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ORBIT TRANSFER SYSTEMS WITH EMPHASIS ON SHUTTLE APPLICATIONS — 1986-1991

By Program Development

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16. ABSTRACT

The problems of orbit transportation have been addressed significantly during the past 5 years. An Interim Upper Stage (IUS) and a Spinning Solid Upper Stage (SSUS) are being developed for operation in the early 1980's. Current long-range planning efforts indicate a need for extended space operations capabilities which are greater than that provided by IUS and SSUS.

This is a systems study for a transportation system which will follow the IUS and SSUS. Included are concepts, concept comparisons, trends, parametric data, etc. associated with the future system. Relevant technical and programmatic information is developed. This information is intended to focus future activity to identify attractive options and to summarize the major issues associated with the future development of the system. A comprehensive summary of the study is included in the body of the report in section XVI.

It is primarily the developing need for Earth synchronous orbit capabilities which gives cause for further consideration of orbital transportation systems at this time. Transportation needs for manned and unmanned synchronous orbit systems are foreseen. Total recoverability and reusability with minimum refurbishment are goals for future orbit transport systems.

To establish a common basis for identifying current transportation concepts, an Orbit Transfer Vehicle (OTV) is defined as a propulsive (velocity producing) rocket or stage. When used with a crew transfer module, a manned sortie module or other payloads, the combination becomes an Orbit Transfer System (OTS). Standardization of OTV's and OTS's is required.

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TECHNICAL MEMORANDUM X-73394

ORBIT TRANSFER SYSTEMS WITH EMPHASIS ON SHUTTLE APPLICATIONS – 1986-1991

I. BACKGROUND

The problems of orbit transportation have been addressed significantly during the past 5 years. Early efforts defined a Space Tug which used high energy cryogenic propellants, and considerable technology development effort has occurred on this type transportation element. Primarily due to programmatic considerations, the cryogenic Space Tug concept was replaced by the Interim Upper Stage (IUS) and Spinning Solid Upper Stage (SSUS) which use solid motor propulsion. These systems are being developed and will be available in the early 1980's for use as an upper stage with the Space Shuttle.

In the meantime many new space initiatives have been conceived by the National Aeronautics and Space Administration (NASA). Considerable long-range planning, which is now underway, will lead to the need for extended space operations capabilities which are greater than that provided by IUS and SSUS. While firm plans for development of the space resources have not been completed at this time, the general trend for development after low Earth orbit seems to be toward development of the synchronous Earth orbit resource first, then toward returning to and development of the lunar resources and further exploration and development of the resources of the other planets. The lunar and planetary developments receive very little consideration, and the nature and timing of their development will be largely dependent on what eventually takes place in the development of the Earth orbit capabilities. It is primarily the developing need for Earth synchronous orbit capabilities which gives cause for further consideration of orbital transportation systems at this time.

The Earth synchronous orbit transportation capability with current United States rocket technology is not an easy one to achieve. Total recoverability and reuseability with minimum refurbishment are goals for future orbit transport systems. Previous study efforts and Space Shuttle developments have led to these goals primarily on an economic basis. Accommodation of the goals requires return of the rocket elements, certain payload carrier elements, and sometimes the rocket payload.

The rocket to be used for Earth synchronous orbit applications must provide a characteristic velocity increment exceeding 28 000 ft/sec. This is several thousands of feet per second greater than past and present expendable or recoverable single stage systems. It is only a few hundreds of feet per second less than would be required for a single stage to low Earth orbit launch vehicle. Under the best conditions, this mission requirement will cause the transportation cost for payloads to be many times more than the low Earth orbit transportation cost for payloads.

II. INTRODUCTION

Contemporary NASA planning activities have recognized and defined many different concepts or types of orbit transfer systems (OTS) and orbit transfer vehicles (OTV). At various times and in various study efforts, many different names or terms have been used to describe or identify the concepts. To establish some common basis for identifying the current concepts, the following terminology for the various elements of the transport system has been established.

- OTV is a propulsive (velocity producing) rocket or stage

- When an OTV is used with some other hardware element such as a manned module, cargo module, a payload, etc., the combination forms an OTS which provides transportation between two orbital locations. Standardization of OTV's for operation with either type payload is required.

- In future space transportation systems there may be several OTV's.

- More than one OTV may exist at any particular time.

- A particular OTV may change as time passes.

Using this terminology, the following types of OTV's which may be applicable to the Space Shuttle, Heavy Lift Launch Vehicles (HLLV), etc. are being considered:

1. High performance, liquid propellant velocity stages for general usage.

2. Solid propellant velocity stages, which may be desirable for use with liquid propellant velocity stages, to form two-stage propulsive vehicles for large payload transportation capabilities.

3. Velocity stages to be used for service vehicles, etc.

4. Advanced propulsion velocity stages.

To date primary emphasis in the in-house activity has been given to item 1. Item 2 was introduced early in the in-house study effort after problems associated with using multiple stages represented by item 1 were recognized. The need or desire for service vehicles has been recognized for several years. Although major use of advanced propulsion velocity stages is not expected before the last decade of this century, the long term planning and technology development which must precede the practical implementation in a learned manner necessitate their consideration at this time.

Potential near term applications for the OTS being considered, beginning with orbit flight tests in the 1986 time frame, are:

1. Eight to ten flights per year to replace or supplement the IUS.

2. Several tens of flights per year (depending on concept to be selected, lower stage capabilities to be selected, etc.) to satisfy orbit transportation to be required by future programs which are now being planned.

Primarily the purpose of this study is to:

1. Generate data to fill gaps in available OTV technical and planning information.

2. Determine and illuminate major OTV issues

3. Compare proposed OTV concepts

4. Determine OTV technology requirements.

The study emphasis is for OTV and OTS applications with the Space Shuttle. This report consists of a narrative with supporting material (Appendices A, B, and C). The narrative portion was prepared primarily to organize and illuminate the important issues and findings associated with the study activity, and Appendices A and B include supporting data or study data not covered by the narrative.

Where possible, previous study results have been used. It should be noted that much of the data included have been normalized to a common base. It is not expected that normalization will cause a variance of the technical data by more than a few percent. Further use of the data presented should be preceded by careful consideration of the qualifications indicated for the data and, if possible, a discussion regarding the planned data usage with the originator(s) of the data.

A listing and telephone numbers of the study participants are included as Appendix C.

A comprehensive summary of this report is given in the body of the report beginning on page 139.

III. SIGNIFICANT EARLY FINDINGS

The in-house OTS study effort at Marshall Space Flight Center (MSFC) was initiated in June 1976. Shortly thereafter certain findings were developed which have affected the course of the activity which followed. These preliminary findings were recognized as having significant impact on the selection of future transport systems. In each case, the early findings mentioned here will appear later and in some cases throughout the document so that the reader may recognize their importance as they are discussed. They are summarized in Figure 1.

Early in the study effort, certain hardware elements weighing up to 30 000 lb were identified which would require delivery to synchronous orbit. The elements are part of expected manned station or manned base complexes. The high performance OTV systems which are applicable to the current 65 000 lb to low Earth orbit Shuttle, which has been identified previously, only exhibited delivery capabilities of approximately 8000 to 13 000 lb. Previously it was assumed that multiple launches of the high performance stages would be used to provide the larger capabilities. Problems exist with this concept. For the dual Shuttle launch cases, one-half of the payload would have to be carried on each launch. This may not be practical since the station elements were of unitized design weighing as much as 30 000 lb. The two and three Shuttle launch cases suffer significant offloading — Shuttle payload load factor penalty. In all cases, very near simultaneous Shuttle launches would be required or significant design penalties could be expected in the OTV rocket. Also, significant additional orbital operations capability would be required.

The future OTV will also have to transport manned modules. For the aeromaneuvering concept using lox/hydrogen propellants, the 65 000 lb Shuttle will only deliver and return a very minimal (approximately 6500 to 7000 lb) four-man module. For the all-propulsive concept with lox/hydrogen propellants, two Shuttle launches would be required to deliver and return a very minimal four-man module. Previous synchronous orbit studies have indicated the

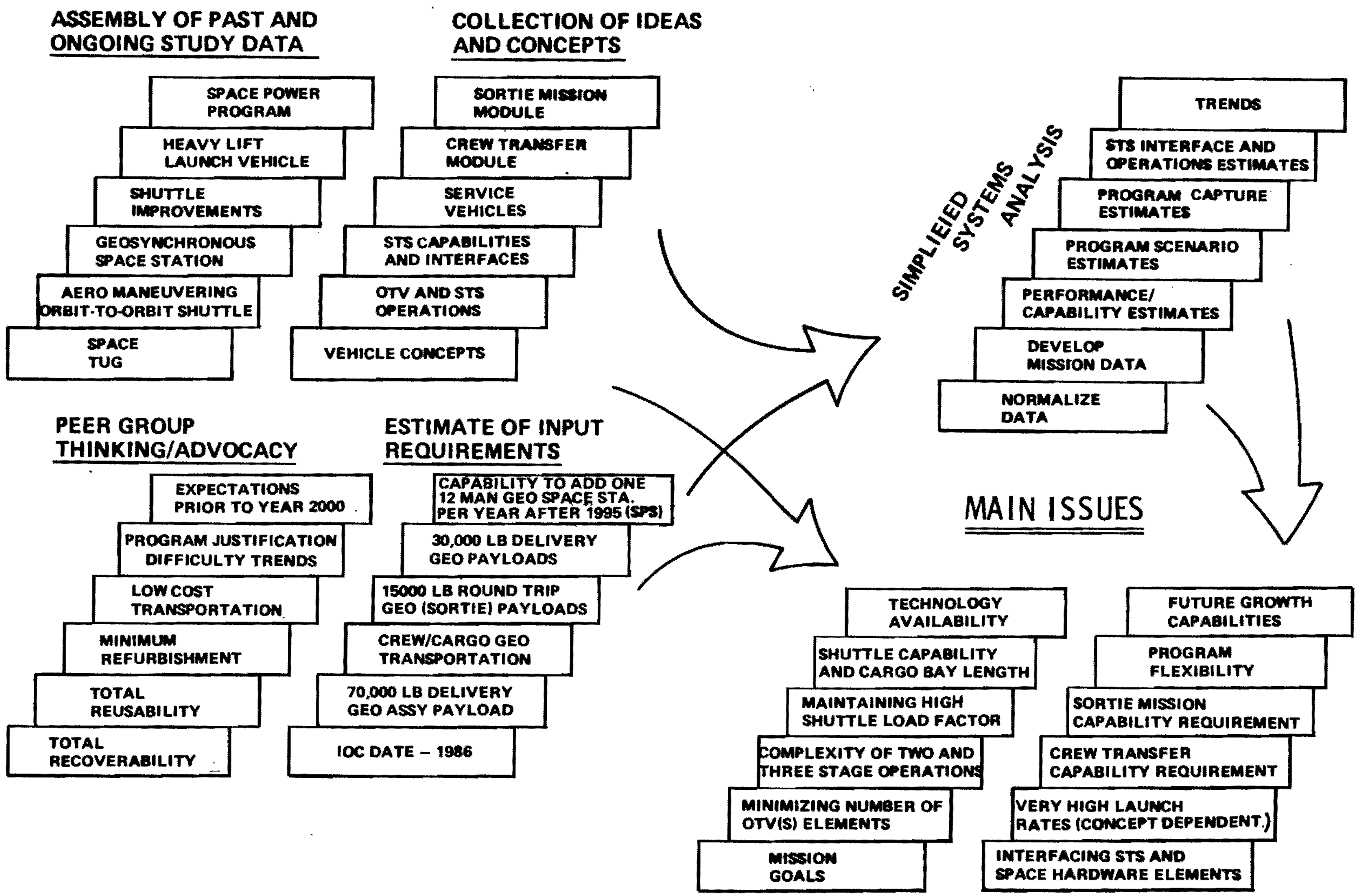


Figure 1. Study beginning and early findings.

desirability to have manned sortie capabilities. This capability requires an equivalent round trip (delivery and return) of approximately 12 000 to 15 000 lb.

Requirements may also exist for delivery-only payloads above 30 000 lb. These requirements are based on low orbit assembly options and are expected to range from 50 000 to 100 000 lb. Some previous studies have also identified desirable round trip capabilities ranging from 18 000 to 25 000 lb.

For these reasons, Space Shuttle capabilities between 65 000 and 125 000 lb to low Earth orbit have been studied. For Shuttle type applications, OTV design data have been parameterized over this range. Also solid motor boost stages are being considered for the case where dual Shuttle launches (two orbit stages) are involved and would be used as the first orbit stage with the high performance liquid propellant stage used as the second orbital stage.

The combination of round trip and delivery mission to synchronous orbit also presents a problem in stage design. Stages used for round trip payloads require more propellant if the full Shuttle capability is to be used. If a common stage is used for both type missions, the delivery missions incur a significant penalty. This penalty is different for different OTV concepts.

The nature of these early findings is such to suggest that at best there will be many compromises in final OTV selection. Solutions to these problems may be expected to have significant effect on Shuttle capabilities which are required on the eventual design of the payloads to be delivered and the nature of orbital operations to be required.

IV. ORBIT TRANSFER TRANSPORTATION REQUIREMENTS

The ongoing OTV study effort is taking place simultaneously with several long-range planning efforts which are to define various payload programs, various capability development, and various hardware and vehicle developments. The various documents which are available to select candidate missions for OTV are:

1. The 1973 Shuttle mission model

2. The 1976 Shuttle mission model

3. The 1976 Space Industrialization project/element model

4. Other ongoing study results are mentioned below.

The 1975 study by MSFC, which defined several Space Station program options for geosynchronous orbit for the 1985-2000 time period, projects several different paths in which the geosynchronous orbit programs may evolve. In-house and contracted geosynchronous Space Construction Base study efforts are currently underway and have produced certain element characteristics which are helpful in projecting future OTV requirements. Space power system study efforts project needs for significant payload capabilities in geosynchronous orbit in the post-1990 time period.

The most important requirement issues for OTV seem to be:

1. The ability to perform manned sortie missions

2. The ability to deliver or transfer rather large station or base elements and the ability to deliver or transfer rather large payloads

3. The ability to efficiently transfer man between low Earth orbit and geosynchronous orbit.

Table 1 presents the large geosynchronous Space Station elements which were identified in the 1975 geosynchronous Space Station study by MSFC. The weights have been increased 25 percent here to allow for the addition of radiation protection which has been identified as needed since the 1975 study. Whether these elements should be assembled in low Earth orbit or assembled in geosynchronous orbit is an issue which is important in OTV selection.

Table 2 presents the large geosynchronous Space Station elements which have been identified in the ongoing in-house MSFC Space Construction Base study. These values include the necessary radiation protection for geosynchronous orbit application. Whether these elements should be assembled in low Earth orbit or assembled in geosynchronous orbit is also an important issue. The major difference from Table 1 is that the Habitability and Subsystems Module have been combined.

Table 3 presents the weight requirements for transferring crews from low Earth orbit to geosynchronous orbit. During the 1985-1990 time period, transfer of a crew of 4 has been assumed and after 1991 transfer of a crew of 12 has been assumed.

Table 3 also presents the weight requirements for a four-man sortie mission to geosynchronous orbit. In addition to the weights of the module shown, it is desirable that extra payload capability ranging from 500 to 2500 lb be available.

TABLE 1. GEOSYNCHRONOUS ORBIT — FOUR-MAN STATION[a]

Element	Number Required	Weight[b] (lb)	Length (ft)	Function
Habitability Module	1	22 100	25	Crew Quarters, Hygiene, Stowage
Subsystems Module	1	24 900	26	Power, Stabilization, etc.
Logistics Module	1	17 300	23	Fluids, Bulk Cargo, Waste Stowage
Docking Module	1	10 400	8	Docking and Connection of Elements
Payload Module	1	18 800	—	As required
Total Complement		93 500	82	

a. Reference Geosynchronous Space Station Options, MSFC, July 28, 1975.

b. Weights increased 25 percent from reference to include radiation protection, etc.

TABLE 2. GEOSYNCHRONOUS ORBIT — FOUR-MAN STATION[a]

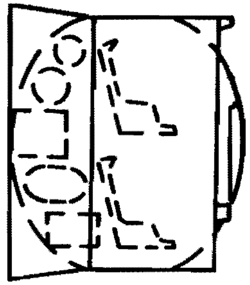
Element	Number Required	Weight (lb)	Length (ft)	Function
Habitability/ Subsystems Module	1	44 200	46	Crew Quarters, Power Stabilization, Data Management, etc.
Docking Module	2	5 600 (ea)	12	Allows Docking and Connection of Elements
Logistics Module	1	23 600	18	Fluids, Bulk Cargo, Waste Storage, etc.
General Purpose Laboratory	1	20 000	20	Laboratory Functions
Total Complement		99 000	108	

a. 1976 In-House Study — Assembled in Low-Earth Orbit.

TABLE 3. DERIVED CREW TRANSFER AND FOUR-MAN SORTIE CAPABILITY REQUIREMENTS

Crew Transfer

4 Man	5 000 lb	Round Trip
12 Man	12 000 lb	Round Trip



4-Man Sortie

	Round Trip (lb)		Equipment Delivery (lb)
7 Days	6 400	Plus	500 - 2 500
14 Days	9 500	Plus	500 - 2 500
21 Days	11 000	Plus	500 - 2 500
30 Days	12 400	Plus	500 - 2 500

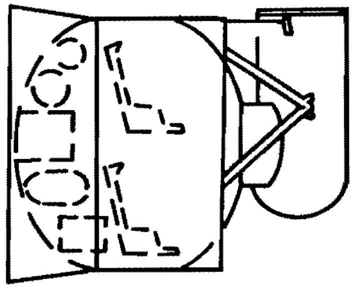


Table 4 presents several miscellaneous candidate payloads for OTV. The payloads were selected from the 1973 and 1976 Shuttle mission models and from the 1976 Space Industrialization project/element model. The configuration (length and diameter) of the automated payloads shown in Table 4 is an important issue for the future OTV and the future Shuttle system. The current configurations do not fit well in the Space Transportation System (STS) payload envelope capability. Previous standard spacecraft studies have identified this problem and have indicated that many of these payloads could be accommodated by a standard spacecraft which is very short and approximately 14 ft in diameter. It is suggested that, where possible, these payloads be redesigned to a 14 ft diameter. The configuration of these payloads is an issue which should be resolved in the near future.

Table 5 presents a tabulation of candidate missions for the high performance OTV for the 1986-1995 time period. These missions are representative of the 1973 and 1976 Shuttle mission models and the 1976 Space Industrialization project/element model. Planetary missions are typical of 1976 plans. In certain cases, additions have been made to balance the model. The candidate missions have been listed by two types: the first being tabulated simply as mission payload weight and the second where individual or particular mission flights are indicated. The missions presented in Table 5 are hereafter referred to as the nominal program for OTV analysis and characterization.

The nominal program model shown in Table 5 is representative of a rather ambitious space program during the 1986-1995 time period. Although this model seems ambitious today, major programs being planned, such as the space power program or extensive development of the public services program, could result in a program much more ambitious than shown. It is not expected, however, that this type increase in programs would have a major effect on the transportation systems being considered. However, a less ambitious program may have some effect and is introduced here to determine the effects of a reduced activity.

Table 6 presents a tabulation of candidate missions for the high performance OTV with major reductions in activities. Table 6 is similar to Table 5 with the major difference being a 10 year delay in the space power program and major reductions or delays in other programs. It is noteworthy that the manned sortie mission capability is probably more important in the reduced program than in the nominal program.

The manned sortie mission capability is an important issue for OTV and future Space Shuttle capability selection and requirements should be firmly established and characterized in the near future.

TABLE 4. MISCELLANEOUS CANDIDATE PAYLOADS FOR OTV[a]

Code	Element	Weight (lb)	Length (ft)	Diameter (ft)	Remarks
SPS03	Sortie/Test	TBD	TBD	TBD	
PSP02	Applications Technology Facility	21 600	—	—	Assembly in LEO
PSP03	Public Service Platform	31 700	—	—	Assembly in LEO
STO03	Solar Weather Satellite	TBD	TBD	TBD	May not be in GEO
STO04	Solar Terrestrial Observatory Manned Module	28 600	TBD	TBD	
EO413	Synchronous Earth Orbit Satellite	3 100	11	8	Suggest Design to 14 ft dia.
EO5E	Special Purpose Satellite	700	10	5	Suggest Design to 14 ft dia.
EO7	Synchronous Meteorological Satellite	1 100	11	8	Suggest Design to 14 ft dia.
NN/D1	INTELSAT	4 500	13	9	Suggest Design to 14 ft dia.
NN/D-2B	US Domestic Communication Satellite	4 500	13	9	Suggest Design to 14 ft dia.
NN/D-5	Foreign Communication Satellite	1 000	13	6	Suggest Design to 14 ft dia.
NN/D-9	Foreign Synchronous Meteorological Satellite	900	11	9	Suggest Design to 14 ft dia.
NN/D-10	Geosynchronous Operational Meteorological Satellite	900	11	6	Suggest Design to 14 ft dia.
NN/D-12	Earth Resources	3 100	11	8	Suggest Design to 14 ft dia.
NN/D-13	Foreign Synchronous Earth Orbit Satellite	3 100	11	8	Suggest Design to 14 ft dia.
AST-8	Large Radio Observatory	2 800	25	10	Suggest Design to 14 ft dia.

a. Reference 1973 and 1976 Shuttle model, 1976 Space Industrialization Project/Element model.

TABLE 5. NOMINAL PROGRAM OPTION CANDIDATE MISSIONS — OTV[a]

Units	Program	Calendar Year 86	87	88	89	90	91	92	93	94	95	Remarks
Mission Weight (1000 lb)	Station Elements	40	60[b]	40	60[c]	60	60[d]				[e]	HLLV after 92
	Station Cargo		30	30	90	150	120	30	30	30	30	Mostly HLLV after 92
	Satellite Power System — Test/Development Hardware	30	75	60	60	45						HLLV after 91
	Space Construction Base Miscellaneous			60				75	45	90		
	Public Service Platform			30	45	45	30	30	30	45	15	
	Solar Terrestrial Observatory	44					15		15			
	Public Service Platform and Solar Terrestrial Observatory Miscellaneous		15		15		15		30		30	To balance model
	Automated or Cluster Payload	20	20	40	40	40	40	60	40	60	60	
	Total	134	200	260	310	340	280	195	190	225	135	
Mission Flights	4-Man Crew Transfer		4	4	6	8	12		4			Including Station Supplies
	12-Man Crew Transfer							4[f]	4	6	8	
	4-Man Sortie	2	2	1	2	1	2	1	2	2	2	
	Planetary	2	1	2	0	2	1	2[g]	2	2	2	
	Lunar	1[h]	1	1	1	2	2	1	1	2	1	
	High Altitude and Heliocentric Orbit	1			1			1			1	
	Total	6	8	8	10	13	15	9	13	12	14	

a. Reference 1976 Space Industrialization Project/Element Model, 1973 and 1976 Shuttle Model.

b. 4-Man Station

c. 8-Man Station

d. 12-Man Station

e. Capability to Add 12-Man Station Each Year

f. Station Supplies Excluded

g. 93-95 Added to 76 Model

h. 73 Model

TABLE 6. LOW PROGRAM OPTION CANDIDATE MISSIONS — OTV[a]

Units	Program	Calendar Year										Remarks
		86	87	88	89	90	91	92	93	94	95	
Mission Weight (1000 lb)	Station Elements			40	60[b]	40[c]				40	40	
	Station Cargo					45	45	45	45	60	45	
	Satellite Power System — Test/Development Hardware	30[d]	30							45	60	
	Space Construction Base Miscellaneous			30				30				To Balance Model
	Public Service Platform	15	15		15			15	15		15	
	Solar Terrestrial Observatory		15			30			15			
	Public Service Platform and Solar Terrestrial Observatory Miscellaneous			15			15		30			To Balance Model
	Automated or Cluster Payload	20	20	40	40	40	40	60	40	60	60	Same as Nominal Program
	Total	65	80	125	115	155	100	140	135	205	220	
Mission Flights	4-Man Crew Transfer				3	4	6	4	6	4	6	Including Station Supplies
	12-Man Crew Transfer	None										
	4-Man Sortie		2	2	2	1	2	1	2	1	2	
	Planetary			2		2		2[e]		2[f]		
	Lunar	None										
	High Altitude and Heliocentric Orbit	None										
	Total		2	4	5	7	8	7	8	7	8	

a. Reference 1976 Space Industrialization Project/Element Model, 1973 and 1976 Shuttle Model (major reductions assumed).

b. 4-Man Station

c. 4-Man Station (8-Man Station Part Time)

d. SPS Program Delayed 10 Years

e. Added to Model

V. OTV CONCEPTS (CONFIGURATIONS)

A. Lox/Hydrogen Propellant Concepts

The lox/hydrogen high performance vehicle has been considered the primary candidate for the post-1985 time period in the overall OTV study activities. Early in the latest study activity, it was determined that a capability somewhat larger than could be provided by the current 65 000 lb Shuttle capability might be desirable. For this reason, configuration data for Shuttle capabilities from 65 000 to 125 000 lb have been investigated, and parametric data for the range have been developed.

1. <u>All-Propulsive Orbit Transfer Vehicle (APOTV)</u>.[1] A Shuttle compatible APOTV has been extensively studied by MSFC and MSFC contractors. The resulting design configuration has been selected as a baseline configuration for the in-house OTV study activity. This baseline stage utilizes an RL-10-Category IIB engine (see section on propulsion and Appendix A) with I_{sp} approximately 456.5 sec for lox/hydrogen when used at a 6:1 (lox/hydrogen) mixture ratio.

The baseline APOTV configuration is shown in Figure 2. It should be noted that this design is for delivery only and has a usable propellant load of approximately 52 200 lb. If the configuration was used in a round trip mode, the tankage would be inadequate for utilization of the full 65 000 lb Shuttle capability. The latest configuration concepts utilize a somewhat shorter engine system and have considered both 6:1 and 7:1 propellant mixture ratios. The appropriate APOTV for these characteristics is shown in Figure 3.

As the propellant loading of the stage increases, the lox tank is permitted to grow in diameter to equal the diameter of the hydrogen tank. Figure 4 shows the APOTV for a 125 000 lb Shuttle capability.

Previous OTV studies have included a tilt table and accessories which would remain in the Shuttle. The tilt table would increase the dimensions shown in Figures 2 and 4 by approximately 2 ft. The tare weight in the Shuttle would be 2.9 percent of the Shuttle capability. Shuttle capability in each case has been reduced by the tare weight.

The APOTV length versus propellant loading is shown in Figure 5. Propellant capacities used for Figure 5 cover the range needed for the 65 000 to 125 000 lb Shuttle capabilities. Shuttle attachment length is not considered here.

1. Formerly Space Tug.

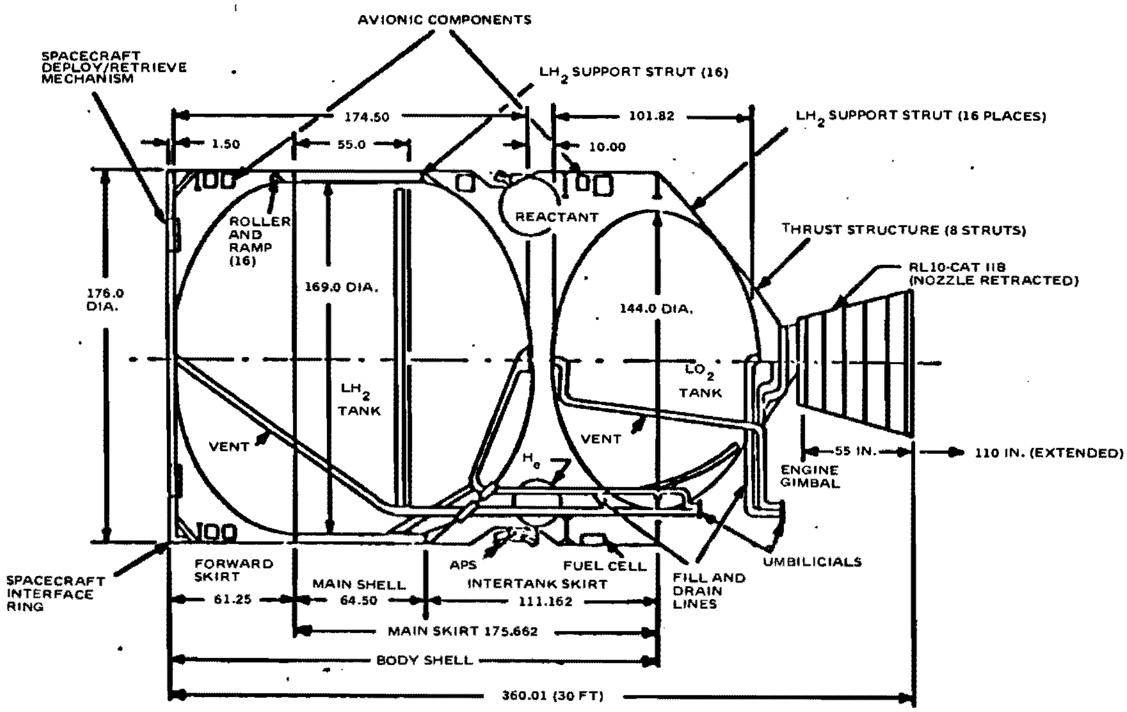


Figure 2. Baseline APOTV configuration.

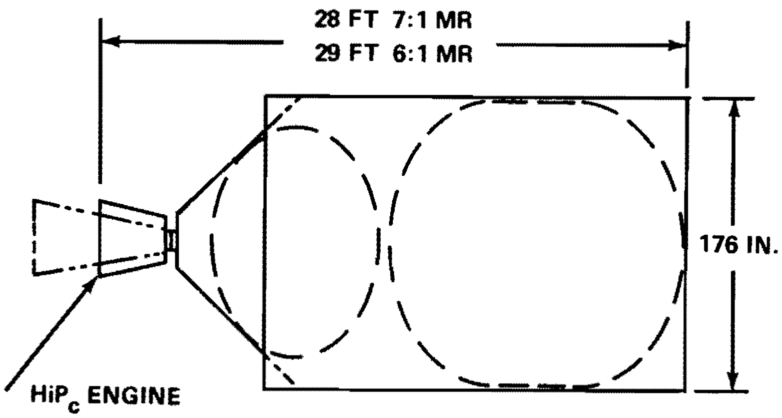


Figure 3. APOTV — 50 200 lb propellant for 65 000 lb Shuttle.

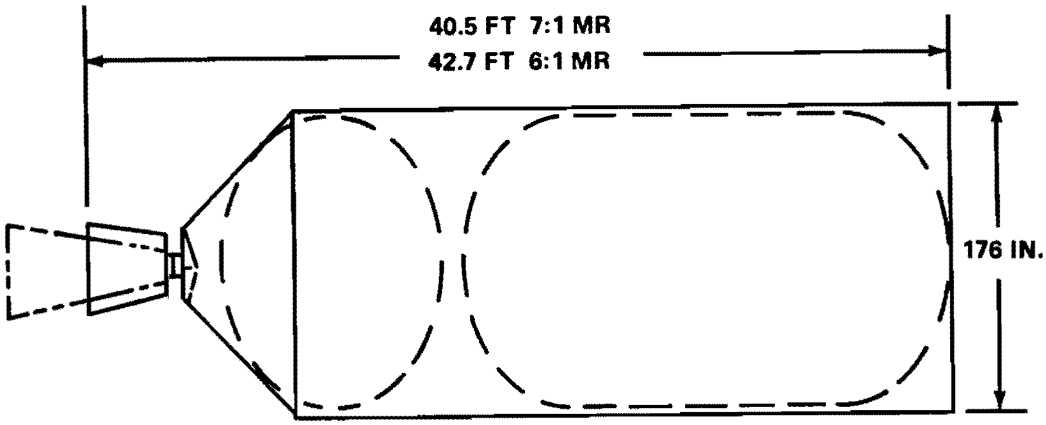


Figure 4. APOTV — 95 000 lb propellant for 125 000 lb Shuttle.

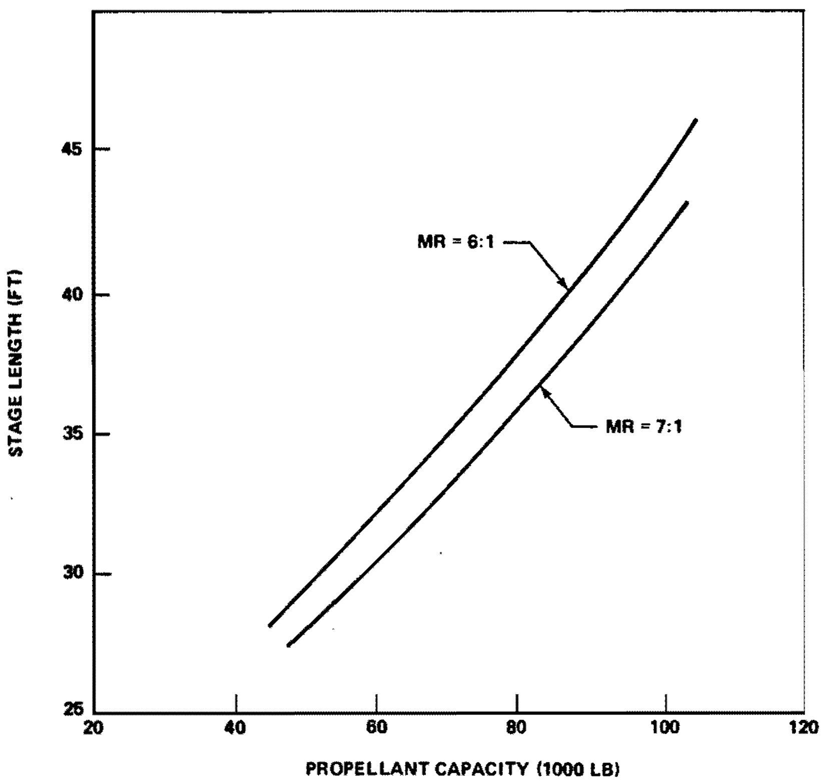


Figure 5. APOTV length versus propellant loading.

2. Aeromaneuvering Orbit to Orbit Shuttle (AMOOS).[2] A Shuttle compatible AMOOS has also been studied for several years by MSFC to obtain better round trip payload capabilities than is possible using the APOTV concepts. The concept is similar to the APOTV except that on Earth return the system uses the Earth's atmosphere for a single pass braking maneuver and reduces the propulsive energy required of the system. (See the section on OTV performance for further detail of the systems flight profile.) The majority of the AMOOS study effort has been performed by Lockheed Missiles and Space Company (LMSC). The engineering laboratories of MSFC, together with Ames Research Center (ARC) and Langley Research Center (LaRC), have also been involved in the configuration development of this concept.

A 34 ft LMSC configuration, as shown in Figure 6, has been chosen as the baseline concept for this study. It should be noted that the configuration

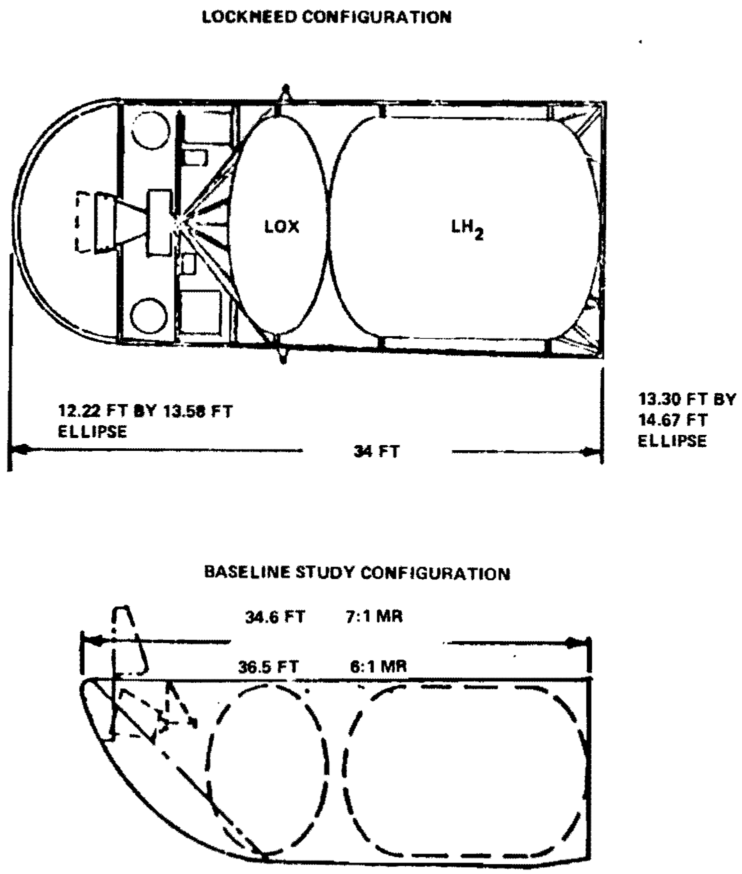


Figure 6. Baseline AMOOS configuration.

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2. Sometimes referred to as Aeromaneuvering Orbit Transfer Vehicle (AMOTV).

involves both ogival/elliptical shapes and tapers along the external length of the stage. The configuration shown was designed to accommodate 48 500 lb of propellant which is required for a round trip mission. It uses 6:1 mixture ratio with a 456.6 sec I_{sp} RL-10-IIB engine. It is used with a 65 000 lb Shuttle capability.

If the AMOOS were designed for delivery only, as was the case with the APOTV, only 42 000 to 43 000 lb of propellant would be required, and the stage could be somewhat shorter.

The tankage bulkhead designs by LMSC are somewhat flatter than that used for the APOTV. To make the AMOOS data more comparable with APOTV data, the tanks were resized and reshaped using $\sqrt{2}$ elliptical bulkheads. A later propulsion system concept was also used. The resulting AMOOS configuration for the 65 000 lb Shuttle, which is directly comparable with the APOTV shown earlier, is shown in Figure 7.

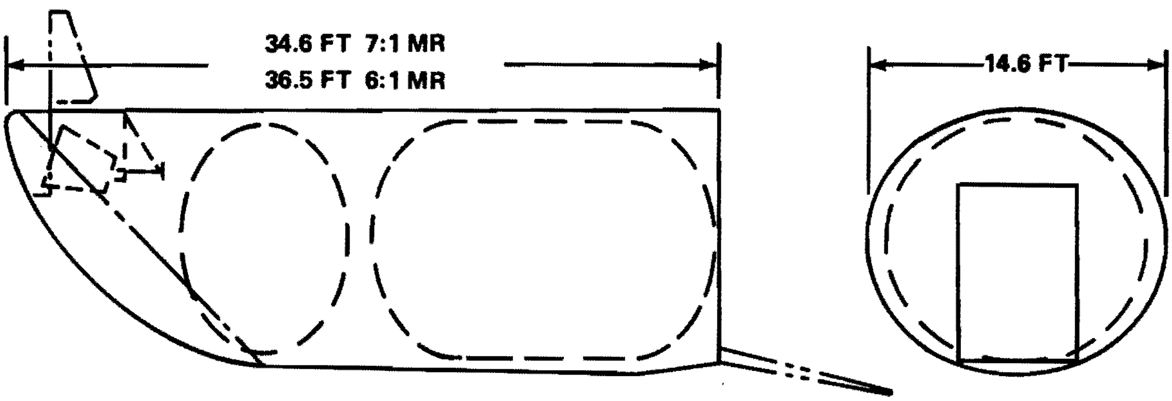


Figure 7. AMOOS — 48 500 lb propellant for 65 000 lb Shuttle capability.

The LMSC studies do not involve using the APOTV-type tilt table for Shuttle deployment. Shuttle deployment and support of the concept are still issues for the AMOOS. For the purpose of this study, a Shuttle tare weight of 2.9 percent (same as APOTV) of the Shuttle capability has been assumed.

The AMOOS length versus propellant loading is shown in Figure 8. These propellant capacities cover the range needed for the 65 000 to 125 000 lb Shuttle capabilities. In developing these AMOOS configurations, it has been assumed that the same external taper angle used on the baseline configuration would be maintained. This results in using a somewhat different tank diameter

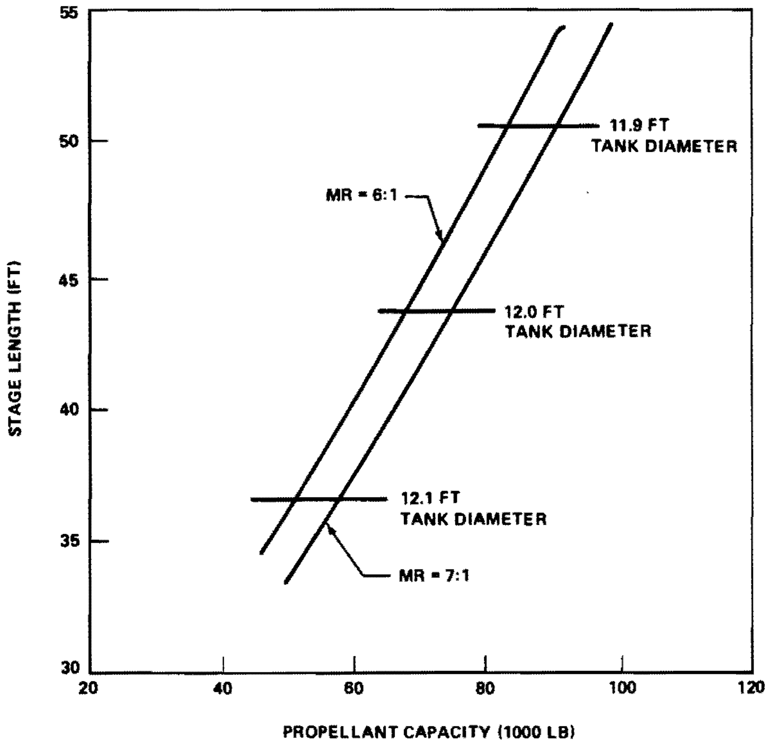


Figure 8. AMOOS length versus propellant loading.

as the vehicle length increases. Whether this is actually necessary or satisfactory is an issue which must be determined in later studies. The reduction in tank diameter assumed here is also shown in Figure 8.

Figure 9 shows the AMOOS configuration sized for a 125 000 lb Shuttle capability.

