(\frac{\pi}{2}\Delta i\right)}$$

Where:

V_{co} = circular velocity at changeover altitude

Δi = plane change required between changeover orbit and synchronous orbit

V_{sync} = circular velocity at synchronous altitude

Inherent in the equation is the assumption that the thrust is so low that the vehicle is in a nearly circular orbit at each point in its spiraling trajectory.

d. The value of the Tug payload weight deployed to or retrieved from the changeover orbit (for the characteristic velocity found in "b" above) was obtained from a linear interpolation of the Tug performance capabilities in a weight constrained mode of operation.

With the above assumptions, the task of choosing a changeover orbit to maximize the deployed or retrieved payload was relatively simple and was done in the following manner.

a. For a given round trip time and a given payload mode (deployment or retrieval) various values of changeover orbit altitude are selected.

b. For each of the above orbital altitudes the corresponding inclination is found such that the payload which the space Tug can deploy (or retrieve) to the orbit is equal to the payload which the SEPS can deploy (or retrieve) from that orbit to synchronous equatorial orbit. This represents the maximum weight for that particular changeover orbit.

c. Utilizing the preceding, plots of payload weight and changeover orbit inclination as functions of changeover orbit altitude were made.

d. From each curve of payload versus changeover orbit altitude, the altitude (and therefore inclination) is chosen to maximize the payload weight.

Performance computations of the Tug-SEPS combination (with the SEPS operating in the space-based mode) were made for round trip mission durations of 100, 150 and 200 days. A summary of the optional payload-orbit combination as a function of mission duration is given in Table 3-5. Though the performance was computed for other mission durations, the 200-day mission was the only one analyzed because of time and budget limitations.

3.7 Storable Propellant Tug Operations/Performance

The basic definition of the storable propellant Tug was obtained from the NASA JSC documentation of an in-house study (Ref 4). Basically, the Tug was operated as a reusable vehicle and one which was capable of rendezvous and docking with payloads in order to retrieve them from orbit. As far as the program was concerned, this Tug was handled in the same way that the NASA MSFC Tugs were handled. All performance, mass properties, and cost data required to assimilate the vehicle into the DORCA program were obtained from the NASA JSC document.

3.8 Multiple Payload Limitations

For purposes of the analyses conducted (on both the 1971 mission model and the 1972 excursion to it), limitations were placed on the number of payloads that could be flown simultaneously on the various vehicles. These limitations were consistent with those applied in other NASA studies being conducted at the time. The limitations applied are listed below.

Vehicle or Stage	1971 Model	1972 Excursion
Shuttle	4 payloads	5 payloads
Tug	3 payloads	5 payloads
Centaur	3 payloads	3 payloads
Centaur/Kick	3 payloads	3 payloads
Centaur/B2	N/A	3 payloads
Agena	2 payloads	3 payloads
Delta	1 payload	3 payloads

As can be seen the limitations were more restrictive in the analyses of the 1971 model than they were in the analyses of the 1972 excursion. The

Table 3-5. SEPS Space-Based Performance Summary

PARAMETERS	ROUND TRIP SORTIE TIME		
	200 DAYS	150 DAYS	100 DAYS
Payload Deployment			
Payload Capability - kg (lb)	6802 (14995)	6121 (13495)	5389 (11880)
Fuel per Sortie - kg (lb)	562 (1239)	421 (929)	281 (619)
Changeover Orbit Alt - km (nmi)	12964 (7000)	16668 (9000)	20372 (11000)
Changeover Orbit Inclin. - Deg.	10	10	7.8
Payload Retrieval			
Payload Capability - kg (lb)	5928 (13070)	5044 (11120)	4087 (9010)
Fuel per Sortie - kg (lb)	562 (1239)	421 (929)	281 (619)
Changeover Orbit Alt - km (nmi)	12964 (7000)	14816 (8000)	18520 (10000)
Changeover Orbit Inclin. - Deg.	11.6	10	8.9

limits were opened up somewhat in the 1972 excursion case in order to ease, somewhat, the arbitrary restrictions that had applied previously.

3.9 Vehicle Operations (Flight) Costs

The cost of a Shuttle flight was assumed to be \$10.5 million, an acceptable value at the time the analyses were conducted. The \$10.5 million included a \$6.0 million charge which amortized the cost of the vehicle (\$600 million) over its flight lifetime (100 flights). The \$10.5 million did not, however, include any RDT&E costs.

The cost of Tug flights was computed in a similar manner. Since a number of different Tugs were used in the analysis, and, since the flight costs include a part of the procurement cost of the vehicle, each Tug had a different cost per flight. The flight costs were computed using the following equation, which agrees in substance with the NASA MSFC definition.

$$\text{Flight Cost} = \$0.75 \text{ million} + \frac{0.9 \times \text{First Unit Cost}}{\text{Flight Lifetime}}$$

Resultant Tug operating (flight) costs used in the analyses were:

TUG	OPERATIONS (Flight) COSTS
LTND	\$1.26 million
LBND	1.28 million
LTRD	1.36 million
LTFX	1.79 million
BL	1.83 million

Flight costs for the expendable upper stages were obtained from Reference 1.

3.10 Cost Discounting

In the analyses of the 1971 mission model the yearly program costs generated by the model were discounted at a rate of 10 percent to arrive at a discounted total program cost. The procedure basically determines the "present worth" of the program presuming one could otherwise earn 10 percent on his money in future years. The computations were performed by a separate computer routine according to the following formulation:

$$\text{Discounted Total} = (f)\ (\text{1st FY Cost}) + (f)^2\ (\text{2nd FY Cost}) + \ldots\ldots + (f)^n\ (n^{th}\ \text{FY Cost})$$

First year costs were taken to be FY 1975.

Discounting was not performed on the cost data resulting from the analyses of the 1972 excursion to the 1971 mission model.

3.11 Launch Site Availability

The Eastern Test Range (ETR) was presumed to be available for Shuttle launches from the time the Shuttle became operational in both the analyses of the 1971 model and the 1972 excursion to it.

In the intervening time between analyses of the 1971 mission model and analyses of the 1972 excursion, estimates of the date the Western Test Range (WTR) would be available for Shuttle launches had changed. Consequently, an operational date of 1980 was used in the 1971 mission model analyses while 1981 was used in the analyses of the 1972 excursion.

3.12 Multiple Payload Delta V Penalty

No additional deployment delta V was added to that required to attain operational orbit in those cases where multiple payloads were delivered to the same orbit on the same vehicle flight. Some delta V increments for rendezvous and docking were incorporated in most operational orbit delta V budgets; however, they were basically single deployment increments. Since it was not known in advance how many or what type payloads the program would load aboard a vehicle, it was impossible to know in advance how much additional delta V to add for distributing the payloads in orbit. Therefore, the only thing that could have been done was to add an "average" increment to all orbits to account for multiple payload deployment. This could have proved, in the case of single deployment, as unrealistic as adding no delta V. The final decision was to add no additional delta V, but to scrutinize carefully the vehicle load factor for multiple deployment cases, to make certain a reasonable performance cushion existed to give assurance that on-orbit distribution could be accomplished.

4. METHODOLOGY

The analyses of the 1971 Mission Model encompassed fourteen cases while eleven cases were investigated in the analyses of the 1972 excursion to the basic model. All of the analyses were performed using the DORCA computer program that was developed by Aerospace Corporation for NASA HQ (MTE). The basic inputs required for the program are:

1. Definitions of the legs (trajectories) that the vehicles are to fly.
2. Definitions of the vehicles that are to "fly" specific legs.
3. Definitions of the payloads comprising the payload model.
4. Traffic (deploy/retrieve) schedule for the payloads.
5. Cost and cost distribution information for both payloads and vehicles.

Given the above information the DORCA program performs the following functions.

1. Computes vehicle performance capabilities on the various mission legs.
2. Segregates payloads by FY and subsequently loads them onto vehicles for transport.
3. Maximizes vehicle load factors to greatest possible extent.
4. Computes propellant required to "fly" the payloads to their ultimate destinations.
5. Offloads propellant from the vehicles where possible.
6. Flies the missions.
7. Summarizes the following parameters:
   a. Vehicle flight rates.
   b. Vehicle inventories required.
   c. Vehicle utilization (by payload).
   d. Mission costs (by payload).
   e. Total program costs.

The above descriptions are an oversimplification of the DORCA program requirements and functions; however, they do depict accurately the general types of information required and the types of computations performed.

For the most part the ground rules and assumptions described in the preceding section can be imposed on the program via a discrete entry in the data input (e.g., restricting the number or length of payloads a Tug may carry). There are a few situations, however, which must be accommodated by input data manipulation or by making iterative computer runs (e.g., limiting the number of Shuttle flights that may be made in the early years of a program). However, in one way or another all ground rules and assumptions were accommodated in the analyses.

The sensitivity analyses performed on the 1971 model were conducted using Tug option nine which provides for Centaur and Agena vehicles in the 1979-1984 time frame and the full capability, baseline Tug thereafter. This option represents the present baseline operational concept. Tug weight and length were varied to determine sensitivity to Tug size. Payload weight was varied to assess payload effects; mission Delta V was varied to determine sensitivity with respect to orbital rendezvous and phasing velocity requirements.

5. RESULTS/CONCLUSIONS

The results obtained from the analyses of 14 cases involving the 1971 Mission Model (and derivatives thereof) are presented in Tables 5-1 through 5-12. Table 5-1 gives the vehicle traffic and total costs associated with the NASA/Non-NASA segment of the mission model. Table 5-2 displays the same information for the DoD segment. Table 5-3 summarizes and combines the cost information from Tables 5-1 and 5-2 and, in addition, presents the discounted values for those cost figures. Figure 5-1 and 5-2 present the comparative Shuttle and Tug traffic for the various cases included in the analysis. The traffic rates represent the combined NASA/Non-NASA and DoD traffic. Figure 5-3 and 5-4 present, for comparative purposes, the total cost of each of the 14 cases in current and discounted dollars respectively. The costs presented represent the combined NASA/Non-NASA and DoD costs. Figure 5-5 through 5-7 shows the total program cost as a function of the various phased Tug concepts and as a function of the time of phase-in of the final Tug configuration. To assess the effect of final Tug phase-in time, it was assumed that both Tugs were produced regardless of when the phase-in was implemented. The two end points on the curves (1979 and 1997) were obtained by assuming the program was accomplished using only one of the Tugs and adding to that cost the incremental cost required to develop the second Tug. The intermediate point (1985) on the curves was obtained from the results of the analyses employing phased-Tug operations. While not exact (due to the lack of additional points) the curves do represent a first order approximation to the actual curve relating total program cost to final Tug phase-in. Figure 5-8 presents (on one chart) a summarization of Figures 5-5 through 5-7. Figures 5-9 through 5-12 present data on the sensitivity of the mission model to various program parameters; i. e., payload weight, Tug inert weight, Tug length and mission delta V (for synchronous equatorial missions).

Results of this analyses (11 cases) of the 1972 excursion to the 1971 Mission Model are presented in Table 5-4 and Figures 5-13 through 5-18.