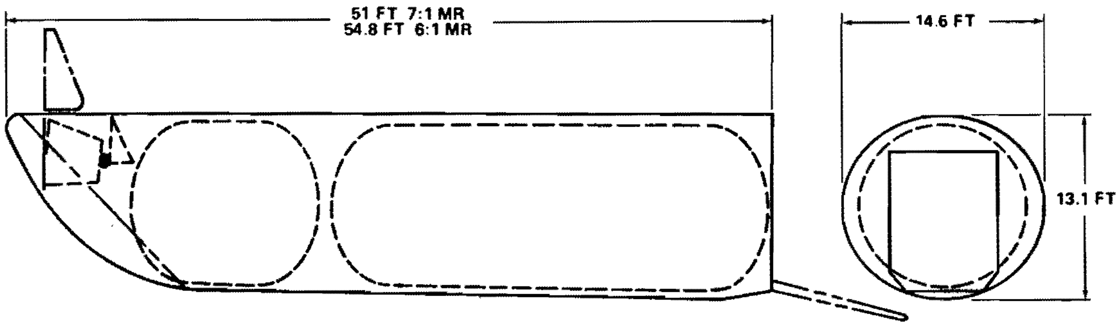


Figure 9. AMOOS — 90 200 lb propellant.

The internal arrangement and external configurations of the AMOOS require further study effort. It is expected that significant reductions in stage length may be possible. The subject is discussed further in the section on cargo bay length issues.

B. Space Storable Propellant Concepts

Extended mission duration problems associated with cryogenic hydrogen, cargo bay length, and general space storability associated with liquid hydrogen have dictated the need for a propellant combination with high bulk propellant density and which is somewhat easier to store in space. For this reason, two different propellant combinations have been considered. In the first case lox and rocket propellant (RP), where lox is considered a space storable, were investigated. In the second case nitrogen tetroxide (N_2O_4) and monomethyl hydrazine (MMH) were investigated.

The two storable configurations have not been studied to the same detail level as have the lox/hydrogen configurations. However, parametric configuration, weight, and performance data have been developed. The configurations studied include the AMOOS and the APOTV concepts.

Configuration sketches for the storable propellant configurations are shown in Figures 10 and 11. To simplify weight calculations and permit ease of developing parametric data, the configurations studied have used rather conventional tankage design. These designs do not efficiently utilize the Shuttle cargo bay, and if the storable propellant systems are to be considered as serious competitors, further configuration development is required.

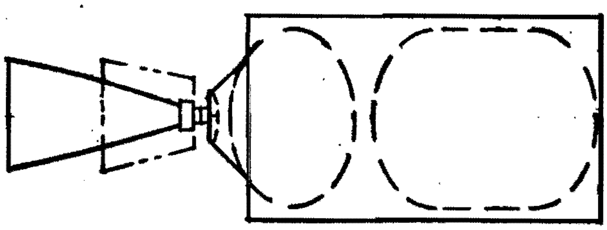


Figure 10. APOTV lox/RP and N_2O_4/MMH.

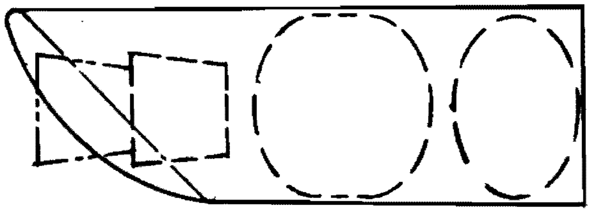


Figure 11. AMOOS lox/RP and N_2O_4/MMH.

C. Convertible Cargo/Man Module

It is expected that future synchronous orbit applications will involve the transfer of man and Space Station supplies from low orbit to synchronous orbit. Several hardware concepts which can be used in OTV studies have been developed over the past years. The configuration selected for use here was developed in the AMOOS studies performed by LMSC.

The module configuration, shown in Figure 12, was designed to accommodate four men. The configuration can be used with either the APOTV or AMOOS. The external shell would carry an ablative insulation for the AMOOS case. The diameter of the shell is approximately 14 ft, and the diameter of the pressurized module is approximately 12 ft. The length shown is for an OTV capability of 6000 to 7000 lb round trip payload. For larger capabilities, the configuration is similar with the module being somewhat longer to accommodate the capability. The convertible cargo/man module has not been extensively studied in the in-house OTV activity. Further study and design development are required in the near future.

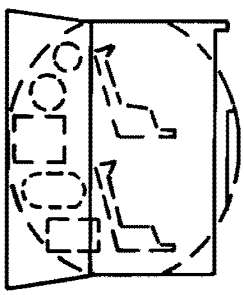


Figure 12. Convertible cargo/man module.

D. Emergency Return Vehicle Configurations

As is the case with ships on the high seas, it is likely that a lifeboat type system will be provided for use in emergency situations. It has been assumed here that such a system should be able to return directly to the Earth with an option of stopping in low Earth orbit. It seems most likely that any system used for this purpose would utilize aeromaneuvering or aerobraking.

Figure 13 shows a configuration using the Apollo concept, which was introduced in the 1975 Space Station studies. Such a system would weigh approximately 20 000 lb with accommodations for four to six men. The system could utilize either storable liquid propellants or solid motor propellants.

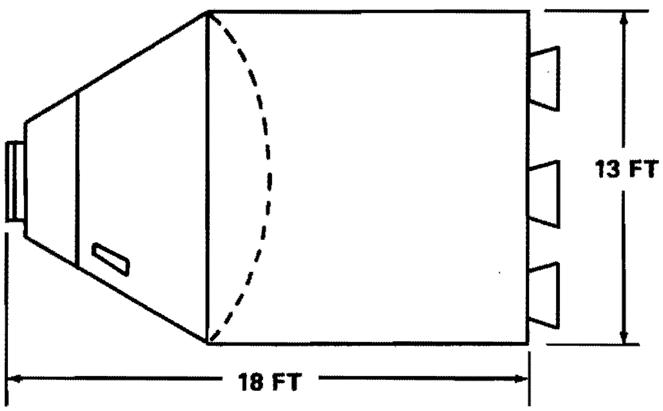


Figure 13. Emergency return vehicle — Apollo concept.

Figure 14 shows an aeromaneuvering vehicle concept derived from the AMOOS study. This system, designed for four-man accommodations, weighs approximately 13 500 lb and is called the Aeromaneuvering Reentry System (AMRS). Storable liquid propellants or solid motor propellants can be utilized.

The emergency return vehicle concepts previously shown were conceived for the specific purpose of permitting the crew to escape in case of emergencies. As such the vehicle would remain in orbit until used and serve no other purpose.

The concepts which follow were conceived to operate as functional parts of the AMOOS OTS, although the same or similar concepts could be developed for the APOTV if the appropriate payload capability is available.

Figure 15 shows a configuration of the AMRS which could be nominally used for the transfer of crew and/or supplies. The module is sized for a crew

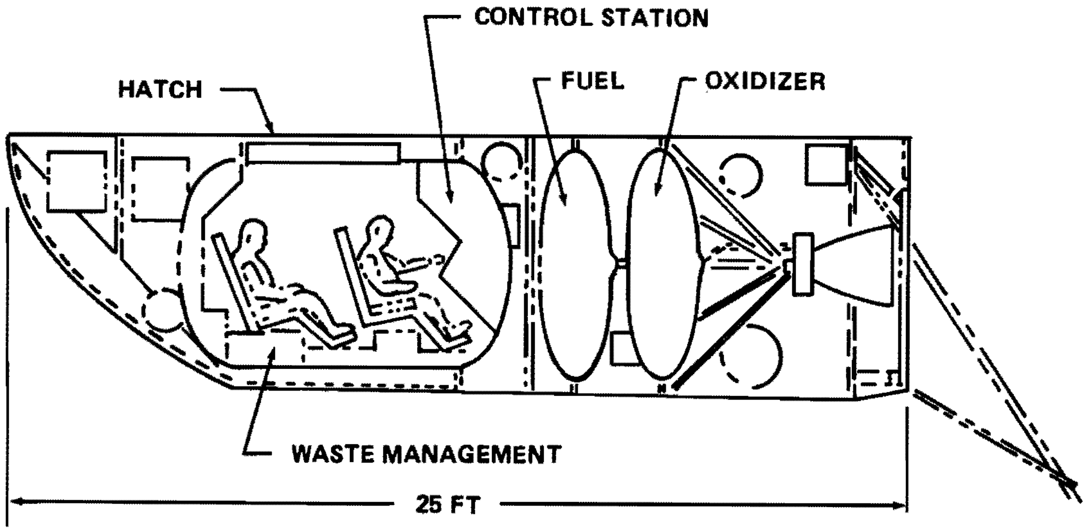


Figure 14. Aeromaneuvering Reentry System.

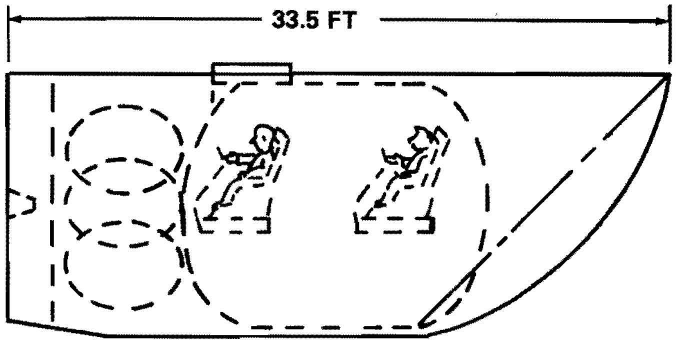


Figure 15. Aeromaneuvering Reentry System (crew and cargo accommodations).

of four and for station supplies for a crew of four for 90 days. The system could be converted to accommodate a crew of 12 or more. The configuration as shown in Figure 15 could use portions of the external shell of the AMOOS high performance stage. It would remain with the crew for the period the crew remained on orbit. It could then, or at any time an emergency arises, return to low Earth orbit or directly to Earth.

It is envisioned that the station supplies would only be off-loaded as required and at least during the early portion of the orbit stay would remain onboard for crew usage if needed. This capability would permit the crew to remain on orbit and perhaps perform emergency operations, if required, after abandoning the station.

The storable propulsion system would always be used to deorbit the AMRS, and the OTV would usually be used only as a delivery system.

The OTV study activity, to date, indicates that this mode of operation would require approximately the same payload capability as the convertible cargo/man module concept. The operations cost, however, would be considerably higher because there would be two stages plus heat shields to refurbish after each launch. Also a Shuttle capability greater than 100 000 lb is probably required.

Figure 16 shows an AMRS configuration which avoids the stage and heat shield refurbishment on each launch. As with the previously described configuration, crew and cargo are accommodated. In this case, however, only the cargo/man module is transferred between orbits each time. The AMRS serves as a berth for the convertible cargo/man module while it is on orbit.

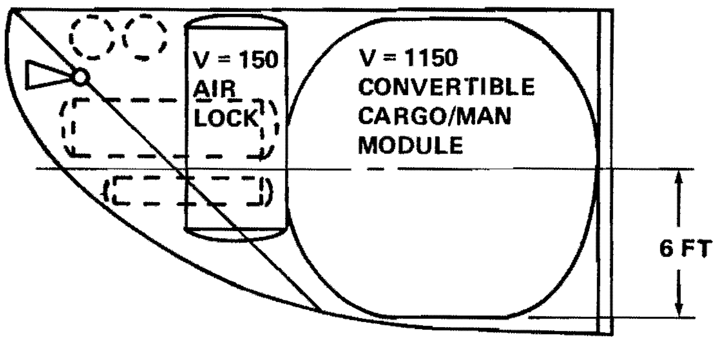


Figure 16. Aeromaneuvering Reentry System (convertible cargo/man module berth).

This concept is somewhat shorter since the propulsion system is located at the forward end. Since the AMRS is only transported to synchronous orbit one time, an airlock can be provided without significant transportation cost penalty.

E. Orbit-Based Service Vehicles

Although it is recognized that some type of manned service vehicle will be used in the synchronous operation, very little development effort has been performed on it. The main consideration here has been to identify concepts whereby the service vehicle would be a derivative of other hardware involved in the OTS. It is assumed that some type airlock would be desirable on any service vehicle.

Figure 17 shows a service vehicle derived from hardware of the small AMRS (lifeboat).

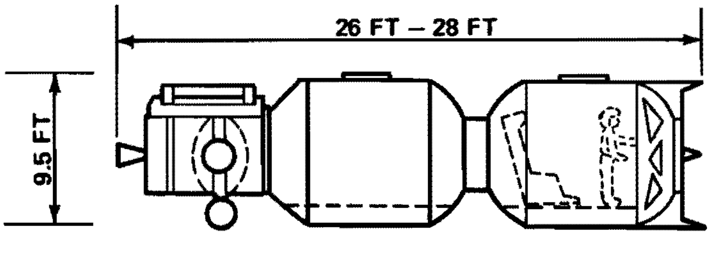


Figure 17. Service vehicle (a derivative of the AMRS lifeboat).

Figure 18 shows a service vehicle derived from the convertible crew/cargo module, or one of the larger AMRS concepts, hardware.

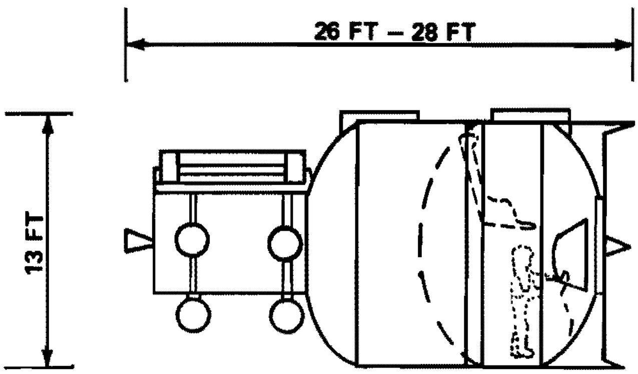


Figure 18. Service vehicle (a derivative of the convertible cargo/crew module).

Figure 19 shows a service vehicle which is derived from the AMRS (convertible cargo/man module berth).

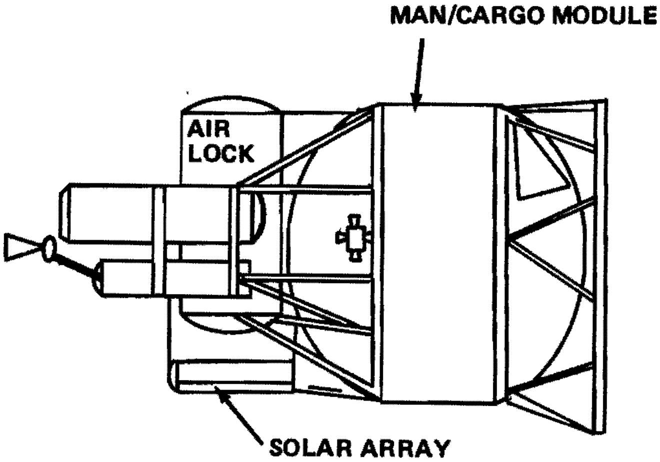


Figure 19. Service vehicle (a derivative of the AMRS module berth).

F. Manned Sortie Mission Hardware

The principal issue involved in the manned sortie mission hardware selection is the permissible orbit stay time the OTV can accommodate and the desired length of time for which the sortie mission is planned. Other issues involve whether or not a Space Station is in low Earth orbit, the orbit stay time capability of the Shuttle, etc. It is desirable to eliminate these issues. The only apparent way to eliminate these issues is to provide a self return to Earth and orbit maneuvering capability on the sortie mission hardware. If this is desirable, a configuration like the AMRS (convertible/man module berth) shown in Figure 16 must be used.

Manned sortie mission hardware can also utilize the convertible cargo/crew module hardware and a Shuttle type airlock. This concept is shown in Figure 20. The concept shown is for the AMOOS high performance system which could readily be adapted to the APOTV. The system would be approximately 20 ft long, depending on the crew module size and the airlock configuration. It should be noted that this concept requires the OTV to remain on orbit for the duration of the sortie mission and requires either a Shuttle or Space Station to be in orbit at the appropriate return time.

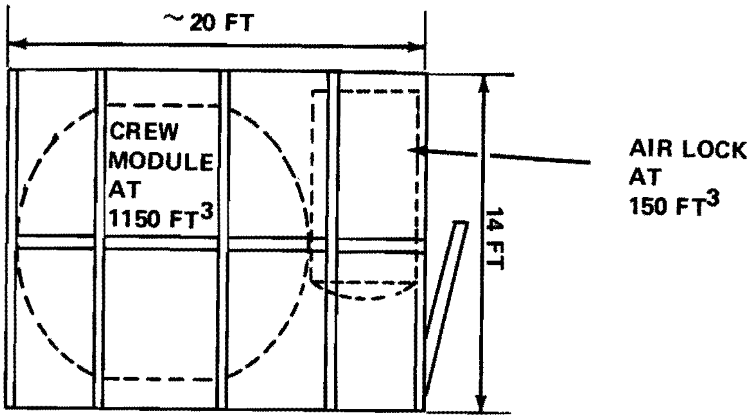


Figure 20. Manned sortie configuration (convertible cargo/crew module).

G. Docking (Loading/Unloading) Module Configuration

Space Station studies, to date, have not developed appropriate station element configurations for the OTS hardware concepts which have been developed in this study. Low Earth orbit stations must interface with the Space Shuttle system which is somewhat different than the OTS. Also, low Earth orbit stations do not assume the need for lifeboat or emergency return type systems. Transfer transportation to synchronous orbit is very expensive, and the eventual selected docking module concept must favor, as much as possible, the OTV or OTS because it is only delivered to orbit one time (i.e., if a penalty is necessary or desirable, it should be placed on the docking module and not on the OTS).

The docking module concept shown in Figure 21 is introduced to illustrate the desirable accommodations from an OTV point-of-view. This configuration and the operation concept sketches which follow are illustrative of OTV requirements on the Space Station.

It has been assumed that it would be desirable to have some overlap of crew accommodations during the crew exchange period. This requires accommodations for multiple crew modules. It is assumed that it may be desirable to have accommodations for extra cargo modules and perhaps a service vehicle. It has also been assumed that some type of airlock between any berth and the Space Station proper is required.

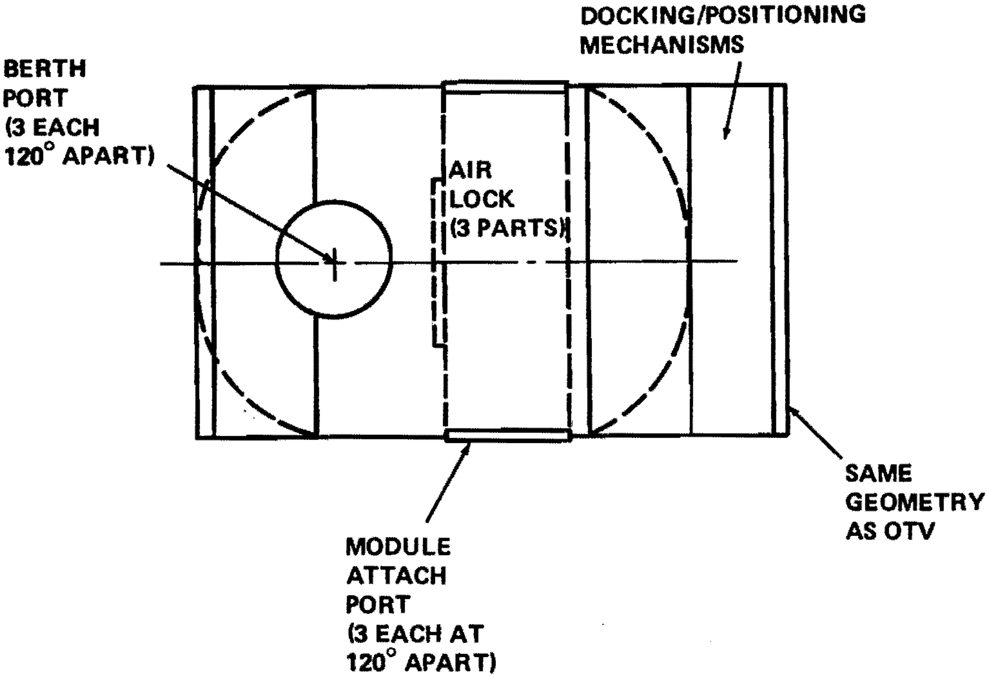


Figure 21. Docking (loading/unloading) module.

Figure 22 illustrates a typical docking maneuver and AMRS cargo/crew module berth placement. Figure 23 illustrates a typical docking for a convertible cargo/crew module berthing. Figure 24 illustrates a typical berthing

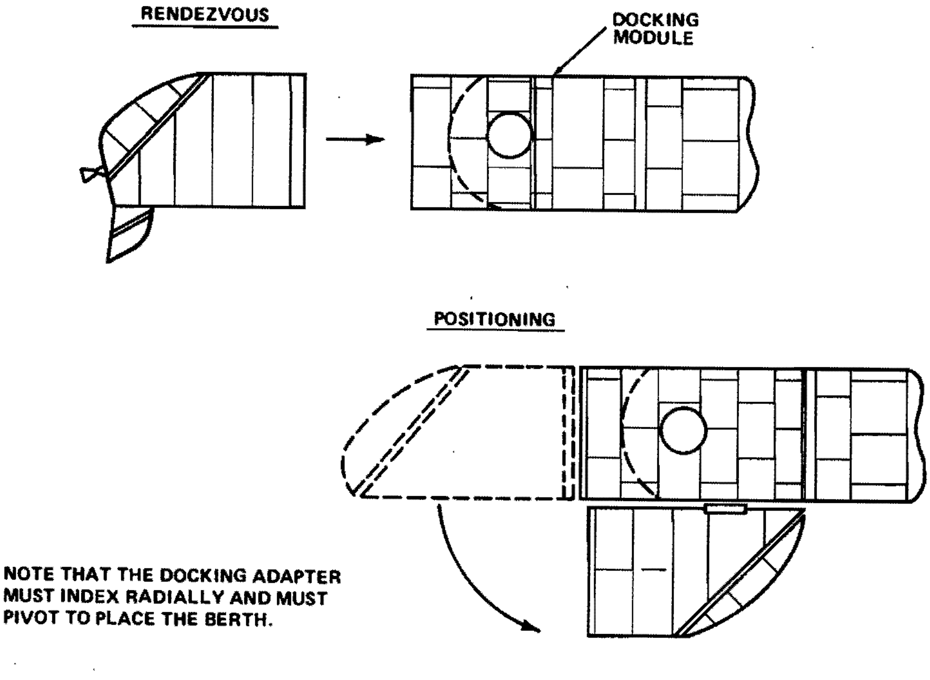


Figure 22. Docking/positioning AMRS/module berth.

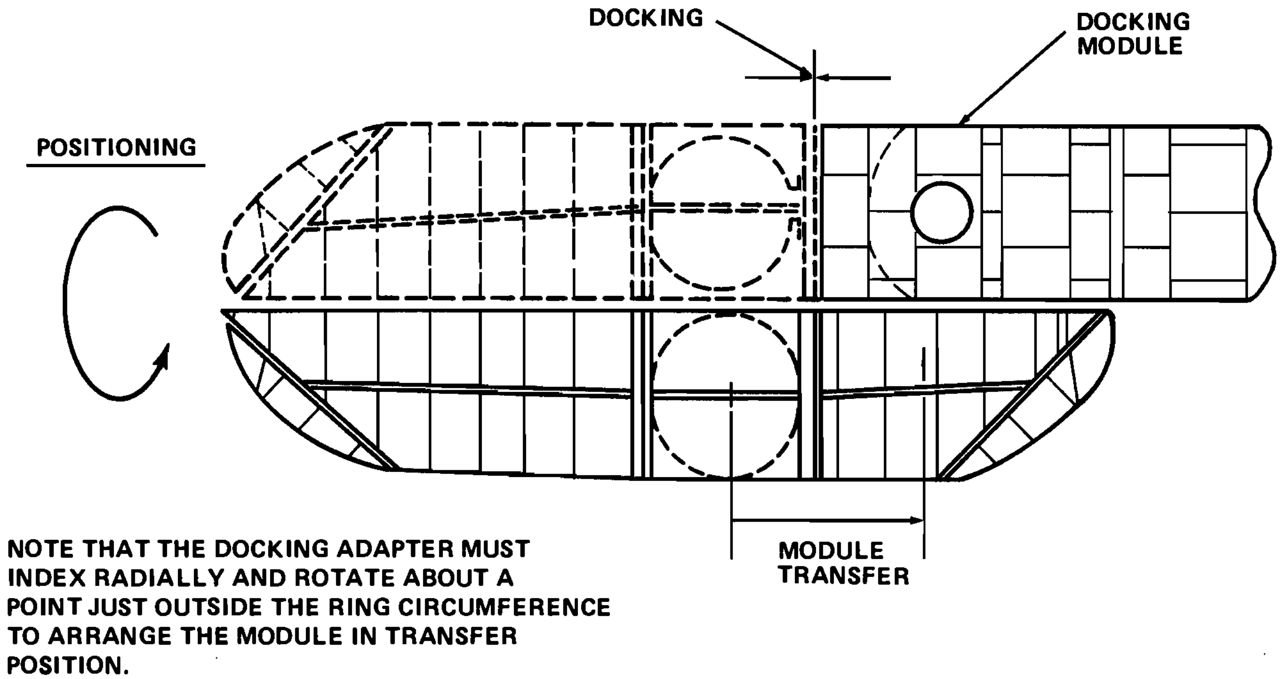


Figure 23. Docking/positioning/module transfer.

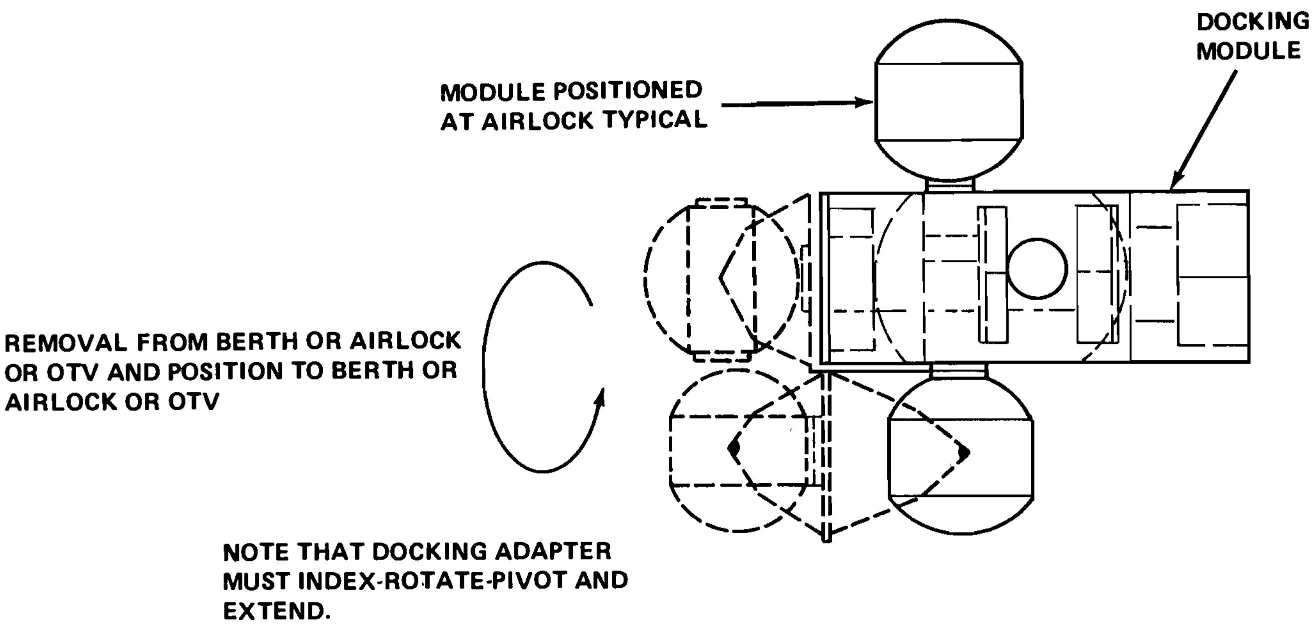


Figure 24. Module transfer/placement.

or placement of a cargo module or storage of a crew module. Figure 25 presents an end view of the orbital assembly. Specific requirements on the docking and placement hardware are mentioned. The configurations shown are typical of the AMOOS utilization; however, APOTV requirements would be similar.

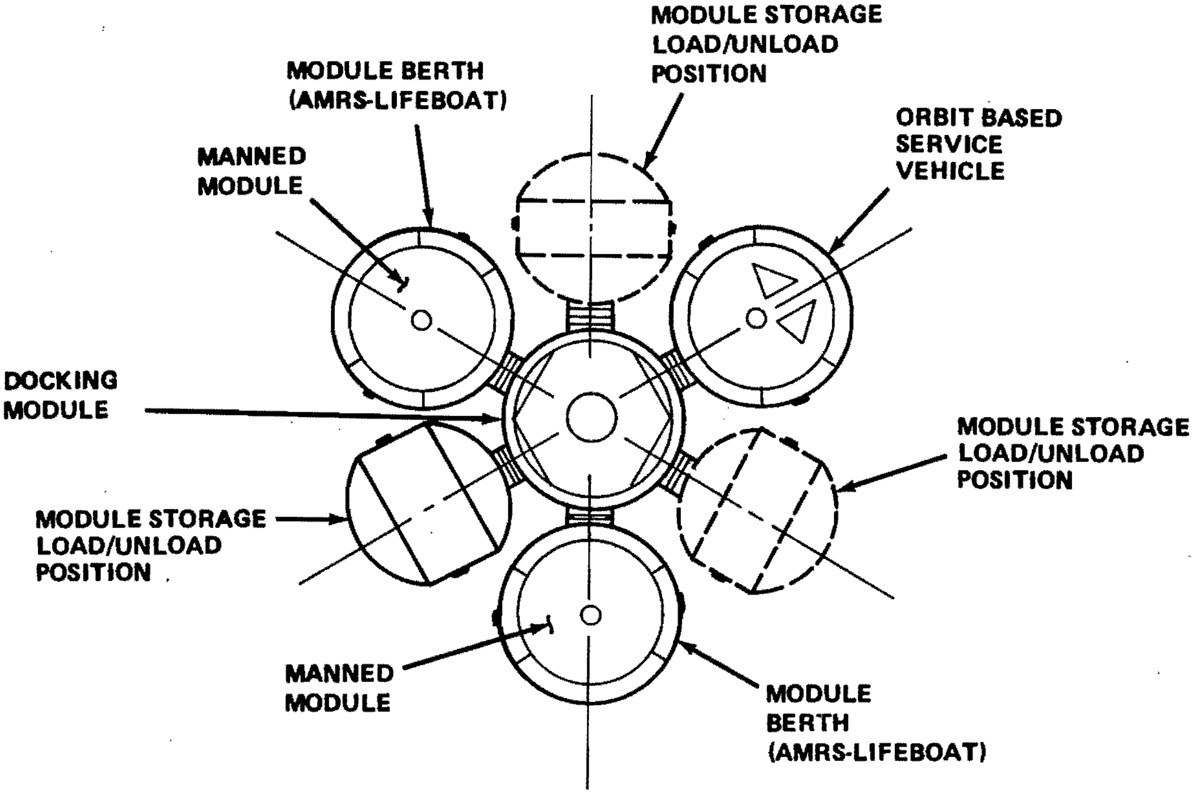


Figure 25. End-view — docking system.

H. Unique Designs to Obtain Shorter Stages

Shuttle cargo bay length availability may necessitate unique designs for OTV to be able to carry the OTV and payloads in the same Shuttle. This is particularly true if the Shuttle capability is improved significantly and if the cargo bay length is not extended beyond 60 ft.

The configurations shown in Figures 2 through 9 involved somewhat conventional design with $\sqrt{2}$ ellipsoidal bulkheads as shown on the AMOOS configuration in Figure 26. This particular configuration is sized for a round trip mission for a 100 000 lb Shuttle payload capability. As can be seen, the stage is approximately 45 ft long, which is probably unacceptable, and if the design is unchanged the 100 000 lb Shuttle capability would probably be impractical.

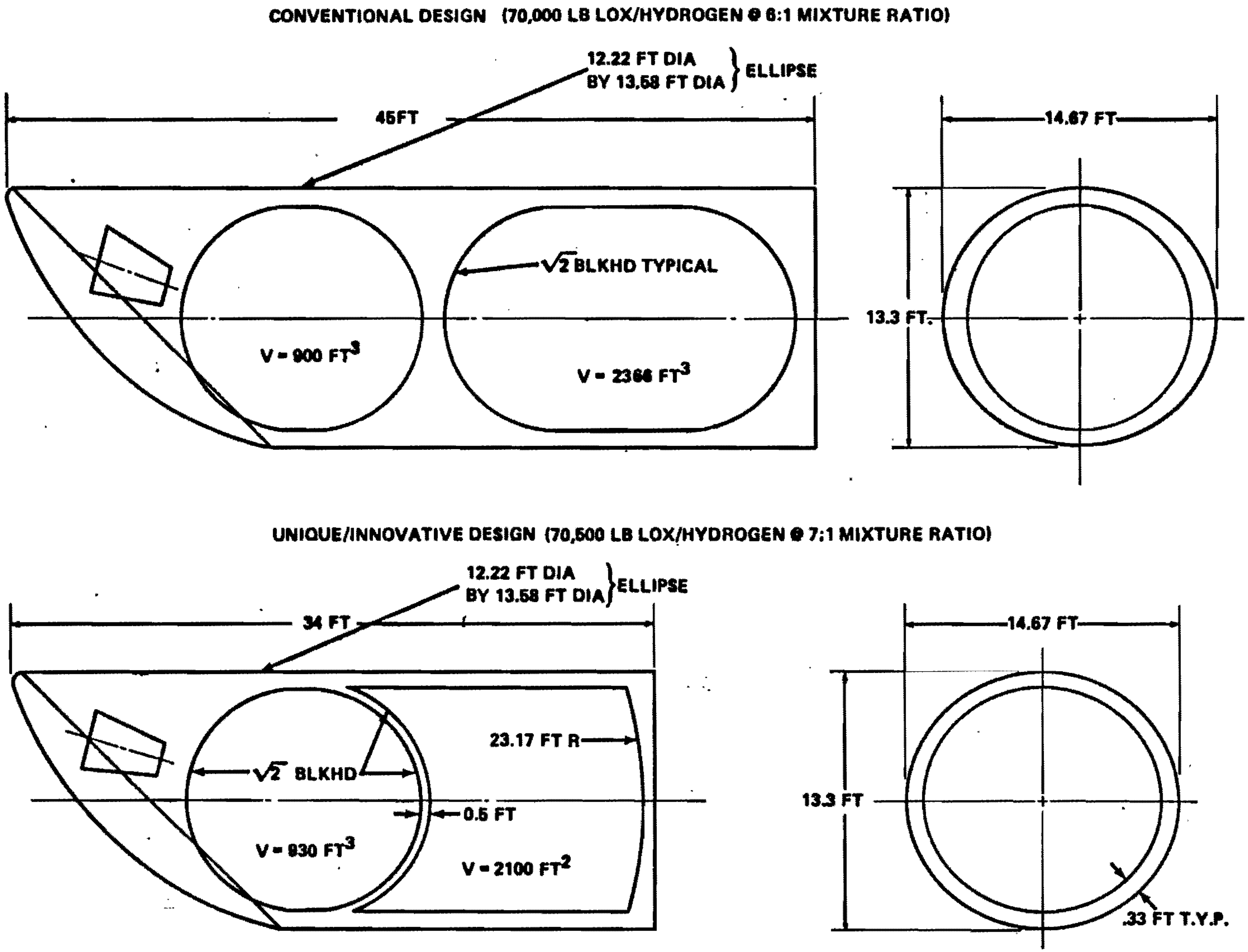


Figure 26. AMOOS design for cargo bay length restraints.

Figure 26 also shows a unique/innovative design using nestled central bulkheads and a very low profile forward bulkhead to improve volumetric efficiency. The tanks would be tapered and elliptical in cross section to match the external shell of the AMOOS. A somewhat simpler, but similar, design could be devised for the APOTV.

The unique design also uses a 7:1 (lox/hydrogen) mixture ratio which saves approximately 2 ft. A 6 percent ullage space is provided for both cases. Other possibilities for reducing stage length are:

1. Reduce ullage to 4 percent @ ≈ 0.4 ft

2. Use 8:1 mixture ratio @ ≈ 1.5 ft

3. Use 9:1 mixture ratio @ ≈ 2.7 ft

4. Use slush hydrogen @ ≈ ???? ft

5. Reshape exterior configuration @ ???? ft.

The problem of unique design to obtain shorter stage length is an issue of paramount importance and should be investigated in the near future. The problem is discussed further in the section on cargo bay length considerations.

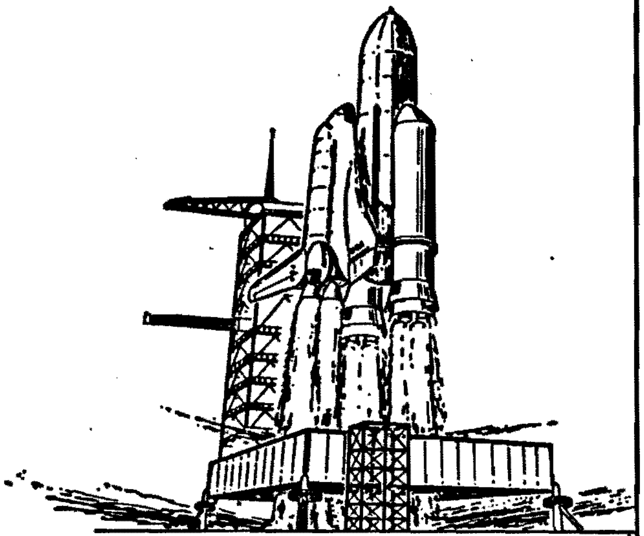
I. 100 000 lb Capability Shuttle/AMOOS Cargo Bay Configurations

It is difficult to visualize the problems associated with OTV, OTV payloads, and the 60 ft cargo bay. In this section an attempt has been made to correlate the payloads and OTV in a manner where both can be included in one 60 ft cargo bay. It is assumed that the appropriate AMOOS (unique/innovative design) can be limited to 34 ft length and that payloads can be limited to 24 ft length. Figure 27 shows the AMOOS type OTS Shuttle cargo bay configurations which were previously described.

The Shuttle airlock is used nominally for the crew transfer flights. Since the sortie mission hardware includes an airlock (and since there is not enough cargo bay length to use a Shuttle airlock), it is assumed that the sortie airlock would be used for crew loading and unloading.

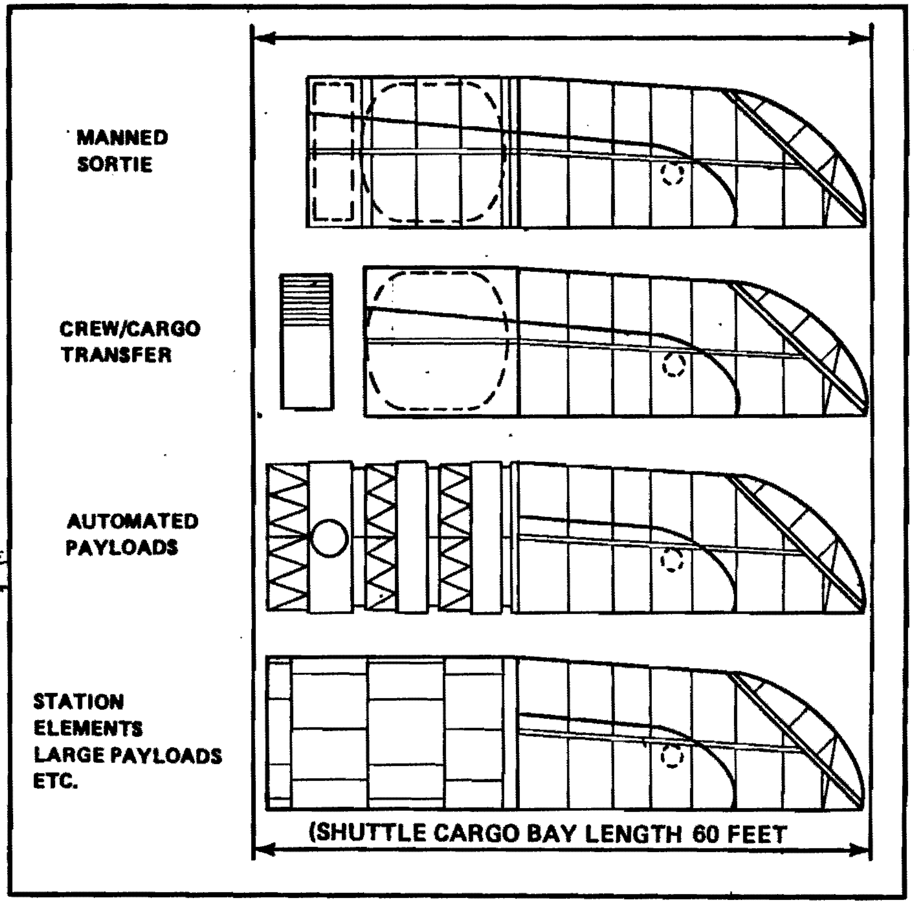
Figure 28 shows typical AMOOS flight configurations when the system is being used for major propulsion events. The AMRS orbital and landing configurations are also shown.

SINGLE SHUTTLE LAUNCH



SHUTTLE PAYLOAD (LOW EARTH ORBIT) CAPABILITY @ 100,000 LB	
STAGE AND PAYLOAD IN SAME SHUTTLE CARGO BAY—LENGTH @	60 FT
AMOOS LENGTH ALLOWABLE (REQUIRES UNIQUE DESIGN, i.e. NESTLED BULKHEADS, TAPERED-OGIVAL TANKS, 7:1 MIXTURE RATIO, etc.)	34 FT
PAYLOAD LENGTH ALLOWABLE	24 FT
LENGTH TOLERANCE	2 FT

CARGO BAY CONFIGURATIONS



CAPABILITIES (SYNCHRONOUS ORBIT)

DELIVERY PAYLOADS	21,000–22,000 LB
ROUND TRIP PAYLOADS	12,500–13,000 LB

Figure 27. Single Shuttle/AMOOS (100 000 lb Shuttle payload capability).