Table 5-1. Operations and Cost Results, NASA/Non-NASA Payloads, 1971 Mission Model

Case or Option	Tug	Flight Results — Flts						Cost Results — $B				
	Description	Ph I EOS	Ph II EOS	Ph I Tug	Ph I TD Tug	Ph II Tug	Ph II TD Tug	Veh DDT&E	P/L Costs	Ops Costs	Total	1979 Peak
1	Centaur Agena	431	-	99/203	-	-	-	5.150	15.951	6,753	27.854	3.356
2	LTND	496	-	265	21	-	-	5.445	15.951	5.928	27.325	3.528
3	BL	548	-	314	16	-	-	5.850	13.200	6.782	25.831	3.632
4	LTRD	629	-	225	105	-	-	5.525	13.200	7.601	26.326	3.458
5	LTFX	596	-	298	49	-	-	5.770	13.200	7.362	26.332	3.600
6	LTND + '85 BL	159	401	91	8	220	12	6.035	13.684	6.821	26.540	3.422
7	LTRD + '85 BL	173	397	76	25	219	11	6.050	13.199	6.992	26.242	3.458
8	LTND + '85 LTRD	159	452	91	8	150	83	5.565	13.684	7.340	26.589	3.422
9	Centaur/Agena + '85 BL	128	401	55/53	-	220	12	5.850	13.684	7.006	26.540	3.267
10	Centaur/Agena + '85 LTRD	128	452	55/53	-	150	83	5.525	13.684	7.525	26.734	3.267
11	LTND + '85 LTFX	159	431	91	8	206	35	5.930	13.684	7.184	26.798	3.422
12	LTND + '83 LTRD	99	519	59	5	171	98	5.565	13.472	7.435	26.472	3.422
13	LTRD + '85 LTFX	173	431	76	25	206	36	6.010	13.199	7.406	26.615	3.458
14	LBND + '85 BL	144	401	97	2	220	12	6.065	13.684	6.658	26.408	3.417

BL — NASA/MSFC Baseline Tug

LTND — NASA/MSFC Low Technology Tug - Without Rendezvous and Docking Capability

LTRD — NASA/MSFC Low Technology Tug - With Rendezvous and Docking Capability

LBND — NASA/MSFC Low Technology Tug - With Baseline Structure/Tankage - Without Rendezvous and Docking Capability

LTFX — NASA/MSFC Low Technology Tug - With Rendezvous and Docking Capability - With Extended Cycle RL-10 Engine

Table 5-2. Operations and Cost Results, DoD Payloads, 1971 Mission Model

Case or Option	Tug Description	Flight Results — Flts: Ph I EOS	Ph II EOS	Ph I Tug	Ph II TD Tug	Ph II Tug	Ph II TD Tug	Cost Results — $B: Veh DDT&E	P/L Costs	Ops Costs	Total	1979 Peak
1	Centaur Agena	365	-	32/203	-	-	-	-	9.170	5.597	14.767	0.928
2	LTND	409	-	227	0	-	-	-	9.170	4.929	14.099	0.906
3	BL	394	-	204	12	-	-	-	6.800	4.918	11.717	0.809
4	LTRD	430	-	184	40	-	-	-	6.800	5.237	12.038	0.820
5	LTFX	418	-	181	29	-	-	-	6.800	5.197	11.997	0.821
6	LTND + '85 BL	105	316	54	-	165	10	-	7.211	5.190	12.401	0.847
7	LTRD + '85 BL	119	284	57	6	147	10	-	6.800	5.001	11.801	0.821
8	LTND + '85 LTRD	105	346	54	-	146	34	-	7.211	5.457	12.668	0.847
9	Centaur/Agena + '85 BL	89	316	14/39	0	165	10	-	7.211	5.294	12.505	0.861
10	Centaur/Agena + '85 LTRD	89	346	14/39	0	146	34	-	7.211	5.561	12.772	0.861
11	LTND + '85 LTFS	105	335	54	0	153	25	-	7.211	5.414	12.625	0.847
12	LTND + '83 LTRD	118	339	28	0	171	38	-	6.795	5.532	12.327	0.847
13	LTRD + '85 LTFX	119	303	57	6	135	25	-	6.800	5.238	12.018	0.821
14	LBND + '85 BL	105	316	54	-	165	10	-	7.211	5.191	12.402	0.847

BL — NASA/MSFC Baseline Tug

LTND — NASA/MSFC Low Technology Tug - Without Rendezvous and Docking Capability

LTRD — NASA/MSFC Low Technology Tug - With Rendezvous and Docking Capability

LBND — NASA/MSFC Low Technology Tug - With Baseline Structure/Tankage - Without Rendezvous and Docking Capability

LTFX — NASA/MSFC Low Technology Tug - With Rendezvous and Docking Capability - With Extended Cycle RL-10 Engine

Table 5-3. NASA/Non-NASA, DoD and Total Cost Summaries, 1971 Mission Model

CASE NO.	TOTAL NASA COST $ B	DISCOUNTED TOTAL NASA COST $ B	TOTAL DOD COST $ B	DISCOUNTED TOTAL DOD COST $ B	GRAND TOTAL COST $ B	DISCOUNTED GRAND TOTAL COST $ B
1	27.854	12.328	14.767	4.833	42.621	17.161
2	27.325	12.281	14.099	4.658	41.424	16.939
3	25.831	11.904	11.717	4.084	37.548	15.988
4	26.326	11.899	12.037	4.109	38.363	16.008
5	26.332	12.022	11.997	4.099	38.329	16.121
6	26.540	12.099	12.401	4.289	38.941	16.388
7	26.242	11.991	11.801	4.111	38.043	16.102
8	26.589	12.044	12.668	4.294	39.257	16.338
9	26.540	12.040	12.505	4.336	39.045	16.376
10	26.734	12.066	12.772	4.340	39.506	16.406
11	26.798	12.141	12.625	4.285	39.423	16.426
12	26.472	12.006	12.327	4.222	38.799	16.228
13	26.615	12.070	12.018	4.110	38.633	16.180
14	26.408	12.038	12.402	4.240	38.810	16.278

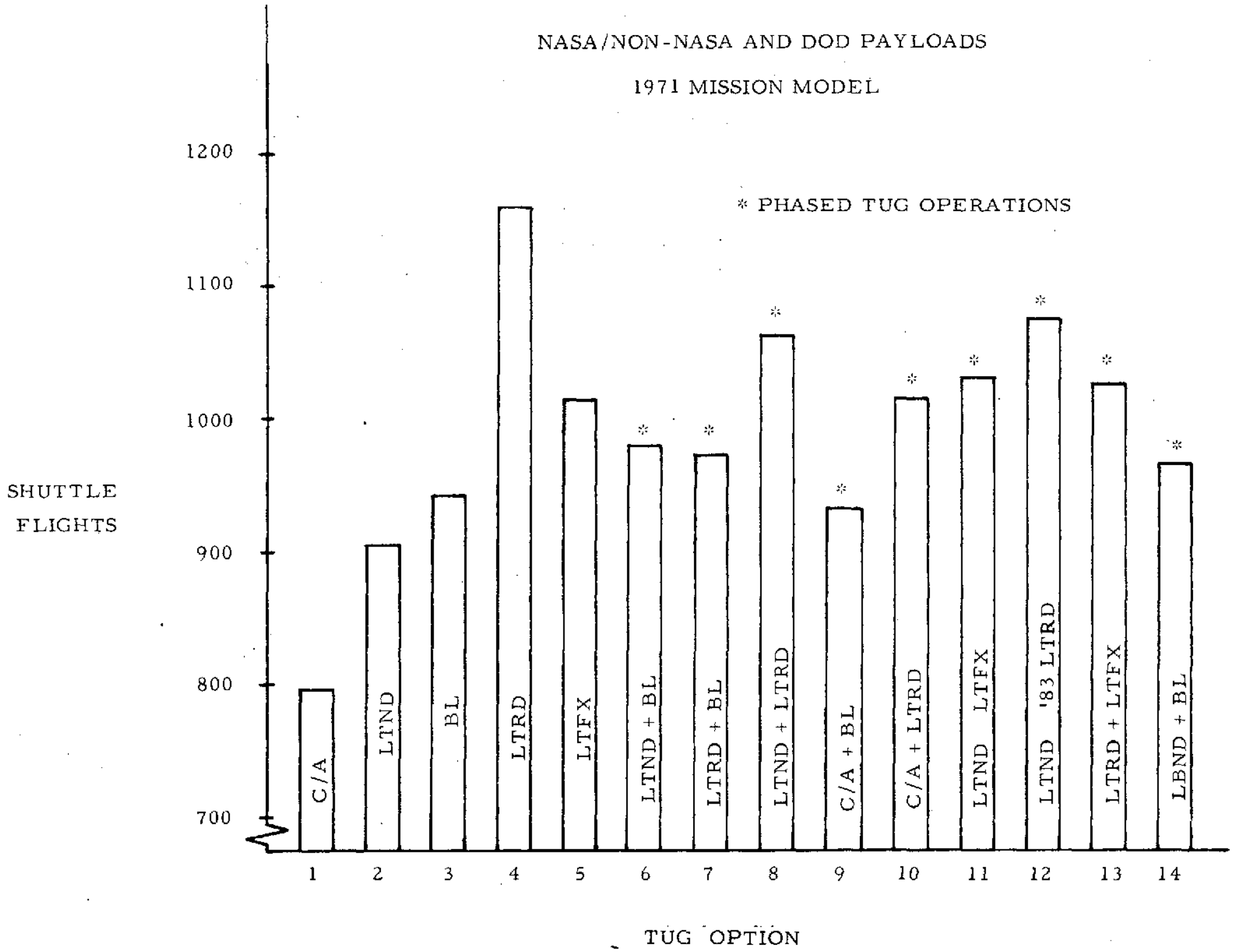

Figure 5-1. **Shuttle Flights as a Function of Tug Option Used**

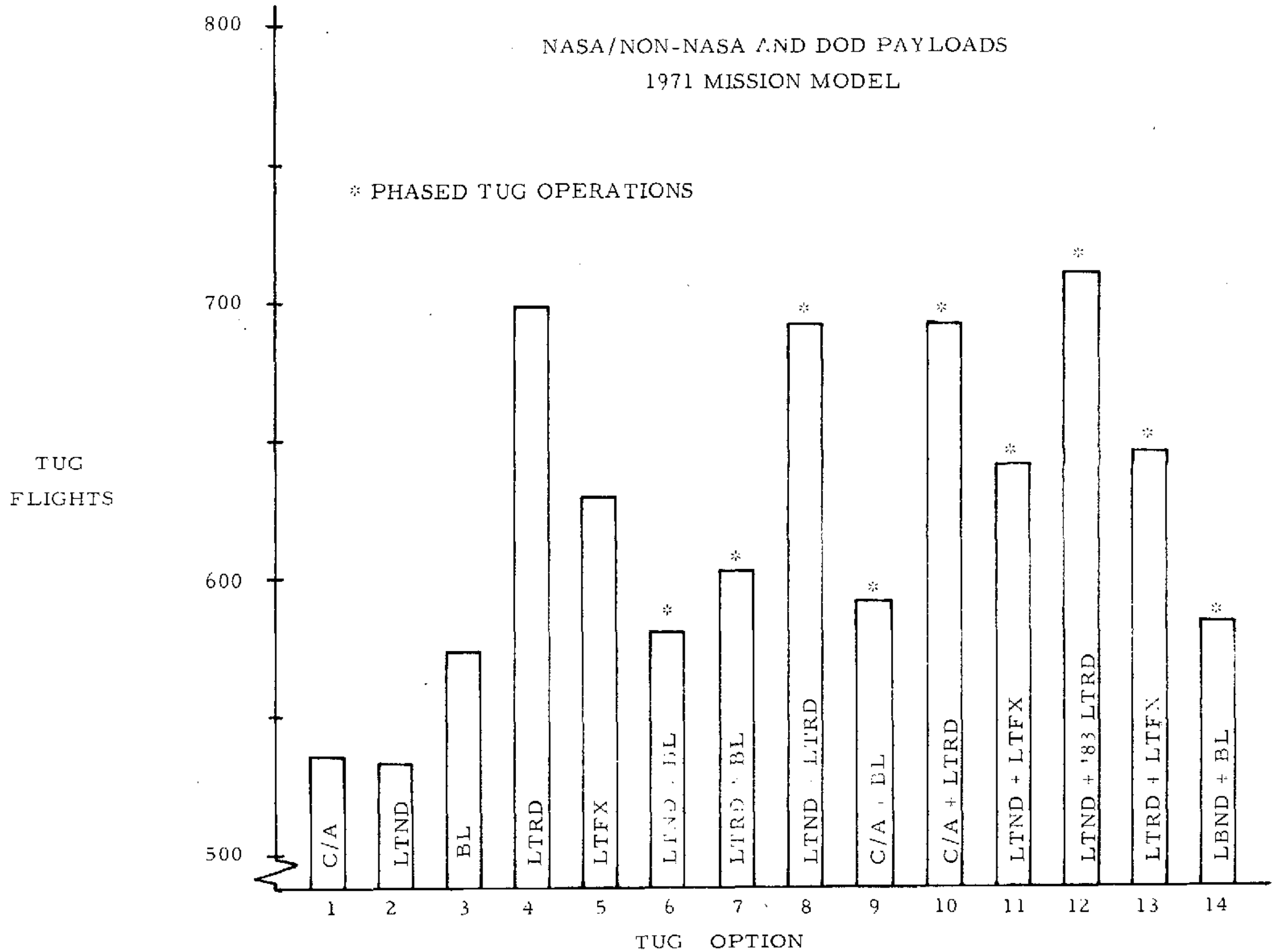

Figure 5-2. Tug Flights as a Function of Tug Option Used

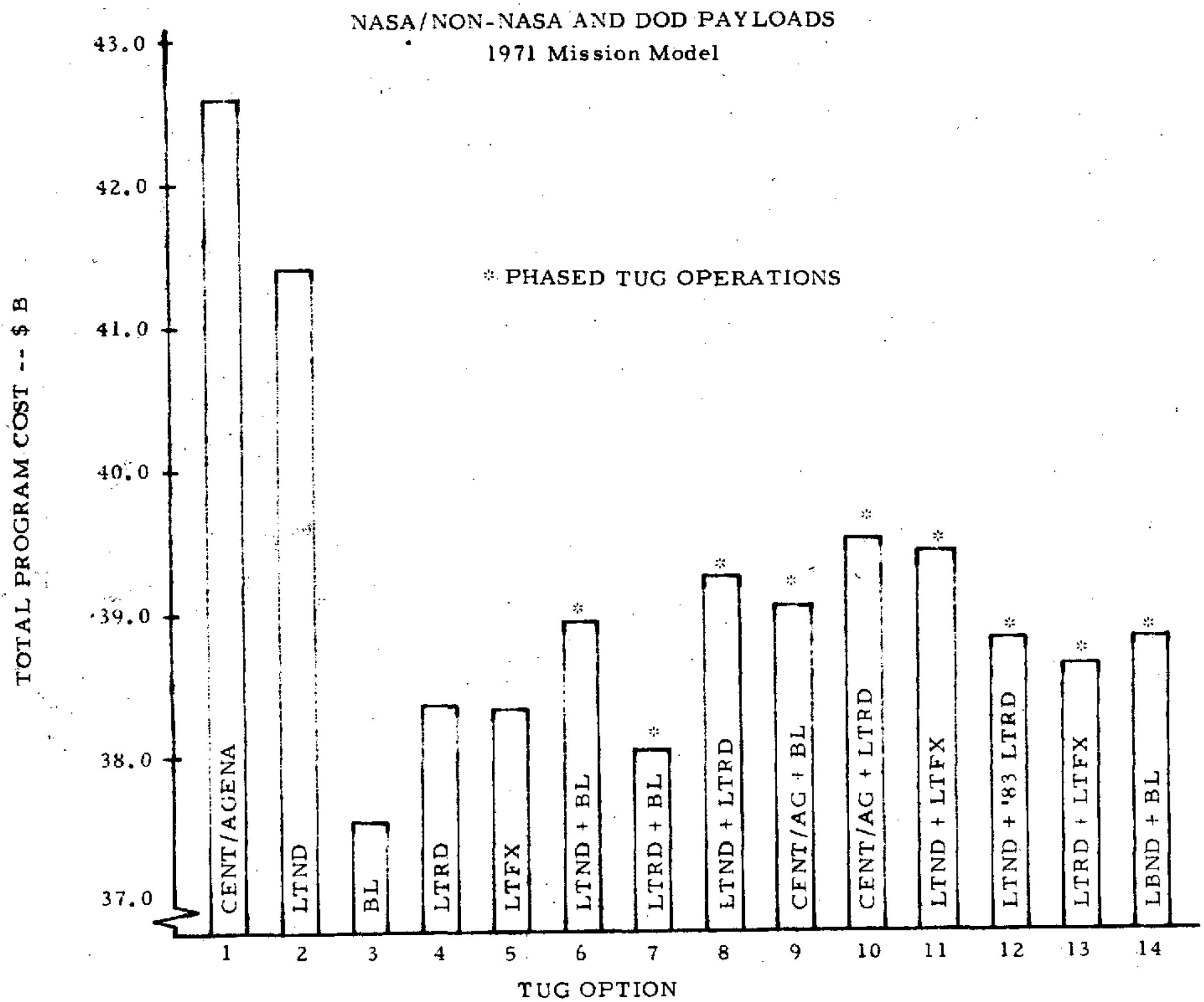

Figure 5-3. Total Program Cost as a Function of Tug Option Used

NASA/NON-NASA AND DOD PAYLOADS
1971 Mission Model

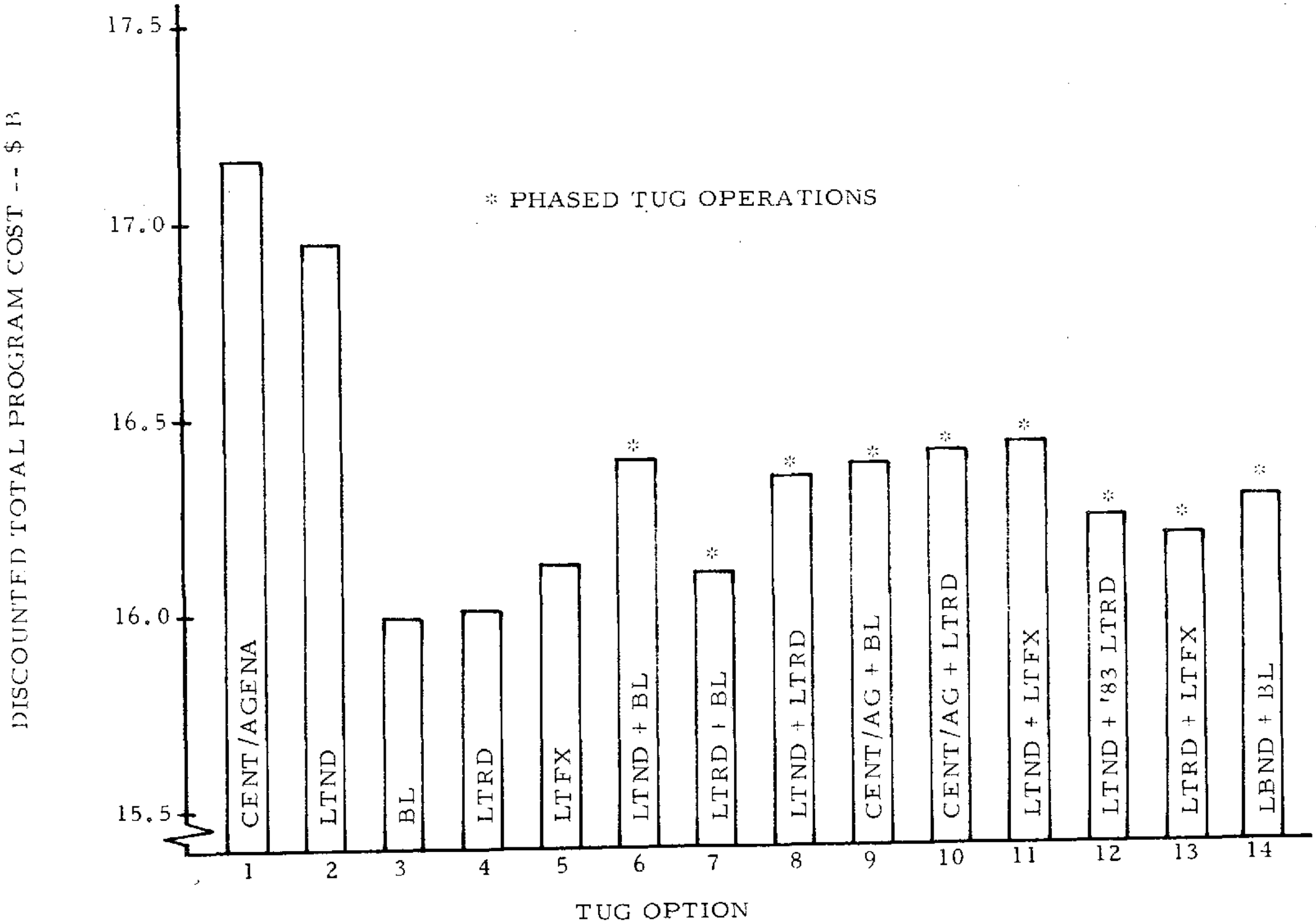

Figure 5-4. Discounted Total Program Cost as a Function of Tug Option Used

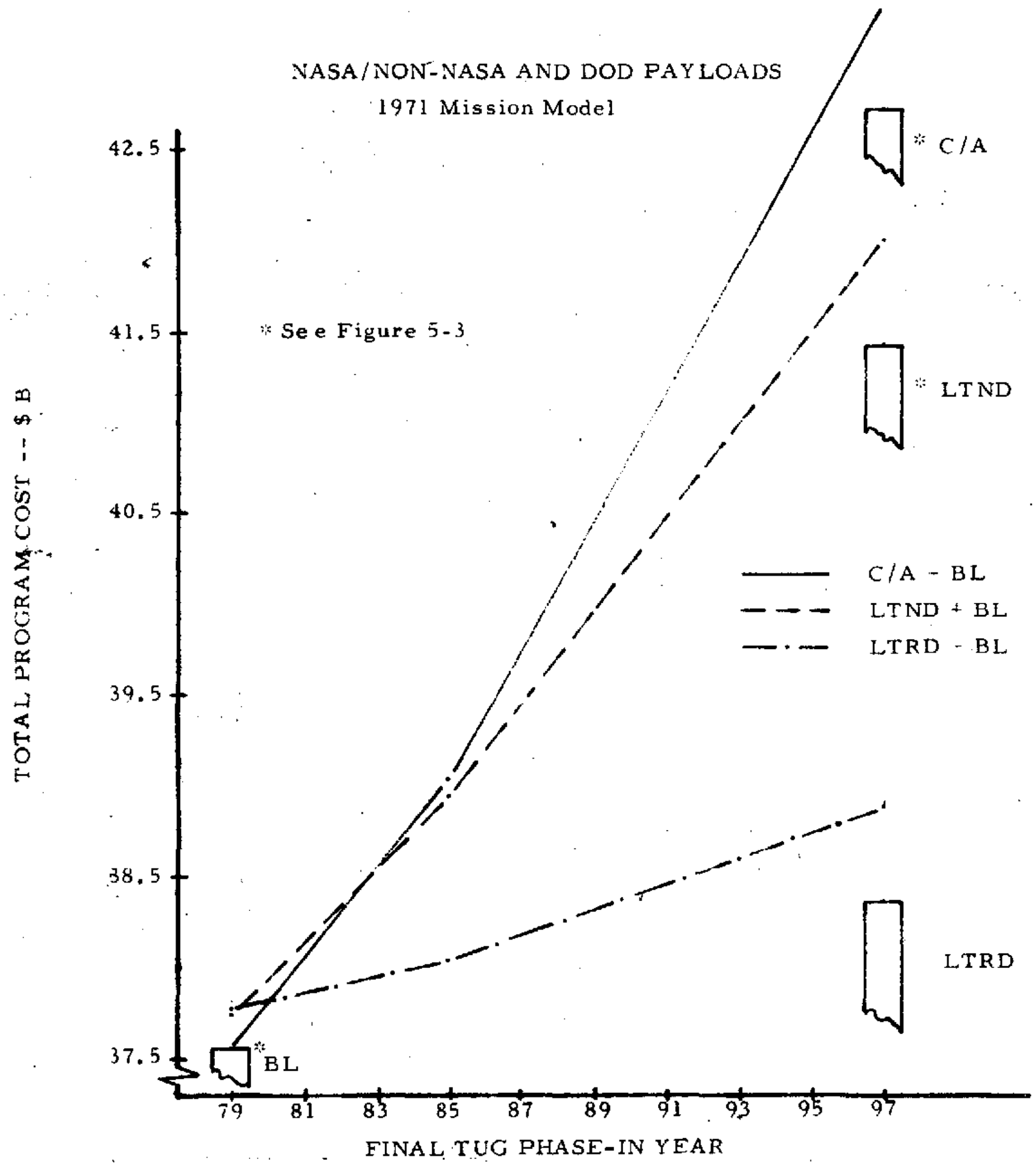

Figure 5-5. Effect of Tug Option and Time of Final Tug Phase-In on Total Program Cost - BL as Final Tug