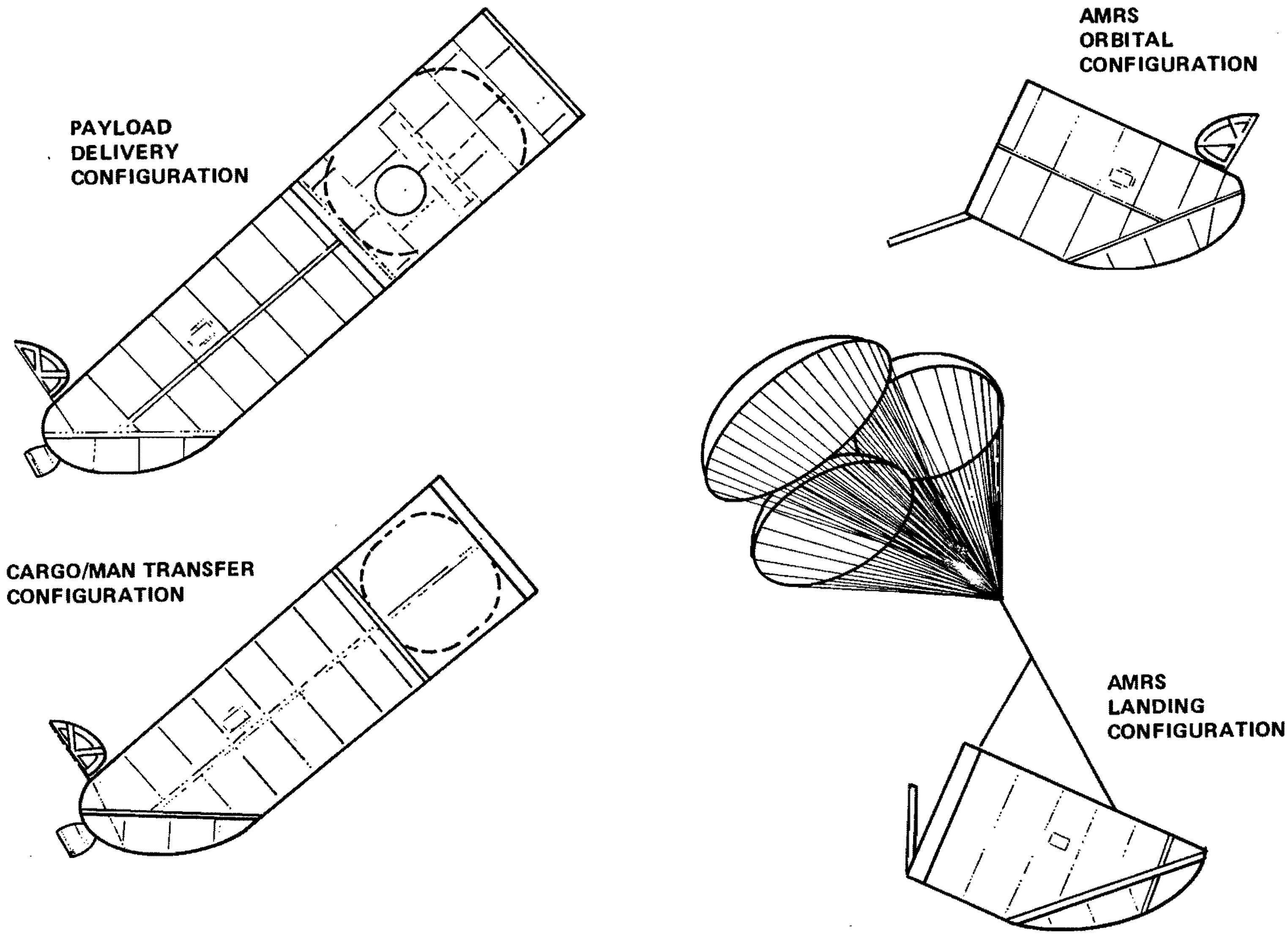


Figure 28. Typical AMOOS flight configurations.

J. Unmanned Payload Configurations

Previous transportation studies have shown the desirability to provide more efficient cargo bay utilization by unmanned payloads. The unmanned orbital platform study performed for MSFC by Rockwell International (RI) developed a payload concept which could be used to obtain the desired effect. RI also showed that the concept would be applicable to most automated payloads and could be considered as a standard spacecraft (Fig. 29).

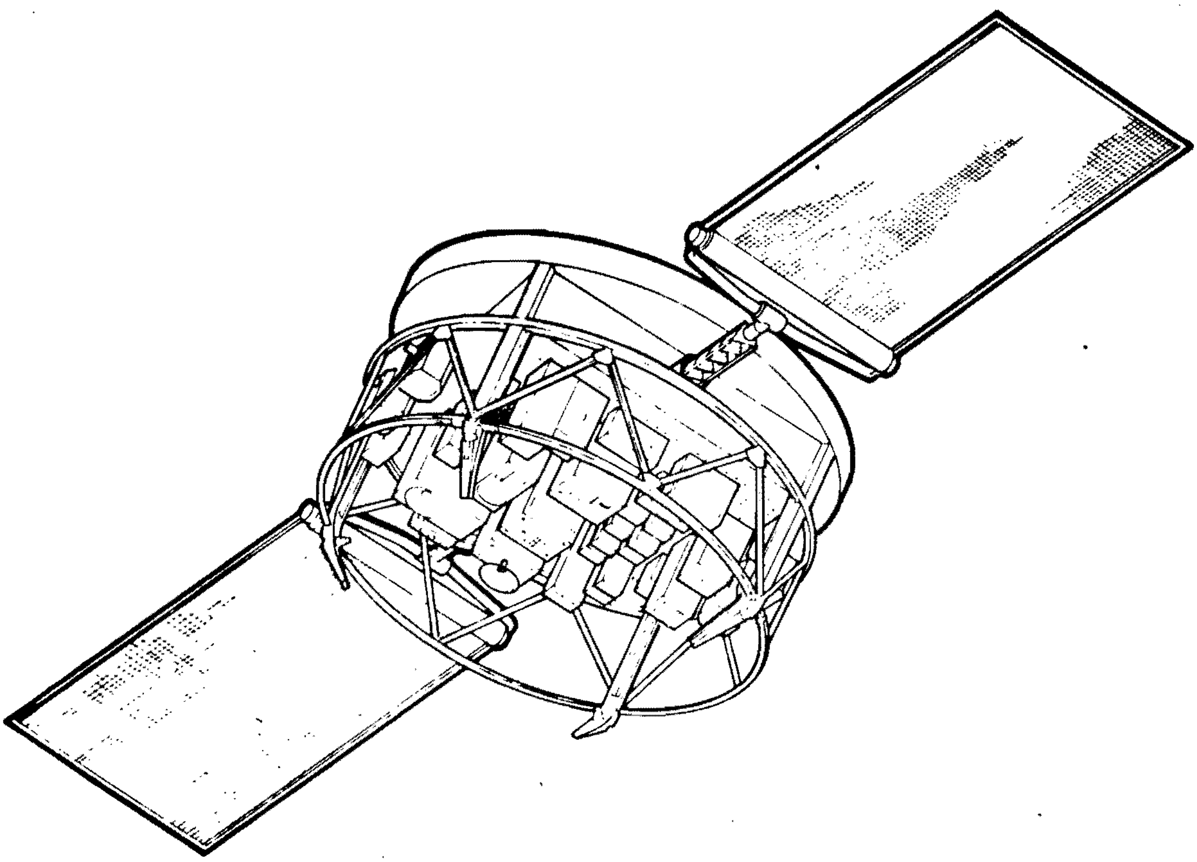


Figure 29. Unmanned orbital platform.

VI. WEIGHT DATA

Several previous study and design efforts are available for weight references for OTV. Primarily the reference data deal with hydrogen- and oxygen-type stages. Baseline stage weights for the APOTV used herein were taken from report MSFC 68 M00039-2, "Baseline Space Tug Configuration Definition," dated July 15, 1974. Baseline stage weights for the AMOOS, the AMRS, and the small man module were taken from report LMSC-HREC TR D49633, "Application Study of Aeromaneuvering Orbit-to-Orbit Shuttle (AMOOS)," dated January 1976. These baseline data were taken as a starting point for the parametric weight data which follow. It is recognized that in some cases the baseline data are not exactly comparable. The error, however, should only be on the order of a few hundred pounds. Future OTV studies should deal with correcting these discrepancies.

A. Lox/Hydrogen Propellant Stages

Weight data for the AMOOS and APOTV concepts are included here. In addition a drop tank system using lox/hydrogen is given.

The baseline weights used for the APOTV are shown in Table 7. This system was designed for a 65 000 lb Shuttle capability delivery mission.

Weights for higher propellant loadings are shown in Tables 8 and 9. Parametric weight data for APOTV reflecting propellant capacities suitable for Shuttle capabilities ranging from 65 000 to 125 000 lb are shown in Figure 30.

The baseline weights for the AMOOS are shown in Table 10. This system was designed for a 65 000 lb Shuttle capability round trip mission. Weights for higher propellant loads are shown in Tables 11 and 12. Parametric weight data for AMOOS reflecting capacities ranging from 65 000 to 125 000 lb are shown on Figure 31.

B. Lox/Hydrogen Propellant Drop Tanks

Several NASA transportation studies have considered using recoverable lox/hydrogen stages with expendable drop tanks used to supplement the basic stage propellant loading. Weights for such a drop tank with 50 000 lb of lox/hydrogen propellant are given in Table 13. These weights were derived by using the design weights developed for the baseline APOTV tankage. Parametric weight data for drop tanks with propellant loadings between 50 000 lb and 100 000 lb are given in Figure 32.

TABLE 7. APOTV BASELINE WEIGHTS

Structures		Thermal Control	
Body Shell	914	Active Thermal Control	70
Fuel Tank and Supports	425	Fuel Tank Insulation	90
Oxidizer Tank and Supports	243	Oxidizer Tank Insulation	40
Thrust Structure	29	Insulation Purge	200
Mounting Structure	100	Passive Thermal Control	41
Payload and Umbilical Interface	263	Total Subsystem Weight	441
Total Subsystem Weight	1947		
Propulsion		Avionics	
Engine	442	Guidance, Navigation, and Control	154
Feed, Fill, Drain, and Vent	256	Data Management	158
Pneumatic and Pressurization	234	Communication	72
Hydraulic	63	Measuring System	92
Propellant Loading and Measuring	50	Electrical Power and Distribution	410
APS	301	Rendezvous and Docking	35
Total Subsystem Weight	1346	Total Subsystem Weight	921
		10 Percent Growth	468
Propellant: Lox/hydrogen Mixture Ratio: 6:1		Total System Dry Weight	5150

TABLE 8. APOTV WEIGHTS FOR 83 255 lb PROPELLANT LOAD

Structures		Thermal Control	
Body Shell	1691	Active Thermal Control	108
Fuel Tank and Supports	715	Fuel Tank Insulation	150
Oxidizer Tank and Supports	521	Oxidizer Tank Insulation	67
Thrust Structure	45	Insulation Purge	295
Mounting Structure	154	Passive Thermal Control	67
Payload and Umbilical Interface	404	Total Subsystem Weight	687
Total Subsystem Weight	3530		
Propulsion		Avionics	
Engine	680	Guidance, Navigation, and Control	169
Feed, Fill, Drain, and Vent	275	Data Management	158
Pneumatic and Pressurization	306	Communication	72
Hydraulic	70	Measuring System	92
Propellant Loading and Measuring	65	Electrical Power and Distribution	451
APS	463	Rendezvous and Docking	35
Total Subsystem Weight	1859	Total Subsystem Weight	977
		10 Percent Growth + Contingency	979
Propellant: Lox/hydrogen			
Mixture Ratio: 6:1		Total System Dry Weight	8032

TABLE 9. APOTV WEIGHTS FOR 99 248 lb PROPELLANT LOAD

Structures		Thermal Control	
Body Shell	2199	Active Thermal Control	135
Fuel Tank and Supports	892	Fuel Tank Insulation	186
Oxidizer Tank and Supports	717	Oxidizer Tank Insulation	83
Thrust Structure	56	Insulation Purge	374
Mounting Structure	192	Passive Thermal Control	89
Payload and Umbilical Interface	505	Total Subsystem Weight	867
Total Subsystem Weight	4561		
Propulsion		Avionics	
Engine	850	Guidance, Navigation, and Control	175
Feed, Fill, Drain, and Vent	300	Data Management	158
Pneumatic and Pressurization	381	Communication	72
Hydraulic	126	Measuring System	92
Propellant Loading and Measuring	81	Electrical Power and Distribution	496
APS	578	Rendezvous and Docking	35
Total Subsystem Weight	2316	Total Subsystem Weight	1028
		10 Percent Growth + Contingency	1229
Propellant: Lox/hydrogen			
Mixture Ratio: 6:1		Total System Dry Weight	10 001

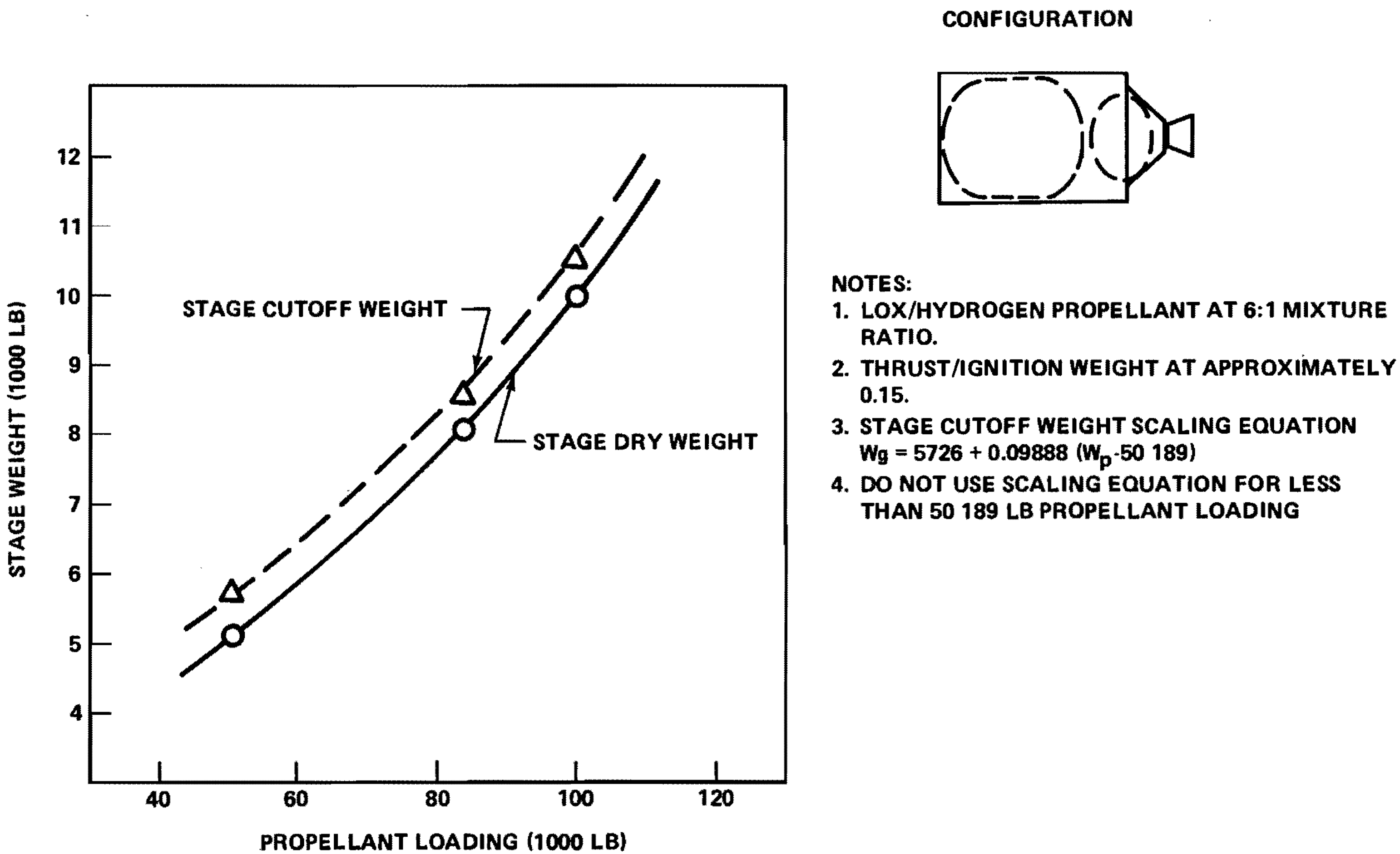


Figure 30. Lox/hydrogen propellant APOTV weight versus propellant loading.

TABLE 10. BASELINE AMOOS WEIGHTS

Structures	
Gimbal	30
Fuel Tank and Support	417
Oxidizer Tank and Support	238
Thrust Structure	29
Mounting Structure	100
Nose Actuator	100
Shell Structure	1013
Aft Ring Interface	30
Total Subsystem Weight	1957
Propulsion	
Engine	442
Feed, Fill, Drain, and Vent	256
Pneumatic and Press	234
Hydraulic	63
Propellant Load and Measuring	50
APS	500
Total Subsystem Weight	1545
Thermal Control	
Tank Insulation	130
Purge and Control System	311
Thermal Protection System	1036
Total Subsystem Weight	1477
Avionics	
Guidance, Navigation, and Control	154
Data Management	158
Communications	72
Measuring Systems	92
Electrical Power and Distribution	410
Rendezvous and Docking	35
Total Subsystem Weight	921
Unbudgeted Contingency	210
10 Percent Contingency	590
Total System Dry Weight	6700

Propellant: Lox/hydrogen
Mixture Rate: 6:1

TABLE 11. AMOOS WEIGHTS FOR 72 000 lb PROPELLANT LOAD

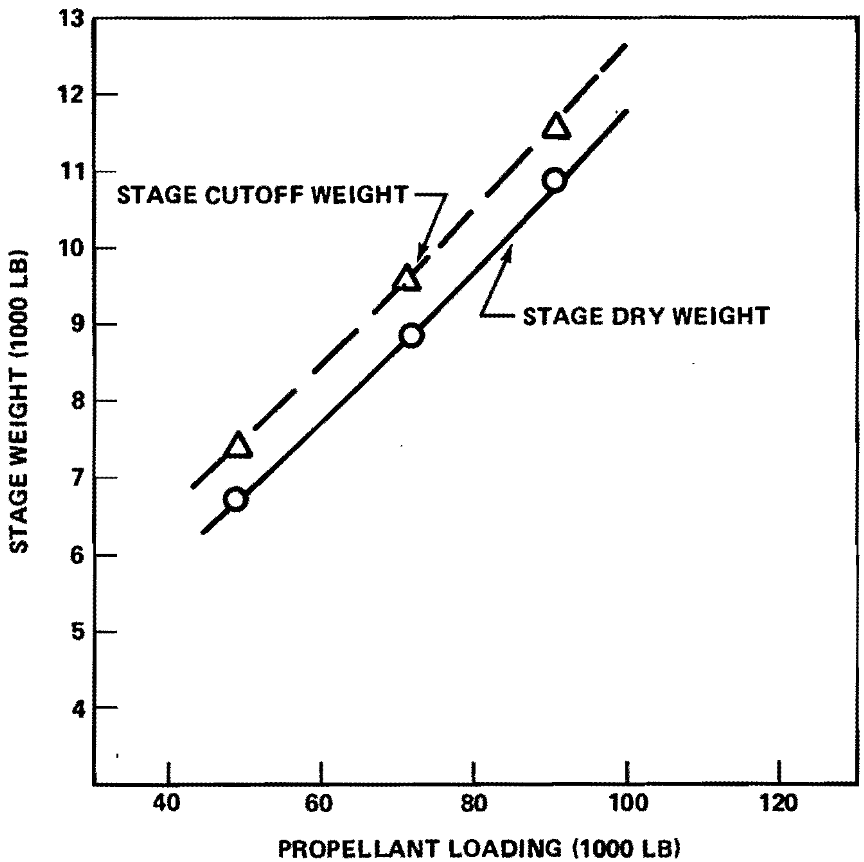
Structures		Thermal Control	
Gimbal	46	Tank Insulation	191
Fuel Tank and Support	616	Purge and Control System	458
Oxidizer Tank and Support	448	Thermal Protection System	1036
Thrust Structure	45	Total Subsystem Weight	1685
Mounting Structure	154	Avionics	
Nose Actuator	100	Guidance, Navigation, and Control	169
Shell Structure	1646	Data Management	158
Aft Ring Interface	45	Communications	72
Total Subsystem Weight	3100	Measuring Systems	92
Propulsion		Electrical Power and Distribution	451
Engine	680	Rendezvous and Docking	35
Feed, Fill, Drain, and Vent	275	Total Subsystem Weight	977
Pneumatic and Press	306	Unbudgeted Contingency	320
Hydraulic	70	10 Percent Contingency	780
Propellant Load and Measuring	65		
APS	635		
Total Subsystem Weight	2031	Total System Dry Weight	8893

Propellant: Lox/hydrogen
Mixture Rate: 6:1

TABLE 12. AMOOS WEIGHTS FOR 90 200 lb PROPELLANT LOAD

Structures		Thermal Control	
Gimbal	58	Tank Insulation	243
Fuel Tank and Support	787	Purge and Control System	582
Oxidizer Tank and Support	632	Thermal Protection System	1036
Thrust Structure	56	Total Subsystem Weight	1861
Mounting Structure	192		
Nose Actuator	100	Avionics	
Shell Structure	2192	Guidance, Navigation, and Control	175
Aft Ring Interface	60	Data Management	178
Total Subsystem Weight	4077	Communications	72
		Measuring Systems	92
Propulsion		Electrical Power and Distribution	496
Engine	850	Rendezvous and Docking	35
Feed, Fill, Drain, and Vent	300	Total Subsystem Weight	1028
Pneumatic and Press	381	Unbudgeted Contingency	400
Hydraulic	126	10 Percent Contingency	950
Propellant Load and Measuring	81		
APS	730		
Total Subsystem Weight	2468	Total System Dry Weight	10 784

Propellant: Lox/hydrogen
Mixture Rate: 6:1



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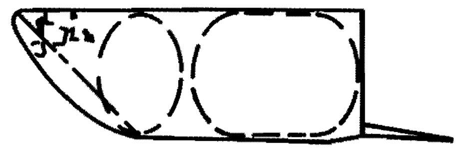


NOTES:

1. LOX/HYDROGEN PROPELLANT AT 6:1 MIXTURE RATIO.
2. THRUST/IGNITION WEIGHT AT APPROXIMATELY 0.15.
3. STAGE CUTOFF WEIGHT SCALING EQUATION $W_g = 7425 + 0.09784\ (W_p - 48\ 500)$
4. DO NOT USE SCALING EQUATION FOR LESS THAN 48 500 LB PROPELLANT LOADING.

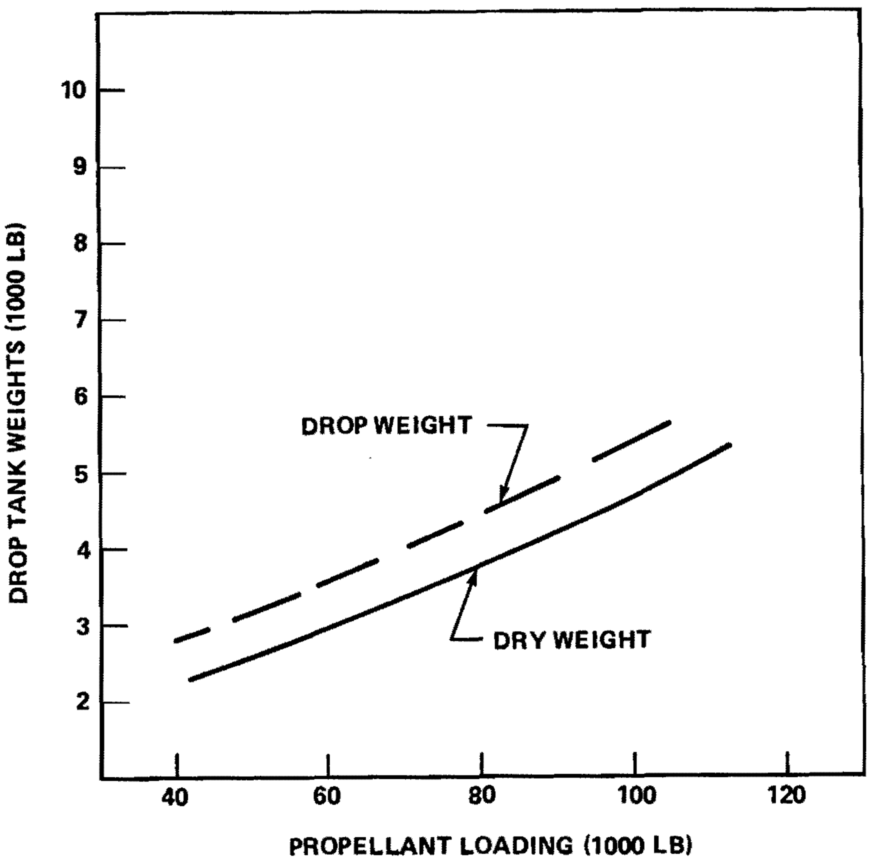
Figure 31. Lox/hydrogen propellant AMOOS weight versus propellant loading.

TABLE 13. DROP TANK WEIGHTS

Drop Tank Weights for 50 000 lb Usable Propellant Loading		
Structure Subsystem		1995
Body Shell	1023	
Fuel Tank and Support	476	
Oxidizer Tank and Support	272	
Mounting Structure	112	
Umbilical Interface	112	
Propulsion Subsystem		540
Fill, Feed, Drain, and Vent	256	
Pneumatic and Pressure	234	
Propellant Load and Measuring	50	
Thermal Control Subsystem		141
Active Thermal Control	35	
Fuel Tank Insulation	45	
Oxidizer Tank Insulation	20	
Passive Thermal Control	41	
Total Dry Weight		2676

Notes:

1. 176 in. Shell Diameter
2. Lox/Hydrogen Propellant at 6:1 Mixture Ratio
3. Unusables at 545 lb
4. Thermal Control for 24 hr
5. Drop Tanks are Expendable



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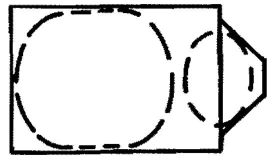

NOTES:

1. 176 IN. SHELL DIAMETER
2. LOX/HYDROGEN PROPELLANT AT 6:1 MIXTURE RATIO
3. THERMAL CONTROL FOR 24 HR.
4. CUTOFF WEIGHT SCALING EQUATION $W_g = 3221 + 0.0474\ (W_p - 50\ 000)$
5. DROP TANKS ARE EXPENDABLE

Figure 32. Lox/hydrogen propellant drop tank weight versus propellant loading.

C. Earth and Space Storable Propellant Stages

To compare the performance of the lox/hydrogen propellant stages with Earth and space storable propellant stages, weight data for lox/RP and N_2O_4/MMH propellants have been estimated for the APOTV and AMOOS concepts. APOTV data are shown in Tables 14 through 17 and in Figures 33 and 34. AMOOS data are shown in Tables 18 through 21 and in Figures 35 and 36.

D. Manned Modules and Emergency Vehicles

Weight data for the AMRS (which would serve as a lifeboat type system and which uses AMOOS type aeromaneuvering) have been developed under study contract with LMSC. Data for a minimum manned module concept to carry four men for 7 days have also been developed. These data may be found in the report LMSC-HREC TR D 496644. The weight data are summarized in Table 22.

The manned module weight data were for use on the AMOOS concept which requires reentry thermal protection. An appropriate manned module weight for use with the APOTV is derived by subtracting the reentry thermal protection. Weight data for the APOTV manned module are also given in Table 22.

It is emphasized that the AMRS and manned module weight data represent very minimal missions, and no payload is included. The AMRS includes no extravehicular activity (EVA) capability, and the manned module includes weights for EVA by two of the crew.

The weight required for the crew module is a significant issue in the selection of an OTV concept. For this reason the manned module weights have been compared with other systems or design data which represent similar hardware. References for this comparison are all manned module data taken from:

1. "Pre-phase A Technical Study for Use of Saturn V, Int 21, and Other Saturn V Derivatives to Determine an Optimum Fourth Stage," NASA Document CR-103004 Space Tug Volume I of II, February 26, 1971.

2. The Lunar Excursion Module (LEM) data were obtained from the "Apollo Operations Handbook Spacecraft," LMA790-3-LM, dated February 1, 1970.

3. The AMOOS Module Data were obtained from "Applications Study of Aero-Maneuvering Orbit-to-Orbit Shuttle (AMOOS)" LMSC-HREC TR D496644, January 1976.

TABLE 14. APOTV WITH 52 394 lb LOX/RP1 PROPELLANT LOAD

Structures		Thermal Control	
Body Shell	474	Active Thermal Control	60
Fuel Tank and Supports	146	Fuel Tank Insulation	30
Oxidizer Tank and Supports	268	Oxidizer Tank Insulation	40
Thrust Structure	29	Insulation Purge	72
Mounting Structure	100	Passive Thermal Control	41
Payload and Umbilical Interface	263	Total Subsystem Weight	243
Total Subsystem Weight	1280		
Propulsion		Avionics	
Engine	442	Guidance, Navigation, and Control	154
Feed, Fill, Drain, and Vent	256	Data Management	158
Pneumatic and Pressurization	234	Communication	72
Hydraulic	63	Measuring System	92
Propellant Loading and Measuring	50	Electrical Power and Distribution	410
APS	301	Rendezvous and Docking	35
Total Subsystem Weight	1346	Total Subsystem Weight	921
		10 Percent Growth	379
Propellant: Lox/RP1			
Mixture Ratio: 3.2:1		Total System Dry Weight	4169

TABLE 15. APOTV WITH 99 865 lb LOX/RP1 PROPELLANT LOAD

Structures		Thermal Control	
Body Shell	733	Active Thermal Control	106
Fuel Tank and Supports	268	Fuel Tank Insulation	57
Oxidizer Tank and Supports	584	Oxidizer Tank Insulation	76
Thrust Structure	39	Insulation Purge	119
Mounting Structure	108	Passive Thermal Control	79
Payload and Umbilical Interface	336	Total Subsystem Weight	437
Total Subsystem Weight	2068		
Propulsion		Avionics	
Engine	475	Guidance, Navigation, and Control	154
Feed, Fill, Drain, and Vent	341	Data Management	158
Pneumatic and Pressurization	444	Communication	72
Hydraulic	84	Measuring System	92
Propellant Loading and Measuring	95	Electrical Power and Distribution	410
APS	579	Rendezvous and Docking	35
Total Subsystem Weight	2018	Total Subsystem Weight	921
		10 Percent Growth	835
Propellant: Lox/RP1			
Mixture Ratio: 3.2:1		Total System Dry Weight	5988

TABLE 16. APOTV WITH 56 595 lb N_2O_4/MMH PROPELLANT LOAD

Structures		Thermal Control	
Body Shell	409	Active Thermal Control	50
Fuel Tank and Supports	197	Fuel Tank Insulation	20
Oxidizer Tank and Supports	275	Oxidizer Tank Insulation	40
Thrust Structure	29	Insulation Purge	62
Mounting Structure	100	Passive Thermal Control	41
Payload and Umbilical Interface	263	Total Subsystem Weight	213
Total Subsystem Weight	1273		
Propulsion		Avionics	
Engine	442	Guidance, Navigation, and Control	154
Feed, Fill, Drain, and Vent	256	Data Management	158
Pneumatic and Pressurization	234	Communication	72
Hydraulic	63	Measuring System	92
Propellant Loading and Measuring	50	Electrical Power and Distribution	410
APS	301	Rendezvous and Docking	35
Total Subsystem Weight	1346	Total Subsystem Weight	921
		10 Percent Growth	375
Propellant: N_2O_4/MMH			
Mixture Ratio: 2.2:1		Total System Dry Weight	4128

TABLE 17. APOTV WITH 99 865 lb N_2O_4/MMH PROPELLANT LOAD

Structures		Thermal Control	
Body Shell	634	Active Thermal Control	96
Fuel Tank and Supports	573	Fuel Tank Insulation	38
Oxidizer Tank and Supports	730	Oxidizer Tank Insulation	76
Thrust Structure	39	Insulation Purge	119
Mounting Structure	108	Passive Thermal Control	79
Payload and Umbilical Interface	336	Total Subsystem Weight	408
Total Subsystem Weight	2420		
Propulsion		Avionics	
Engine	475	Guidance, Navigation, and Control	154
Feed, Fill, Drain, and Vent	341	Data Management	158
Pneumatic and Pressurization	444	Communication	72
Hydraulic	84	Measuring System	92
Propellant Loading and Measuring	95	Electrical Power and Distribution	410
APS	579	Rendezvous and Docking	35
Total Subsystem Weight	2018	Total Subsystem Weight	921
		10 Percent Growth	577
Propellant: N_2O_4/MMH			
Mixture Ratio: 2.2:1		Total System Dry Weight	6344

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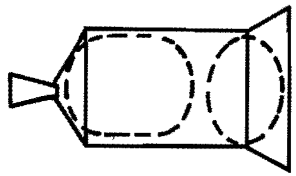


NOTES:

1. LOX/RP PROPELLANT AT 3.2:1 MIXTURE RATIO
2. THRUST/IGNITION WEIGHT AT APPROXIMATELY 0.15
3. STAGE CUTOFF WEIGHT SCALING EQUATION $W_g = 4733 + 0.04167\ (W_p\text{-}55\,000)$
4. DO NOT USE SCALING EQUATION FOR LESS THAN 55 000 LB PROPELLANT LOADING

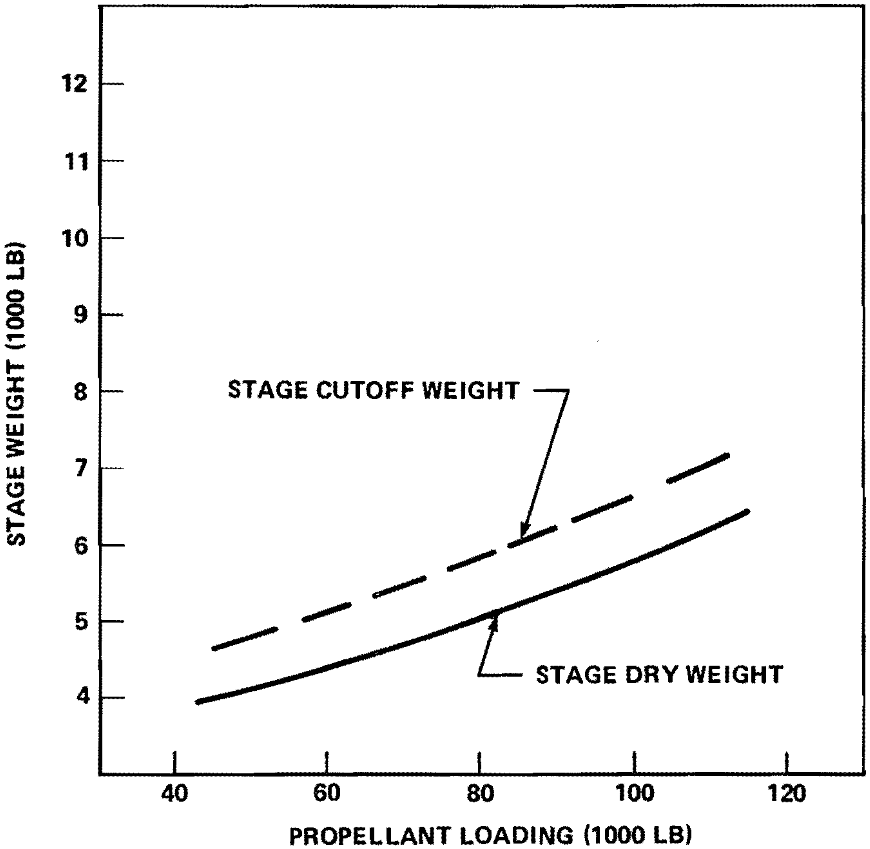
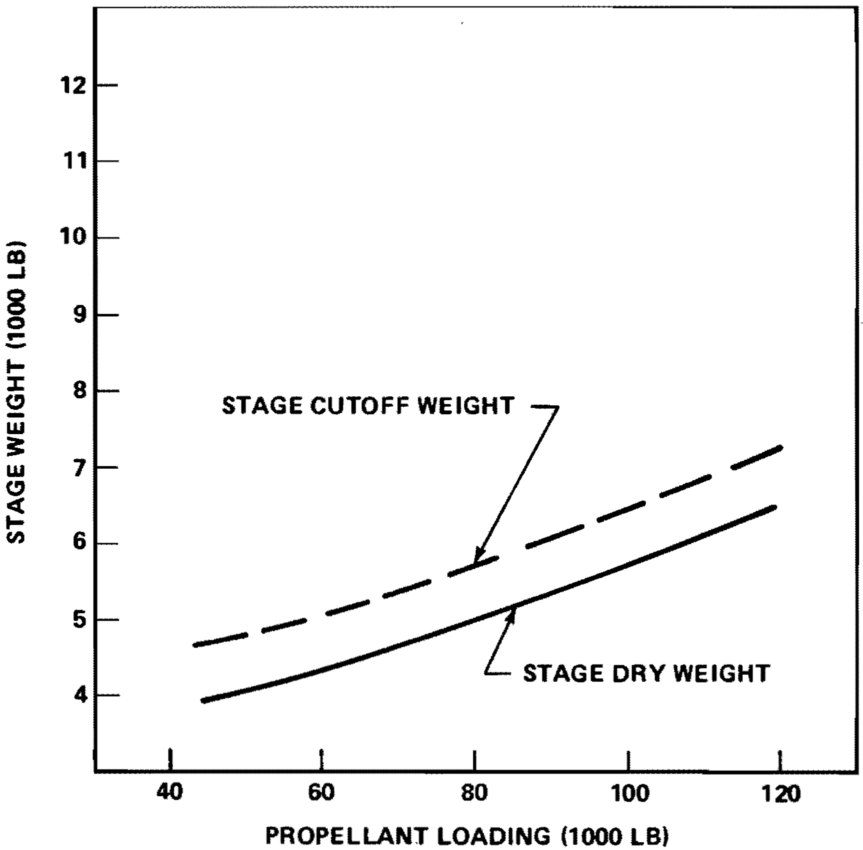


Figure 33. Lox/RP propellant APOTV weight versus propellant loading.



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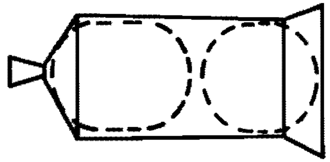


NOTES:

1. N_2O_4/MMH PROPELLANT AT 2.2:1 MIXTURE RATIO
2. THRUST/IGNITION WEIGHT AT APPROXIMATELY 0.15
3. STAGE CUTOFF WEIGHT SCALING EQUATION $W_g = 5500 + 0.04155\ (W_p - 56\,400)$
4. DO NOT USE SCALING EQUATION FOR PROPELLANT LOADING LESS THAN 56 400 LB

Figure 34. N_2O_4/MMH propellant APOTV weight versus propellant loading.