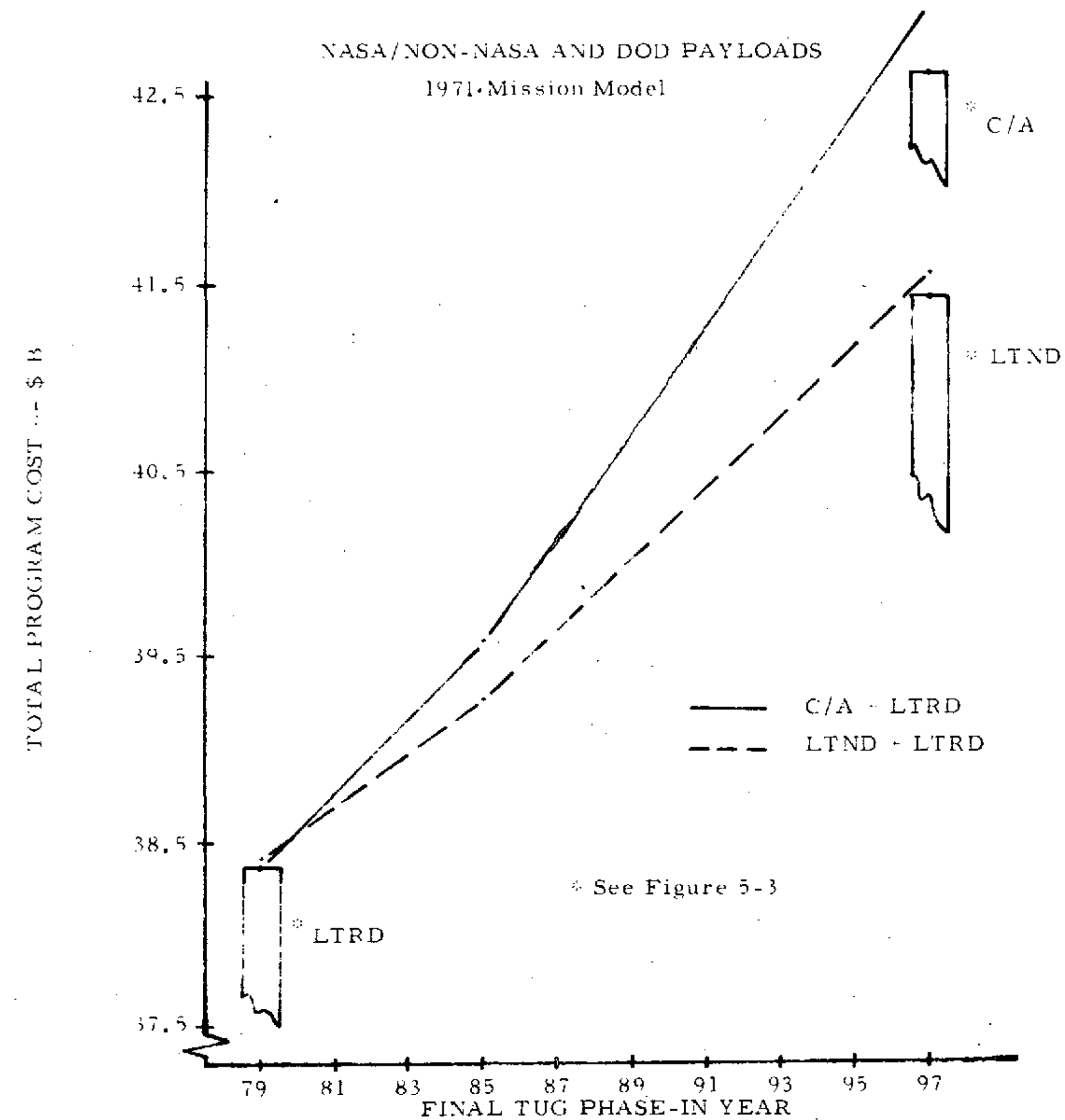

Figure 5-6. Effect of Tug Options and Time of Final Tug Phase-In on Total Program Cost - LTRD Tug as Final Tug

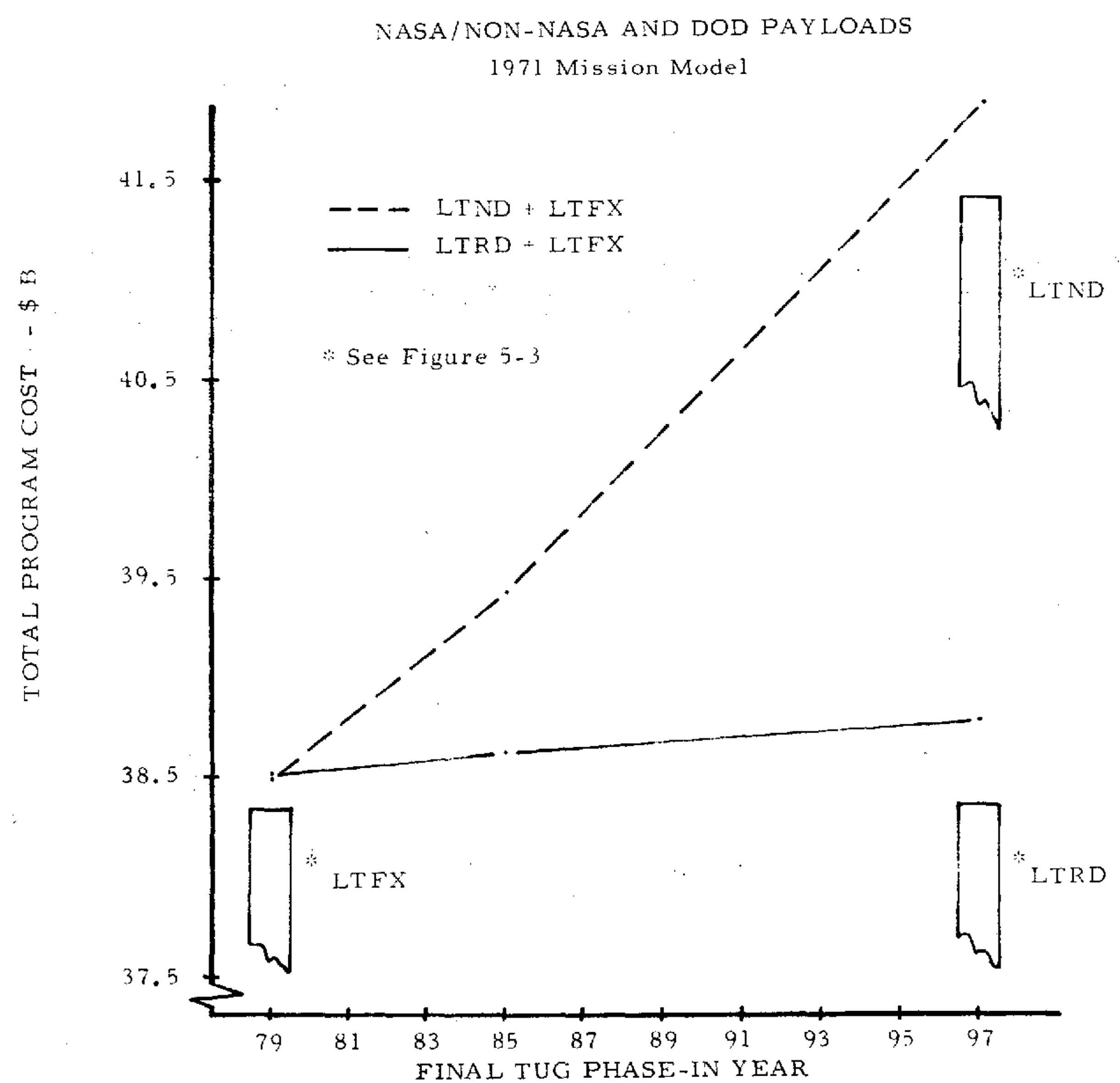

Figure 5-7. Effect of Tug Option and Time of Final Tug Phase-In on Total Program Cost - LTFX Tug as Final Tug

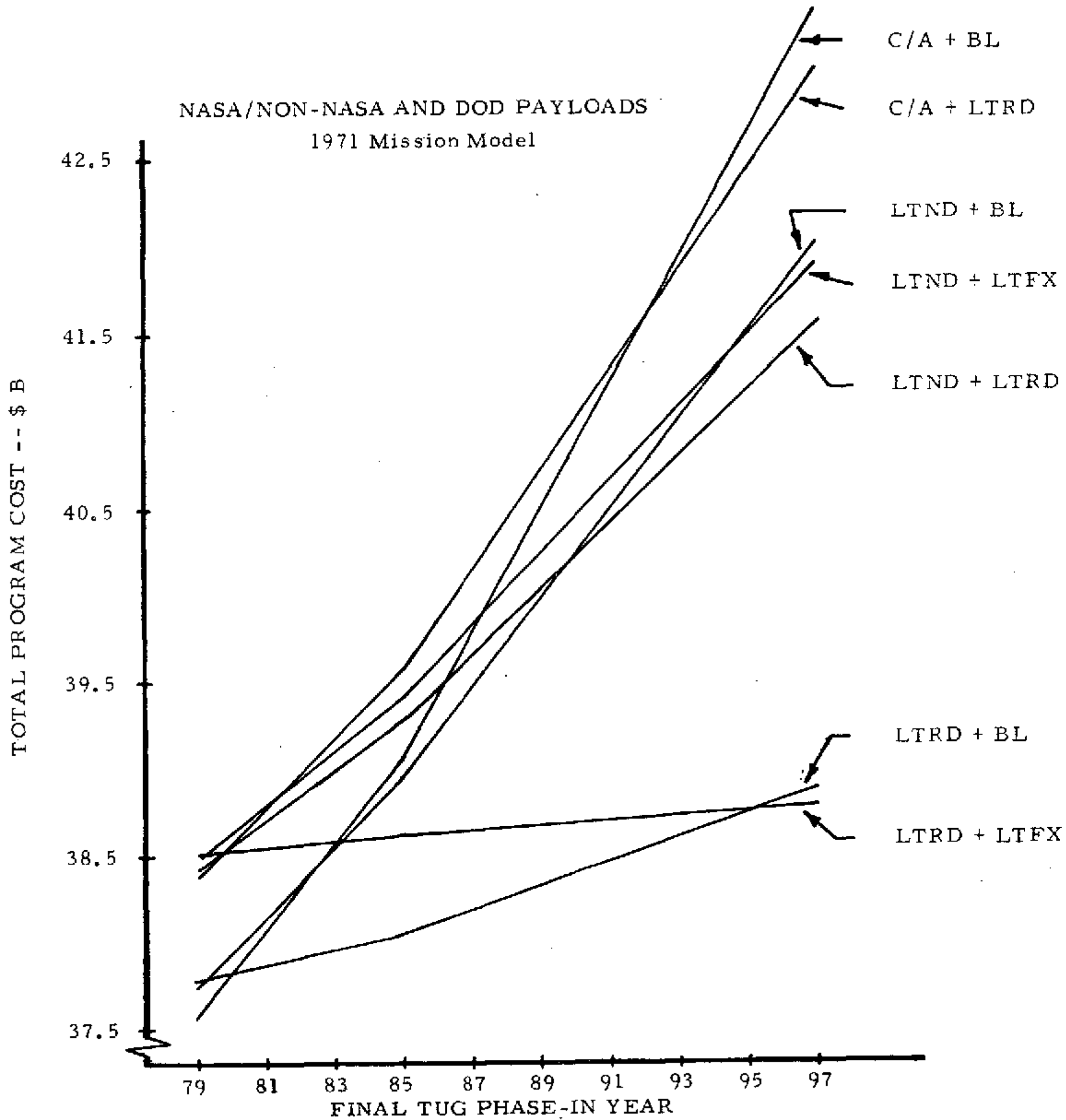

Figure 5-8. Effect of Tug Option and Time of Final Tug Phase-In on Total Program Cost - Summary

NASA/NON-NASA AND DOD PAYLOADS
1971 MISSION MODEL
OPTION 9 - CENTAUR/AGENA + BL

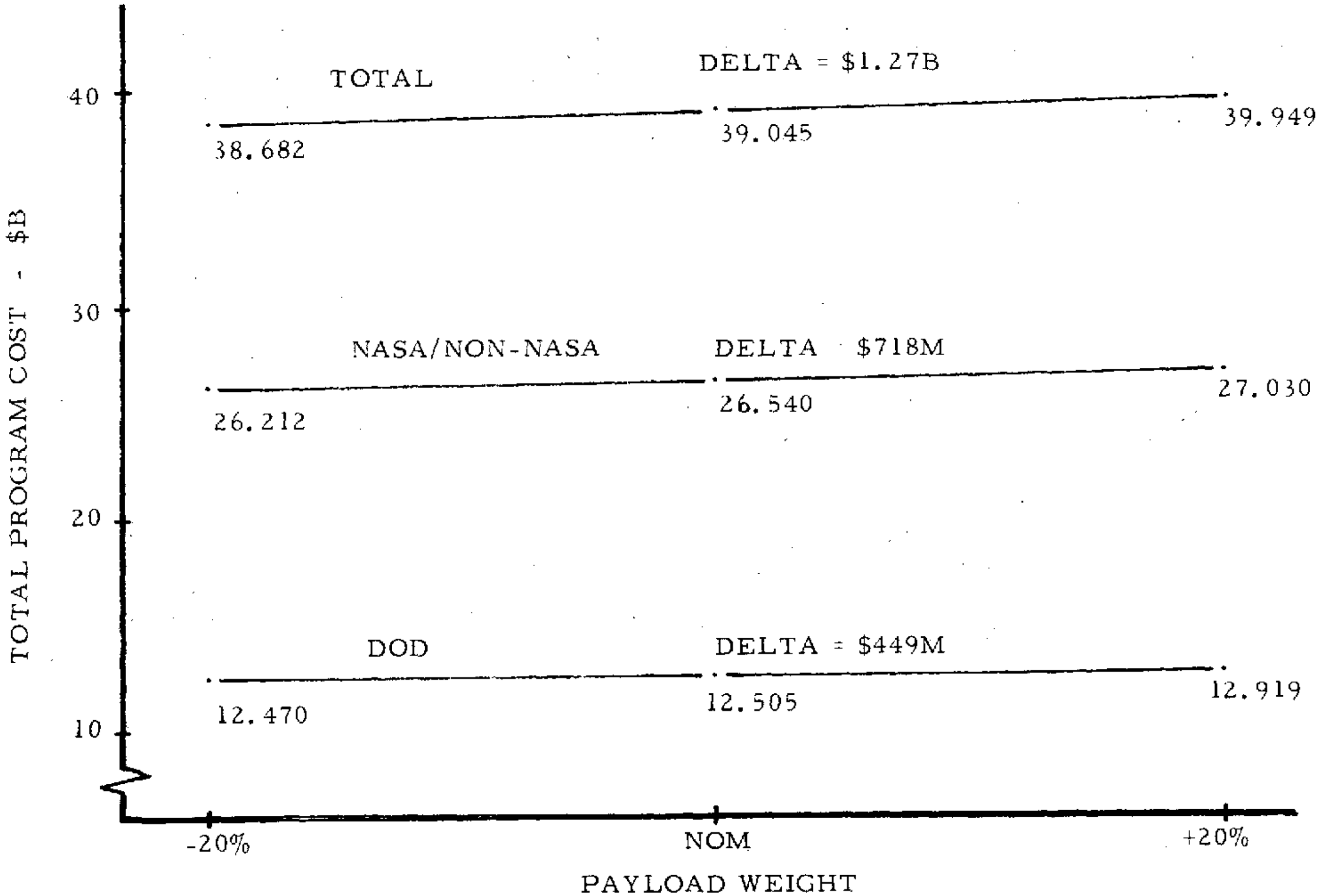

Figure 5-9. Sensitivity of Total Program Cost to Variations in Payload Weight

NASA/NON-NASA AND DOD PAYLOADS

1971 MISSION MODEL

OPTION 9 - CENTAUR/AGENA + BL

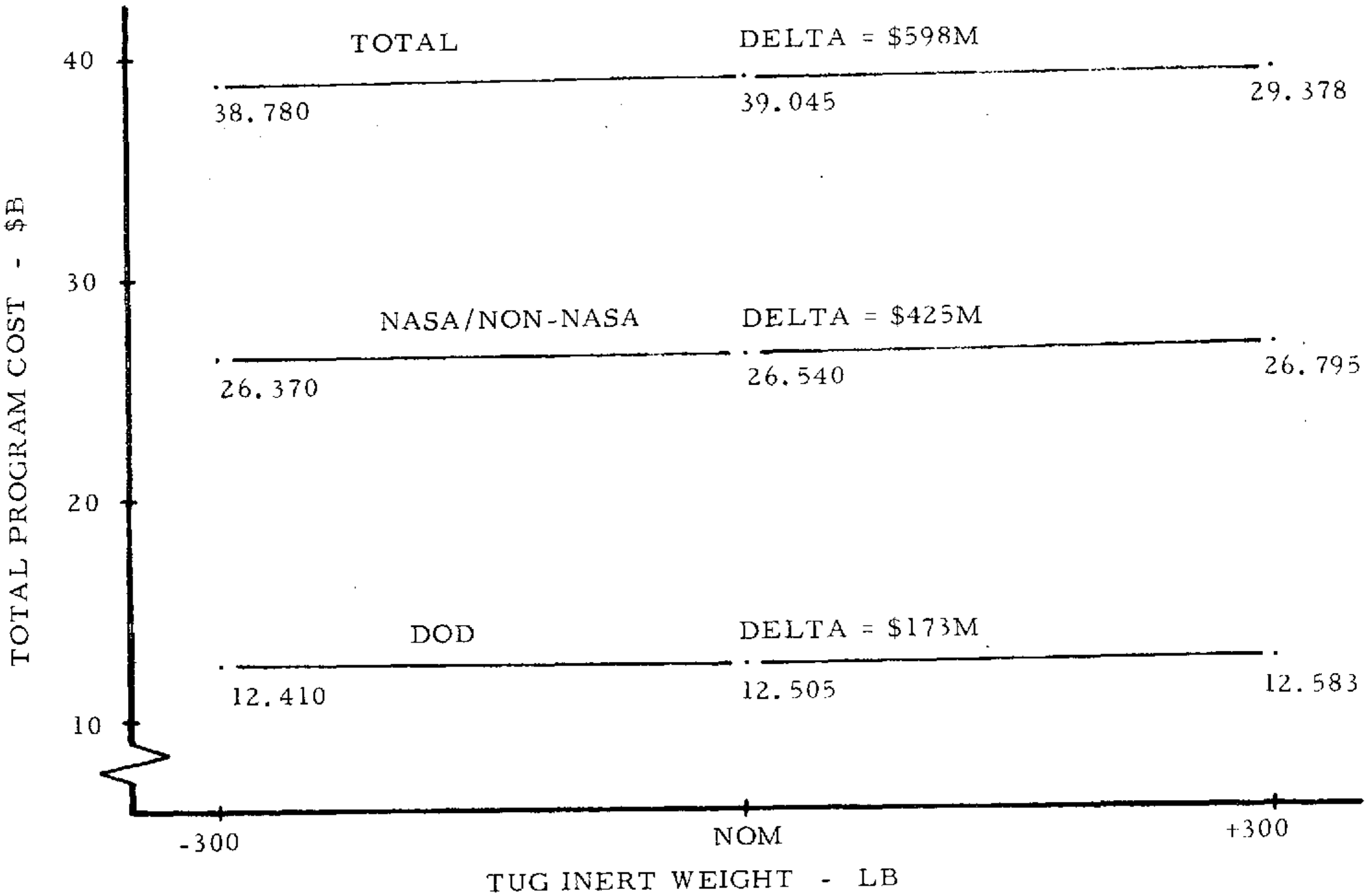

Figure 5-10. Sensitivity of Total Program Cost to Variations in Tug Inert Weight

NASA/NON-NASA AND DOD PAYLOADS
1971 MISSION MODEL

OPTION 9 - CENTAUR/AGENA + BL

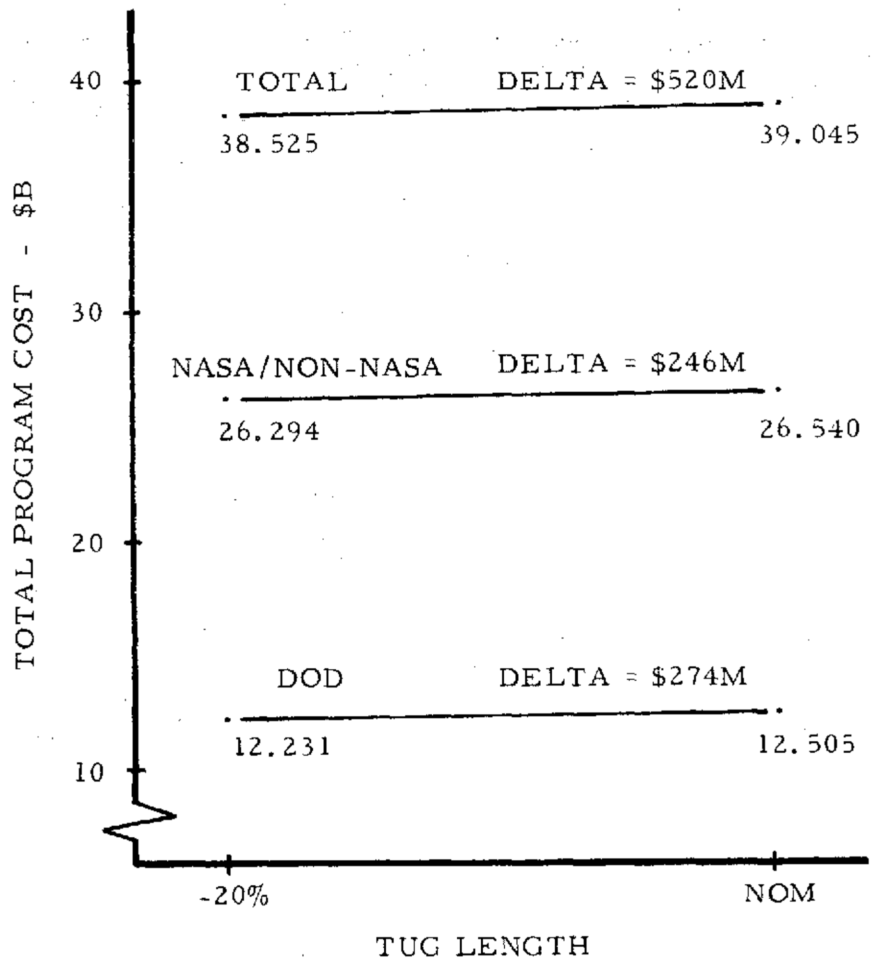

Figure 5-11. Sensitivity of Total Program Cost to Variations in Tug Length

NASA/NON-NASA AND DOD PAYLOADS

1971 MISSION MODEL

OPTION 9 - CENTAUR/AGENA + BL

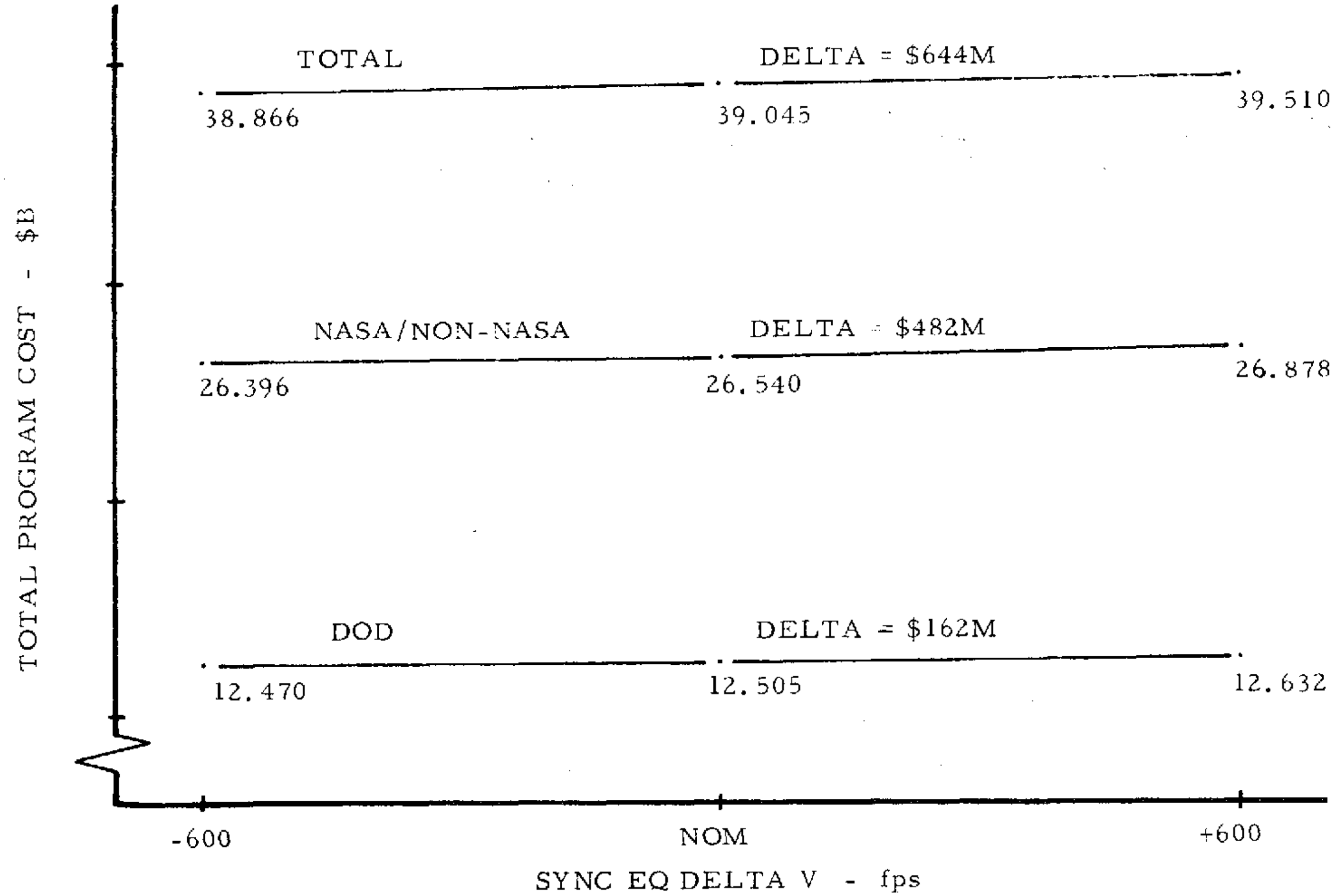

Figure 5-12. Sensitivity of Total Program Cost to Variations in Mission Delta V - Sync Eq Mission