TABLE 18. AMOOS WITH 52 391 lb LOX/RP1 PROPELLANT LOAD

Structures	
Gimbal	30
Fuel Tank and Support	146
Oxidizer Tank and Support	268
Thrust Structure	29
Mounting Structure	100
Nose Actuator	100
Shell Structure	704
Aft Ring Interface	24
Total Subsystem Weight	1401
Propulsion	
Engine	442
Feed, Fill, Drain, and Vent	256
Pneumatic and Press	234
Hydraulic	63
Propellant Load and Measuring	50
APS	500
Total Subsystem Weight	1545
Thermal Control	
Tank Insulation	78
Purge and Control System	187
Thermal Protection System	719
Total Subsystem Weight	953
Avionics	
Guidance, Navigation, and Control	154
Data Management	158
Communications	72
Measuring Systems	92
Electrical Power and Distribution	410
Rendezvous and Docking	35
Total Subsystem Weight	921
Unbudgeted Contingency	144
10 Percent Contingency	496
Total System Dry Weight	5461

Propellant: Lox/RP1
Mixture Rate: 3.2:1

TABLE 19. AMOOS WITH 99 911 lb LOX/RP1 PROPELLANT LOAD

Structures		Thermal Control	
Gimbal	50	Tank Insulation	148
Fuel Tank and Support	268	Purge and Control System	355
Oxidizer Tank and Support	584	Thermal Protection System	935
Thrust Structure	38	Total Subsystem Weight	1438
Mounting Structure	107		
Nose Actuator	100	Avionics	
Shell Structure	914	Guidance, Navigation, and Control	174
Aft Ring Interface	46	Data Management	158
Total Subsystem Weight	2107	Communications	72
		Measuring Systems	92
Propulsion		Electrical Power and Distribution	410
Engine	475	Rendezvous and Docking	35
Feed, Fill, Drain, and Vent	341	Total Subsystem Weight	941
Pneumatic and Press	444	Unbudgeted Contingency	206
Hydraulic	84	10 Percent Contingency	709
Propellant Load and Measuring	95		
APS	962		
Total Subsystem Weight	2401	Total System Dry Weight	7802

Propellant: Lox/RP1
Mixture Rate: 3.2:1

TABLE 20. AMOOS WITH 52 412 lb N_2O_4/MMH PROPELLANT LOAD

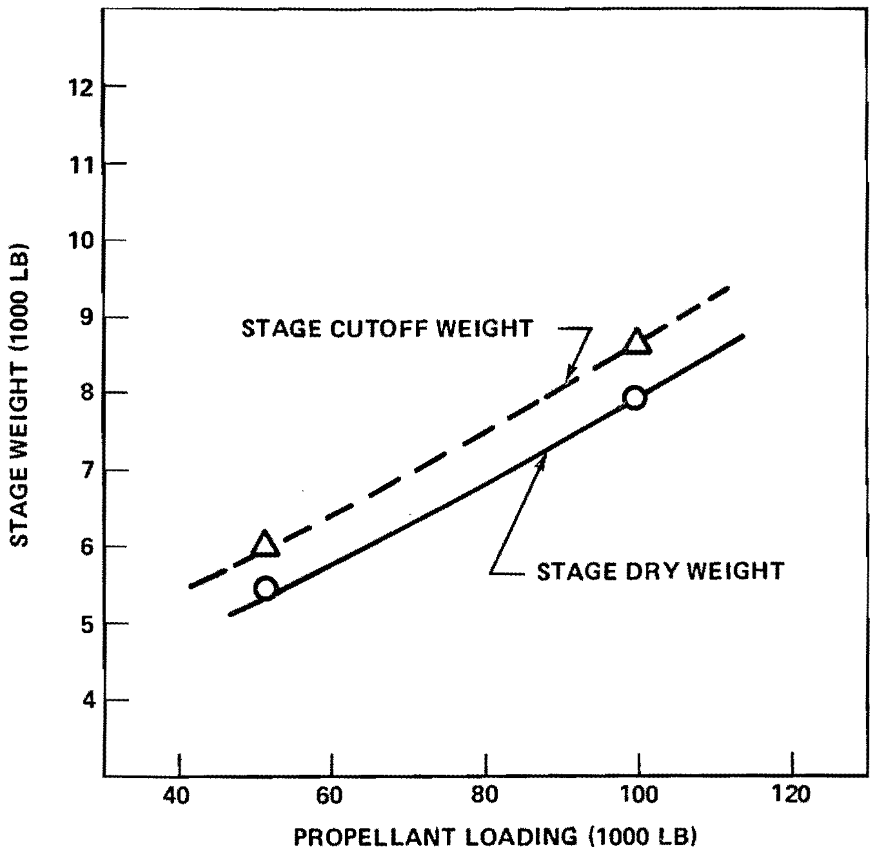
Structures	
Gimbal	30
Fuel Tank and Support	197
Oxidizer Tank and Support	275
Thrust Structure	29
Mounting Structure	100
Nose Actuator	100
Shell Structure	667
Aft Ring Interface	24
Total Subsystem Weight	1422
Propulsion	
Engine	442
Feed, Fill, Drain, and Vent	256
Pneumatic and Press	234
Hydraulic	63
Propellant Load and Measuring	50
APS	500
Total Subsystem Weight	1545
Thermal Control	
Tank Insulation	26
Purge and Control System	62
Thermal Protection System	682
Total Subsystem Weight	770
Avionics	
Guidance, Navigation, and Control	154
Data Management	158
Communications	72
Measuring Systems	92
Electrical Power and Distribution	410
Rendezvous and Docking	35
Total Subsystem Weight	921
Unbudgeted Contingency	140
10 Percent Contingency	480
Total System Dry Weight	5278

Propellant: N_2O_4/MMH
Mixture Rate: 2.2:1

TABLE 21. AMOOS WITH 99 865 lb N_2O_4/MMH PROPELLANT LOAD

Structures	
Gimbal	40
Fuel Tank and Support	573
Oxidizer Tank and Support	730
Thrust Structure	39
Mounting Structure	108
Nose Actuator	100
Shell Structure	1055
Aft Ring Interface	60
Total Subsystem Weight	2705
Propulsion	
Engine	475
Feed, Fill, Drain, and Vent	341
Pneumatic and Press	444
Hydraulic	84
Propellant Load and Measuring	95
APS	961
Total Subsystem Weight	2400
Thermal Control	
Tank Insulation	49
Purge and Control System	118
Thermal Protection System	1078
Total Subsystem Weight	1245
Avionics	
Guidance, Navigation, and Control	174
Data Management	158
Communications	72
Measuring Systems	92
Electrical Power and Distribution	410
Rendezvous and Docking	35
Total Subsystem Weight	941
Unbudgeted Contingency	219
10 Percent Contingency	751
Total System Dry Weight	8260

Propellant: N_2O_4/MMH
Mixture Rate: 2.2:1



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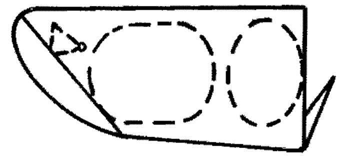
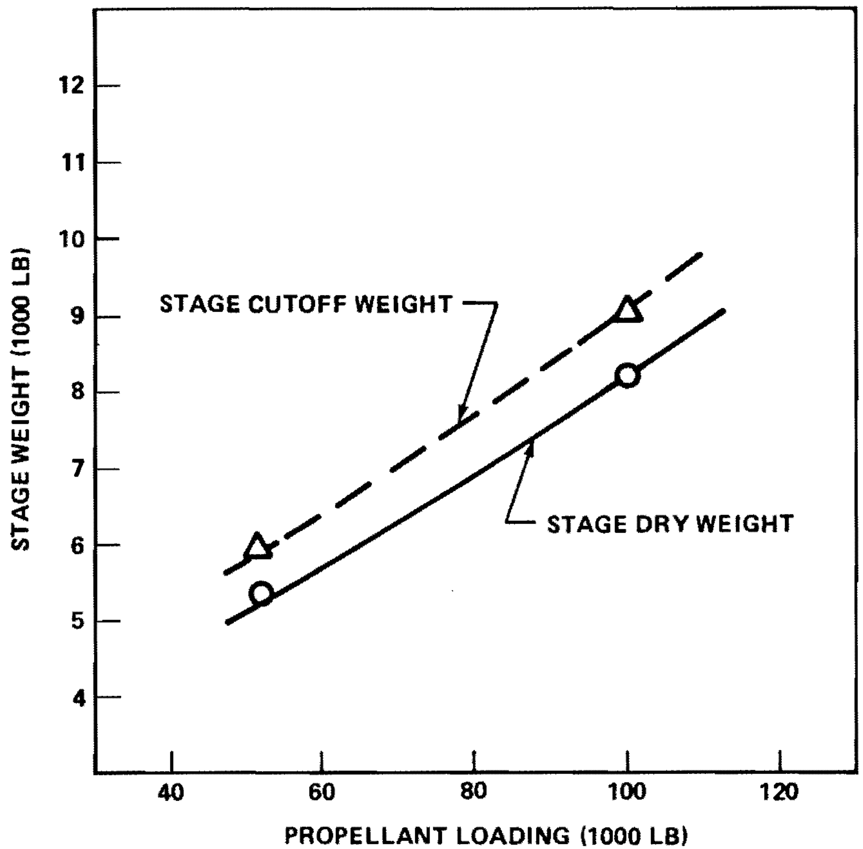


NOTES:

1. LOX/RP PROPELLANT AT 3.2:1 MIXTURE RATIO
2. THRUST/IGNITION WEIGHT AT APPROXIMATELY 0.15
3. STAGE CUTOFF WEIGHT SCALING EQUATION
   $W_g = 6070 + 0.05326\ (W_p - 52\,400)$
4. DO NOT USE SCALING EQUATION FOR LESS THAN 52 400 LB PROPELLANT LOADING

Figure 35. Lox/RP propellant AMOOS weight versus propellant loading.



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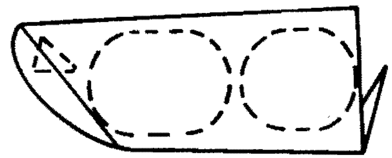


NOTES:

1. N_2O_4/MMH PROPELLANT AT 2.2:1 MIXTURE RATIO
2. THRUST/IGNITION WEIGHT AT APPROXIMATELY 0.15
3. STAGE CUTOFF WEIGHT SCALING EQUATION $W_g = 5900 + 0.06723\ (W_p\text{-}52\ 400)$
4. DO NOT USE SCALING EQUATION FOR PROPELLANT LOADING LESS THAN 52 400 LB

Figure 36. N_2O_4/MMH propellant AMOOS weight versus propellant loading.

TABLE 22. WEIGHT SUMMARY — MANNED CARRIERS (WEIGHT IN lb)

Vehicle Element	AMRS[a]	Man Module[a] (AMOOS Configuration)	Man Module (APOTV Configuration)
Crew and Supplies	1664	2873	2873
Structures	1542	1671	1671
Thermal Protection	395	335	N/A
Propulsion	867	N/A	N/A
Avionics	1065	725	725
EVA Equipment	N/A	372	372
Miscellaneous	00	40	40
10 Percent Growth	477	604	569
Total Dry Weight	6010	6620	6250
Propellant	6500	N/A	N/A

a. Reference LMSC-HREC TR D 496644.

A comparison with the data being used is shown in Figure 37. As can be seen, the minimum module weight for four men for 7 days is approximately 6500 lb. This is also the approximate weight needed for crew transfer to geosynchronous orbit and return to low Earth orbit. These data are not necessarily applicable for either the crew transfer or the sortie missions, and the data which follow in Paragraph E should be used for the crew transfer and sortie mission cases.

E. Manned Sortie Mission Weights

Previous OTV study as well as other NASA planning studies indicate the desirability for man-sortie mission capability. The data given in Paragraph D may be applicable for short sortie missions where shielding is not important.

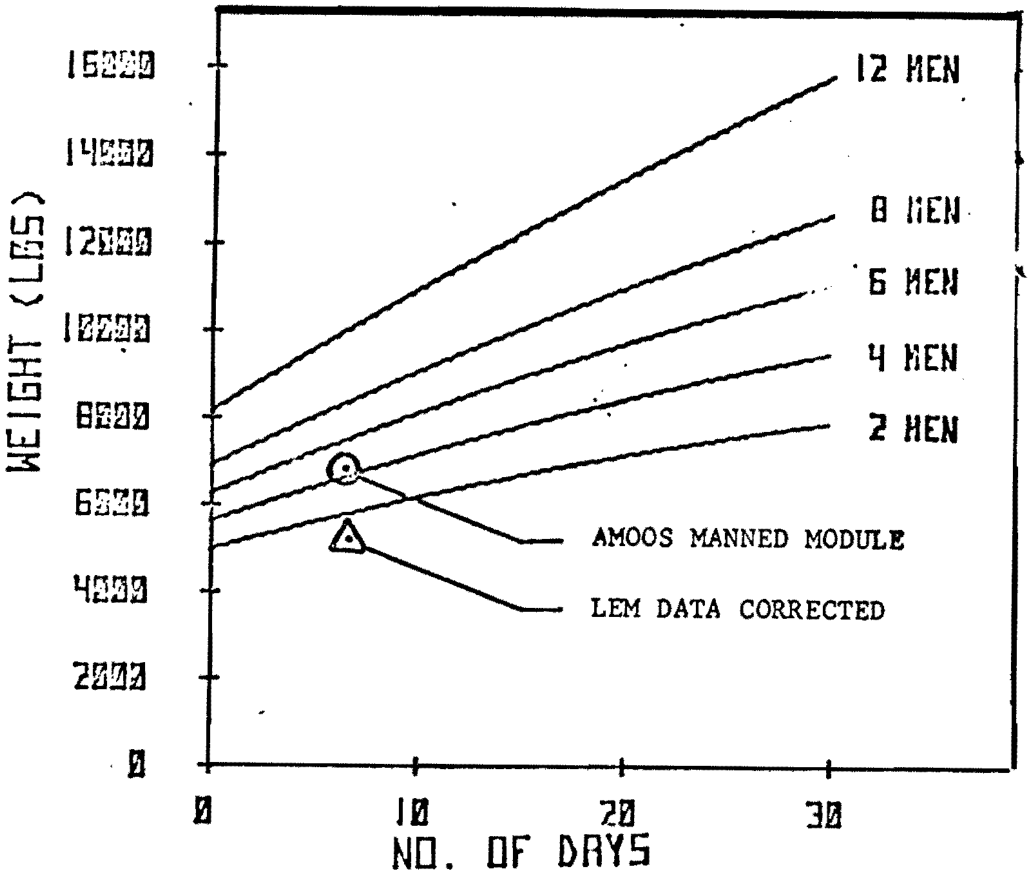


Figure 37. Crew module weight versus man days.

Also, the data assume rather large crew modules. The data which follow in this section were derived to determine the effects of stay time on crew module size and to incorporate current shielding requirements.

Table 23 shows the manned sortie mission volume requirements for a four-man crew for mission times of 2, 7, 14, 21, and 30 days. Table 24 shows the corresponding weight which is required for these missions. No weight is included for the external OTV shell because it is assumed that the shell would contribute to the radiation shield and that the shielding weight would be reduced by the OTV shell weight. This should be satisfactory for the longer missions but may be marginal for shorter missions. The weight values are approximately 20 percent lower than previously given. The OTV power supply would not be designed to accommodate the longer missions. The manned module would be equipped with a power system using fuel cells and solar arrays. This system would supply OTV power during the long mission.

TABLE 23. TRANSPORTATION/SORTIE MISSION MANNED VOLUME REQUIREMENTS

System Closure	4 Man Crew				
	2 Days (ft^3)	7 Days (ft^3)	14 Days (ft^3)	21 Days (ft^3)	30 Days (ft^3)
Structural Subsystem	(308)	(598)	(754)	(934)	(1054)
Module Volume	158	448	604	784	904
Airlock Volume	150	150	150	150	150
Crew Subsystems	(150)	(156)	(167)	(183)	(191)
Food	3	9	18	27	38
Furnishing	144	144	144	144	144
Medical	1	1	1	1	1
Personnel Effects	2	2	4	6	8
Environmental Control and Life Support Subsystems	(5)	(14)	(27)	(41)	(57)
Airlock Atmosphere	1	2	4	6	8
Module Atmosphere	1	3	5	8	11
Water	1	3	6	9	13
Waste Management	2	6	12	18	25
Electrical Subsystem	(6)	(66)	(66)	(66)	(66)
Solar Arrays	—	64	64	64	64
Electrical Distribution and Control	6	2	2	2	2
Communication and Data Management	12	12	14	14	14
Instrumentation	10	13	18	18	18
Controls	4	4	4	4	4
Expendables	4	4	4	4	4
Miscellaneous Equipment	10	10	10	10	10
Packaging Efficiency (85 Percent)	76	131	159	191	212
Totals (ft^3)	585	1008	1223	1414	1630

TABLE 24. TRANSPORTATION/SORTIE MISSION MANNED MODULE WEIGHT REQUIREMENTS

	4 Man Crew				
	2 Days (lb)	7 Days (lb)	14 Days (lb)	21 Days (lb)	30 Days (lb)
Structure	(1126)	(1598)	(3090)	(3348)	(3642)
Frame and Shell	369	528	596	654	720
Airlock	276	276	276	276	276
Shielding	231	634	2058	2258	2486
Docking Mechanism	160	160	160	160	160
Crew Furnishing	(186)	(325)	(494)	(666)	(886)
Bunks and Seats	120	140	140	140	140
Food	30	105	210	315	450
Medicine and Personal Effects	18	18	18	22	26
Clothing and Hygiene	18	62	126	189	270
Crew Equipment	(1258)	(1470)	(1764)	(2058)	(2436)
Man	748	748	748	748	748
EVA Suits	124	124	124	124	124
PLSS	124	124	124	124	124
Miscellaneous Equipment and Interior Suits	180	180	180	180	180
Waste Management (Including Water)	82	294	588	882	1260
Electricity	(490)	(935)	(1115)	(1225)	(1285)
Power and Distribution and Batteries	140	140	140	140	140
Fuel Cells and Charging Equipment and Solar Arrays	—	320	400	460	520
Communication and Data Management and Instrument	450	475	575	625	625
Cabin Pressurization Plus Leakage	36	130	255	385	550
Controls (RCS)	60	60	60	60	60
Expendables and Miscellaneous	310	340	380	420	460
10 Percent Growth	347	486	716	816	932
Totals (lb)	3813	5344	7874	8978	10 251

The data in this section and in Section D were reviewed, and the weight data shown in Table 25 were selected for further OTV analysis.

TABLE 25. WEIGHTS REQUIRED FOR CREW TRANSFER AND SORTIE MISSIONS

Mission	Crew Size	Mission Duration	Weight (lb) Round Trip[a]
Crew Transfer	4	N/A	5 000
	12	N/A	12 000[b]
Man-Sorties	4	7	6 400
	4	14	9 500
	4	21	11 000
	4	30	12 400

a. Does not include any mission equipment weight
b. Reference LMSC 1977 AMOOS Study

Figure 38 shows the data given in Tables 23, 24, and 25 in curve form. As can be seen, the four-man sortie mission weight required is rather linear with mission time. The volume also increases linearly after approximately 7 days. Also referenced on the chart are crew transfer volume requirements as determined by LMSC in the 1977 AMOOS Applications Study. The weight required for a four-man 30 day sortie is approximately the same as that required for a 12-man crew transfer mission.

F. OTV Propellant Loading — Propellant Weight Required

To say that "the sizing of an OTV for a particular Shuttle capability is difficult" is a gross understatement. The propellant loading required for a particular Shuttle capability is determined by:

1. The payload weight

   — Delivery only or

   — Round trip or

   — Combination delivery and round trip

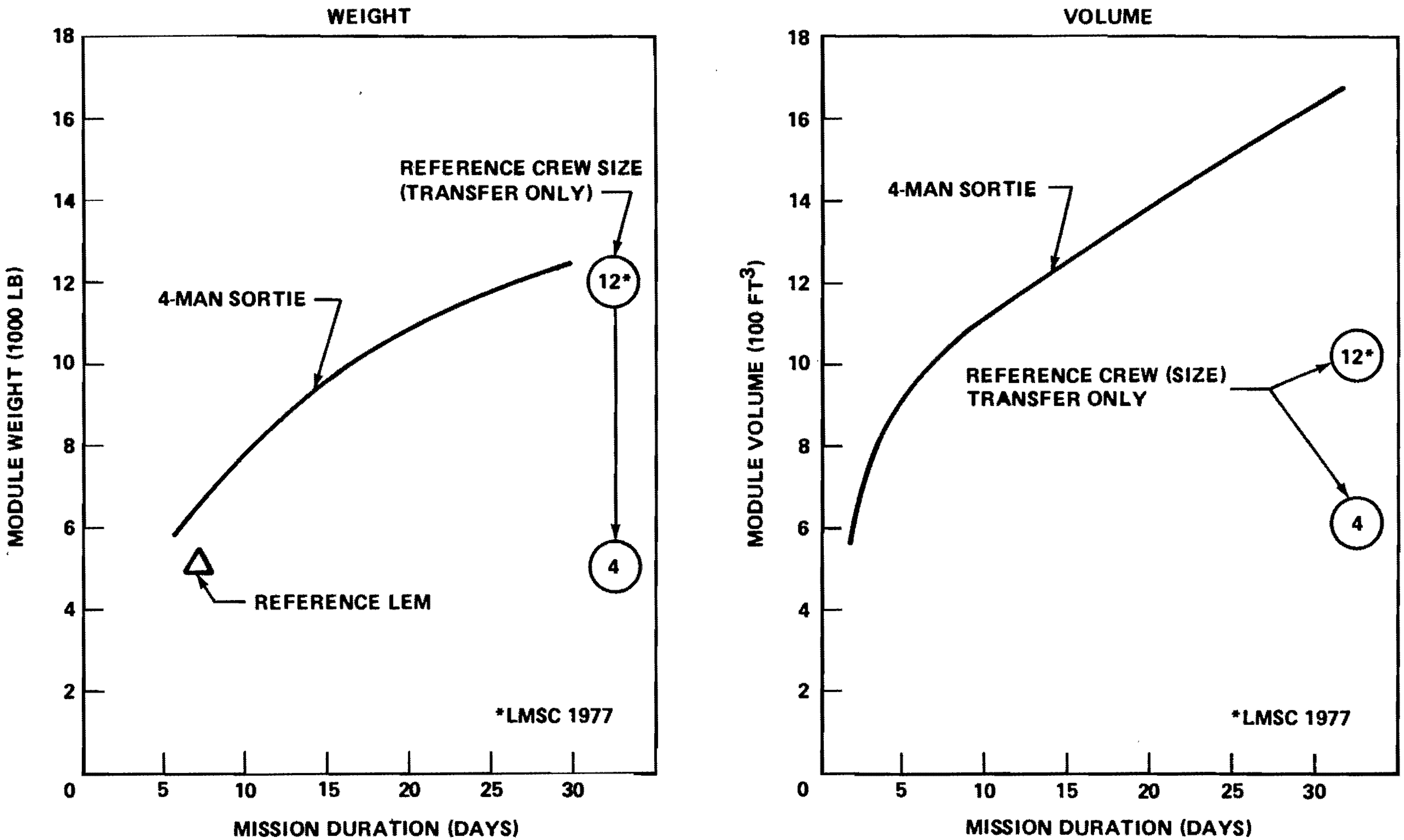


Figure 38. Four-man sortie mission module (reference crew transfer module) weight and volume requirement.

2. The stage weight

   — Dry and

   — Cutoff

3. The Shuttle capability weight

4. Propellant characteristics

   — Type propellant and

   — Engine performance with the propellant

5. Boiloff losses

6. Etc.

To illustrate this problem the various propellant stage weights (dry) for the AMOOS and APOTV concepts versus Shuttle capability are shown in Figure 39. The corresponding propellant loadings are shown in Figure 40. Both weights data are based on single stage performance with an attempt to maintain a 100 percent Shuttle load factor.

As the reader will note, it is virtually impossible to make direct comparison of OTV concepts. The reader may also note that unless all parameters are considered simultaneously for any one particular case, a considerable error may result.

VII. OTV FLIGHT PROFILES

Previous studies reflecting OTV capabilities display several different flight profiles for the various OTV mission applications. In this section the geosynchronous mission flight profile will be discussed for the single stage APOTV and AMOOS configurations. Since the geosynchronous mission probably represents the most stringent requirements on OTV, it probably represents the case which will drive the OTV design. Various issues which show involvement with interfacing systems will also be discussed. Finally, a simplified mission profile for single stage application of the APOTV and AMOOS will be shown. The determination, analysis, and selection of the OTV mission profile is an issue which will have significant effect on OTV system and subsystem design as well as the interfacing STS system and orbital payload hardware. Resolution of this issue should be given high priority in the near future.

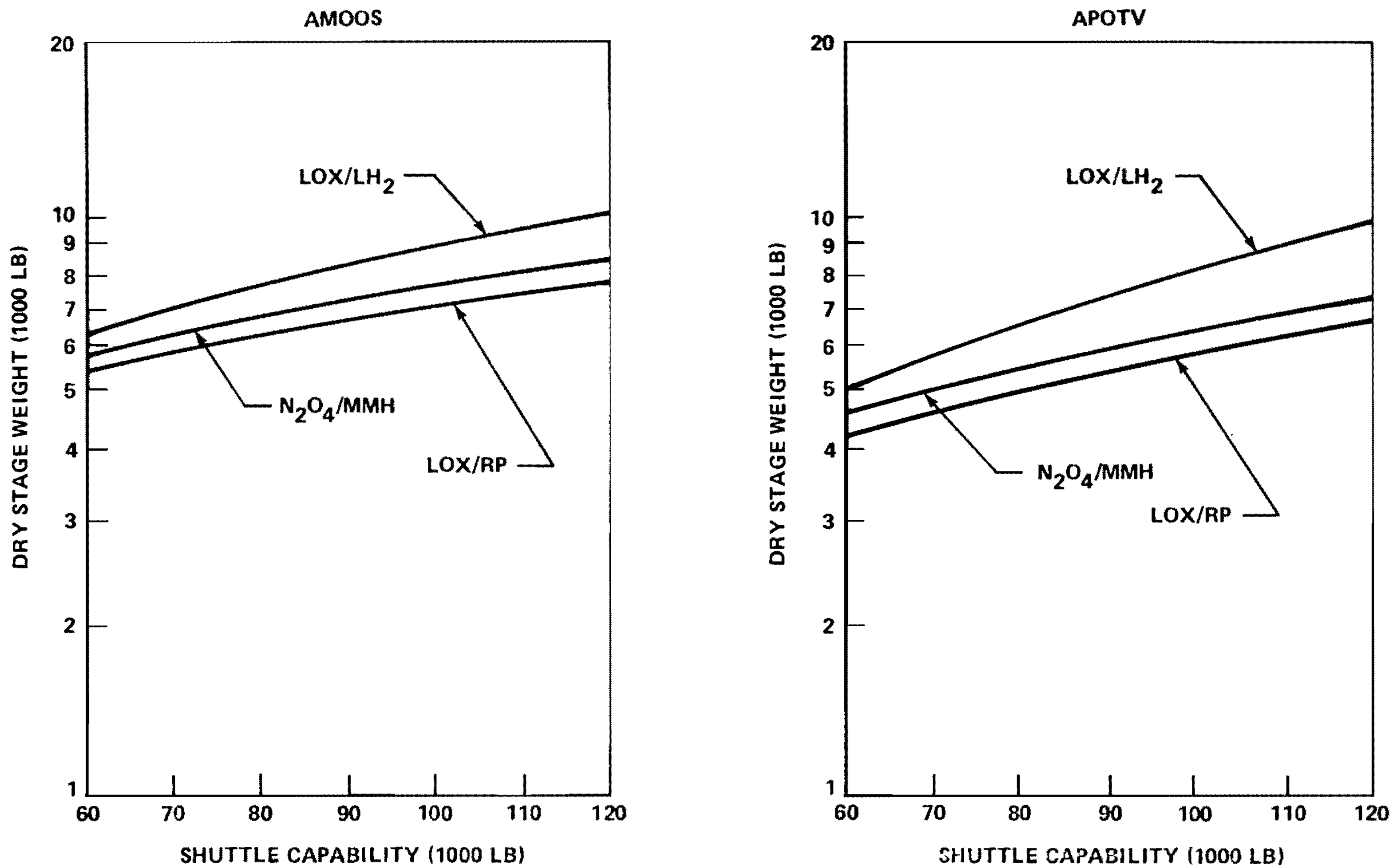


Figure 39. Stage weights versus Shuttle capability.

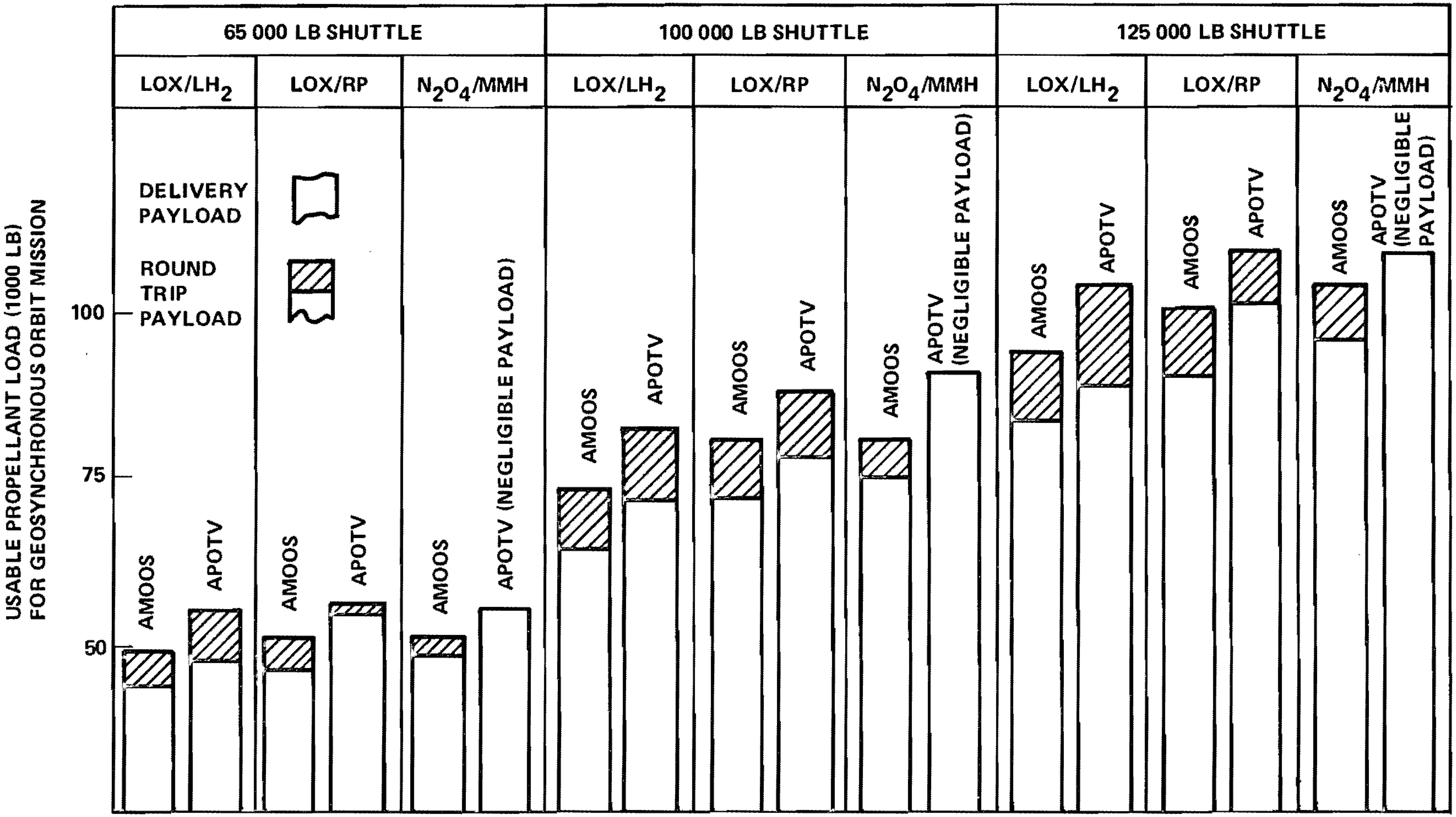


Figure 40. OTV propellant loading — propellant weight required.

A. Events and Issues

The following discussion identifies typical events and some of the issues related to these events. The events are numbered as they would occur during the mission sequence.

Events	Issues
1. Shuttle injection into low Earth orbit	Is orbit circular or elliptical? At what altitude for each different type of mission? Shuttle capability for this orbit?
2. Separate from Shuttle	Is this event performed by the OTV or the Shuttle? What if OTV is Space Station based? Main or auxiliary propulsion?
3. Phase in Shuttle orbit	Does the OTV perform a maneuver or does the Shuttle perform the maneuver here? Main or auxiliary propulsion?
4. Insert to synchronous orbit apogee with plane change (transfer ellipse)	Is this event performed in one or two burns? Can proper phasing be accomplished by event 3? Effects on avionics?
5. Midcourse in transfer ellipse	Is this required? Effects on avionics? Is this destination dependent? Guidance system updating? Main or auxiliary propulsion?
6. Insert to geosynchronous orbit mission phasing orbit	Insertion accuracy? What about multiple payloads delivered to different locations — should their design be affected? Mission dependence?
7. Rendezvous at destination (Space Station, spacecraft, point in space, etc.)	Functions performed by OTV and/or target? Use main and/or auxiliary propulsion? Mission dependence? Multiple rendezvous at different destinations? Activities before and after rendezvous?

Events	Issues
8. Deliver payload	Positioning accuracy? Check out payload? Multiple payloads?
or	
9. Dock	Docking peculiar hardware and/or avionics carried on target or OTV? Number of dockings per mission?
10. On orbit stay	Length of time? Functions to be performed while on orbit? Effects on Shuttle waiting in low Earth orbit? Boiloff? Effects on subsystems?
11. Separate from target or depart location	Guidance update? Time phasing? Is total orbit mission complete?
12. Move to next target	Phasing? Main or auxiliary propulsion?
or	
13. Insert to low Earth orbit transfer ellipse	Guidance update? Time phasing? What portion of plane change to make propulsively (AMOOS only)? Number of burns?
14. Midcourse correction	Entry corridor? Altitude and longitude requirement? Subsystem effects? Timing of correction? Guidance updating?
15. Low Earth orbit injection burn (APOTV only)	Number of burns? Altitude error? Inclination error? Phasing? Period in high radiation environment?
or	
16. Low Earth orbit aeromaneuver (AMOOS only)	Large Reaction Control System (RCS) required. Number of passes? Communications during maneuver? Plane change to perform? Payload protection? Apogee altitude? Minimum altitude?
17. Raise perigee (AMOOS only)	Initiate by timer or by guidance/reference system? Main or auxiliary propulsion? Communications?

Events	Issues
18. Insert to Shuttle phasing orbit	Shuttle position? Guidance update? Ground support? Maneuver by Shuttle or OTV? What about Space Station case? Main or auxiliary engines?
19. Orbit trim maneuvers	Shuttle or OTV?
20. Burn for Shuttle rendezvous orbit	Shuttle or OTV? Main or auxiliary propulsion? Space Station case?
21. Rendezvous burn	Burn by Shuttle or OTV? Functions by Shuttle or OTV? Space Station case?
22. Shuttle docking and loading	OTV Hardware? Shuttle hardware? AMOOS temperature? Residual(s) disposal? Tank insulation protection? Tank pressurization? Load and attach? Transfer man to Shuttle cabin? Safety check?

Resolution of the OTV flight profile and event sequencing requires simultaneous considerations of interfacing space hardware and the Shuttle or Space Station functions as well as some type of standardized space operations procedures. The events and associated issues previously given are only typical of the situations which could arise. Practical solutions to these issues will certainly have significant influence on the eventual OTV design.

B. Single Stage APOTV

Figure 41 shows a simplified flight profile for the APOTV. Events are numbered with explanation given in Table 26. This profile was determined in the past high performance Tug studies. Whether this profile would still be applicable or optimum for APOTV application under the current mission planning is uncertain.

C. Single Stage AMOOS

Figure 42 shows a simplified flight profile for the AMOOS. Events are numbered with explanation given in Table 27.

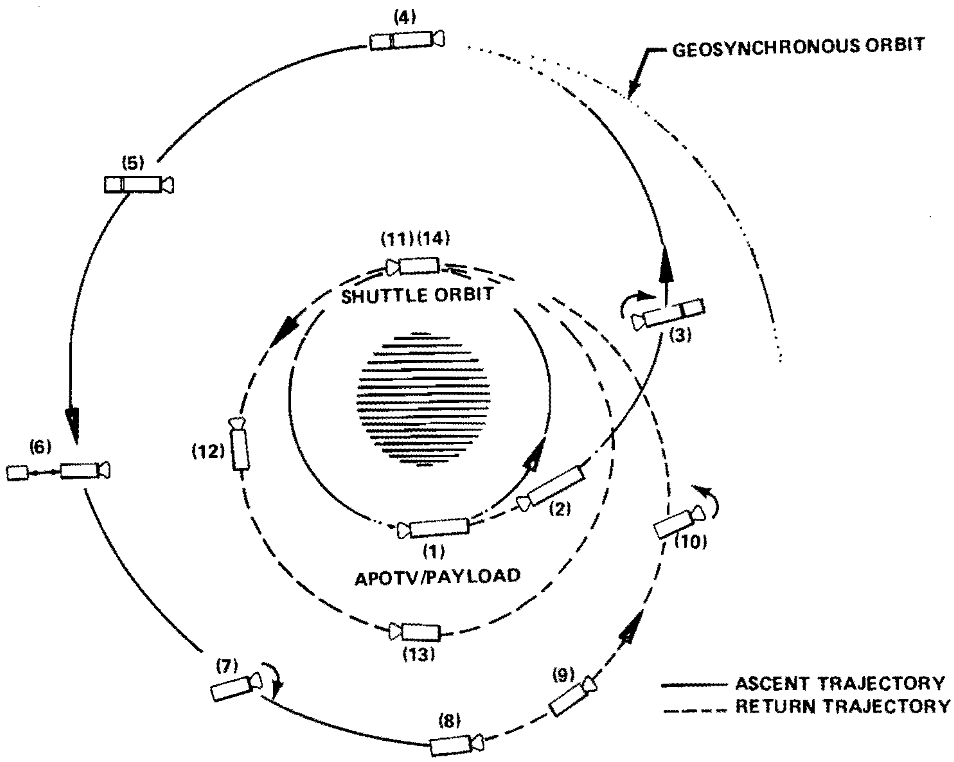


Figure 41. APOTV flight profile.

TABLE 26. SEQUENCE OF EVENTS FOR APOTV FLIGHT PROFILE

(1)	OTV Main Engine Burn for Synch Orbit Transfer Injection ΔV = 8062 ft/sec
(2)	OTV Check Guidance Platform Alignment
(3)	OTV Maneuvers into Geosynchronous Injection Burn Orientation
(4)	OTV Main Engine Burn for Geosynchronous Orbit Insertion ΔV = 5875 ft/sec (26 Degrees Plane Change)
(5)	Geostationary Orbit Trim Maneuvers
(6)	Deploy Payload
(7)	OTV Maneuvers into Deorbit Burn Orientation
(8)	OTV Main Engine Burn for Low Earth Orbit Transfer ΔV = 5875 ft/sec (26 Degrees Plane Change)
(9)	OTV Check Guidance Platform Alignment
(10)	OTV Maneuvers into Low Earth Orbit Injection Burn/Aerobraking Orientation
(11)	APOTV Main Engine Burn for Shuttle/APOTV Phasing Orbit Insertion (ΔV = 4230 ft/sec, Apogee Altitude 4400 n.mi.)
(12)	APOTV Coast One Rev in Phasing Orbit
(13)	APOTV Phasing Orbit Trim Maneuvers
(14)	APOTV Main Engine Burn for Shuttle Rendezvous Orbit ΔV = 3832 ft/sec

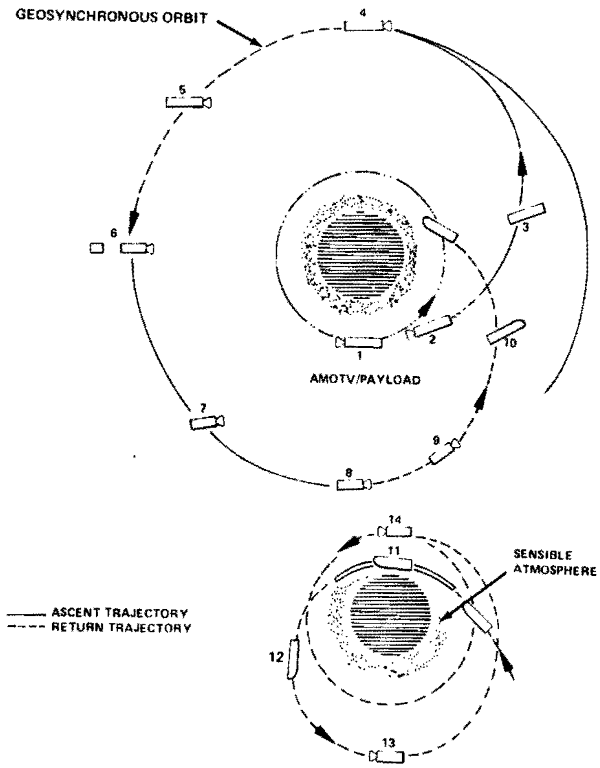


Figure 42. AMOOS flight profile.

TABLE 27. SEQUENCE OF EVENTS FOR AMOOS FLIGHT PROFILE

(1)	OTV Main Engine Burn for Synch Orbit Transfer Injection ΔV = 8062 ft/sec
(2)	OTV Check Guidance Platform Alignment
(3)	OTV Maneuvers into Geosynchronous Injection Burn Orientation
(4)	OTV Main Engine Burn for Geosynchronous Orbit Insertion ΔV = 5875 ft/sec (26 Degrees Plane Change)
(5)	Geostationary Orbit Trim Maneuvers
(6)	Deploy Payload
(7)	OTV Maneuvers into Deorbit Burn Orientation
(8)	OTV Main Engine Burn for Low Earth Orbit Transfer ΔV = 5875 ft/sec (26 Degrees Plane Change)
(9)	OTV Check Guidance Platform Alignment
(10)	OTV Maneuvers into Low Earth Orbit Injection Burn/Aerobraking Orientation
(11)	AMOTV Performs Aerobraking Maneuver (Minimum Altitude = 37 n.mi.) Apogee Altitude = 388 n.mi. ± 54
(12)	AMOTV Coast One Rev in Phasing Orbit
(13)	AMOTV Phasing Orbit Trim and Perigee Raise Maneuver ΔV = 220 ft/sec
(14)	AMOTV Main Engine Burn for Shuttle Rendezvous Orbit ΔV = 400 ft/sec

As can be seen from Figures 41 and 42 and Tables 26 and 27, the major differences in the APOTV and AMOOS profiles are the manner in which the system performs the braking maneuver into low Earth orbit. The APOTV performs all maneuvers propulsively, and the AMOOS performs the later maneuver by aerobraking/maneuvering. The AMOOS may also perform a plane change of approximately 7 degrees.

It is during this phase of the flight profile that the AMOOS gains a performance advantage over the APOTV. The actual advantage may be observed in the performance section of this report.

D. Emergency Vehicle

Flight profiles for the AMRS may be found in report LMSC-HREC TR D496644. It is similar to the AMOOS profile except that it can return to the Earth's surface.

E. Two-Stage Application

Flight profiles for two-stage applications of the AMOOS may be found in LMSC-HREC TR D496644. Profiles for APOTV may be found in previous Tug vehicle documentation.

VIII. OTV PERFORMANCE/CAPABILITIES

Comparable performance data for the various OTV systems under consideration are presented in this section. Insofar as possible comparable assumptions have been made in all cases. It is expected that the difference in the level of study and design depth of the various reference data, as well as the assumptions made therein, will cause some difference in the level of confidence in the numbers given. Eventual resolution of flight profile and operations issues as well as more detailed design on the various systems will also have some effect on OTV performance. The data, however, are well representative of expected OTV performance, and payload capabilities indicated should be accurate within a few hundred pounds.

The OTV performance data have been referenced to specific Shuttle capability. Unless otherwise stated, 2.9 percent tare weight for the Shuttle has been deducted from the stated Shuttle capability to obtain the start weight for the OTS.

For the most part the lox/hydrogen APOTV and AMOOS reference data were based on an engine I_{sp} of 456.5 sec (RL 10 Category IIB engine), and the data given here are primarily for this engine performance. Advanced engines are expected to provide approximately 470 sec I_{sp}. A comparison of the 456.5 and 470 sec performance will be shown.

The reader should note the I_{sp} values shown for the storable and solid systems are slightly optimistic. This was intentional to ensure that the competitiveness of these systems be maximized.

A. OTV Single Stage Capabilities

Comparable payload capabilities for lox/hydrogen, lox/RP, and N_2O_4/MMH propellants are shown for the APOTV and AMOOS concepts in Figure 43. Capabilities for 65 000, 100 000, and 125 000 lb Shuttle capabilities are shown. As indicated, the payload capabilities for lox/RP and N_2O_4/MMH are very low or negligible for the APOTV concept. Parametric data for each case are shown in Figure 44.

B. Staging Effects on OTV Capability — One Shuttle Launch

Single stage, dual stage, and drop tank plus stage for a 100 000 lb Shuttle capability are shown in Figure 45. It should be noted that a 456.5 sec I_{sp} was used in this case. Even though the drop tanks were expended in this case, the capability is only slightly greater than the dual stage case. The dual stage and the drop tank cases shown here would probably require cargo bay lengths greater than 60 ft.

C. Capability Comparison for One- and Two-Shuttle Launches

Figure 46 shows capabilities for the 65 000 and 100 000 lb Shuttle capabilities for one- and two-Shuttle launches. As noted, the payload for the two-stage case must be split and carried on each of the two Shuttle launches. As may be expected, the major problem with multiple Shuttle launches is maintaining a high Shuttle load factor. This creates the problem of dividing the payload for the two-launch case. Since the stages are designed for single launch, they must be offloaded.