Unlike the analyses of the 1971 Mission Model, no DoD segment was included in the analysis of the 1972 excursion. Neither were the costs associated with the 1972 excursion discounted as they were in the case of the 1971 Mission Model. The primary purpose of analyzing the 1972 excursion was to determine if any of the changes that were implemented in the excursion would invalidate the results obtained previously with the 1971 model. Table 5-4 presents the vehicle traffic and total costs associated with the NASA/ Non-NASA segment of the 1972 excursion to the 1971 model. Figures 5-13 and 5-14 present the comparative Shuttle and Tug traffic for the eleven cases included in the analyses. Figure 5-15 repeats, in bar chart form, the non-discounted total cost of the eleven cases included in the analyses. Figures 5-16 and 5-17 show the total program cost as a function of the various phased Tug concepts and as a function of the time that the final Tug is phased into the program. These curves were derived in the same way that the phased Tug curves for the 1971 Mission Model were derived. Figure 5-18 presents the data of Figures 5-16 and 5-17 on one chart for easy comparison.

5.1 1971 Mission Model

The data resulting from the analyses of the 1971 Mission Model indicate that the total cost of a given program is very much a function of the Tug or Tug combinations utilized in the program. As a class, the five cases (three single Tug and two phased-Tug) providing a retrieval capability from the start (1979) of the program, resulted in the lowest program costs. The next lowest cost case resulted from a phased Tug program in which the retrieval capability was provided in 1983. Following the 1983 case came a class of six cases (two single and four phased-Tug) where the Tug with payload retrieval capability was provided in 1985. Bringing up the rear with the highest costs was a class containing two cases (both single Tug) where a retrieval capability was never provided in the program.

Table 5-4. Operations and Cost Results, NASA/Non-NASA Payloads
1972 Excursion

CASE OR OPTION	TUG DESCRIPTION	FLIGHT RESULTS PH I EOS	PH II EOS	PH I TUG	PH II TUG	PH I TD/TUG	PH II TD/TUG	COST RESULTS - $B VEH DDT&E	P/L COSTS	OPS COSTS	TOTAL
1	BASELINE TUG	609		317		6		5.85	23.70	7.54	37.09
2	LTRD TUG	670		206		91		5.27	23.70	8.14	37.11
3	LTRD TUG/BL TUG	87	531	38	264	13	5	6.12	23.70	7.65	37.47
4	EXP VEH/LTRD TUG	50	580	39	169	17	76	5.27	24.20	8.03	37.50
5	EXP VEH/BL TUG	50	527	39	260	17	5	5.85	24.20	7.53	37.58
6	LTND TUG/BL TUG	54	527	16	260	3	5	6.04	24.20	7.48	37.73
7	LTND TUG/LTRD TUG	54	580	16	169	3	76	5.57	24.20	7.98	37.75
8	LTND TUG	608		348		7		5.44	28.30	6.97	40.71
9	EXP VEHS	585		329*		14***		5.15	28.30	7.56	41.01
10	ST TUG	676		154		101		5.36	23.70	8.00	37.06
11	BL TUG/SEP	574		294		134**		6.00	23.70	7.42	37.12

* CONSISTS OF 23 AGENA, 93 CENTAUR AND 213 DELTA FLIGHTS

** SEP FLIGHTS

*** CENTAUR/B2 FLIGHTS

BL — NASA/MSFC Baseline Tug

LTND — NASA/MSFC Low Technology Tug - Without Rendezvous and Docking Capability

LTRD — NASA/MSFC Low Technology Tug - With Rendezvous and Docking Capability

ST — NASA/JSC Storable Propellant Tug (Model 025) - With Rendezvous and Docking Capability

BL TUG-SEPS — NASA/MSFC Baseline Tug combined with NAR defined Solar Electric Propulsion System