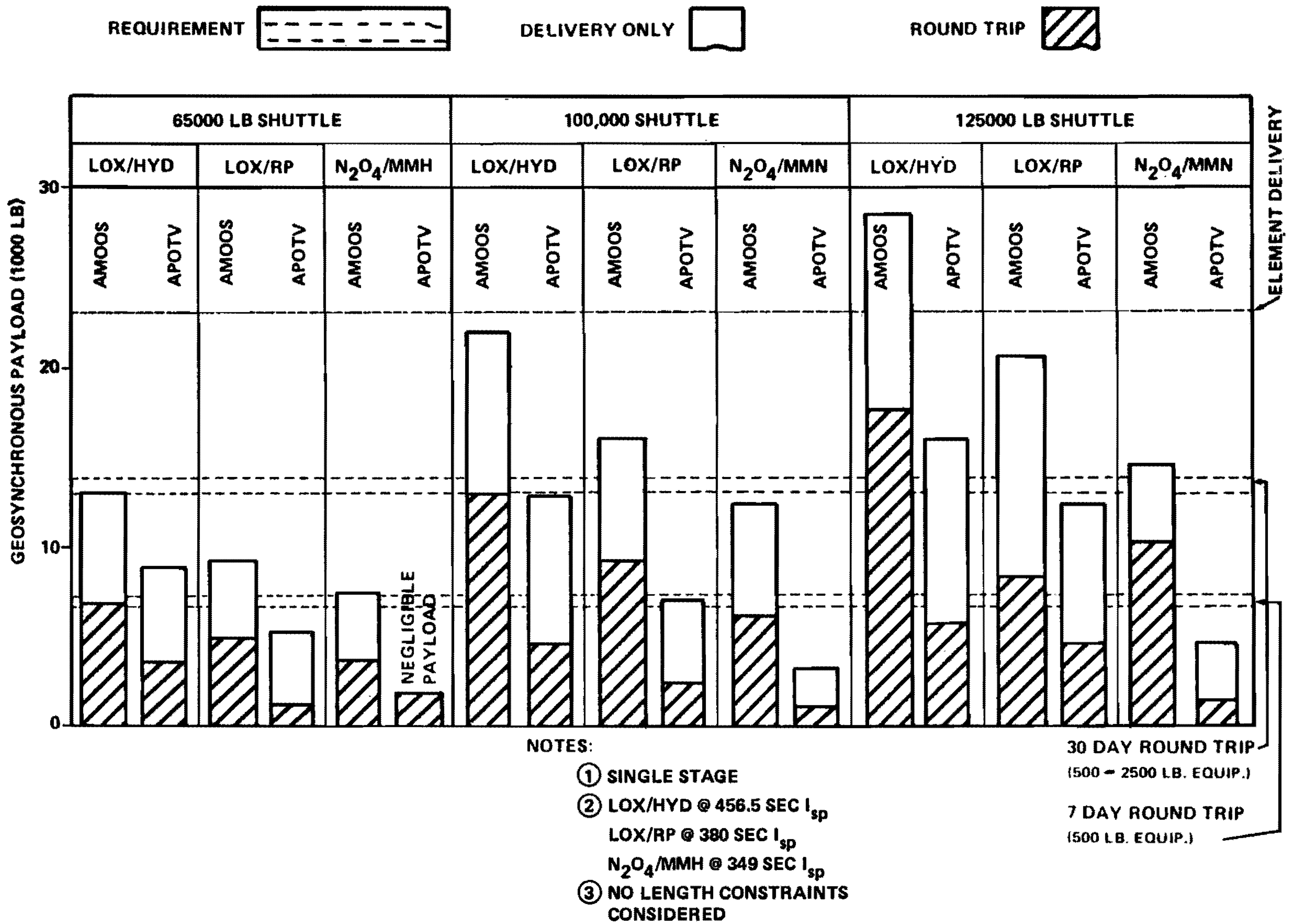


Figure 43. Single stage OTV performance comparison.

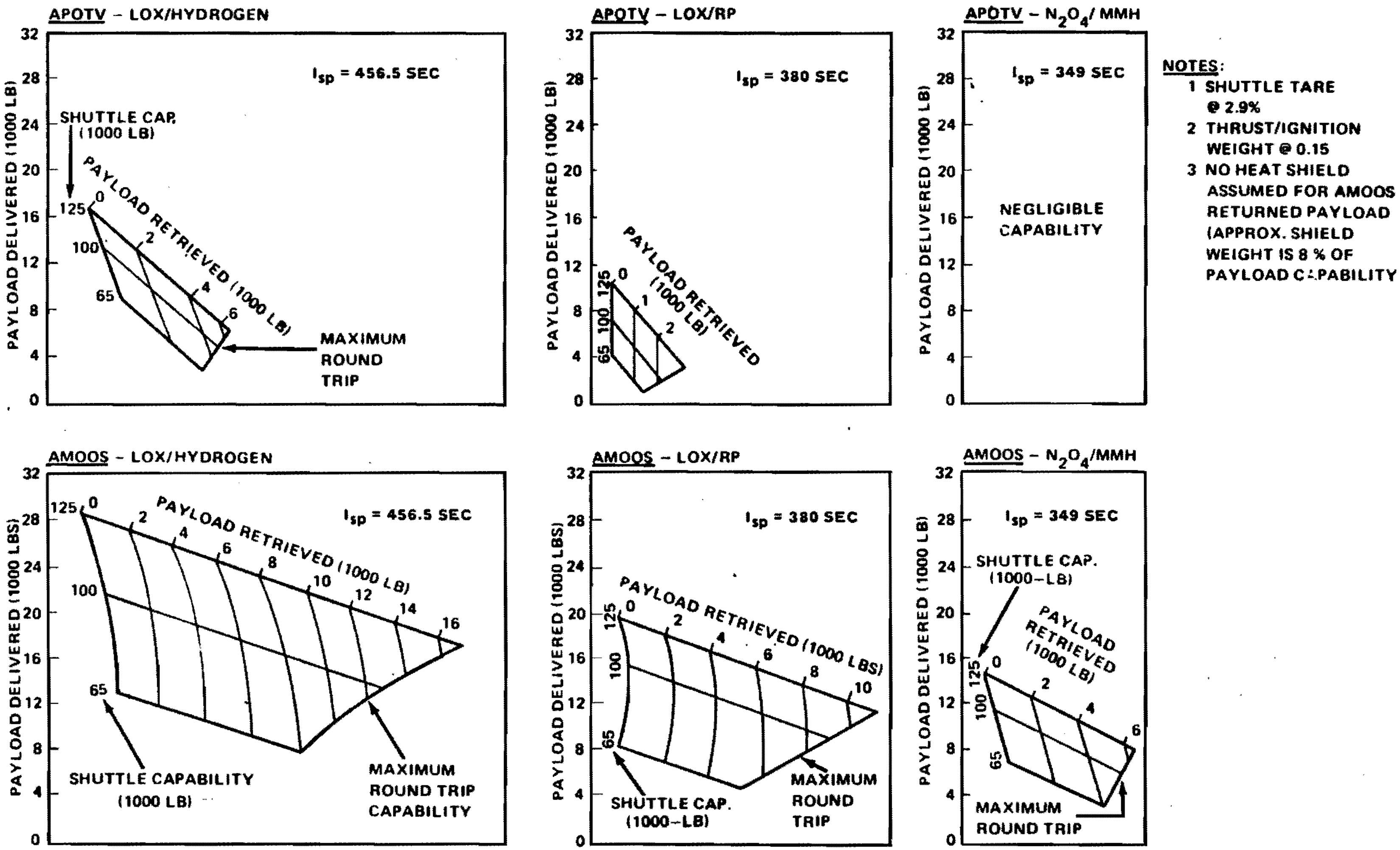


Figure 44. Single stage OTV performance/capabilities.

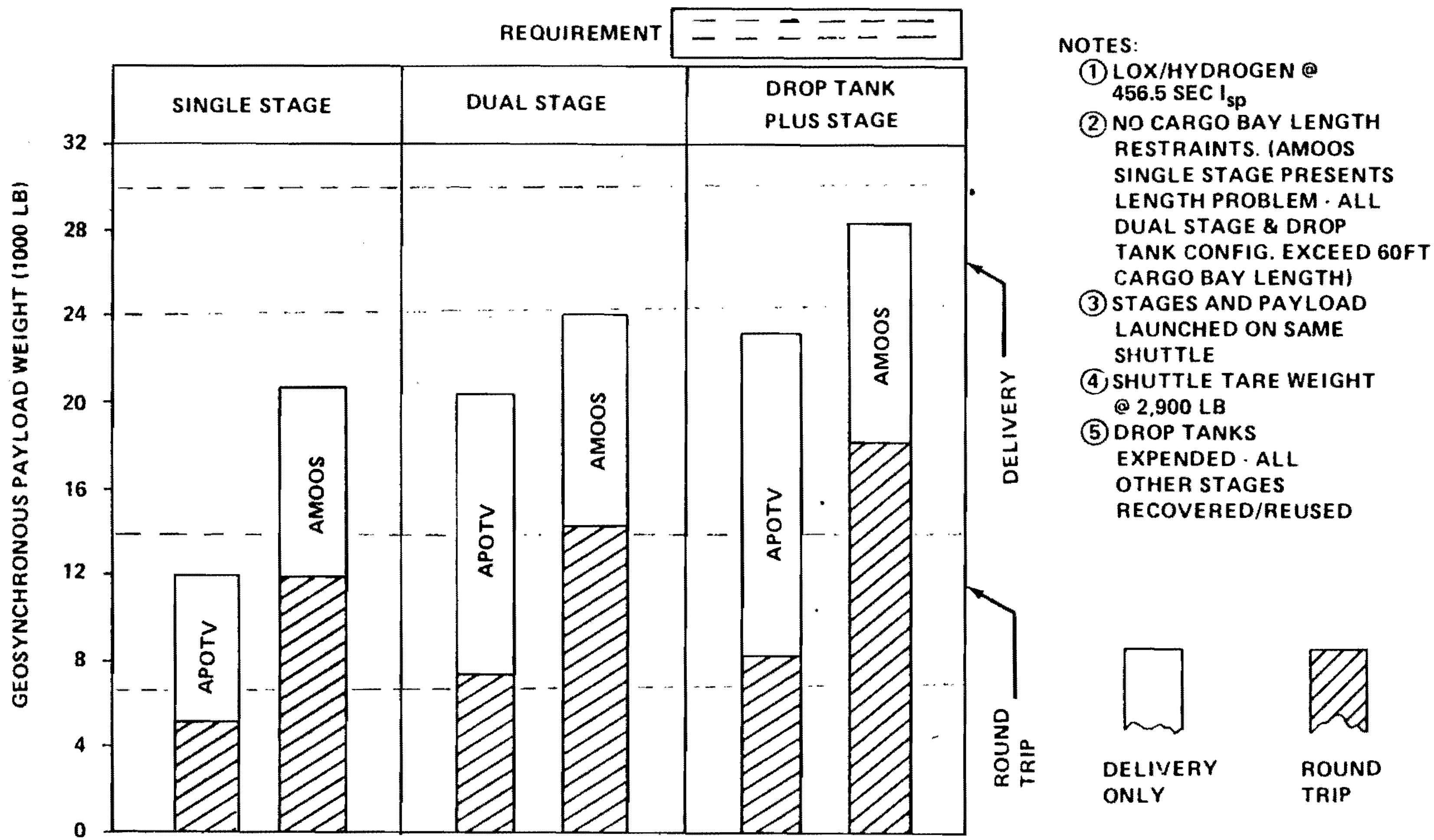


Figure 45. Staging effects for OTV systems (100 000 lb Shuttle capability).

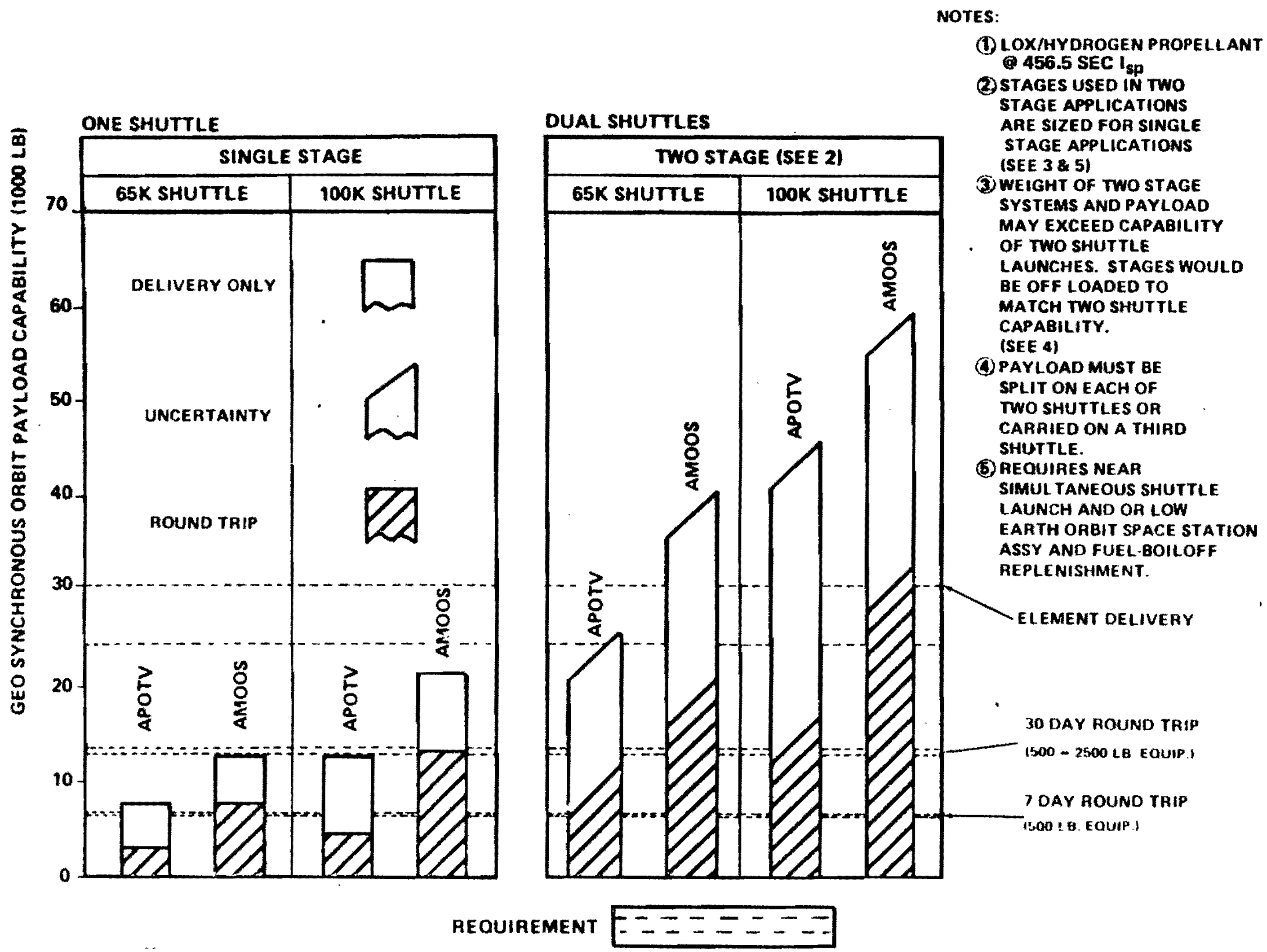


Figure 46. Single/dual Shuttle performance/capabilities.

D. Expendable Solid Boosters for Multiple Shuttle Launches

Expendable solid boosters may offer attractive options for obtaining large payload transfer capabilities. The data shown in Figure 47 show the capability using a solid system with an AMOOS designed for a single launch round trip capability. Capabilities for the APOTV would be slightly less than shown.

For the solid motor case shown in Figure 47, the solid motor was sized to use the total Shuttle capability. The other two Shuttle launches, carrying the high performance stage and payload, would suffer load factor penalties.

The solid boost concepts offer options which would simplify orbital storage. It may also be possible to conceive practical solid concepts which would offer higher Shuttle load factors and relieve the need for near simultaneous Shuttle launches for the multiple launch cases required to transfer very large payloads.

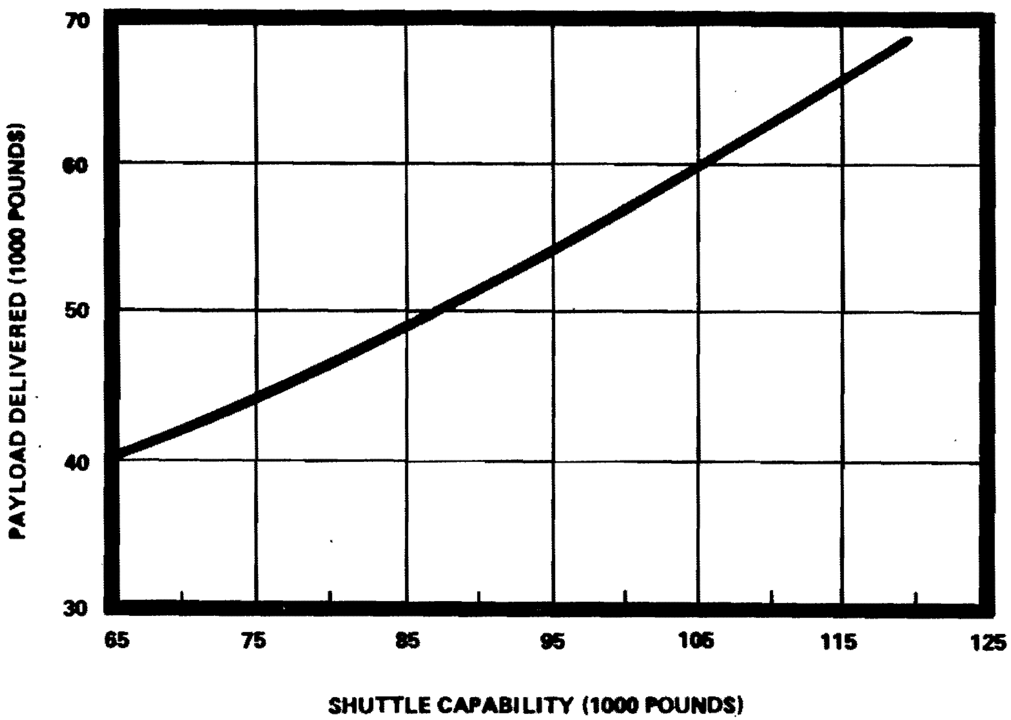
Further concepts of the solid motor for two-stage and multiple launch cases should be studied and comparisons made with the two-stage liquid systems.

E. Engine I_{sp} Effects for Lox/Hydrogen Cases

As previously mentioned, OTV payload capabilities have been calculated for lox/hydrogen propellants using I_{sp} of 456.5 and 470 sec. Figures 48 and 49 show the effects of the different I_{sp} for the APOTV and AMOOS concepts.

F. Payload Partial Sensitivity for OTV Using Lox/Hydrogen for Geosynchronous Orbit Missions

Payload partial sensitivities for the APOTV and AMOOS are shown in Table 28. Partials are given for payload-to-Shuttle capability, for payload-to-burnout weight, and for payload-to-I_{sp}. The effects of a ±10 percent change in stage burnout weight are shown graphically in Figure 50. It should be noted that AMOOS weights could increase approximately 3000 and 6000 lb for round trip and delivery only payloads, respectively, before the APOTV and AMOOS systems exhibit comparable capabilities. The 3000 lb value represents a 40 percent increase in stage weight for the AMOOS concept.



ASSUMPTIONS:

- **3 SHUTTLE LAUNCHES USED IN EACH CASE**
  1) SOLID MOTOR
  2) PAYLOAD
  3) AMOOS
- SOLID MOTOR EXPENDED
- SOLID MOTOR I_{sp} = 288.9 SEC
- AMOOS ENGINE I_{sp} = 456.5 SEC
- AMOOS RETURNS TO SHUTTLE ORBIT
- SCALING EQUATION USED:

  SOLID MOTOR: $W_{BURNOUT}$(LBS) = 1105 + .063X (PROPELLANT)

  AMOOS: $W_{BURNOUT}$(LBS) = 2880 + '0078 X(PROPELLANT)

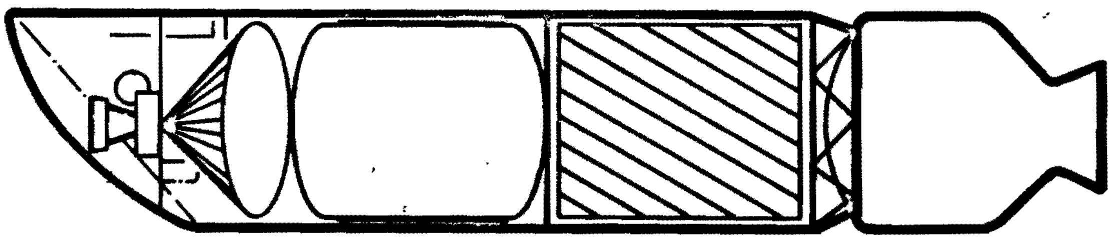
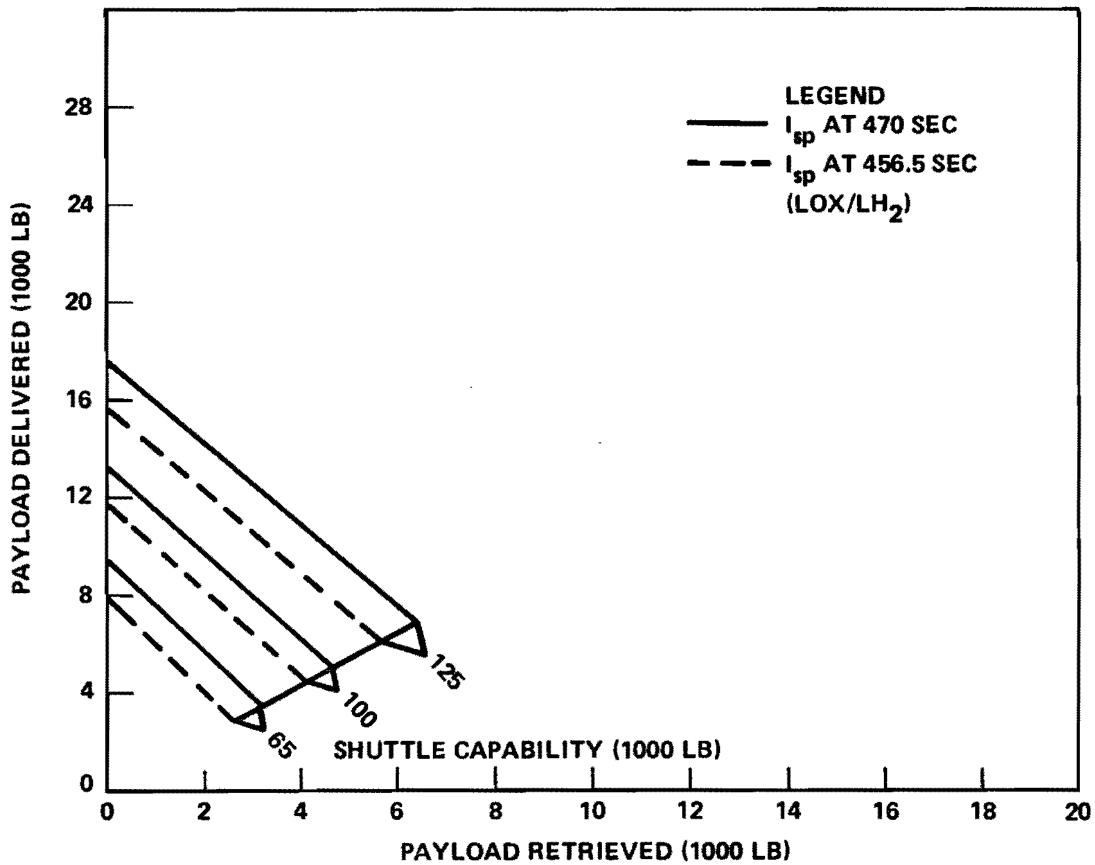


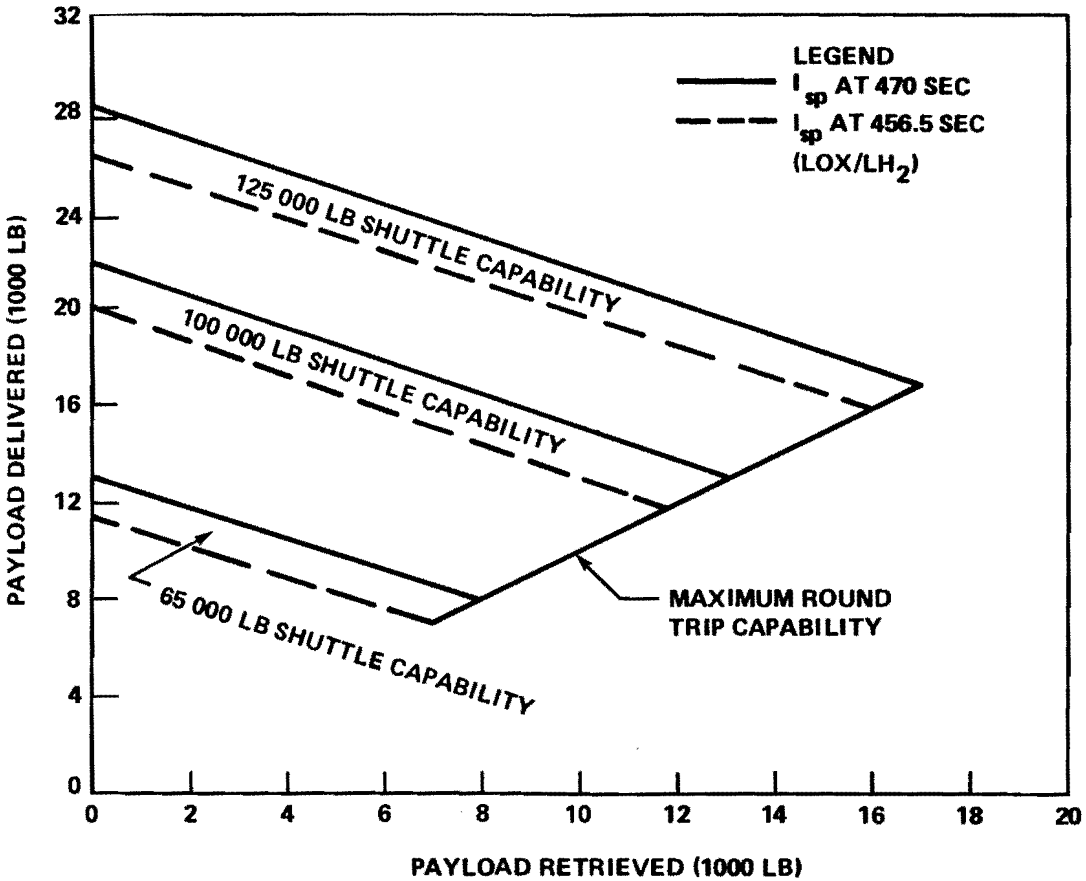
Figure 47. Solid boosters for large payloads geosynchronous capability.



ASSUMPTIONS

1. I_{sp} AS SHOWN ON CHART
2. NO CARGO BAY LENGTH RESTRAINT
3. STAGE-DRY WEIGHT
   - –65 000 SHUTTLE AT 5150 LB
   - –100 000 SHUTTLE AT 8030 LB
   - –125 000 SHUTTLE AT 10 000 LB
4. SHUTTLE TARE WEIGHT AT 2.9 PERCENT OF SHUTTLE CAPABILITY
5. THRUST/IGNITION WEIGHT AT 0.15

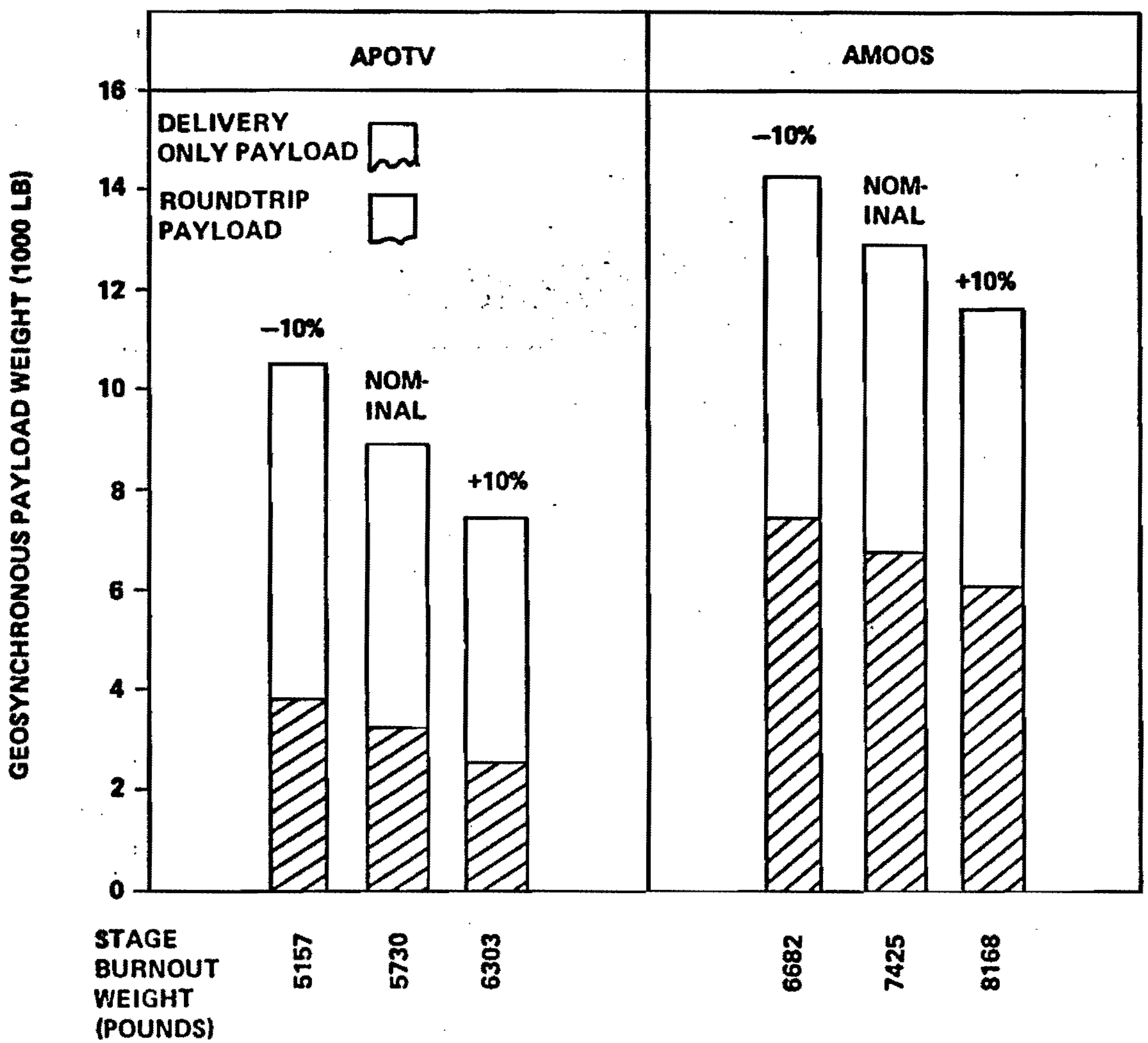
Figure 48. I_{sp} effects on the geosynchronous orbit APOTV payload capability.



ASSUMPTIONS:

1. I_{sp} AS SHOWN ON CHART.
2. NO CARGO BAY LENGTH RESTRAINT
3. STAGE DRY WEIGHT
   - –65 000 SHUTTLE AT 6700 LB
   - –100 000 SHUTTLE AT 8900 LB
   - –125 000 SHUTTLE AT 10 800 LB
4. NO HEAT SHIELD PROVIDED FOR RETURN PAYLOAD – APPROXIMATE WEIGHT OF SHIELD WOULD BE 80 LB PER 1000 LB PAYLOAD RETURNED
5. SHUTTLE TARE WEIGHT AT 2.9 PERCENT OF SHUTTLE CAPABILITY
6. THRUST/IGNITION WEIGHT AT 0.15.

Figure 49. I_{sp} effects on the geosynchronous orbit AMOOS payload capability.



NOTES
1 HYDROGEN/OXYGEN PROPELLANTS @ 456.5 SEC I_{sp}
2 NO REDUCTION IN AMOOS ROUND TRIP CAPABILITY FOR PAYLOAD HEAT SHIELD. APPROX. VALUE IS 8% OF ROUND TRIP PAYLOAD
3 NO REDUCTIONS OR INCREASES IN PROPELLANT DUE TO CHANGE IN STAGE CUT-OFF WEIGHT
4 SHUTTLE TARE WEIGHT @ 2.9% OF SHUTTLE CAPABILITY

Figure 50. OTV payload capability — sensitivity to burnout weight (65 000 lb Shuttle).

TABLE 28. GEOSYNCHRONOUS PAYLOAD PARTIAL SENSITIVITY

Partial			APOTV	AMOOS
Payload Delivery				
$\frac{\partial \text{ (Payload)}^{a}}{\partial \text{ (Shuttle Capability)}}$	lb/lb		0.1283	0.2496
$\frac{\partial \text{ (Payload)}}{\partial \text{ (Burnout Weight)}}$	lb/lb		-2.6187	-1.6016
$\frac{\partial \text{ (Payload)}}{\partial \text{ } (I_{sp})}$	lb/sec	65 K Shuttle	83	61
		125 K Shuttle	160	118
Payload Round Trip				
$\frac{\partial \text{ (Payload)}^{a}}{\partial \text{ (Shuttle Capability)}}$	lb/lb		0.0501	0.1550
$\frac{\partial \text{ (Payload)}}{\partial \text{ } (I_{sp})}$	lb/sec	65 K Shuttle	39	47
		125 K Shuttle	74	90

a. Includes the associated change in stage weight.

G. Oxidizer – Fuel Mixture Ratio Considerations for OTV

When used for delivery only missions, the OTV requires several thousand pounds less propellant than when used for round trip missions. This is true for APOTV and AMOOS concepts. It should be advantageous if only one size tankage could satisfy both cases with a minimum effect on payload.

Figure 51 shows an example, using the AMOOS concept, where the nominal stage would be designed for full tankage for the round trip mission and to use a 7:1 lox/hydrogen mixture ratio. The delivery mission would then be operated at a 6:1 mixture ratio with the oxidizer tank slightly offloaded.

MIXTURE RATIO (O:F)	6:1		7:1	
TANKAGE	ROUND TRIP	DELIVERY ONLY	ROUND TRIP*	DELIVERY ONLY
HYDROGEN	6900	6200	6200	5500
OXYGEN	41600	37000	43000	38500
TOTAL	48500	43200	49200	44000

*NOMINAL STAGE DESIGN FOR BOTH DELIVERY AND ROUND TRIP MISSIONS.
SHUTTLE CARGO BAY EFFECTS AND STAGE WEIGHT EFFECTS MUST BE INCLUDED.

HYDROGEN STORED @ 500 LB/FT - STAGE LENGTH
OXYGEN STORED @ 7900 LB/FT - STAGE LENGTH

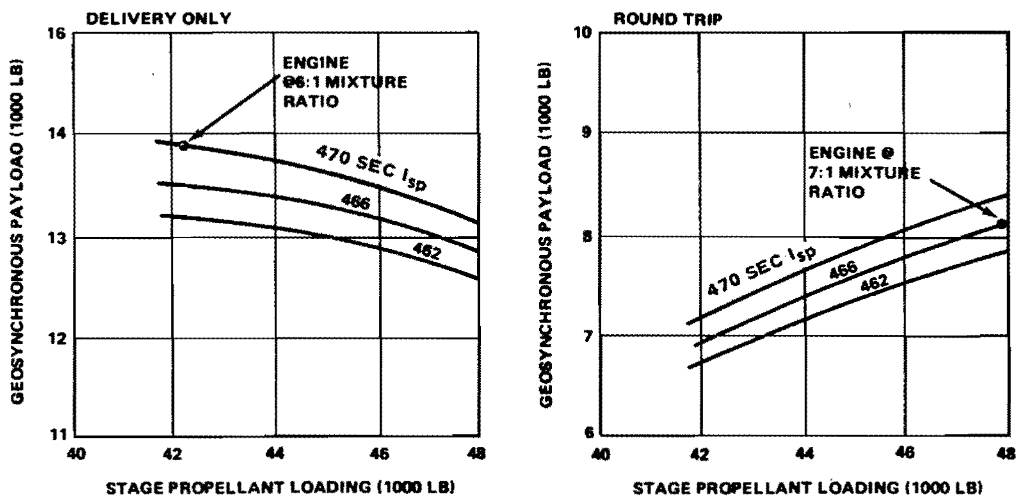


Figure 51. Oxidizer — fuel mixture ratio considerations for OTV AMOOS with lox/hydrogen — 65 000 lb Shuttle capability.

Figure 51 also shows the corresponding effects on vehicle performance for this case. Operating the engine at the varying mixture ratios is an issue which should be resolved in OTV engine development.

A similar arrangement can be developed for the APOTV if desirable. The resulting capability effects would be similar.

IX. SHUTTLE CARGO BAY LENGTH CONSIDERATIONS

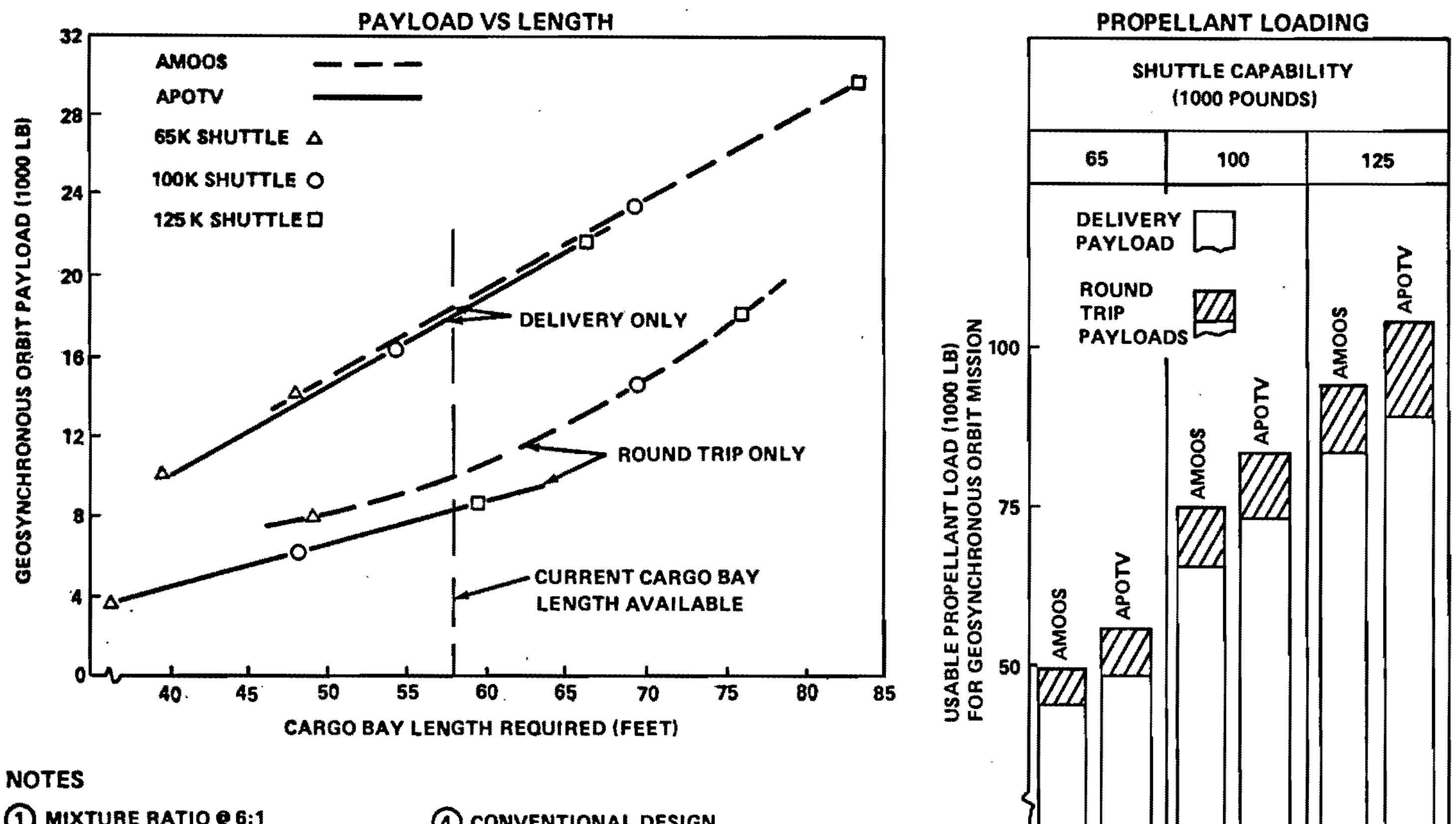
A major problem associated with the OTV is the available length of the cargo bay. For the single Shuttle launch cases, the OTV and the payload must be carried in the same cargo bay. For the dual Shuttle launch case, it has been assumed that one-half of the payload weight would be carried in each of the cargo bays. This section deals primarily with the single launch case with lox/hydrogen propellants.

The length of the OTV plus payload is a function of the Shuttle payload capability minus the Shuttle tare weight, the OTV payload capability, and the OTV weight and propellant loading. As shown in the configuration, weight, and performance capability sections, these values are significantly different for the various OTV concepts. Payload weight and length characteristics may be found in the requirements section.

Shuttle improvement studies have indicated a need to maintain the 15 by 60 ft dimension of the current Shuttle. Early in the OTV study activity, it was determined that this could present some problems over the Shuttle capability range from 65 000 to 125 000 lb, particularly for the AMOOS. The same is true for APOTV at different capabilities within the range.

A. Single Shuttle Launch OTV — Lox/Hydrogen Propellants

The payloads carried by the OTV may be represented by density to obtain a volume needed by the payload. Figure 52 shows the AMOOS and APOTV cargo bay length requirements versus the geosynchronous payload capability. As shown for the delivery mode, the two concepts display essentially the same length requirement for equal payloads. The APOTV requires significantly more length than the AMOOS for the round trip payloads. It can also be noted that the APOTV requires much larger Shuttle capability than AMOOS.



NOTES

① MIXTURE RATIO @ 6:1

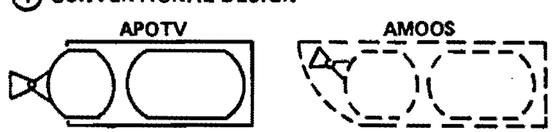
② PAYLOAD DIAMETER @ 14 FT

③ PAYLOAD DENSITY

– DELIVERY ONLY @ 6 LB/FT^3

– ROUND TRIP @ 4 LB/FT^3

④ CONVENTIONAL DESIGN



⑤ VEHICLES SIZED FOR MISSION (DELIVERY ONLY OR ROUND TRIP ONLY)

Figure 52. APOTV-AMOOS cargo bay requirements comparison (lox/hydrogen at 470 sec I_{sp}).

A review of the payload requirements, particularly the station elements, indicate that a capability ranging from 18 000 to 25 000 lb and a cargo bay length of 18 to 26 ft are required. This value satisfies all station elements except the 44 000 lb, 46 ft long habitability subsystem module. This module can not be launched by a single Shuttle launch OTV because of the weight of this payload.

Figure 53 shows propellant requirements and stage length, with payload capability referenced, for the AMOOS and the APOTV. To deliver this range of payloads, the AMOOS requires a Shuttle capability of approximately 115 000 lb and a cargo bay length of approximately 70 to 78 ft for the 18 to 26 ft payloads. The APOTV requires a Shuttle capability exceeding the 140 000 lb range on the chart and a cargo bay length somewhat longer than the AMOOS.

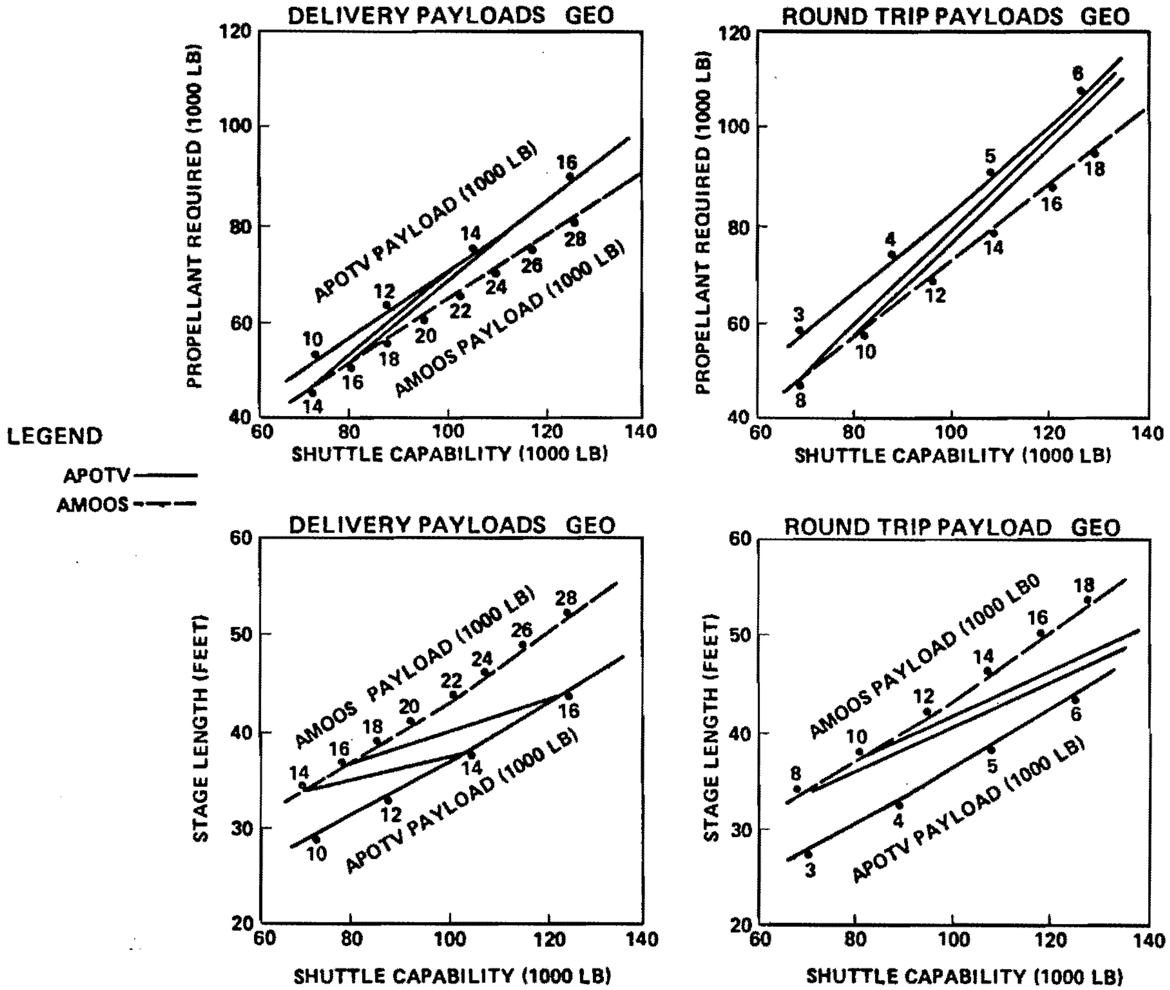
Assume that the round trip capability being sought is approximately 13 000 lb and that this payload length would be approximately 24 ft. The AMOOS would again require a Shuttle capability of approximately 115 000 lb and approximately an 82 ft cargo bay length. The APOTV does not have this capability because of payload capability limitations.

To get a comparison of APOTV and AMOOS, assume that the round trip payload requirement is 6000 lb and the length is 20 ft. For this payload, the AMOOS requires approximately 55 000 lb Shuttle capability and a cargo bay length of approximately 50 ft. The APOTV requires a Shuttle capability of approximately 125 000 lb and a cargo bay of approximately 63 ft.

The payload density analysis and the specific payload characteristic analysis indicate that the AMOOS and APOTV concepts have the same cargo bay length problem for equal payloads. This appears to hold within a 10 to 15 percent difference which is within the accuracy of the calculation. The more significant difference is that the APOTV requires much greater Shuttle capability. Also the 60 ft long cargo bay of the current Shuttle will not accommodate the weight and length requirements if the OTV is conventionally designed and if the Shuttle capability is over approximately 70 000 lb.

A unique, innovative design much shorter than the conventional design was developed for the AMOOS in the configuration section. The same type concept is also applicable to the APOTV. However, the reduction in length for APOTV is somewhat less because the 14 ft diameter was already utilized in the conventional design.

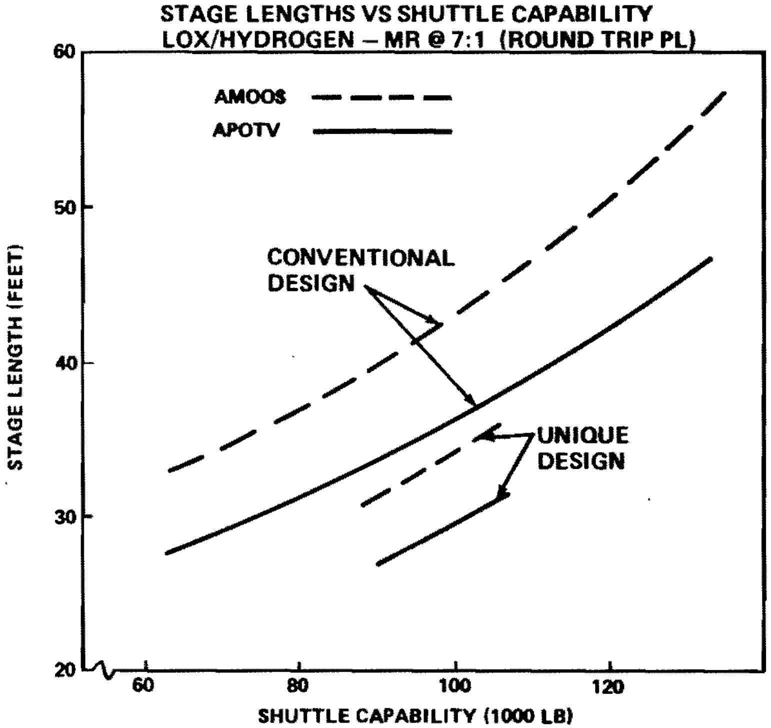
Figure 54 shows the effects of the unique design on the cargo bay length requirement. It can be seen that with the 60 ft cargo bay the AMOOS concept could use approximately a 100 000 lb Shuttle capability, and the APOTV could



NOTES:

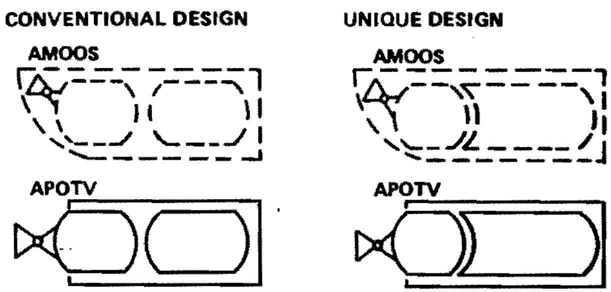
1. OTV ONLY–PAYLOAD NOT INCLUDED
2. CONVENTIONAL DESIGNS FOR LOX/HYDROGEN
3. TANK DESIGNED FOR ROUND TRIP AND DELIVERY –DELIVERY @ 6:1 MR – ROUND TRIP @ 7:1 MR

Figure 53. OTV length issues (lox/hydrogen).



WEIGHT AND LENGTH LIMITS FOR 60 FOOT CARGO BAY LENGTH ACCOMMODATION

AMOOS:	
SHUTTLE CAPABILITY	100 000 LB
AMOOS LENGTH	34 FT
PAYLOAD LENGTH	24 FT
LENGTH TOLERANCE	2 FT
DELIVERY ONLY PAYLOAD	21 000–22 000 LB
ROUND TRIP PAYLOAD	12 500–13 000 LB
APOTV:	
SHUTTLE CAPABILITY	12 500 LB
APOTV LENGTH	34 FT
PAYLOAD LENGTH	24 FT
LENGTH TOLERANCE	2 FT
DELIVERY ONLY PAYLOAD	15 500–16 000 LB
ROUND TRIP PAYLOAD	5500–6000 LB



OTHER POSSIBILITIES TO REDUCE LENGTH

- REDUCE ULLAGE FROM 6 % TO 4 % @ ≈ 0.4 FT
- USE 8:1 MIXTURE RATIO @ ≈ 1.5 FT
- USE 9:1 MIXTURE RATIO @ ≈ 2.7 FT
- USE SLUSH HYDROGEN @ ≈ ? ?
- RESHAPE EXTERIOR CONFIGURATION @ ? ?

Figure 54. Unique design to meet cargo bay length restraint.

use up to approximately 125 000 lb of Shuttle capability. Figure 54 also shows similar data for the conventionally designed OTV. The analysis indicates that these values are the approximate upper limits. Longer (lower density) payloads, heavier payloads, or more conventional OTV design is probably not a practical possibility and would require a longer cargo bay.

Limits on payload weights and lengths can now be established. These must be accompanied by specific lengths for the OTV (Fig. 54). Redesign of payloads may change the limits slightly; however, major changes are not expected.

Figure 55 depicts the conventionally designed OTV in a 60 ft cargo bay. This design would yield payload capabilities approximately the same as those given in Figure 54.

It is emphasized that while additional cargo bay length is very desirable, the redesign of the Orbiter would be quite expensive and weighty. Johnson Space Center (JSC) estimates that the Orbiter weight would increase by 685 lb/ft of length added to the cargo bay. The additional Orbiter weight would make Shuttle payload capability improvement significantly more difficult.

X. CHEMICAL ENGINE SYSTEMS FOR OTS

Consideration of potential engine systems suitable for OTV's in the 65 000 to 125 000 lb gross weight class has been restricted to chemical systems, which include cryogenic and storable liquid propellants and solid propellants. Electric (ion/plasma) and nuclear (solid/gas core) engine systems, which may be appropriate for post-1990 vehicles, have been excluded from this discussion.

Additional technical descriptions and parametric data can be found in Appendices A and B.

A. Cryogenic Propellant Systems

As a point of departure, the lox/hydrogen RL10 Category IIB engine system was selected to characterize the 65 000 to 125 000 lb class OTV. This engine has reasonably good performance and was the one selected for the MSFC Baseline Space Tug (1974). This engine can be made available with a moderate technological development, and a good data base and extensive parametric data

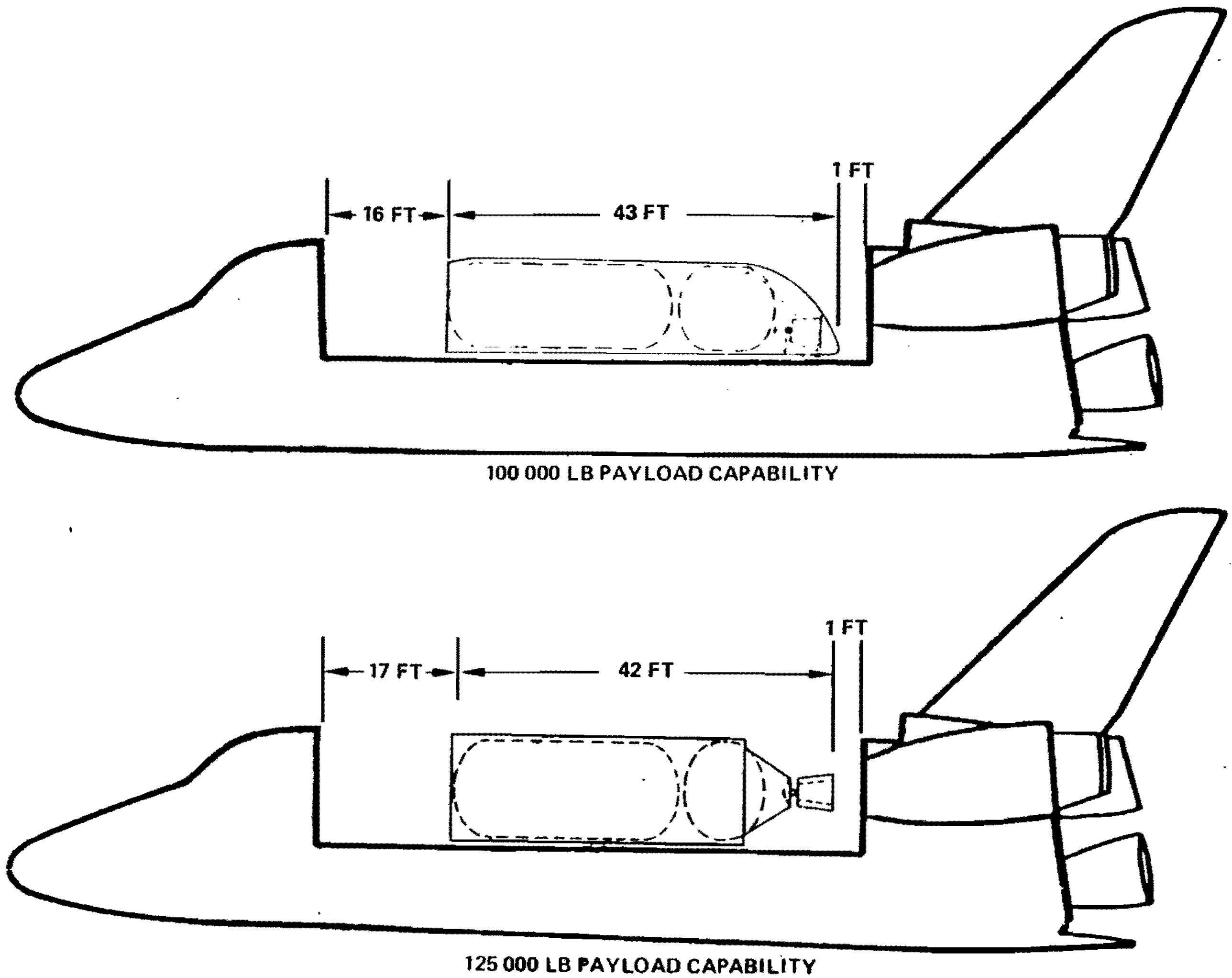


Figure 55. OTV with improved Shuttle (60 ft cargo bay).

exist. Nominal engine performance is based on a retracted nozzle engine length of 55 in. with an expansion ratio of 205:1 (with nozzle extended) and a corresponding I_{sp} of 456.5 sec. Performance, as measured by I_{sp}, may be improved by increasing the nozzle expansion ratio. This expander cycle engine operates at a propellant mixture ratio of 6:1 and a nominal thrust of 15 000 lbf.

The Advanced Space Engine (ASE) was selected to determine the advantages to the OTV of using a higher performing engine system. The ASE has been used for some of the previous in-house MSFC Space Tug studies. A reasonable data base exists, and extensive parametric data are available. Nominal engine I_{sp} is 470 sec at a nozzle expansion ratio of 400:1 and a chamber pressure of 1600 psia. Thrust may be varied as desired over a range of approximately 8000 to 25 000 lbf to maintain whatever gross stage weight to engine thrust ratio is desired. The engine may be equipped with an extendable/retractable nozzle and operates at a nominal propellant mixture ratio of 6:1, although this may be increased somewhat with a corresponding decrease in specific impulse. Propellants are lox/hydrogen, and the engine operates in a staged-combustion power cycle.

Consideration of projected lox/hydrogen propulsion systems has shown two other options which are performance competitive with the ASE. The first of these is the RL10 Category IV, which represents the most efficient expander cycle engine. At an expansion ratio of 400:1 and chamber pressure of approximately 1000 psia, this engine produces an I_{sp} of 470 sec. Nominal thrust is 15 000 lbf, and the engine operates at a propellant mixture ratio of 6:1. An extendable/retractable nozzle is optional.

The second high performance alternative to the ASE is the plug cluster concept, which is a grouping of multiple small engines around an aerodynamically designed central nozzle cone. For OTV application, a lox/hydrogen engine of 1500 lbf with an individual nozzle expansion ratio of 40:1 has been selected. However, when appropriately arranged in the circular plug cluster geometry, the collective expansion ratio is 400:1, resulting in an effective I_{sp} of 466 sec. The number of individual engine modules may be varied to adjust the total thrust as desired. The nominal propellant mixture ratio is 6:1. The plug cluster design is presently undergoing conceptual evaluation and, therefore, must be considered only as theoretically attractive at this time, pending feasibility analysis and the usual demonstration testing.

In previous studies, certain versions of the lox/hydrogen aerospike engine have been considered for upper stage application. This engine, operating in an expander cycle mode at a chamber pressure of 1000 psia, has been projected to produce an I_{sp} of 470 sec at an effective expansion ratio of 200:1. Although theoretically competitive with bell nozzle engines from weight considerations and having certain advantages because of its short length, severe difficulties in demonstration hot firings of prototype aerospike hardware led to cancellation of Air Force Rocket Propulsion Laboratory (AFRPL) and NASA test programs. Development of an aerospike engine is presently considered to be a high risk, high cost program and, therefore, is not included among the principal candidate engine systems for the OTV. Figure 56 gives engine configuration data on the systems discussed here.

B. Storable Propellant Systems

Although lower performing than cryogenic systems, as measured by delivered I_{sp}, storable propellant engine systems may find a role in the OTS if extended orbital stay time is a requirement. In this event, several types of storable propellant systems may be considered. The first of these is an N_2O_4/MMH engine derived from the Shuttle Orbiter 6000 lbf Orbit Maneuvering Engine (OME) (I_{sp} = 313). Significant modifications would be required for OTV application; however, these would not represent advances in the state-of-the-art. Changes would be required for operation in a pump-fed mode instead of the present pressure-fed mode, and increases in engine thrust to higher levels for OTV application would be necessary. Increasing the propellant mixture ratio from 1.65:1 to 2:1 would increase engine performance as would increasing the nozzle expansion ratio. I_{sp} would typically range from 325 to 330 sec.

Improved performance for storable propellant engines may be achieved by increasing the chamber pressure to a practical maximum of approximately 1000 to 1500 psia. The gas-generator and staged-combustion cycle engines have been investigated (e.g., Aerojet contract NAS 8-29806), with all engines using N_2O_4 and MMH as propellants, and are fuel cooled. These engines produce I_{sp} ranging from 335 to 349 sec, depending upon engine thrust, nozzle expansion ratio, chamber pressure, percent fuel used for film cooling (i.e., allowable chamber wall temperature), and overall engine propellant mixture ratio.

A third type of system may be included in this category if liquid oxygen is considered to be a space storable propellant. These systems would use the lox as oxidizer and hydrocarbon or amine fuels. Engine systems of this design would produce I_{sp} ranging from 380 to 388 sec at an expansion ratio of 400:1, with MMH having the higher performance (and cost). Engine design data base is poor, with the result that these engines are not well characterized at this time.

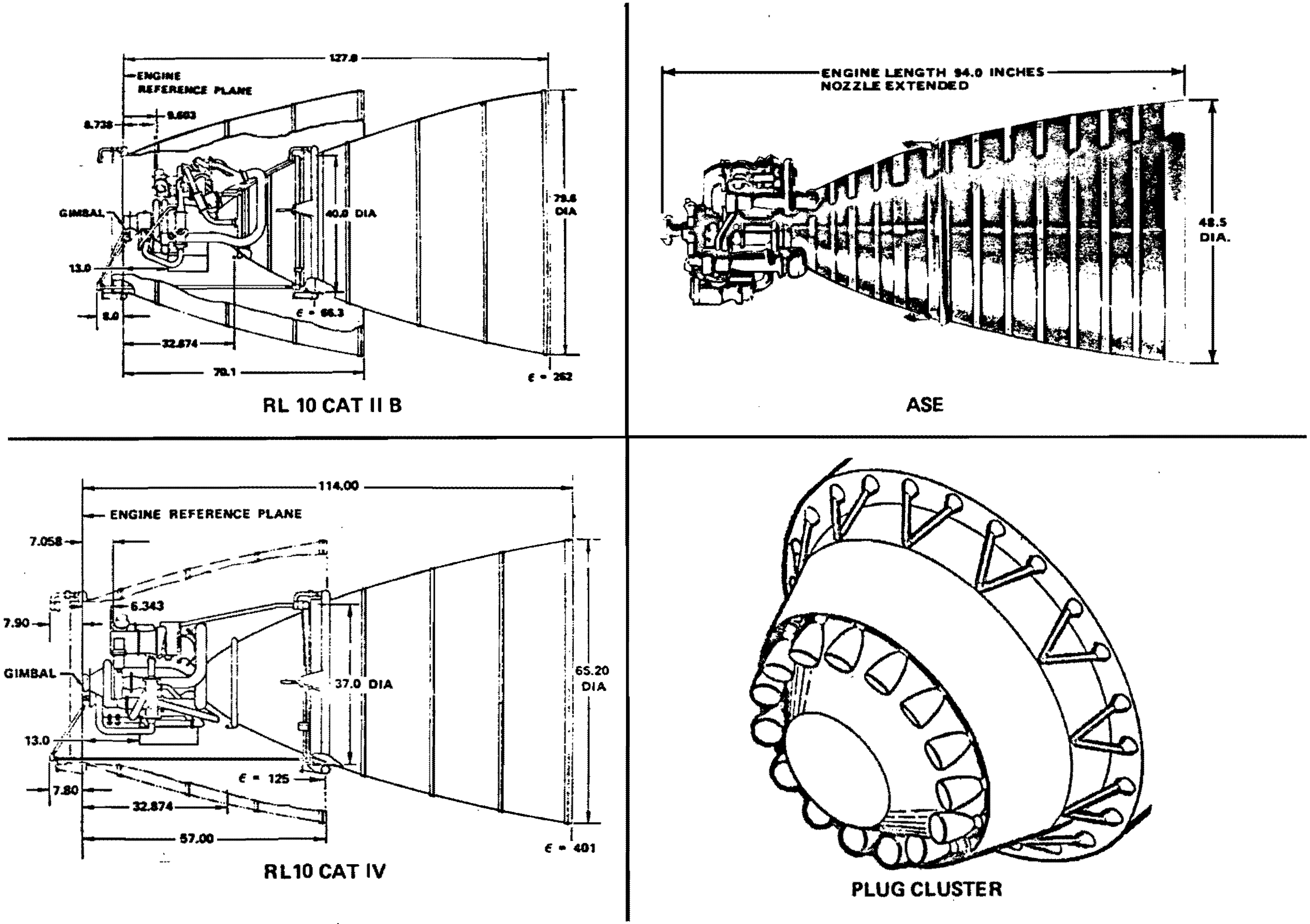


Figure 56. Engine configurations.

C. Solid Rocket Motors

Solid propellant rocket motors offer an alternative to storable propellant engine systems for extended orbit stay time and may be preferable for some applications. An OTV using solids for main propulsion would draw heavily on the technology established for the IUS being developed by the Air Force for Shuttle upper stage application. These vehicles would utilize Class 2 propellants producing I_{sp} ranging from 290 to 300 sec, depending upon nozzle expansion ratio and propellant composition. Solid propellants offer the advantages of high bulk density and reliability and may, over limited ranges, have variable propellant loadings to accommodate different mission impulse requirements. More detailed engine data and development status may be found in Appendix A.

D. Summary

To date, OTV studies have shown the lox/hydrogen engines to be the most desirable systems for the 1985-1990 time frame. Maximum practical engine performance (I_{sp}) is needed. An additional requirement, which evolved in this study, is for the engines to use higher and varying oxidizer-to-fuel mixture ratios. This is an issue which should be addressed in near future technology efforts.

XI. MISSION MODEL CAPTURE FOR 65 000 AND 100 000 lb SHUTTLE CAPABILITIES

Comparisons of the AMOOS and APOTV using lox/hydrogen propellants for the 65 000 and 100 000 lb Shuttle capabilities are given in this section. The capture shown here is consistent with the candidate missions shown in the Requirements section.

For this analysis it has been assumed that the heavier payloads would be designed to fit within the capabilities which would result for each Shuttle capability. Whether single or dual launches were assumed is indicated.

Data are presented for the nominal and low program options defined in the Requirements section. For the Nominal Program Option, an HLLV has been assumed in 1991, and at that time unmanned payload hardwares would be transferred to the HLLV. For the Low Program Option, no HLLV is assumed. Also for the Nominal Program Option, a four-man crew transfer capability is assumed prior to 1991, and a 12-man transfer capability is assumed thereafter. Only a four-man capability is assumed in the Low Program Option.

The capture shown here does not consider cargo bay length restraints. However, the analysis in the section on Shuttle cargo bay length issues indicates that the 60 ft cargo bay will accommodate the capture if the OTV length is limited to approximately 34 ft, which requires unique/innovative OTV structural design. For the 65 000 lb Shuttle capability case, there would be no problem with the conventionally designed OTV for either case, and the qualification here is only for the 100 000 lb Shuttle capability case.

A. 65 000 lb Shuttle Capability Comparison

A tabulated summary of the Shuttle launches by the APOTV with a 65 000 lb Shuttle capability for the Nominal Program Option is shown in Table 29. The majority of the missions require dual Shuttle launches with two-stage OTV's. The capability for a 30 day sortie mission is not possible and would probably require some type of orbital assembly. Also the 12-man crew transfer capability is marginal.

A tabulated summary of the Shuttle launches by the AMOOS with a 65 000 lb Shuttle capability for the nominal program option is shown in Table 30. Approximately 25 to 35 percent of the missions require dual Shuttles with two-stage OTV's. This value may be higher depending on the nature of Satellite Power System (SPS) and Public Service Platform (PSP) payloads. The sortie mission requires dual launches. The 12-man crew transfer would be possible but was not used here.

The nominal program from 1986-1995 will require approximately 643 Shuttle launches if APOTV is selected and approximately 380 Shuttle launches if AMOOS is assumed.

Similar launch requirements for the Low Program Option for APOTV and AMOOS are shown in Tables 31 and 32. The findings are similar with reduced launch rates. The APOTV requires approximately 317 Shuttle launches, and the AMOOS requires approximately 198 Shuttle launches.

B. 100 000 lb Shuttle Capability Comparison

Tabulated values for the Nominal and Low Program Options, with a 100 000 lb Shuttle capability for the APOTV and AMOOS, are shown in Tables 33 through 36.

TABLE 29. NOMINAL PROGRAM OPTION, 65 000 lb SHUTTLE/APOTV

470 I_{sp} — Lox/Hydrogen — Single and Dual Launches

Units	Program	Calendar Year										Remarks
		86	87	88	89	90	91	92	93	94	95	
Shuttle Launches (Mission Weight)	Station Elements	5	8	5	8	8	8					Dual Launch
	Station Cargo		4	4	11	18	15	4	3	4	3	
	SPS - Test/Development Hardware	4	10	8	8	5						
	Space Construction Base Miscellaneous			10				17	5	11		
	PSP			3	5	6	4	4	4	6	2	
	Solar Terrestrial Observatory (STO)	5					2		2			
	PSP and STO Miscellaneous		1		2		2		4		4	
	Automated or Cluster Payload	2	3	5	5	5	5	7	5	7	5	
	Subtotal	16	26	35	39	42	36	32	23	28	14	
Shuttle Launches (Mission Flights)	4-Man Crew Transfer		8	8	12	16	24	24	32	36	52	Dual Launch
	Station Supplies		4	4	6	8	12					
	12-Man Crew Transfer											Marginal
	4-Man Sortie	6	6	3	6	3	6	3	6	18	18	Repair Orbital Assembly
	Planetary	2	1	2	0	2	1	2	2	2	2	
	Lunar	1	1	1	1	2	2	1	1	1	1	
	High Altitude and Heliocentric				1			1			1	
	Subtotal	9	20	18	26	31	45	31	41	57	74	
	Program Total	25	46	53	65	73	81	63	64	85	88	

TABLE 30. NOMINAL PROGRAM OPTION, 65 000 lb SHUTTLE/AMOOS

470 I_{sp} — Lox/Hydrogen — Single and Dual Launches

Units	Program	Calendar Year										Remarks
		86	87	88	89	90	91	92	93	94	95	
Shuttle Launches (Mission Weight)	Station Elements	3	5	3	5	4	5					Dual Launch
	Station Cargo		2	2	6	10	8	2	3	2	3	
	SPS - Test/Development Hardware	2	5	4	5	3						
	Space Construction Base Miscellaneous			4				5	3	6		
	PSP			2	3	3	2	2	2	3	1	
	Solar Terrestrial Observatory (STO)	3					1		1			
	PSP and STO Miscellaneous		1		1		1		2		2	
	Automated or Cluster Payload	2	1	3	3	2	3	4	3	4	4	
	Subtotal	10	14	18	23	22	20	13	14	15	10	
Shuttle Launches (Mission Flights)	4-Man Crew Transfer		4	4	6	8	12	12	16	18	24	
	Station Supplies		4	4	6	8	12					
	12-Man Crew Transfer											None Used
	4-Man Sortie	4	4	2	4	2	4	2	4	8	16	Dual Launch
	Planetary	2	1	2	0	2	1	2	2	2	2	
	Lunar	1	1	1	1	2	2	1	1	2	1	
	High Altitude and Heliocentric	1			1			1			1	
	Subtotal	8	14	13	18	22	31	18	23	30	44	
	Program Total	18	28	31	41	44	51	31	37	45	54	

TABLE 31. LOW PROGRAM OPTION, 65 000 lb SHUTTLE/APOTV

470 I_{sp} — Lox/Hydrogen — Single and Dual Launches

Units	Program	Calendar Year										Remarks
		86	87	88	89	90	91	92	93	94	95	
Shuttle Launches (Mission Weight)	Station Elements			5	7	5				5	5	Dual Launch
	Station Cargo					5	5	5	5	7	5	
	SPS - Test/Development Hardware	4	3							5	7	
	Space Construction Base Miscellaneous			4				4				
	PSP	2	2		2			2	2		2	
	Solar Terrestrial Observatory (STO)		2			4			2			
	PSP and STO Miscellaneous			2			2		4			
	Automated or Cluster Payload	3	2	5	5	5	5	7	5	7	7	
	Subtotal	9	9	16	14	19	12	18	18	24	26	
Shuttle Launches (Mission Flights)	4-Man Crew Transfer				6	8	12	8	12	8	12	Dual Launch
	Station Supplies				3	4	6	4	6	4	6	
	12-Man Crew Transfer											Marginal
	4-Man Sortie		6	6	6	3	6	3	6	3	6	Repair Orbital Assembly
	Planetary			2		2		2		2		
	Lunar											
	High Altitude and Heliocentric											
	Subtotal		6	8	15	17	24	17	24	17	24	
	Program Total	9	15	24	29	36	36	35	42	41	50	

TABLE 32. LOW PROGRAM OPTION, 65 000 lb SHUTTLE/AMOOS

470 I_{sp} — Lox/Hydrogen — Single and Dual Launches

Units	Program	Calendar Year										Remarks
		86	87	88	89	90	91	92	93	94	95	
Shuttle Launches (Mission Weight)	Station Elements			3	4	3				3	3	Dual Launch
	Station Cargo					3	3	3	3	4	3	
	SPS – Test/Development Hardware	2	2							3	4	
	Space Construction Base Miscellaneous			2				2				
	PSP	1	1		1			1	1		1	
	Solar Terrestrial Observatory (STO)		1			2			1			
	PSP and STO Miscellaneous			1			1		2			
	Automated or Cluster Payload	2	1	3	3	3	3	4	3	4	4	
	Subtotal	5	5	9	8	11	7	10	10	14	15	
Shuttle Launches (Mission Flights)	4-Man Crew Transfer				3	4	6	4	6	4	6	
	Station Supplies				3	4	6	4	6	4	6	
	12-Man Crew Transfer											None Assumed
	4-Man Sortie		4	4	4	2	4	2	4	2	4	Dual Launches
	Planetary			2		2		2		2		
	Lunar											
	High Altitude and Heliocentric											
	Subtotal		4	6	10	12	16	12	16	12	16	
	Program Total	5	9	15	18	23	23	22	26	26	31	

TABLE 33. NOMINAL PROGRAM, 100 000 lb SHUTTLE/APOTV

470 I_{sp} — Lox/Hydrogen — Single and Dual Launches

Units	Program	Calendar Year										Remarks
		86	87	88	89	90	91	92	93	94	95	
Shuttle Launches (Mission Weight)	Station Elements	4	5	4	5	5	5					Dual Launches
	Station Cargo		3	5	8	13	10	3	2	3	2	
	SPS - Test/Development Hardware	3	6	5	6	4						
	Space Construction Base Miscellaneous			5				7	4	8		
	PSP			3	4	4	2	3	2	4	1	
	Solar Terrestrial Observatory (STO)	4					1		1			
	PSP and STO Miscellaneous		1		1		1		3		2	
	Automated or Cluster Payload	2	2	4	3	4	3	5	4	5	5	
	Subtotal	13	17	26	27	30	22	18	16	20	10	
Shuttle Launches (Mission Flights)	4-Man Crew Transfer		4	4	6	8	12	12	24	36	48	Dual Launches
	Station Supplies		4	4	6	8	12					
	12-Man Crew Transfer											
	4-Man Sortie	4	4	2	4	2	4	2	4	8	12	
	Planetary	2	1	2	0	2	1	2	2	2	2	
	Lunar	1	1	1	1	2	2	1	1	2	1	
	High Altitude and Heliocentric	1			1			1			1	
	Subtotal	8	14	13	18	22	31	18	31	48	64	
	Program Total	21	31	35	45	52	53	36	47	68	74	

TABLE 34. NOMINAL PROGRAM, 100 000 lb SHUTTLE/AMOOS

470 I_{sp} — Lox/Hydrogen

Units	Program	Calendar Year										Remarks
		86	87	88	89	90	91	92	93	94	95	
Shuttle Launches (Mission Weight)	Station Elements	2	3	2	3	3	3					
	Station Cargo		2	1	4	7	6	2	1	2	1	
	SPS – Test/Development Hardware	2	3	3	3	2						
	Space Construction Base Miscellaneous			3				4	2	5		
	PSP			2	2	3	1	2	1	2	1	
	Solar Terrestrial Observatory (STO)	2					1		1			
	PSP and STO Miscellaneous		1		1		1		1		2	
	Automated or Cluster Payload	1	1	2	2	2	2	3	2	3	3	
	Subtotal	7	10	13	15	17	14	11	8	12	7	
Shuttle Launches (Mission Flights)	4-Man Crew Transfer		4	4	6	8	12					
	Station Supplies											Carried on Crew Transfer Launch or after 1991 on HLLV
	12-Man Crew Transfer							4	8	12	24	
	4-Man Sortie	2	2	1	2	1	2	1	2	4	6	
	Planetary	2	1	2	0	2	1	2	2	2	2	
	Lunar	1	1	1	1	2	2	1	1	2	1	
	High Altitude and Heliocentric	1			1			1			1	
	Subtotal	6	8	8	10	13	17	9	13	20	34	
	Program Total	13	18	21	25	30	31	20	21	32	41	

TABLE 35. LOW PROGRAM OPTION, 100 000 lb SHUTTLE/APOTV

470 I_{sp} — Lox/Hydrogen — Single and Dual Launches

Units	Program	Calendar Year										Remarks
		86	87	88	89	90	91	92	93	94	95	
Shuttle Launches (Mission Weight)	Station Elements			4	5	4				4	3	Dual Launches
	Station Cargo					4	4	4	4	5	4	
	SPS - Test/Development Hardware	2	4									
	Space Construction Base Miscellaneous			3				3				
	PSP	1	2		1			1	2		1	
	Solar Terrestrial Observatory (STO)		1			3			1			
	PSP and STO Miscellaneous			1			2		3			
	Automated or Cluster Payload	2	2	4	3	4	3	5	4	5	5	
	Subtotal	5	9	12	9	15	9	13	14	14	13	
Shuttle Launches (Mission Flights)	4-Man Crew Transfer				6	8	12	8	12	8	12	Dual Launches
	Station Supplies				3	4	6	4	6	4	6	
	12-Man Crew Transfer											
	4-Man Sortie		4	4	4	2	4	2	4	2	4	Capability Marginal
	Planetary			2		2		2		2		
	Lunar											
	High Altitude and Heliocentric											
	Subtotal		4	6	13	16	22	16	22	16	22	
	Program Total	5	13	18	22	31	31	29	36	30	35	

TABLE 36. LOW PROGRAM OPTION, 100 000 lb SHUTTLE/AMOOS

470 I_{sp} — Lox/Hydrogen

Units	Program	Calendar Year 86	87	88	89	90	91	92	93	94	95	Remarks
Shuttle Launches (Mission Weight)	Station Elements			2	3	2				2	2	
	Station Cargo					3	2	2	2	3	3	
	SPS – Test/Development Hardware	2	1							2	3	
	Space Construction Base Miscellaneous			2				1				
	PSP	1	1		1			1	1		1	
	Solar Terrestrial Observatory (STO)		1			1			1			
	PSP and STO Miscellaneous			1			1		1			
	Automated or Cluster Payload	1	1	2	2	2	2	3	2	3	3	
	Subtotal	4	4	7	6	8	5	7	7	10	12	
Shuttle Launches (Mission Flights)	4-Man Crew Transfer				3	4	6	4	6	4	6	
	Station Supplies											
	12-Man Crew Transfer		2	2	2	1	2	1	2	1	2	
	4-Man Sortie			2		2		2		2		
	Planetary											
	Lunar											
	High Altitude and Heliocentric											
	Subtotal		2	4	5	7	8	7	8	7	8	
	Program Total	4	6	11	11	15	13	14	15	17	20	

The APOTV findings are similar to the 65 000 lb case with dual launches being required. The 12-man crew transfer capability and a marginal 4-man 30 day sortie mission using dual Shuttle launches is possible.

The AMOOS findings are somewhat better with the possibility that dual Shuttle launches can be avoided.

The Nominal Program Option requires launching approximately 466 APOTV's or approximately 252 AMOOS's. The Low Program Option requires launching approximately 250 APOTV's or approximately 126 AMOOS's.

C. Annual Launch Rate Comparison

Figure 57 shows graphical comparisons of the Shuttle launches required by the APOTV and AMOOS for the 65 000 and 100 000 lb Shuttle systems, respectively. As can be seen, the AMOOS requires approximately 60 percent as many Shuttle launches as APOTV for the 65 000 lb Shuttle capability. The AMOOS improves slightly for the 100 000 lb Shuttle case and only requires approximately 51 to 54 percent as many launches as APOTV.

Figure 57 also reflects the Shuttle launch rate comparisons for the APOTV and AMOOS and summarizes the same data for a 10 year rate. It can be seen that the AMOOS with the 65 000 lb Shuttle is more attractive than the APOTV with a 100 000 lb Shuttle. Also, the AMOOS can perform the Nominal Program Option with only a few more flights than APOTV can perform the Low Program Option.

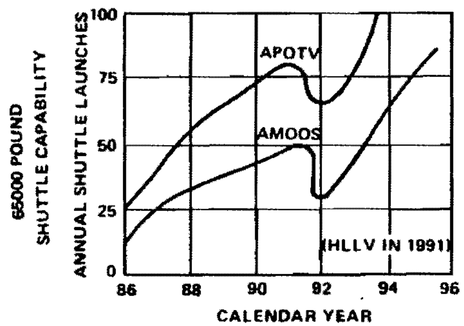
XII. PROGRAM SCHEDULES AND COSTS

The two principal OTV concepts which have been investigated are the APOTV and the AMOOS. In this section AMOOS is sometimes referred to as AMOTV. Program schedules and costs for those OTV's for the high performance lox/hydrogen systems are given in this section. Development, schedules, schedule differences, cost, and cost differences are shown for each stage concept. Finally the two concepts are compared.

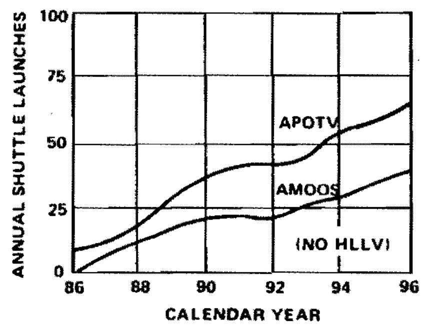
The reader should note that the program schedules and cost information shown from pages 109 through page 120 is for analysis and concept comparison purposes. Schedules and costs for planning usage are given in Section E beginning on page 121.