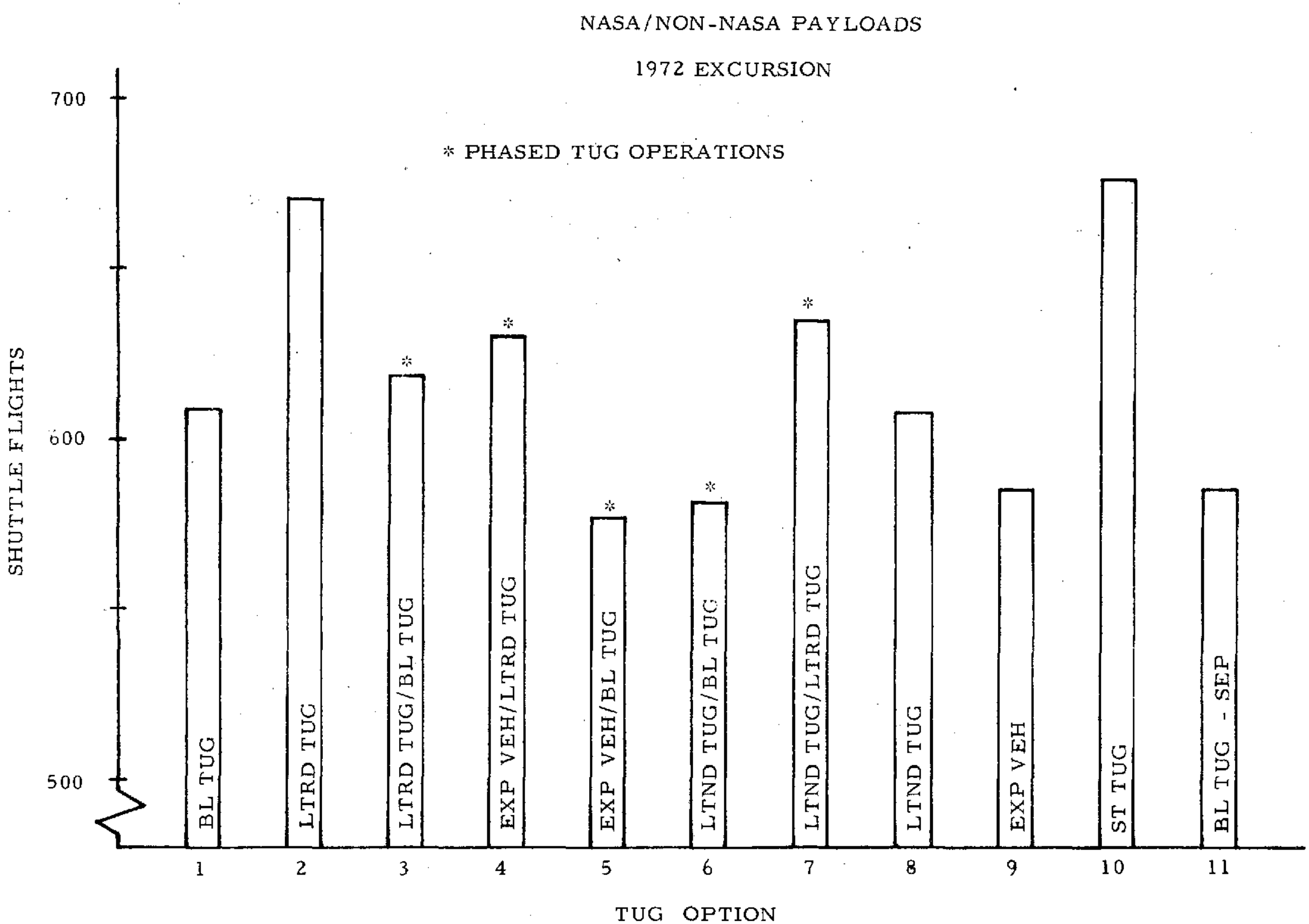

Figure 5-13. Shuttle Flights as a Function of Tug Option

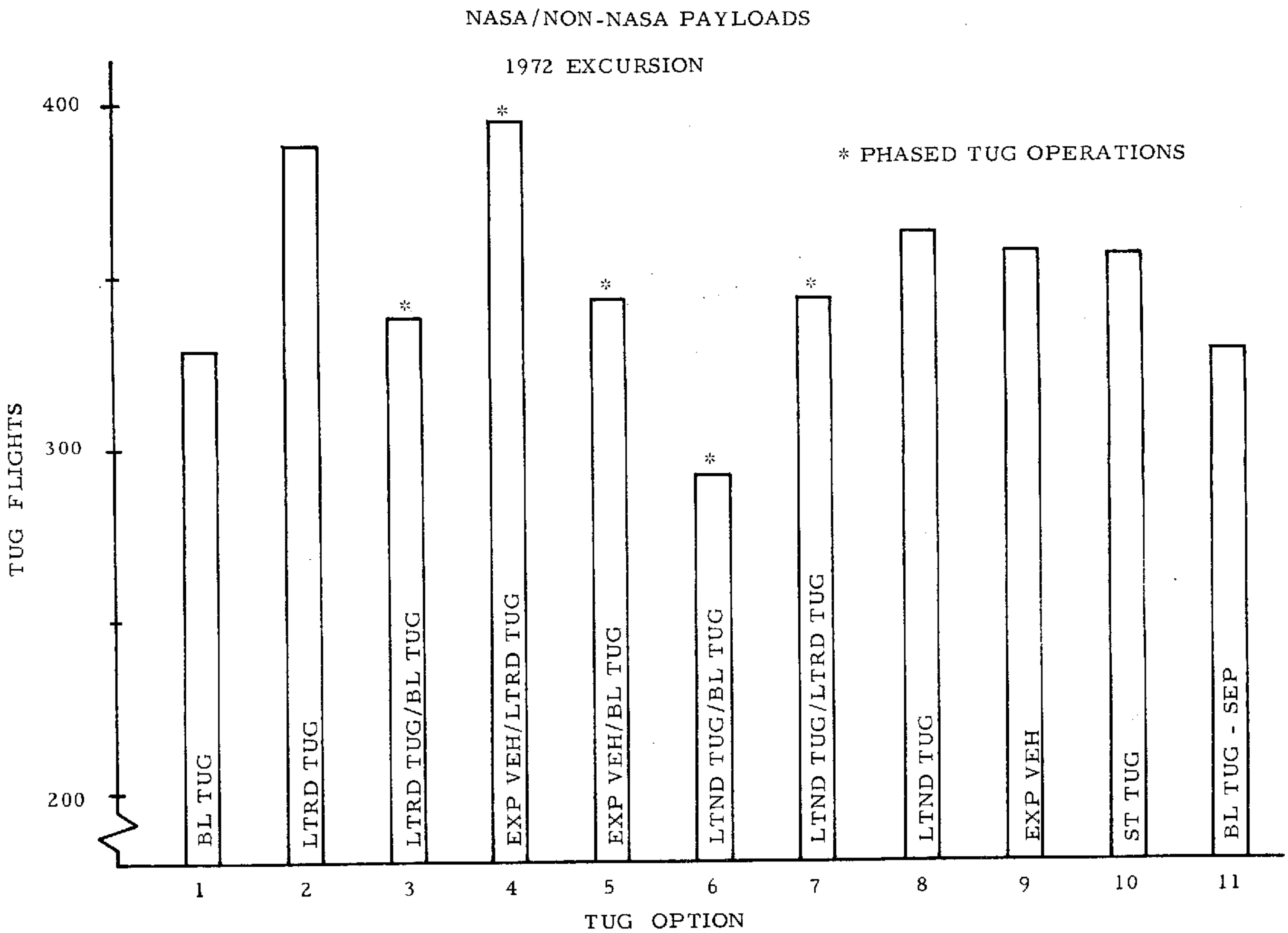

Figure 5-14. Tug Flights as a Function of Tug Option

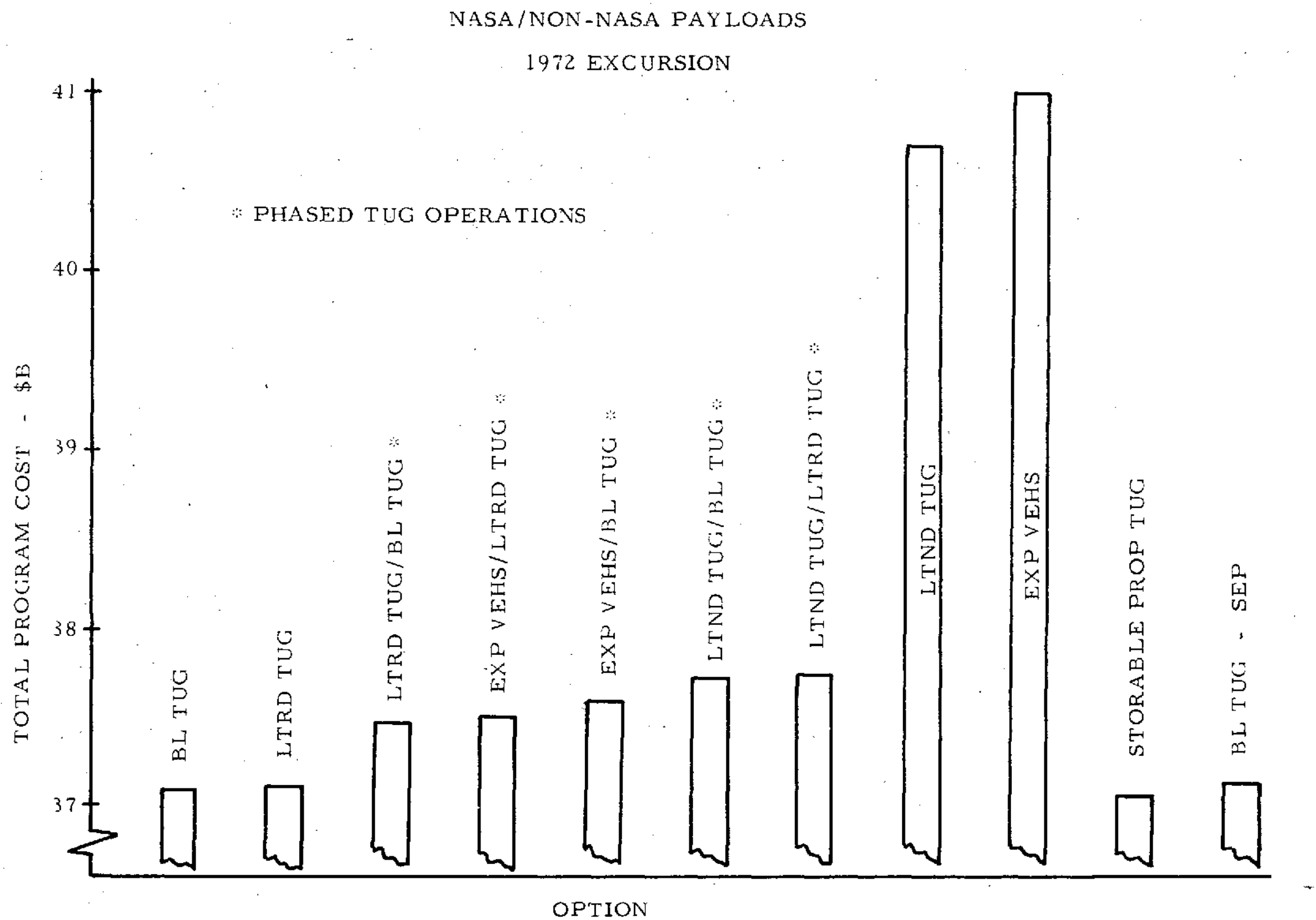

Figure 5-15. Total Program Cost as Function of Tug Option

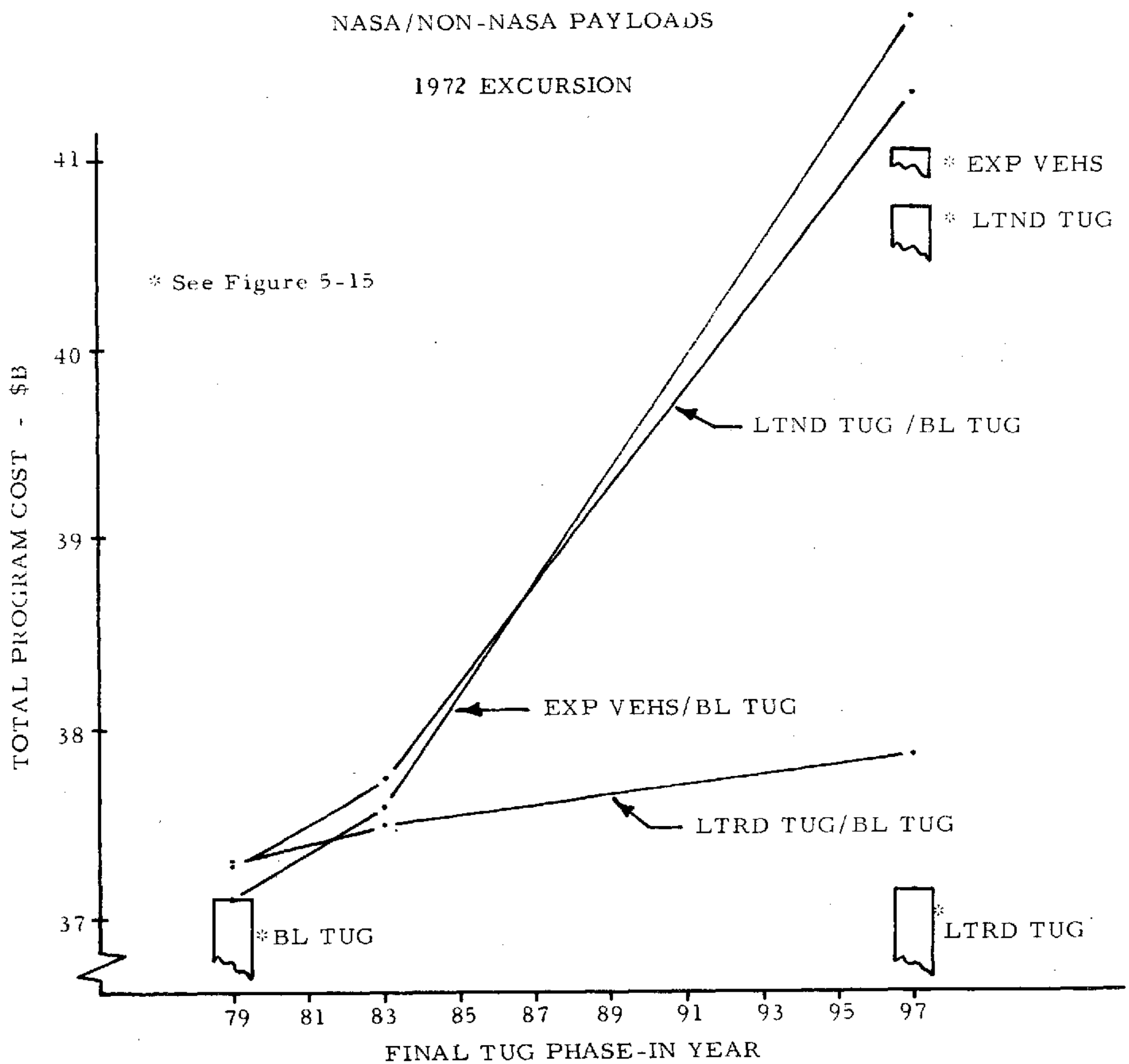

Figure 5-16. Effect on Tug Option and Time of Final Tug Phase-In on Total Program Cost - LTRD as Final Tug

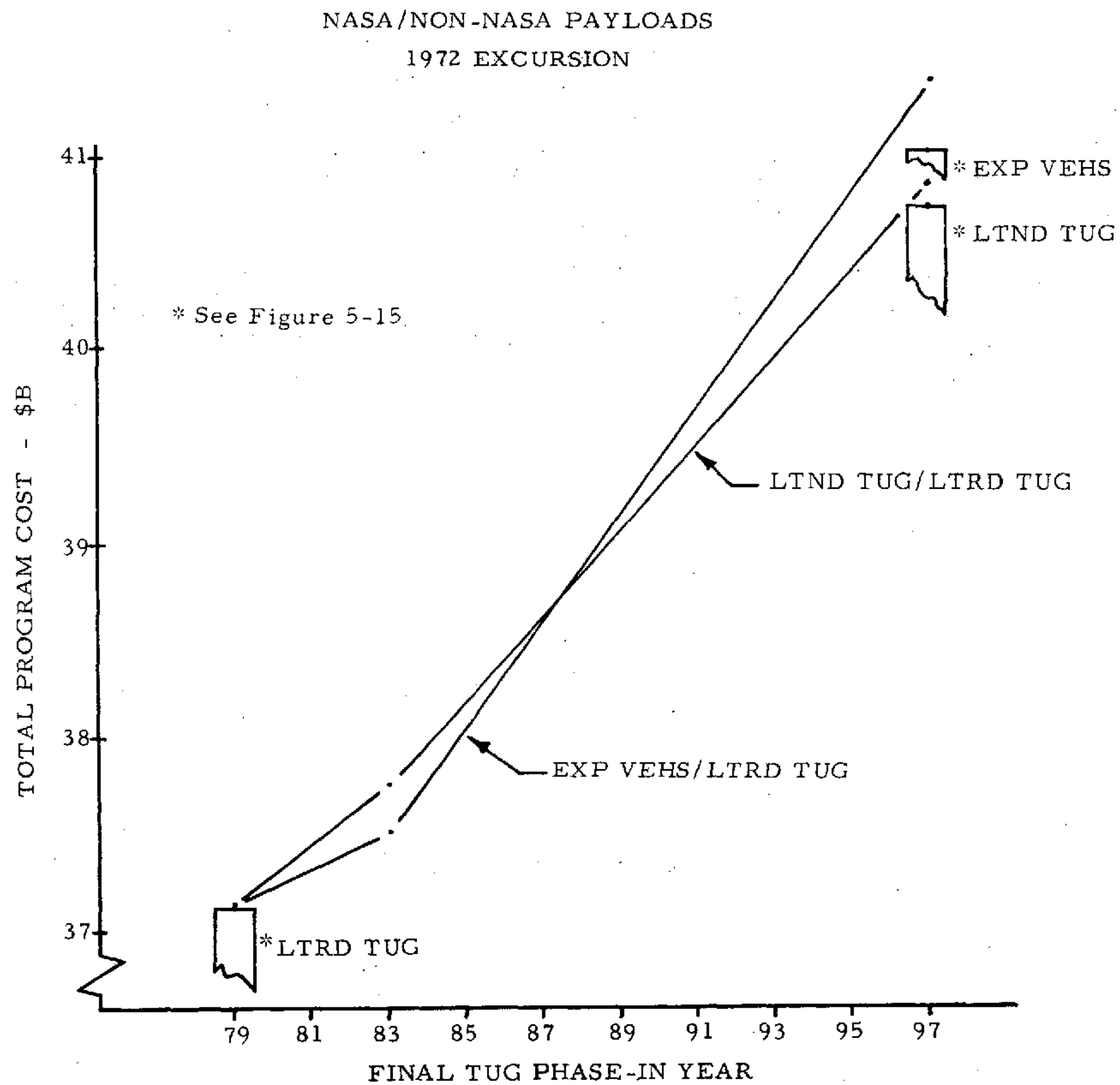

Figure 5-17. Effect on Tug Option and Time of Final Tug Phase-In on Total Program Cost - LTRD as Final Tug