TOTAL PROGRAM CAPTURE/LAUNCHES REQUIRED

NOMINAL PROGRAM



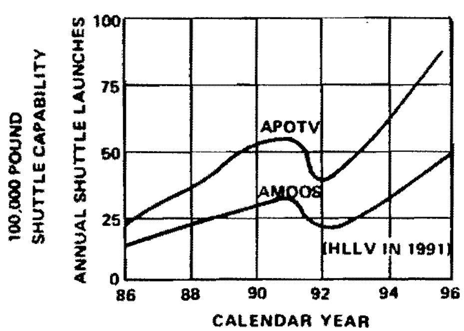
LOW PROGRAM OPTION



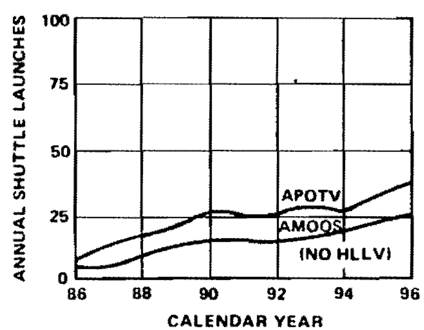
NOTES: AMOOS
① DUAL STAGES FOR HEAVY ELEMENTS AND PAYLOADS
② DUAL STAGES FOR 4 MAN SORTIE MISSIONS

APOTV
① DUAL STAGES FOR HEAVY ELEMENTS HEAVY PAYLOADS AND CREW TRANSFER
② ORB. ASSY. AND/OR SPECIAL HARDWARE REQUIRED FOR 4 MAN SORTIE MISSION

NOMINAL PROGRAM



LOW PROGRAM OPTION



NOTES: AMOOS
① STA. SUPPLIES CARRIED WITH 4 MAN CREW MODULE
② 12 MAN CREW MODULE @ 1991
③ CARGO BAY LENGTH PROBLEM REQUIRES UNIQUE DESIGN.

APOTV
① DUAL LAUNCHES USED FOR HEAVY ELEMENTS, CREW TRANSFER AND 4 MAN SORTIE (CAPABILITY TO PERFORM THE 4 MAN SORTIE IS VERY QUESTIONABLE)

TOTAL SHUTTLE LAUNCHES REQ'D

SHUTTLE CAPABILITY	APOTV		AMOOS	
	NOMINAL PROGRAM	LOW PROGRAM	NOMINAL PROGRAM	LOW PROGRAM
65000 POUNDS	643	317	380	198
100,000 POUNDS	466	250	252	126

Figure 57. Total program capture/launches required.

A. Schedules (For APOTV/AMOOS Comparison)

Guidelines for the program schedules for the OTV concepts which follow are for orbit flight tests in 1985 and initial operations capability (IOC) in 1986. Capture cost comparisons reflect OTV usage for the 10 year period from 1986 to 1995. A Phase C/D start in 1980 is assumed.

B. Engine Development

The lox/hydrogen RL-10 category IIB engine system, as proposed by MSFC and defined by the Pratt and Whitney (P& W) Company, has been extensively used in previous OTV studies. This engine was selected for the MSFC baseline Space Tug in 1974. This engine development schedule as proposed by P& W is shown in Figure 58.

The schedule shows approximately 1 year of flexibility. It does not, however, allow for a new startup which will be required if the current RL-10 A3-3 engine product line is shut down in 1978 as has been indicated by P& W.

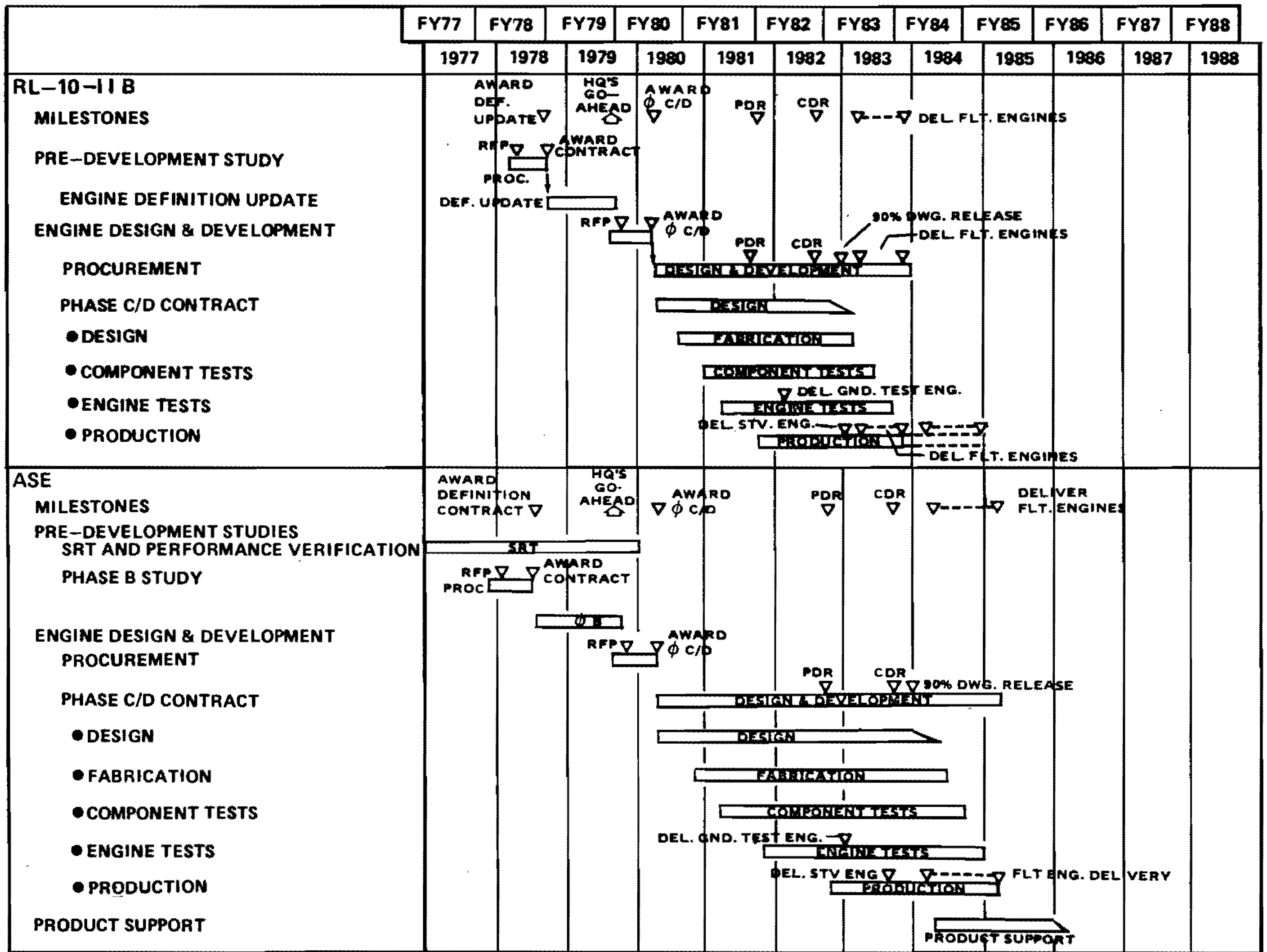
The RL-10-IIB engine technology is partially proven, and the engine performance at an expansion ratio of 205:1 was demonstrated by hot firings at Arnold Engineering Development Center (AEDC) in 1976. Only minimum supporting research and technology (SRT) efforts are required. An engine definition update would be required in FY-79.

The ASE being developed by Rocketdyne and NASA/Lewis Research Center (LeRC) was chosen to be representative of later propulsion system technology. This engine system was extensively studied by MSFC in 1972. The development schedule for the ASE is also shown in Figure 58. Scheduling information developed by P& W for the RL-10-IV was used as a basis for the ASE schedule which is shown.

The ASE requires considerable SRT and performance verification testing. A 15 month Phase B program is required in FY-78/79.

The development schedule for APOTV, in Figure 59, was based on schedules developed in the Phase B Space Tug studies by General Dynamics Corporation (GDC).

A 12 month Phase B activity is required in FY-78/79. Phase C/D begins in April 1980 for first vehicle delivery in October 1984. Vehicle production rate is two per year, and there are no apparent critical scheduling problems.



NOTE: USED P & WS RL–10 CAT. IIB ENGINE SCHEDULE AS A GUIDELINE WHICH DOES NOT ALLOW FOR NEW START UP TIME.

USED P&W'S RL–10 CAT. IV ENGINE SCHEDULE AS A GUIDELINE

Figure 58. Advanced engine comparison schedule.

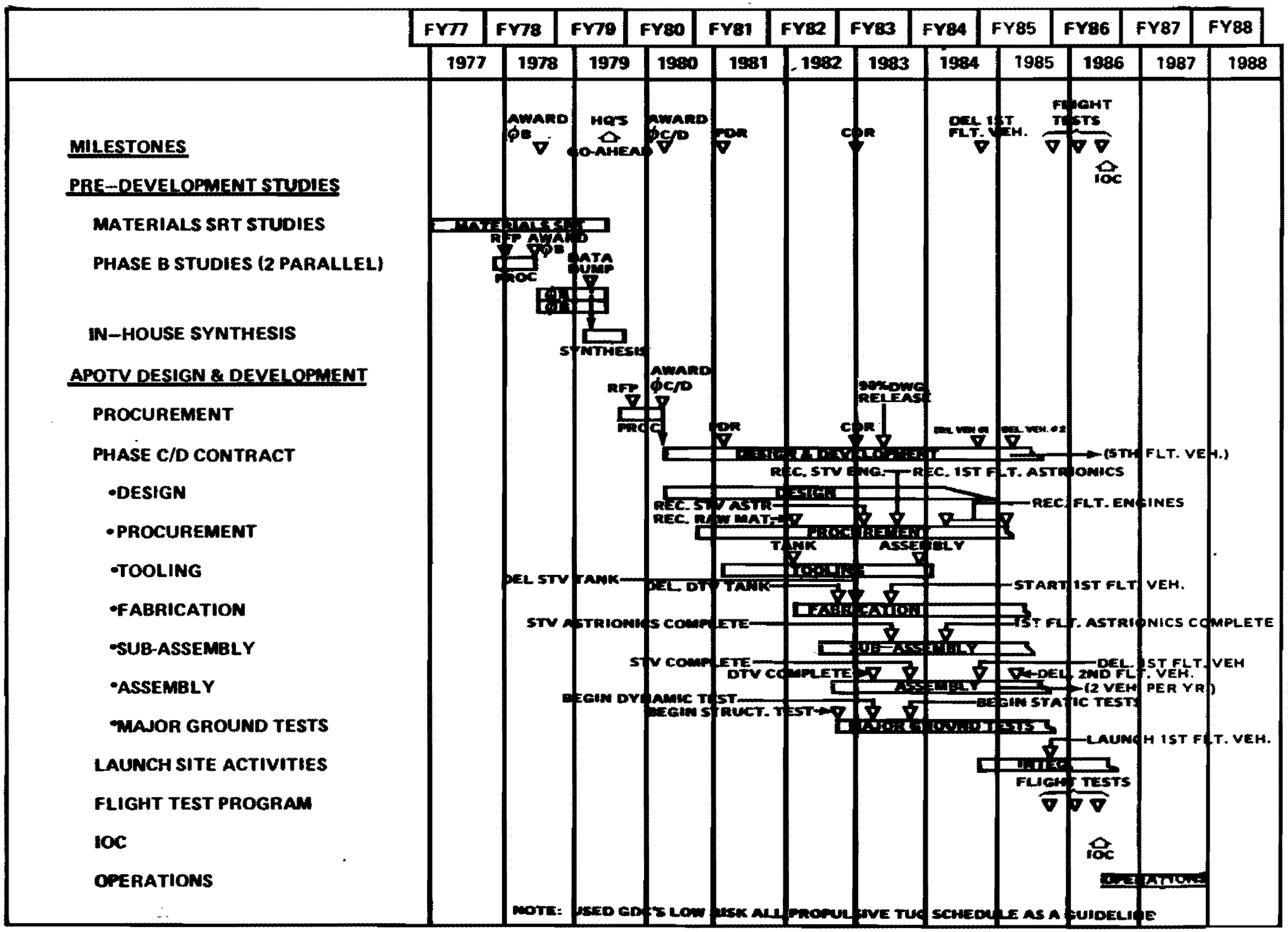


Figure 59. APOTV comparison schedule.

A development schedule for the AMOOS, which is directly comparable with the APOTV schedule previously mentioned, is shown in Figure 60. Major differences in the AMOOS and APOTV schedules are the large vehicle SRT for development of the aeromaneuvering capability, with appropriate guidance and navigation and the ablative heat shield.

The AMOOS also needs a 12 month Phase A which is scheduled for FY-78. If the Phase C/D and OTV delivery dates are held at the same schedule as shown (and as shown for APOTV), the AMOOS schedule shows a critical problem in having adequate procurement time for both Phase A and Phase B studies. The AMOOS schedule shown in Figure 61 reflects a combination Phase A/B which eliminates one procurement cycle and tends to be less time critical.

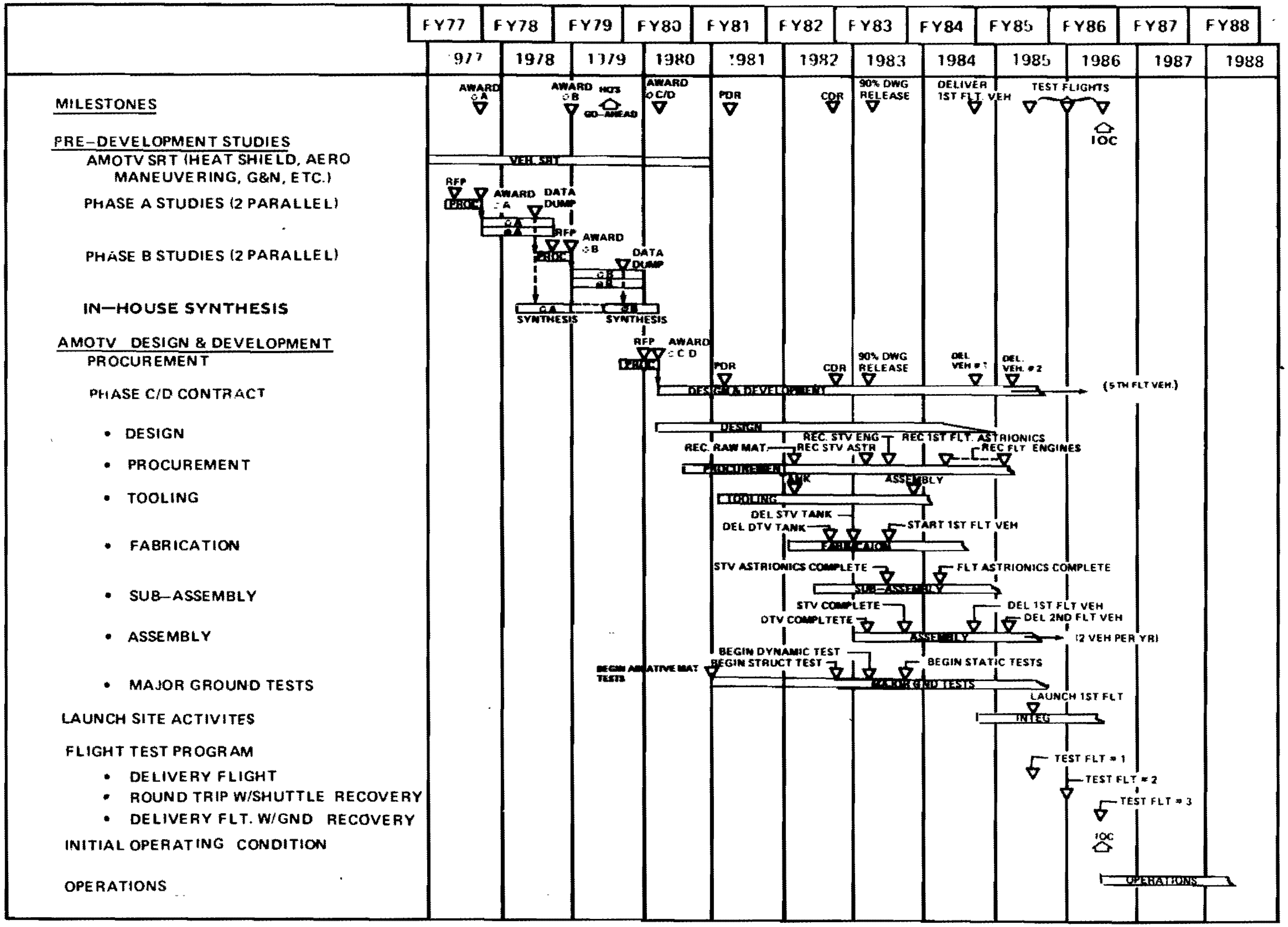
C. Schedule Comparison

The schedule analysis indicates that the RL-10 derivative engine and the ASE can be developed to meet the assumed schedules. The ASE represents a newer technology system, and more development is required. Future OTV study efforts should include further engine development schedule analysis to minimize schedule risk and to assure minimum developmental cost.

The schedule analysis indicates that the APOTV and AMOOS concepts can be developed to meet the assumed schedule. The AMOOS concept requires a tighter schedule to accomplish the design and development needs. To meet the development schedule, the AMOOS concept requires a combined Phase A/B effort. Future OTV study effort should include further schedule analysis to minimize schedule risk and to assure minimum developmental cost.

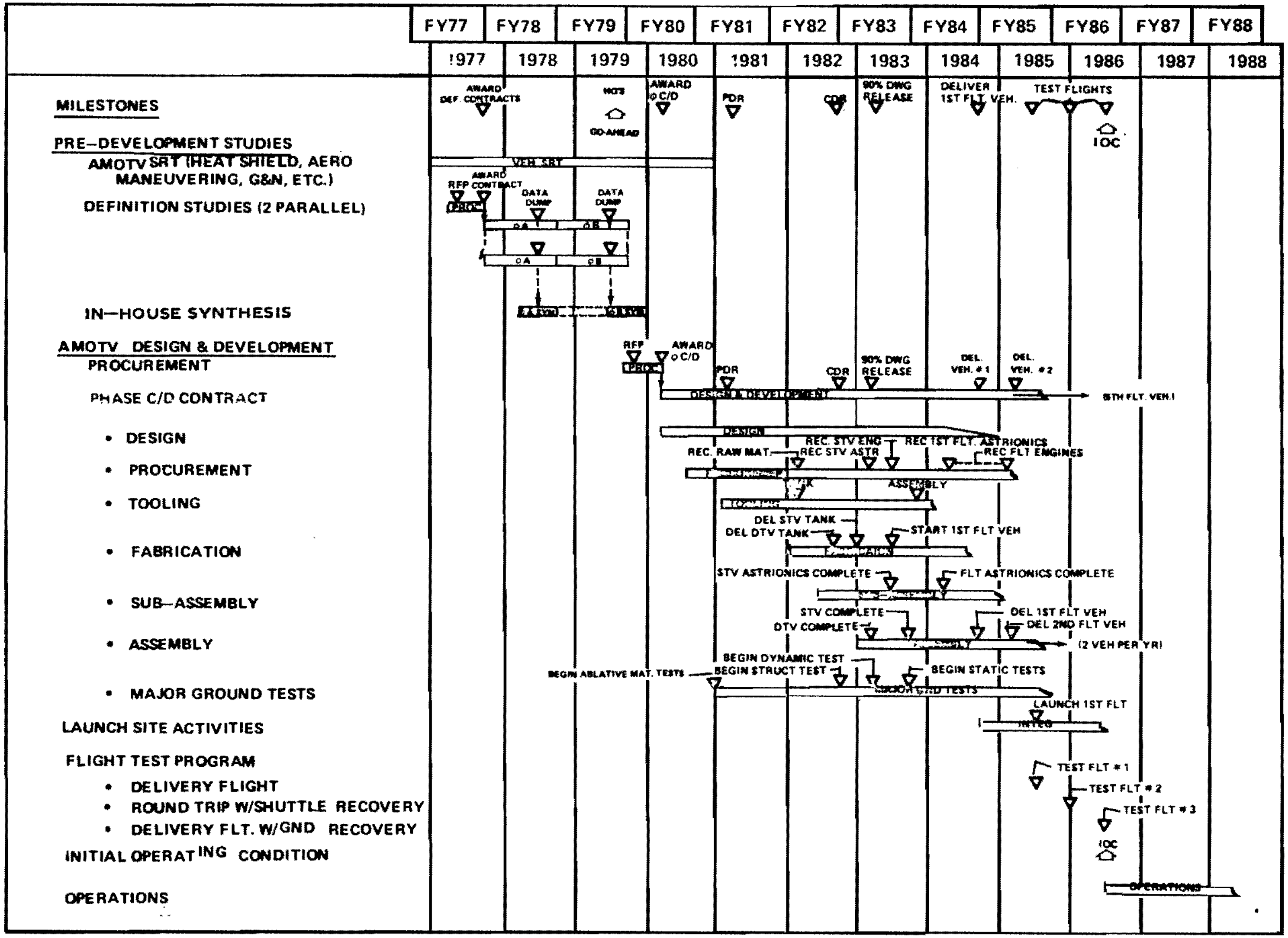
D. Program Costing (Comparison)

Program costs have been determined for the lox/hydrogen propellant APOTV and AMOOS. The cost values which are shown for the two concepts are directly comparable. No costs have been determined for the space storable or Earth storable type OTV systems shown in other sections of the report. The primary purpose of the costing analysis was to determine the cost differences associated with the development and operation of each OTV concept. The effects on the Shuttle, different launch facilities required for the Shuttle due to different launch rates for each concept, any cost on the payloads due to concept differences, etc., were not considered.



NOTE: USED GDC'S LOW RISK ALL PROPULSIVE TUG SCHEDULE AS A GUIDELINE

Figure 60. AMOTV comparison schedule.



NOTE: USED GDC'S LOW RISK ALL PROPULSIVE TUG SCHEDULE AS A GUIDELINE

Figure 61. AMOTV comparison schedule (option).

Costing groundrules and assumptions are as follows:

1. All costs are in constant 1976 dollars

2. Design, development, test and evaluation (DDT& E) costs include:

a. Contingency for 10 percent growth

b. Initial tooling

c. Cost for one operational vehicle plus additional instrumentation for obtaining flight test data

d. 1.75 equivalent vehicles required for ground test program

e. Model test flight plan for AMOTV (test bed)

f. GSE design and development plus two sets of GSE coding, verification, and system analyses for:

(1) On board software

(2) Mission support software

(3) GSE software

h. Prime contractor fee at 10 percent

3. Theoretical first unit cost includes the total estimated cost of procuring the first operational vehicle.

4. Investment cost includes:

a. A fleet of five operational vehicles

b. Initial spares

c. Sustaining tooling

d. Prime contractor fee at 12 percent

5. Operational cost includes all direct and indirect labor, materials (follow on spares) and propellants required to operate and maintain the OTV, and facilities and equipment peculiar to the OTV which were developed and produced during the DDT& E and investment phases.

6. The RL-10-IIB engine development cost is baselined.

Cost factors which were not considered are:

1. Orbiter interface equipment

2. Cost and cost difference for each OTV concept for developing dual stage (with dual Shuttle launches) operations capability

3. Orbital payload or orbital operations cost differences involved with each OTV concept

4. Effects on the Shuttle payload capability or number of Shuttle vehicles needed for each OTV concept

5. Different Shuttle vehicle launch facilities required for each OTV concept to produce similar program operations

6. Any additional OTV cost which might be necessary to meet up to 30 day mission duration to accommodate the manned sortie mission.

A 5 year DDT&E program and a 10 year operational program were assumed. Orbital Flight Test (OFT) is scheduled for 1985 and initial operational capability (IOC) is scheduled for 1986. To analyze accumulative transportation cost comparisons, a mission profile which requires 285 Shuttle/OTV flights for AMOOS and 528 Shuttle/OTV flights for APOTV were used. These AMOOS and APOTV flights are needed by each concept to perform a comparable 10 year program. The cost for each STS flight is $16 200 000.

Table 37 shows the OTV cost summary for the APOTV and AMOOS concepts. The AMOOS concept program cost is considerably higher than the APOTV concept primarily because of the requirement for the ablative thermal protection system (TPS) (heat shield) on the AMOOS. The TPS requires increased development and also results in a higher investment and operations cost. A model test program is assumed for development of the TPS system. It should be noted that the cost summary presented does not include costs for the STS.

Table 37 shows the average cost per flight for AMOOS at $2.4 M and for APOTV at $0.8 M. These values are average for a 10 year program (1986-1995). If these costs are added to other STS costs ($16.2 M per flight), the resulting average total transportation cost per flight is $18.6 M for AMOOS and $17.0 M for APOTV. The average total transportation for each Shuttle/AMOOS flight is

TABLE 37. OTV COST SUMMARY (1976 DOLLARS IN MILLIONS)

Nomenclature	AMOOS	APOTV
DDT&E	$ 608.7	$ 459.4
Investment	$ 132.5	$ 100.7
Operations	$ 692.0	$ 421.3
Total Program	$ 1433.2	$ 981.4
First unit	$ 31.7	$ 23.5
Average unit	$ 26.5	$ 20.1
Average cost/flight	$ 2.4	$ 0.8
Total flights	285.0	528.0
Operations fleet size	5.0	5.0
Duration of operational phase	10 years (1986-1995)	

approximately 9.4 percent more than for each Shuttle/APOTV flight. The average payload delivery capability for each Shuttle/AMOOS is 1.55 times that of each Shuttle/APOTV, and the average round trip payload capability of each Shuttle/AMOOS is 2.85 times that of each Shuttle/APOTV. This results in AMOOS payload delivery costs at approximately 71 percent of the APOTV delivery costs and AMOOS payload round trip cost at approximately 38 percent of APOTV round trip costs.

Figure 62 shows a comparative summary of the nonrecurring costs for the APOTV and AMOOS concepts. The peak annual funding for AMOOS occurs approximately 1 year earlier than for APOTV and is approximately $30.0 M higher. The AMOOS requires approximately $150 M more during the first 4 years of the program. These higher and earlier funding requirements for AMOOS are required to perform the early development work associated with the TPS and the model flight test program.

Figure 63 shows the accumulative cost comparison of the APOTV and AMOOS for 10 years of OTV operations, with the 5 year DDT&E program costs and STS costs at $16 200 000 per flight included. The data show a $3.5 billion higher cost for the Shuttle/APOTV. This cost difference is based on constant year (1976) dollars.

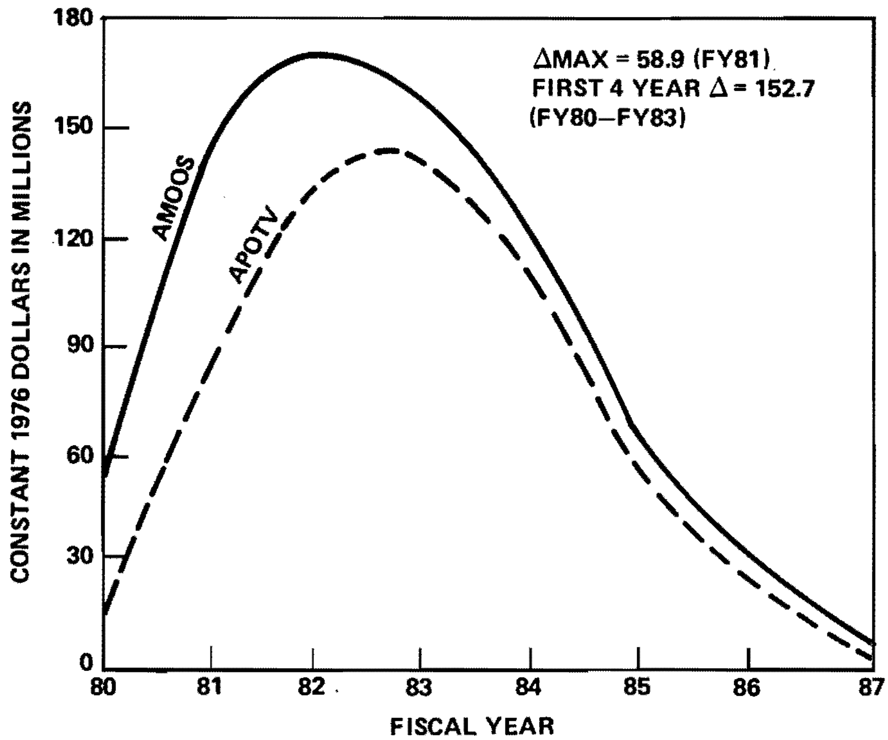


Figure 62. OTV program (comparison) nonrecurring cost summary.

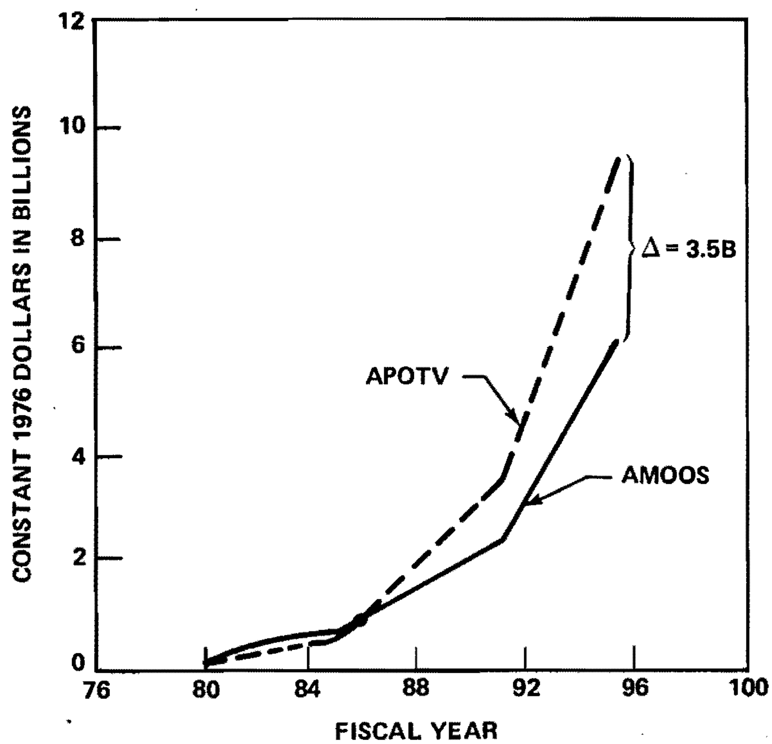


Figure 63. OTV program cost summary (comparison) including Shuttle transportation.

Because the AMOOS requires extensive early year funding, it was considered desirable to discount the expected costs at a 10 percent rate and to determine the comparative cost differences which result. Figure 64 shows this comparison. As can be seen the APOTV is \$1.1 billion higher. The analysis for current year (1976) dollars and the 10 percent discount cases indicate that the crossover point for the additional AMOOS costs occurs in 1986 or 1987, or within 1 to 2 years after operations begin, and the AMOOS has the advantage from the cost point of view.

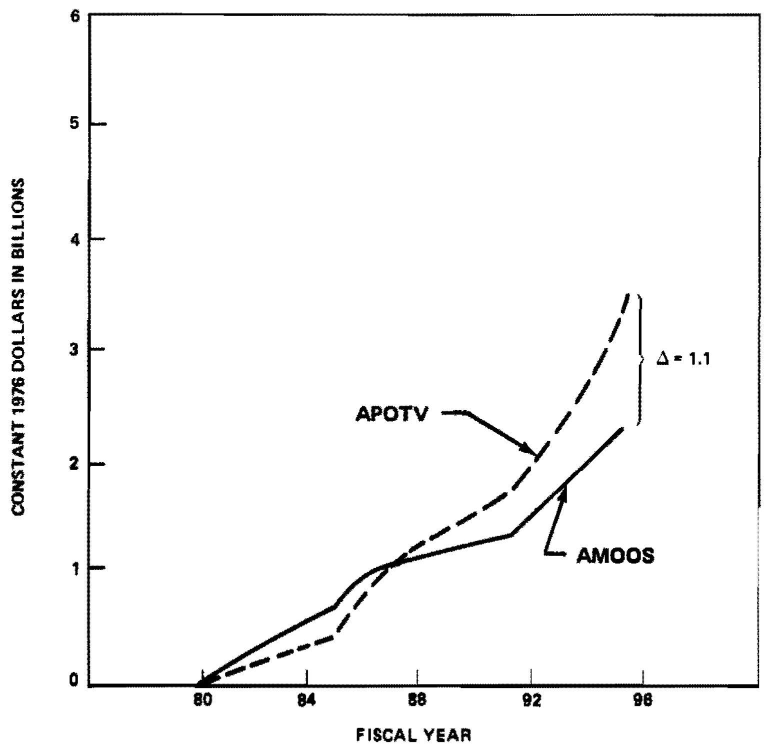


Figure 64. OTV program cost (discounted at 10 percent) summary (comparison) including Shuttle transportation.

Future OTV study effort should include further cost analysis. In addition to including those considerations previously mentioned, some analysis should address the high average flight cost of \$2.4 M for AMOOS. Some SRT or some development effort in ablator refurbishment may result in savings in operations costs. Also, further effort in schedule and cost optimization is desirable to assume a minimum cost OTV program.

E. Schedules and Cost for Planning Usage

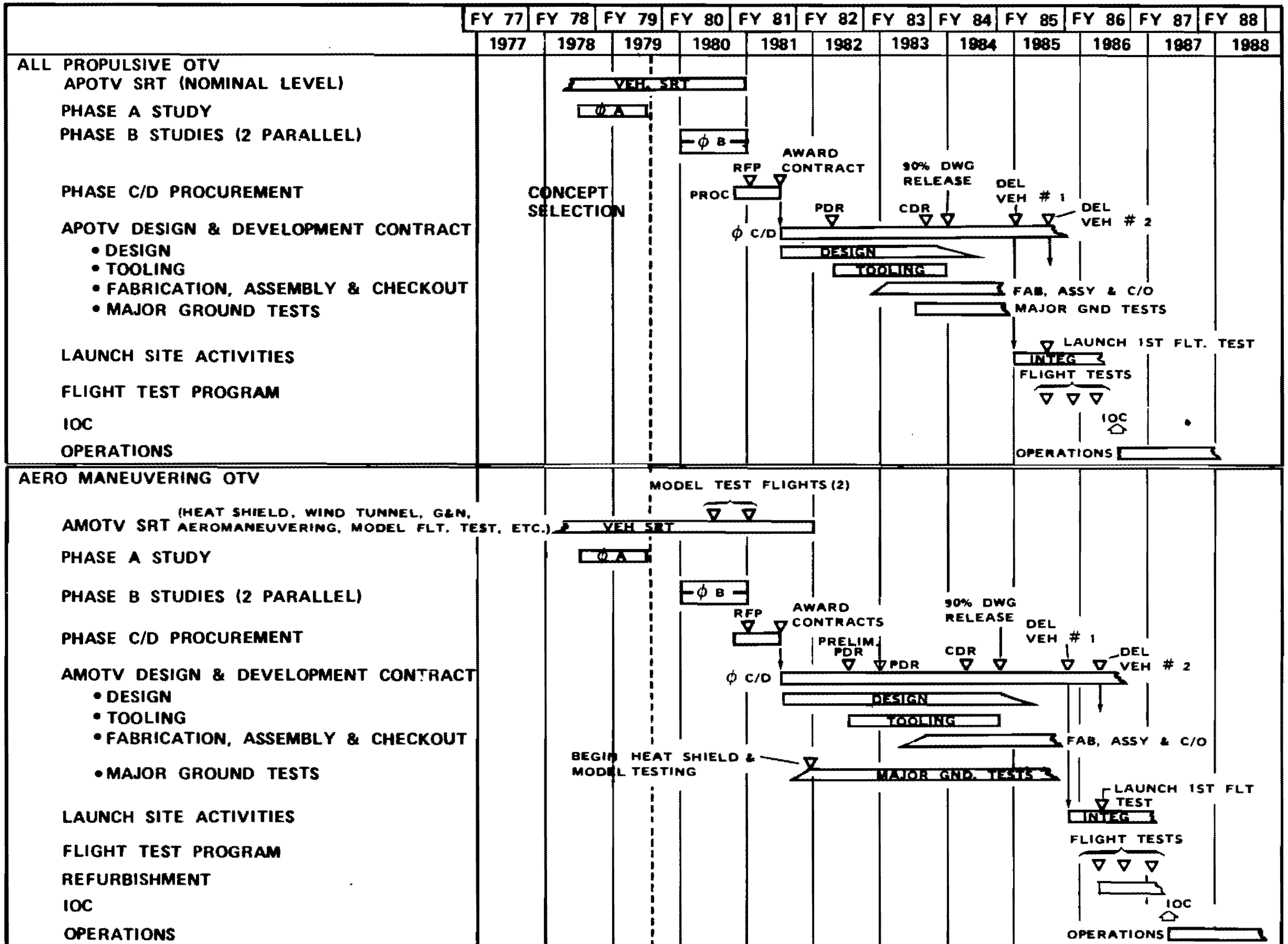
The schedules and costs previously shown were developed for OTV comparison purposes. The OTV schedules and costs shown here should be used for future planning purposes. The schedules for APOTV and AMOOS shown in Figure 65 represent approximately equal risks for either concept. The engine schedules previously given are appropriate. The nonrecurring program cost totals given in Table 37 are applicable. However, for the equal risk schedules, the nonrecurring cost summary shown in Figure 66 should be used. Guidelines and assumptions (APOTV and AMOTV) for these schedules are:

1. Phase A study in FY-78/79; 12 month duration
2. Phase B studies in FY-80 (two parallel); 12 month duration
3. Phase C/D start in 3rd quarter FY-81
4. P& W RL-10 IIB engine assumed
5. Comparable schedule risk
6. Six months planned for Shuttle integration and launch preparation
7. One year flight test program (three flights) prior to IOC.

The APOTV planning schedule includes only nominal SRT, and there are no outstanding risk factors. A new engine development would extend the total program by 9 months. First vehicle delivery is 42 months after Phase C/D contract award (51 months if a new engine development is required). IOC is in July 1986 for the RL-10 IIB engine assumption and in April 1987 if a new engine is required.

The AMOOS planning schedule includes extensive SRT with two model test flights scheduled for July and December in 1980. Primarily, the risk associated with the AMOOS is keyed to the predevelopment SRT and model test flight program achievements. Extensive ground test programs are scheduled in support of the vehicle design and development and for heat shield design and development efforts. A new engine development would not affect schedule planning which shows first vehicle delivery 51 months after Phase C/D contract award and IOC in April 1987.

The cost summary shows significant early year funding for the model test program for the AMOOS concept. The peak funding for AMOOS is slightly higher and approximately 1 year later for AMOOS than for APOTV.



NOTE: P&W RL10 CAT. IIB ENGINE ASSUMED

Figure 65. OTV planning schedules (APOTV and AMOTV).

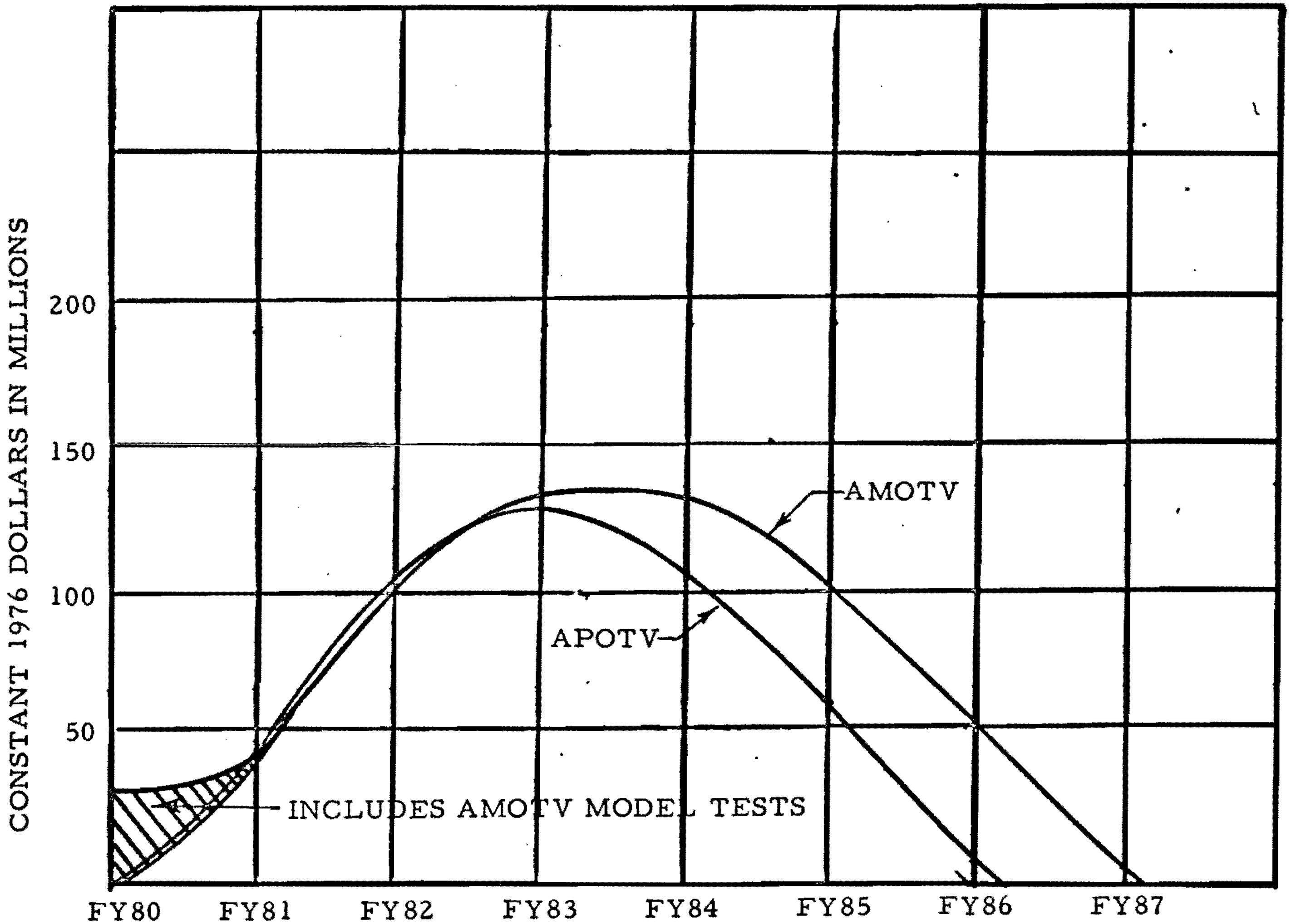


Figure 66. OTV nonrecurring cost summary.