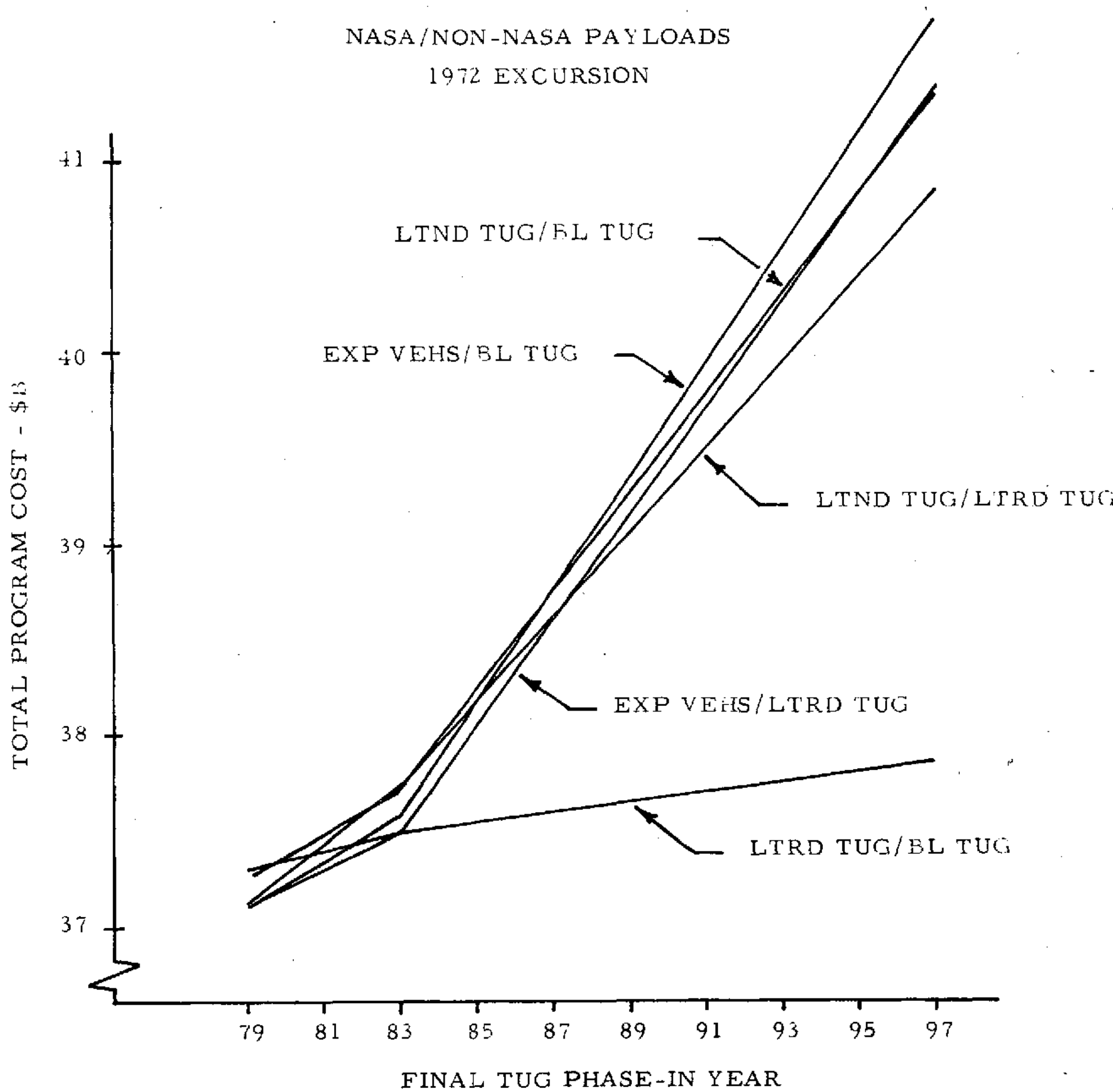

Figure 5-18. Effect of Tug Option and Time of Final Tug Phase-In on Total Program Cost - Summary

There are two general points to be made from the observations of the previous paragraph.

a) It is desirable to have in the program a Tug that has the capability to retrieve payloads from orbit for subsequent refurbishment and redeployment.

b) It is also desirable to provide the payload retrieval capability to the program as early as possible.

The key to the lower costs associated with the payload retrieval capability is the reusable payload. The capability to retrieve and refurbish payloads at a much reduced cost (compared to the purchase of new ones) is the big driver in the reduced costs. The reductions were so significant that they more than compensated for the cost of the additional vehicle flights required to recover the payloads. A reduced number of vehicle flights were obtained for the two cases where no retrieval capability was provided in the program; however, because they required the purchase of new satellites for each scheduled deployment, they were the most costly of the fourteen cases investigated.

Within the lowest cost class of cases investigated, (three single Tug cases and two phased-Tug cases) the single application of the MSFC baseline Tug was the lowest in cost. The ranking of all fourteen cases beginning with the least cost baseline Tug case is:

1.	Case 3 - BL		1979 Payload Retrieval Capability
2.	Case 7 - LTRD + '85 BL		
3.	Case 5 - LTFX		
4.	Case 4 - LTRD		
5.	Case 13 - LTRD + '85 LTFX		
6.	Case 12 - LTND + '83 LTRD		1983 Payload Retrieval Capability
7.	Case 14 - LBND +'85 BL		1985 Payload Retrieval Capability
8.	Case 6 - LTND +'85 BL		
9.	Case 9 - Centaur/Agena +'85 BL		
10.	Case 8 - LTND + '85 LTRD		
11.	Case 11 - LTND + '85 LTFX		
12.	Case 10 - Centaur/Agena + '85 LTRD		
13.	Case 2 - LTND		No Payload Retrieval Capability
14.	Case 1 - Centaur/Agena		

From the list above several additional observations can be made. One is the apparent correlation of program cost to Tug performance. In general, the higher the performance of the machine used in the program, the lower the program cost. The fact is not quite as obvious in those cases employing phased-Tug arrangements as it is where a single Tug is employed throughout the program. However, even with the phased Tug arrangements the statement is generally true.

The other observation is the fact that if a payload retrieval capability is not included on the Tug, it is still desirable to employ a reusable Tug instead of using current design, expendable upper stages; e. g., Centaur or Agena. The cost reductions associated with its reusability far exceed the relatively moderate costs associated with its development.

Discounting the program costs (at a 10 percent rate), rearranges the ranking of the fourteen cases slightly; however, its primary effect was to attenuate the differences between the individual cases. Whereas a maximum difference of approximately 5 billion dollars existed between the extreme cases prior to discounting, the difference was shrunk to slightly over 1 billion dollars after discounting. Those programs whose costs peak in the later years of the program were the primary benefactors in the discounting procedures. In the rankings the eighth and tenth ranked cases switched places as did the eleventh and twelfth. These switches were within a single class; i. e., the class providing payload retrieval capability in 1985. In addition to the above changes, the second ranked case went to third, the third to fourth, and the fourth to second. Here again, the changes were within a single class; i. e., the class providing payload retrieval capability from the start (1979) of the program.

Due to the early year funding constraints contemplated on the Tug development program, phased Tug operations employing a cheaper interim Tug in the early years (with the full capability Tug being provided at a later date) has gained support as an alternate operations approach. As stated earlier, and particularly in the realm of phased Tug operations, it is clear that an early capability to rendezvous and dock Tugs with payloads is desirable in order to take advantage of the benefits derived from employing reusable payloads. Even a low technology Tug, with its relatively poor performance characteristics, is very economical if the Tug has rendezvous and docking capability.

From an inspection of the curves relating to the 1971 Mission Model's phased Tug operations, the following observations can be made.

1. If the baseline Tug (BL) is to be phased in later than 1980, it would be cheaper to build and use a low technology Tug with rendezvous and docking capability for a Phase I vehicle than to utilize Centaurs and Agenas in Phase I.

2. If the baseline Tug (BL) is to be phased in after 1983 and the Phase I vehicle is not to have a rendezvous and docking capability, it would be more economical to build and use a low technology Tug (LTND) in Phase I rather than the Centaurs and Agenas.

3. If Centaurs and Agenas were to be used as Phase I vehicles past 1992, it would be cheaper to build and use a low technology Tug with rendezvous and docking capability (LTRD) for a Phase II vehicle than to build and use a baseline Tug (BL).

4. If on the other hand, low technology Tugs without rendezvous and docking capability were to be used as the Phase I vehicle past 1990, it would be cheaper to employ the low technology Tug with rendezvous and docking capability as the Phase II vehicles rather than the baseline Tug (BL).

5. The full capability Tug utilizing the extended cycle RL-10 engine (LTFX) appears to have very little, if any, cost advantages over the baseline Tug (BL), regardless of phase-in times involved. One or the other of these vehicles should be dropped as a candidate for the full capability Tug.

6. Should a phase-in time of 1985 be established for a Phase II Tug (which is consistent with current thinking), the following combinations are listed in order of preference with respect to total program cost.

Phase I Tug	Phase II Tug
LTRD	BL
LTRD	LTFX
LTND	BL
Centaur/Agena	BL
LTND	LTRD
LTND	LTFX
Centuar/Agena	LTRD

Results of the sensitivity analysis are presented in Figures 5-9 through 5-12. The greatest sensitivity exhibited, with the range of variations used, was approximately 3 percent in total cost. This was obtained by varying the payload weights ±20 percent. Variations in Tug weight and length and variations in mission Delta V to synchronous equatorial orbit resulted in cost variations between 1 percent and 2 percent. Tug weight was varied ±300 lb; Tug length by -20 percent; and mission Delta V by +600 fps. The 3 percent variation in cost obtained by varying the payload weight equates to approximately $1.25 billion.

5.2 1972 Excursion

The results of the analyses of the 1972 excursion to the 1971 model closely corroborate the results obtained from the 1971 mission model in the areas of commonality between the two analyses; i.e., the utilization of cryogenic Tugs and current expendable upper stages for high energy missions. The ranking of the cases common to the 1971 model analysis starting with the least cost case is as follows:

1. Case 1 - BL
2. Case 2 - LTRD
3. Case 3 - LTRD + '83 BL

} 1979 Payload Retrieval Capability

4. Case 6 - Centaur/Agena + '83 LTRD
5. Case 7 - Centaur/Agena + '83 BL
6. Case 8 - LTND + '83 BL
7. Case 9 - LTND + '83 LTRD

} 1983 Payload Retrieval Capability

8. Case 10 - LTND
9. Case 11 - Centaur/Agena

} No Payload Retrieval Capability

As can be seen from the listing, the same general trends evident in the analysis of the 1971 model are evident in the analysis of the 1973 excursion. While the payload compositions and total costs of the two models are significantly different, the relative results are basically the same. Again, the class of cases providing a payload retrieval capability from the start of the program are (as a class) the least costly programs. Likewise, within a given class, the cases employing the higher performance machines are generally less costly than those using the lower performance vehicles. Utilizing a reusable Tug with no payload retrieval capability is again shown to be more cost effective than employing expendable upper stage vehicles.

The NASA-JSC designed Model 025, storable propellant Tug proved in this study to be the least costly vehicle to operate. It proved to be slightly better, costwise, than the NASA MSFC baseline Tug, although, for all practical purposes, they were a toss-up. The cost differential was only 30 million dollars out of a 37 billion dollar program. As a matter of fact, the maximum difference between any of the programs incorporating reusable payloads with payload retrieval capability was less than 2 percent (700 million dollars out of 37 billion dollars).

The program utilizing the baseline Tug and the solar electric propulsion system (SEPS) for the synchronous equatorial missions ranked fourth overall in the analysis. It should be emphasized however that only one of several possible Tug-SEPS operational schemes was investigated in this analysis. It is possible that an analysis combining other Tug configurations, SEPS operational modes or SEPS mission durations could produce a more economical result than the combination chosen for this investigation. Additional analyses need to be conducted in this area to fully explore the potential benefits of the SEPS.

The total cost difference between the first and fourth ranked cases was only 60 million dollars. A cost difference of 350 million dollars existed between the fourth and fifth ranked cases, providing an apparent line of demarcation between the top four cases and the other seven.

A final, general observation applicable to both sets of analyses (1970 mission model and the 1972 excursion) is the apparent correlation between the number of Shuttle flights and the total cost of a program. Within a given class (i.e., the same payload model, "70 best mix," expendable, etc., and the same vehicle type, reusable, expendable, etc.), the number of Shuttle flights is a good indicator of the cost of a program. Within these bounds, programs can be pretty well compared on the basis of Shuttle flights alone. Once the class boundaries have been crossed, however, the correlation breaks down rather badly.

6. REFERENCES

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