XIII. APOTV-AMOOS DESIGN COMPARISONS

The APOTV (formerly Space Tug) and AMOOS concepts have been extensively studied by MSFC. The AMOOS efforts followed the APOTV activity and used, where appropriate, the results of the APOTV design efforts. The APOTV background primarily addressed unmanned payloads, and the AMOOS study has addressed manned capability. The AMOOS studies have mainly addressed problems peculiar to the aeromaneuvering aspects of the system. The APOTV definition, particularly in detailed design, is much more advanced than AMOOS.

While there are differences in the complexities and level of understanding of APOTV and AMOOS, there are no "show stoppers" expected for either concept. The comparisons which follow are illustrative of the differences and concerns related to each concept and should be useful for costing the two concepts and for future activity planning.

In Pre-Phase A activities, \$578 000 and \$291 359 have been spent on contracted studies on the APOTV and AMOOS, respectively. In the Phase A type contracted efforts, \$400 000 has been spent on APOTV and \$50 000 on AMOOS. No Phase B contracted activity has occurred for the AMOOS vehicle; \$1 635 115 has been spent on APOTV.

It is difficult to compare the status of maturity of the two concepts because the requirements and payload capabilities have changed significantly since the major portions of the APOTV studies were performed. Also, a portion of the APOTV study effort and advanced development is directly applicable to AMOOS. The desire to improve the Shuttle payload capability and maintain the current cargo bay length will probably require new unique design approaches for either case.

It seems fair to say that, up to and including significant portions of the Phase A definition efforts, the two concepts are comparable in definition and maturity; thereafter, the AMOOS definition is less than APOTV. This is particularly so in areas such as internal arrangement, specific conceptual design detail of structural closures, TPS (ablative shield) refurbishment, and problems associated with the small atmospheric reentry corridor necessary for AMOOS. Also, problems associated with communication systems, RCS, and their protection during reentry have not been addressed for AMOOS.

A. Detailed Layout — Design Comparison

1. APOTV. For the most part, the APOTV design is relatively mature and few issues exist. Problems associated with Shuttle improvements, interfacing with the Orbiter, payloads, Space Station, etc., are issues.

2. AMOOS. AMOOS studies have primarily addressed the external configuration aspects of the OTV. Generally APOTV internal arrangements, etc., have been used, and as a result no AMOOS optimal design exists. Internal arrangements (in-board profile, structural, propulsion, avionics details) are of concern. Center of gravity/center of pressure relationships and general aerodynamic evaluation for range of payloads and reentry configurations are needed. Engine arrangement and related door openings and sealing problems are issues. Problems associated with Shuttle improvements, interfacing with the Orbiter, payloads, Space Station, etc., are issues.

B. Propulsion

The APOTV and AMOOS concepts studied here use essentially the same main stage propulsion system. Lox and hydrogen have been used as principal engine propellants. Very little effort has been expended on the Earth or space storable systems.

Differences in the RCS of the two concepts are reasonably well known. No problems are anticipated for either in a propulsion sense. The AMOOS requires a rather high thrust (200 lbf) during reentry, and the arrangement and protection of the system are problems.

Comparison of the APOTV and AMOOS for propulsion problems associated with two staging, long orbit stay time, higher mixture ratios, and other problems associated with the OTV mission capture have not been investigated; however, few if any problems are expected.

C. Structures

1. APOTV. Due to the high velocity requirements required by the APOTV type system, weight is a very critical factor. Quite exotic and advanced designs are needed to obtain reasonable and competitive payload capabilities with APOTV. The configuration aspects of the APOTV are significantly more simple or conventional than AMOOS.

2. AMOOS. The AMOOS uses aeromaneuvering/braking with an ablative heat shield which reduces the propulsive velocity required by 25 to 28 percent when compared to APOTV. For this reason the AMOOS has significantly more payload capability, and structural system weight is much less critical. The AMOOS, however, requires a very unconventional structural design in configuration and environment. The AMOOS structure experiences the cold environment of the cryogenics and the hot environment of the atmospheric reentry. It is to be expected that the structural problems of AMOOS are significantly greater than APOTV; for example, the tank support structure must be designed to absorb large thermal gradients. Although most of the structural concepts for AMOOS are current state-of-the-art, they are representative of innovative applications of these arts.

D. Thermal/Thermal Control

Thermal control for cryogenic tankage is the same for the APOTV and AMOTV with slightly more insulation being required for AMOOS. The proposed protection systems seem adequate for up to 7 day systems. Since the previous Space Tug studies, the requirement for up to 30 day sortie missions has been added, and very little is known about the resulting tankage insulation effects. This is an issue which must be addressed in future definition of either system.

1. APOTV. The thermal design of APOTV is relatively simple when compared to AMOOS. Significantly less refurbishment is expected as the APOTV has no heat shield and few sealing problems.

2. AMOOS. The AMOOS has an ablative heat shield covering the entire external surface. The proposed shield material is current state-of-the-art as manufactured by the Martin Marietta Company (MMC) for the Viking program. Sealing problems are expected for the openings and closures of the external surface. Significant problems associated with refurbishment or replacement of the ablator are expected.

E. Guidance, Navigation, and Control

Basically the guidance, navigation, and control (GN& C) problems of the APOTV and AMOOS concepts are the same for all maneuvers prior to the maneuvers which place the OTV in Shuttle compatible rendezvous orbits. Simplified flight profiles depicting these maneuvers are given in the Flight Profile Section. The first significant difference, which affects GN& C, occurs as the OTV's are approaching the insertion window at perigee (APOTV) or atmospheric reentry corridor (AMOOS). The APOTV requires only a 15 n.mi. constraint on the Orbiter compatible rendezvous orbit while the AMOOS has a ±2 n.mi. constraint on the atmospheric entry corridor. The AMOOS contractor, LMSC, has studied this problem and recommends a sextant type system composed of two star trackers and a horizon system for use on the AMOOS.

The AMOOS requires an additional guidance law for the aerobraking maneuver. An additional 5000 words of software are required for AMOOS. This is compared with APOTV.

As the AMOOS ascends from the atmosphere after the atmospheric maneuver, the perigee must be raised so that the AMOOS does not enter again on the next orbit. This maneuver must be made in less than 45 min after atmospheric exit which causes an issue at the approximate time for tracking or position, updating, etc. It may be necessary, or desirable, to perform an additional propulsive maneuver here to circumvent these problems. The additional maneuver would be predetermined but only for the purpose of raising perigee and could be initiated by a timer. The AMOOS would then accommodate the 15 n.mi. constraint Shuttle Orbiter compatible rendezvous orbit.

F. Communication and Data Management

There have been no principal differences identified in the communication and data management subsystems for APOTV or AMOOS except that computer memory must be increased by 5000 words to accommodate the increased guidance and navigation capability for AMOOS. There are, however, differences in operations applicability and subsystems design due to the atmosphere maneuver of AMOOS. These are as follows:

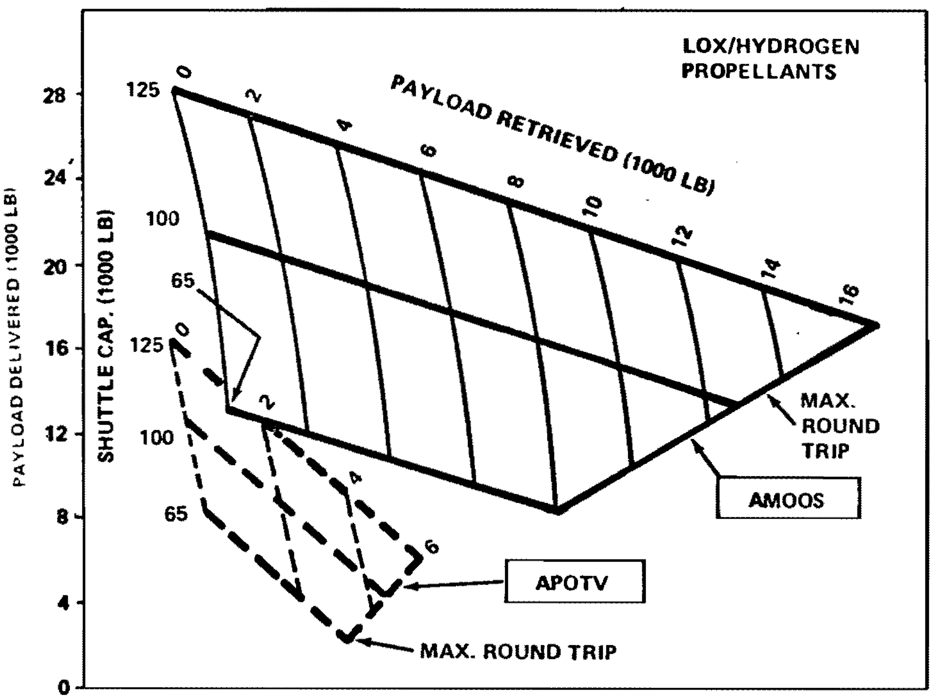
- Ports in vehicle to allow antenna deployment (e.g., communications, docking, etc.)

- Deploy/retract mechanism for antennas and control system.

- Plasma sheath problems (if communication is required during the atmospheric maneuver).

G. Performance/Capability Comparison

A performance/capability comparison for the APOTV and AMOOS concepts is shown in Figure 67. As can be seen, it is increased performance/capability which makes the AMOOS desirable. The payload retrieval shown



NOTES

1 SINGLE SHUTTLE LAUNCH WITH STAGE AND PAYLOAD CARRIED ON SAME SHUTTLE

2 2.9% SHUTTLE TARE WEIGHT ASSUMED

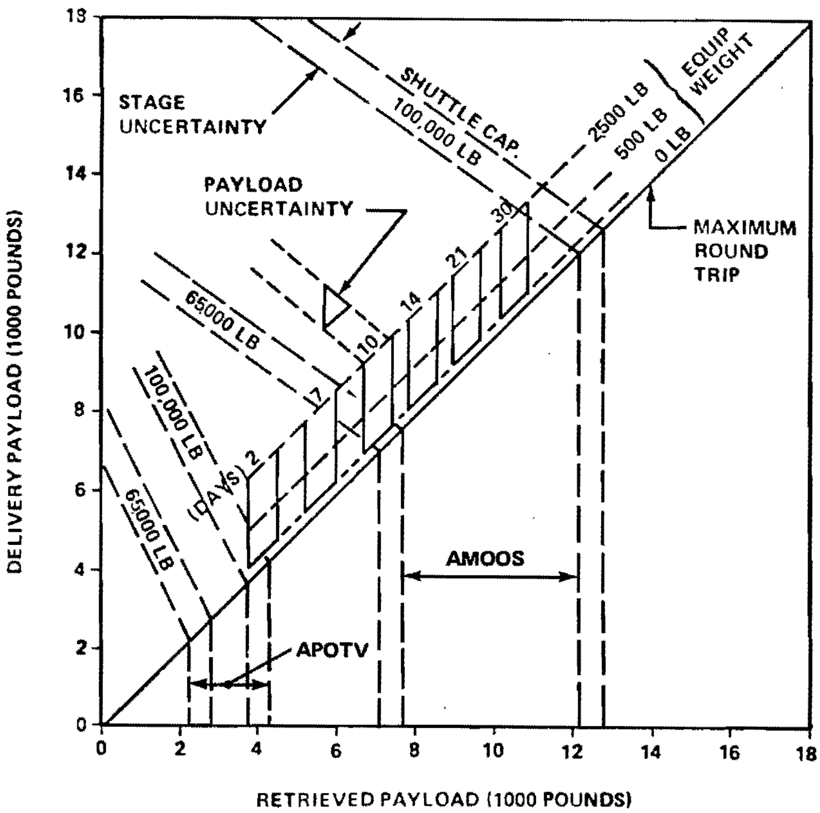
RETRIEVE ONLY CAPABILITY

APOTV		
65K SHUTTLE	–	4,900 LB
125K SHUTTLE	–	9,100 LB
AMOOS		
65K SHUTTLE	–	15,500 LB
125K SHUTTLE	–	34,700 LB

Figure 67. Geosynchronous orbit capability comparison.

assumes the payload would be launched on the same vehicle. If zero payloads were launched, the retrieve only capability would be somewhat higher. Retrieve-only capabilities for the APOTV range from 4900 to 9100 lb for the 65 000 to 125 000 lb Shuttle capability range. Retrieve-only capabilities for the AMOOS range from 15 600 to 34 700 lb for the 65 000 to 125 000 lb Shuttle capability.

The round trip capability advantage of the AMOOS when used in the single Shuttle/stage mode is very significant for the manned OTV missions. A comparison of the manned sortie mission requirements with the lox/hydrogen fueled APOTV and AMOOS concepts is shown in Figure 68. Shuttle capabilities of 65 000 and 100 000 lb are referenced. As can be seen, the APOTV offers little capability while the AMOOS offers up to 30 day sortie mission capability (Table 3).



NOTES:
1 EQUIPMENT WEIGHT DELIVERED BUT NOT RETURNED
2 LOX/HYDROGEN OTV
3 2.9 SHUTTLE TARE
4 UNCERTAINTY REPRESENTS EXPECTED ACCURACY OF ANALYSIS

Figure 68. Four-man Sortie capability requirement (Shuttle/OTV capability referenced).

XIV. DISCUSSION OF THE OTV PROGRAM OPTIONS

As previously mentioned, the OTV analysis data have been parameterized for Shuttle capabilities ranging from 65 000 to 125 000 lb. This section deals with identification and discussion of various options within this Shuttle capability range. The options deal primarily with lox/hydrogen OTV concepts; however, limited discussion with space/Earth storable systems is shown.

A summary of payload transfer capability requirements is shown in Table 3. These capabilities may be expected to change somewhat as more development is completed. It is, however, expected that they are representative of the future needs and that they will change only by a small percent. Also, when an OTV concept together with a corresponding improved Shuttle capability is selected, the payloads can be expected to be designed to conform with the transportation capability.

A. Lox/Hydrogen Propellant Orbit Transfer Vehicles

Twelve options for the single Shuttle stage and dual Shuttle stage OTV are discussed. The single Shuttle stage concepts involve only one Shuttle launch, and the payload and OTV are carried to low Earth orbit in the same Shuttle. For the dual Shuttle stage case, a stage sized for single launch has been used, and one stage and one-half of the payload are carried to orbit on each of two Shuttles.

Summary payload requirements and capabilities are shown in Figures 69 and 70. Figure 69 shows the delivery only case, and Figure 70 shows round trip capability. Figure 71 shows similar summary in simpler form.

1. <u>65 000 lb Shuttle Capability Options.</u> For the single Shuttle stage cases, neither the APOTV nor AMOOS satisfies the required capabilities. The AMOOS does, however, provide limited capability for manned transfer.

For the dual Shuttle stage cases, the APOTV does not adequately provide capability for sortie missions. The AMOOS provides capabilities to perform all missions except the fully assembled stations.

2. <u>100 000 lb Shuttle Capability Options.</u> For the single Shuttle stage case, the APOTV still does not meet any of the capability requirements. It may nearly meet the four-man crew transfer requirement. The AMOOS single Shuttle stage, however, meets nearly all of the requirements except for the fully assembled station.

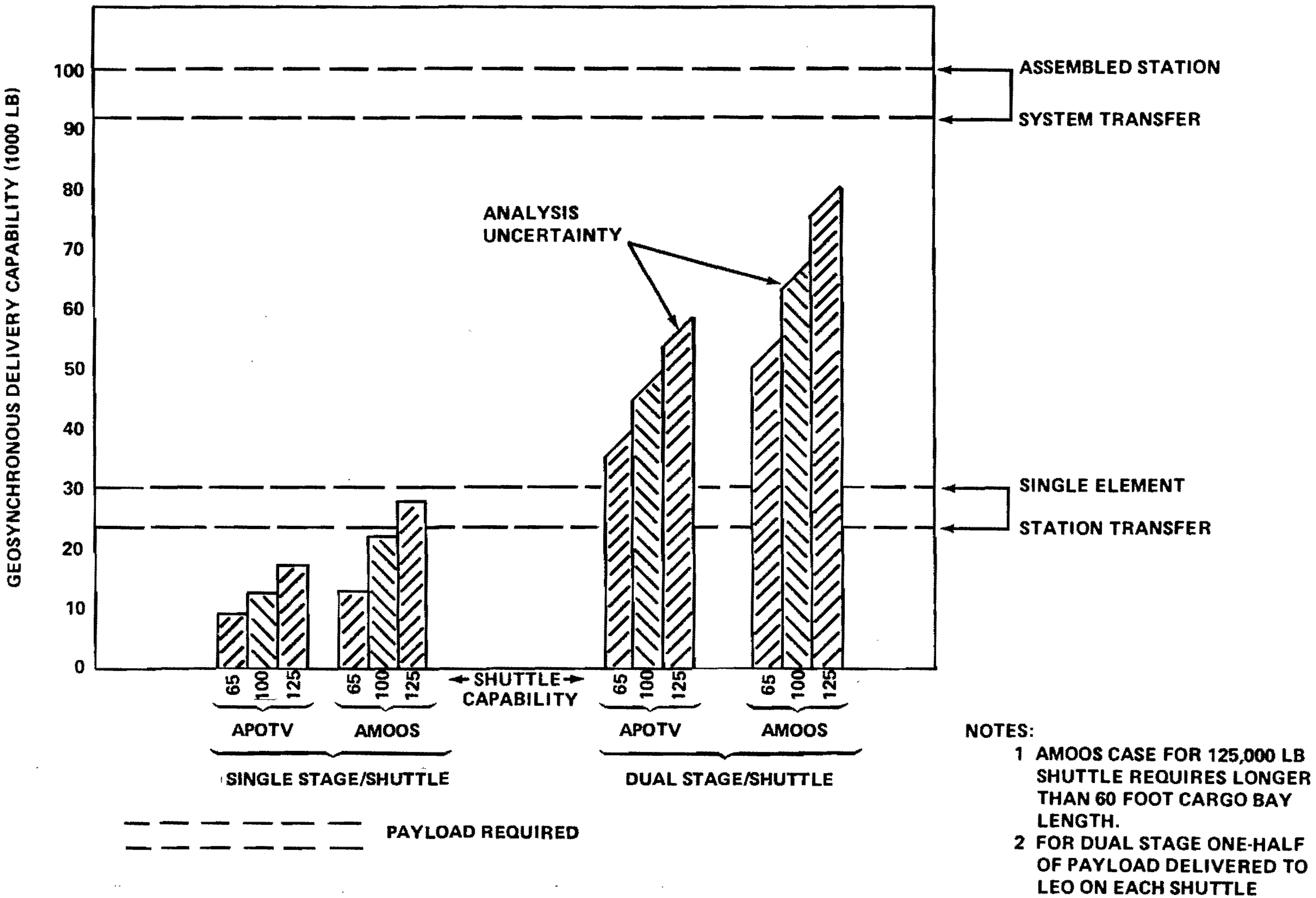


Figure 69. OTV geosynchronous delivery capability (lox/hydrogen) — payload required.

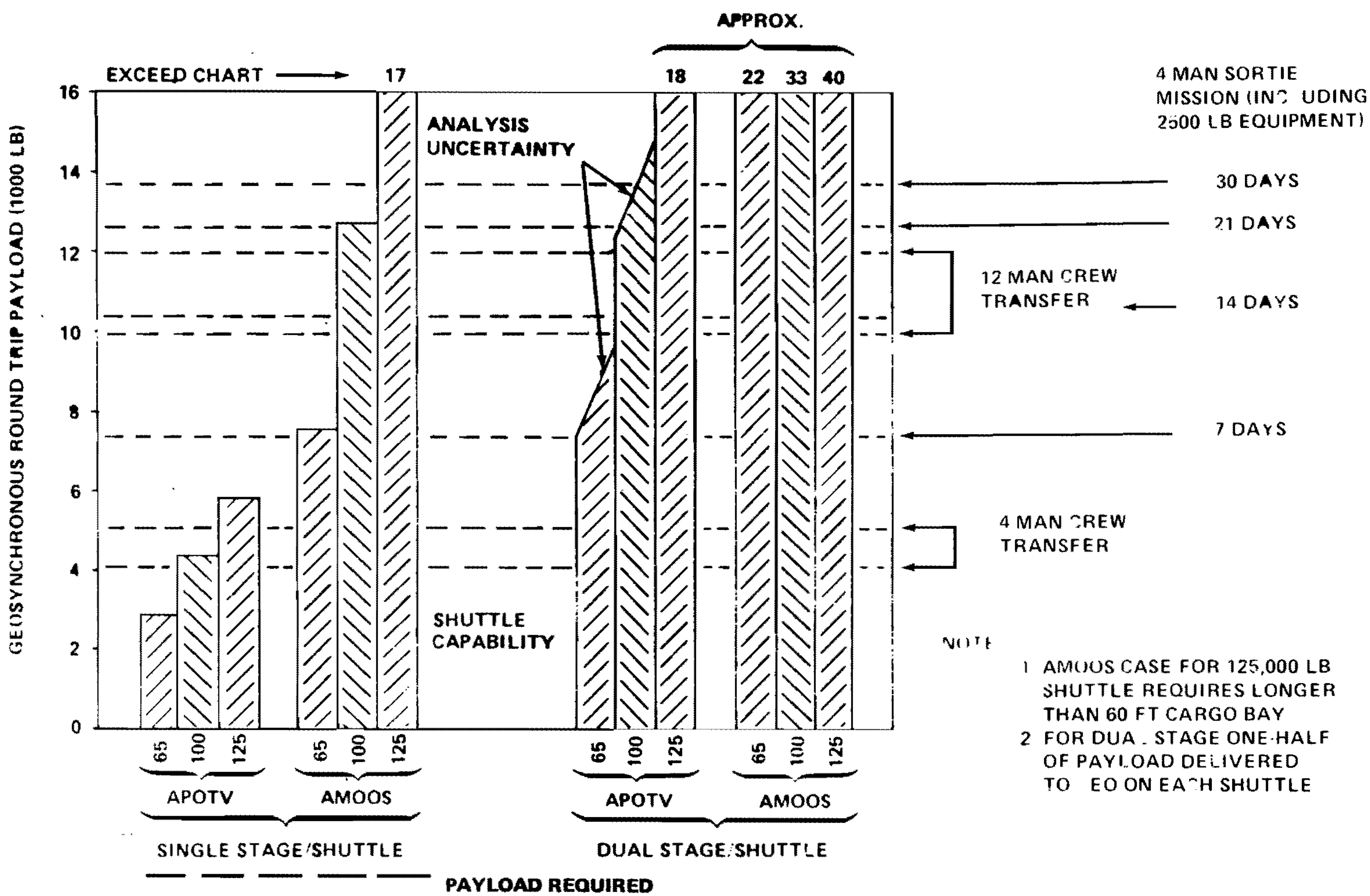


Figure 70. OTV geosynchronous round trip capability (lox/hydrogen) — payload required.

SINGLE SHUTTLE/STAGE

SHUTTLE PAYLOAD CAPABILITY/POUNDS	OTV CONCEPT	STATION ELEMENTS 24000 / 30000	STATION ASSEMBLY 93000 / 100000	CREW TRANSFER (CREW SIZE) 4: UP 5000 / DOWN 5000	CREW TRANSFER (CREW SIZE) 12: UP 12000 / DOWN 12000	4 MAN SORTIE 7 DAY ①: UP 6900 / DOWN 6400	7 DAY ②: UP 8900 / DOWN 6400	14DAY ①: UP 10000 / DOWN 9500	14DAY ②: UP 12000 / DOWN 9500	21DAY ①: UP 11500 / DOWN 11000	21DAY ②: UP 13500 / DOWN 11000	30 DAY ①: UP 12900 / DOWN 12400	30 DAY ②: UP 14900 / DOWN 12400
65000	APOTV												
	AMOOS			X		X							
100000	APOTV			(X)									
	AMOOS	(X)		X	X	X	X	X	X	X	(X)	(X)	
125000	APOTV			X									
	③ AMOOS	X		X	X	X	X	X	X	X	X	X	X

DUAL SHUTTLE STAGE

SHUTTLE PAYLOAD CAPABILITY/POUNDS	OTV CONCEPT	STATION ELEMENTS 24000 / 30000	STATION ASSEMBLY 93000 / 100000	CREW TRANSFER (CREW SIZE) 4: UP 5000 / DOWN 5000	CREW TRANSFER (CREW SIZE) 12: UP 12000 / DOWN 12000	4 MAN SORTIE 7 DAY ①: UP 6900 / DOWN 6400	7 DAY ②: UP 8900 / DOWN 6400	14DAY ①: UP 10000 / DOWN 9500	14DAY ②: UP 12000 / DOWN 9500	21DAY ①: UP 11500 / DOWN 11000	21DAY ②: UP 13500 / DOWN 11000	30 DAY ①: UP 12900 / DOWN 12400	30 DAY ②: UP 14900 / DOWN 12400
65000	APOTV	X		X	(X)	X	X	(X)					
	AMOOS	X		X	X	X	X	X	X	X	X	X	X
100000	APOTV	X		X	X	X	X	X	X	X	X	X	(X)
	AMOOS	X		X	X	X	X	X	X	X	X	X	X
125000	APOTV	X		X	X	X	X	X	X	X	X	X	X
	③ AMOOS	X		X	X	X	X	X	X	X	X	X	X

LEGEND - X MEETS REQUIRED VALUE
-(X) NEARLY MEETS REQURED VALUE

NOTES
① INCLUDING 500 LB PAYLOAD EQUIPMENT
② INCLUDING 2500 LB PAYLOAD EQUIPMENT
③ REQUIRES CARGO BAY LENGTH GREATER THAN 60 FEET LONG
④ FOR SINGLE SHUTTLE/STAGE CASE THE PAYLOAD AND STAGE IS CARRIED ON SAME SHUTTLE
⑤ FOR DUAL SHUTTLE/STAGE CASE ONE STAGE AND ONE-HALF OF THE PAYLOAD IS CARRIED ON EACH SHUTTLE

Figure 71. Capability comparison lox/hydrogen OTV.

For the dual Shuttle stage cases, the APOTV and AMOOS provide the required capability except for the fully assembled station. The APOTV can only perform sortie missions of 14 days duration.

3. 125 000 lb Shuttle Capability Options. For the single Shuttle stage case, the APOTV provides only four-man transfer capabilities. The AMOOS single Shuttle stage case meets all requirements except the fully assembled station.

For the dual Shuttle stage cases, the APOTV and AMOOS provide the required capability except for the fully assembled station.

4. Comparison of APOTV and AMOOS. For the single Shuttle stage cases, the 125 000 lb Shuttle capability is required for APOTV to meet approximately the same capability the AMOOS provides with a 65 000 lb Shuttle capability. For the dual Shuttle stage cases, the 100 000 lb Shuttle capability is required for APOTV to meet approximately the same capability the AMOOS provides with a 65 000 lb Shuttle capability. There is no single Shuttle stage APOTV option which provides the required capability.

5. Shuttle capabilities. The 65 000 lb Shuttle capability is not adequate for meeting orbit transportation requirements in single or dual operations flights if the APOTV option is to remain open. A Shuttle capability of approximately 100 000 lb is needed to make both OTV options viable.

The 100 000 lb Shuttle option, with the AMOOS, is the minimum capability needed to meet the transfer capabilities required with single Shuttle stage operations. It is noteworthy that this combination is the maximum capability which can be accommodated with a 60 ft long cargo bay.

6. Single Shuttle/Dual Stage Options. Data for dual stage in a single Shuttle option for the APOTV and AMOOS are presented in the Performance Capability Section. The dual stage cases provide only modest improvement over the single stage cases. It is expected that cargo bay length problems associated with dual stages would eliminate this small advantage in performance. A stage plus drop tank case is also shown. The drop tank case is not significantly better than the dual stage case even though the drop tanks were expended. Dual stage or stage plus drop tanks in the same Shuttle are not attractive options for the lox/hydrogen propellant stages.

B. Space/Earth Storable Propellant OTV

Capability data for lox/RP and N_2O_4/MMH propellant APOTV and AMOOS are shown in the Performance/Capability Section.

For the APOTV, neither propellant combination provides the needed orbit transfer capability in the single Shuttle stage case. The APOTV with N_2O_4/MMH provides negligible, if any, capability. The data indicate that, in the single Shuttle/stage case, the AMOOS with lox/RP propellant is attractive for Shuttle capabilities exceeding 125 000 lb. N_2O_4/MMH for the single Shuttle stage AMOOS is much less attractive.

Dual Shuttle stage options using the space/Earth storable propellants have not been studied.

XV. TECHNOLOGY REQUIREMENTS

Technology development for OTV has been underway for several years. Some requirements were identified in the early Space Tug activity and development has been started. The requirements which follow were identified in a recent study or were identified earlier and development was not started or was not finished.

A. Aerodynamic/Aerothermal

The AMOOS concept requires an aerodynamic configuration which uses an ablative heat shield to reduce the propulsion requirements of the OTV. Hypersonic wind tunnel testing is required to determine:

1. Loads

2. Aeroheating parameters

3. Configuration optimization

4. Ablative shield optimization.

A model test program has been proposed which would verify the results of this effort. The model would be taken to the appropriate orbital location on an early STS flight and would be released to perform essentially the same aeromaneuvers which are expected for the AMOOS.

B. Ablative Heat Shield

A Viking type ablative heat shield has been proposed for the AMOOS concept. Required technology development is as follows:

1. Shield optimization (weight minimization)
2. Shield refurbishment
3. Sealing (closures)
4. Antenna protection
5. Higher permissible bond line temperatures.

For the long term, a reusable (nonablative if possible) heat shield is desirable. Recent study indicates such a shield is not practical in the 1980 to 1981 timeframe. This technology should proceed with the intent to replace the ablative shield which will be used in early OTV applications.

The AMOOS costing analysis indicates that heat shield refurbishment is a predominant portion of the AMOOS operations cost. The AMOOS operations cost is $1.6 M more than APOTV per OTV flight on an average basis. Technology development aimed at reducing the estimated cost of the ablative shield refurbishment is desirable and will probably prove to be cost effective.

C. Subsystem Hardware

1. Structures. Recent OTV payload capability requirements are higher than were previously determined. Shuttle capability improvement with the current Orbiter cargo bay, which is 60 ft long, is highly desirable. Previous OTV efforts have utilized rather conventional structural/configuration/tankage concepts which limit the usage of improved Shuttle capabilities. OTV structural technology development should be extended to include:

   a. Nestled or common bulkheads

   b. Low profile bulkheads

   c. Tapered/ogival tankage.

2. Propulsion. The propulsion (engine) options for OTV are covered in other sections of this report. The ongoing technology efforts for a new, high performance engine system are desirable and should be continued. A short engine length is needed.

In addition to the ongoing engine technology development, the requirement for the engine to operate at varying and higher oxidizer-to-fuel mixture ratios has been identified. Current lox/hydrogen engine development efforts (ASE) are aimed at oxidizer-to-fuel mixture ratios over a 5:1 to 7:1 range. Development of engine systems which operate at 6:1 to 7:1 (and higher) is needed. In order to provide parametric data for further OTV systems trades in studies related to orbit stay time of the OTV, technology development is also needed on a dual fuel type engine. The dual fuel combination would use lox and LH_2 in one mode and lox and some type of space storable fuel in a second mode using the same engine system.

3. Communications. Previous communication system development for OTV has centered primarily on systems for use with the APOTV concept. To also accommodate the AMOOS concept, the following requirements are added:

a. Investigation of plasma sheath problems during the atmospheric maneuvers.

b. Protection of antenna during atmospheric maneuvers.

4. Guidance and Navigation. Previous guidance and navigation system development for OTV has centered around systems for use with the APOTV concept. To also accommodate the AMOOS concept the following requirements are added:

a. Further development of guidance concepts for the atmospheric maneuver.

b. Development of an autonomous navigation system which will provide a 0.5 n.mi. accuracy to meet the atmospheric entry corridor.

5. Tank Insulation. For the most part, previous OTV tankage insulation concepts for lox/hydrogen systems provided the capability for 7 day missions. To perform man-sortie missions with orbit stay times up to 30 days, insulation concepts need improvement.

6. Miscellaneous. The following systems, unique to the OTV, are required to provide interface capability with other STS and payload hardware.

a. Shuttle support/deployment/retrieval mechanisms.

b. Servicer/manipulator systems

c. Docking mechanisms/adapters.

D. Pumping of Liquids in Space

The current OTV design accommodates only ground based loading of fuels. In the long term, it may be desirable to fuel or refuel the OTV at various orbital locations. Development of the capability for the handling and pumping of liquid fuels in space is needed.

E. Summary Technology Requirements

OTV technology requirements are summarized in two categories in Table 38. The first category includes requirements on which technology development efforts have been completed or are ongoing, and in the second category are requirements on which technology development efforts are needed and should be initiated.

TABLE 38. OTV TECHNOLOGY REQUIREMENTS

Ongoing (or Completed) at MSFC	
• Structures	• Electrical Power
— Light Weight Tanks	— Fuel Cells
• Communications	— Solar Arrays
— Phased Arrays	• Computer
• Guidance and Navigation	• Materials (General)
— Laser-Gyro IMU	— Lubricants
— Laser Radar	• RCS/Attitude Control
• Thermal Control	• Radiation Hazard Instrumentation
— Component (Electronic Equipment Internal — Heatpipes)	• Slush Hydrogen
	— Instrumentation
— Radiators	— Test
— Tank Insulation	• Propulsion (also ASE at LeRC)
— Component/Cryogenic Interface	• Aerodynamic for AMOOS Shaping
— Testing	• Aerodynamic and Load Testing (LeRC)
Needed	
• Aerodynamics/Aerothermal	• Communications
— Loads	— Plasma Sheath
— Aeroheating	— Deployable/Retractable System
• Configuration Optimization Structures	• Guidance and Navigation
	— Autonomous Navigation (Reentry Corridor)
— Nestled and Flat Bulkheads	
— Tapered/Ogival Tankage	• Tankage Insulation
• Heat Shield	— 30 Day Sortie
— Ablative (Near Term)	• Propulsion (Lox/Hydrogen)
— Shield Optimization	— High Performance at Variable Mixture Ratio and Dual Fuel
— Shield Refurbishment	
— Sealing and Closures	• Mechanisms
— Antenna, etc. Protection	— Shuttle Deployment and Retrieval
— Reusable (Far Term)	— Docking/Berthing/Adapting

XVI. SUMMARY

A. Background

The problems of orbit transportation have been addressed significantly during the past 5 years. An IUS and SSUS are being developed for operation in the early 1980's. Current long-range planning efforts indicate a need for extended space operations capabilities which are greater than those provided by IUS and SSUS.

It is primarily the developing need for Earth synchronous orbit capabilities which gives cause for further consideration of OTS at this time. Transportation needs for manned and unmanned synchronous orbit systems are foreseen. Total recoverability and reusability with minimum refurbishment are goals for future OTS.

B. Introduction

To establish a common basis for identifying current transportation concepts, an OTV is defined as a propulsive (velocity producing) rocket or stage. When used with a crew transfer module, a manned sortie module, or other payloads, the combination becomes an OTS. Standardization of OTV's and OTS's is required.

C. Study Approach

As previously mentioned, significant technical and planning information for OTV concepts has been previously developed. These data were assembled, new ideas were introduced, and problem area identification was extensive and wide ranging. These are summarized as issues:

1. Mission goals

2. Interfacing transportation and space hardware elements

3. Technology availability

4. Minimizing the number of OTS elements required

5. Flexibility for operational applications and future growth capabilities.

To determine the effect of these issues, typical mission scenarios were developed and typical OTV and OTS concepts were introduced to satisfy these missions. OTV and Shuttle capability data were parameterized to cover the range of transportation requirements occurring in the scenarios.

D. Significant Early Findings

Earlier preliminary findings in the study indicated that the current 65 000 lb Shuttle capability was insufficient to meet the orbit transfer requirement if single Shuttle launch concepts were to be viable. Previously, dual and triple Shuttle launches had been proposed; however, these concepts presented significant operational problems, low transportation system efficiency, and presented significant problems with payloads.

In this study, data have been developed for the 65 000, 100 000, and 125 000 lb Shuttle capabilities. These three data points give parameterized possibilities over the range from 65 000 to 125 000 lb low Earth orbit capabilities.

E. Orbit Transfer Transportation Requirements

There are several documents available from which orbit transfer requirements may be derived. These are the 1973 and 1976 Shuttle mission models, the 1976 Space Industrialization project/element model, the 1975 geosynchronous orbit Space Station options study by MSFC, and miscellaneous 1976 planning data. These references were used to determine a Nominal Program Option and a Low Program Option. The Nominal Program Option included a 4-man geosychronous orbit station operational capability in 1987, 8-man in 1989, 12-man in 1991, and the capability to add one 12-man system per year after 1995. An HLLV was assumed for operational availability in 1992. The Low Program Option assumed that the space power program would be delayed and that the geosynchronous orbit four-man station capability would be delayed until 1989. The station was assumed to be increased in size to accommodate a four-man visit for short periods after 1991. No HLLV was assumed for the Low Program Option.

The Nominal and Low Program Option requirements are summarized in Tables 5 and 6. Cargo type payloads to synchronous orbit are shown as weight to be transported, and other payloads are shown as specific mission flights.

The nominal programs include a 4-man crew transfer capability prior to 1992 and a 12-man crew transfer capability after 1992. The Low Program Option includes only a four-man crew transfer capability, and both options include a four-man sortie capability. The sortie capability provides significant program flexibility but is probably more important in the Low Program Option. Lunar, planetary, etc., capabilities are also included. It is noteworthy that only a small percentage of the current Shuttle missions are included.

The requirements previously shown are representative of expected OTV missions for the 1986 to 1995 time period. For OTV consideration, it is necessary to know the weight characteristics of each particular type payload to be transferred.

Table 3 shows the OTV payload capability requirements which were derived in this study. For this study it has been assumed that between 500 and 2500 lb of equipment would be needed on sortie missions.

F. OTV Configurations/Concepts

Concepts studied for the OTV and manned carriers are shown in Figure 72. An APOTV (formerly Space Tug) and an AMOOS (sometimes referred to as AMOTV) concept have been studied and compared. Crew transfer and four-man sortie modules have also been studied.

The OTV concepts shown in Figure 72 use lox/hydrogen propellants. Lox/RP, N_2O_4/MMH, and solid propellant systems have also been studied. Parametric configuration data for 65 000 to 125 000 lb Shuttle capabilities were developed.

G. Weight Data

Weights for the liquid propellant APOTV and AMOOS concepts which were studied are shown in summary form in Figures 73 and 74. Weights for the manned systems are summarized in Figure 75. Weights were also calculated for expendable drop tanks for OTV usage and for expendable solid motor applications. These can be found in the Main Weight Data Section and the Performance Section of this report.

Weights were calculated for selected OTV propellant loadings to provide parametric data over the range of Shuttle capabilities being considered. Weights were calculated for the manned systems to give the particular mission capability which was desired.

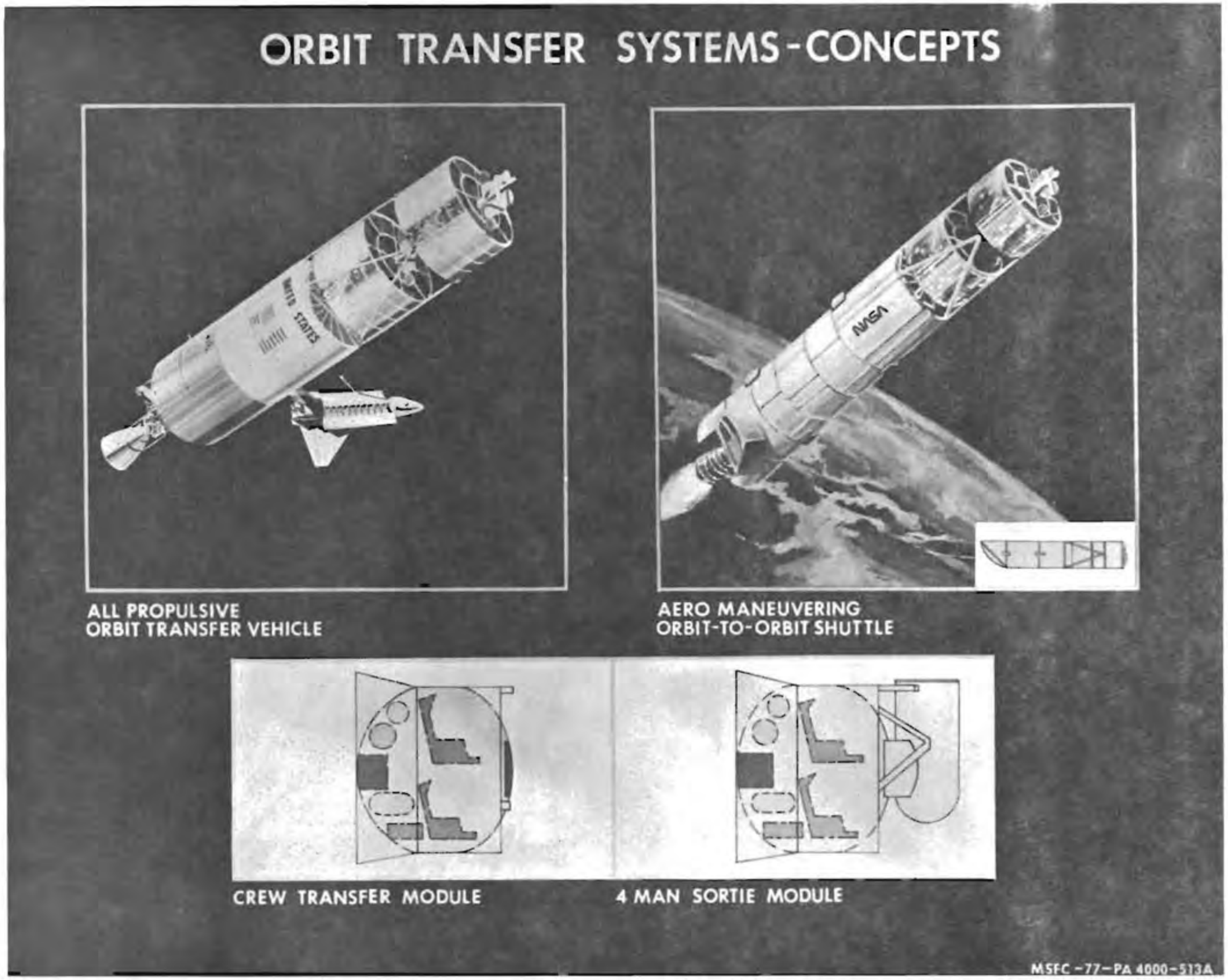


Figure 72. Orbit transfer systems-concepts.

● VEHICLES FOR USE WITH SHUTTLES CAPABLE OF CARRYING 65 TO 125 K POUNDS

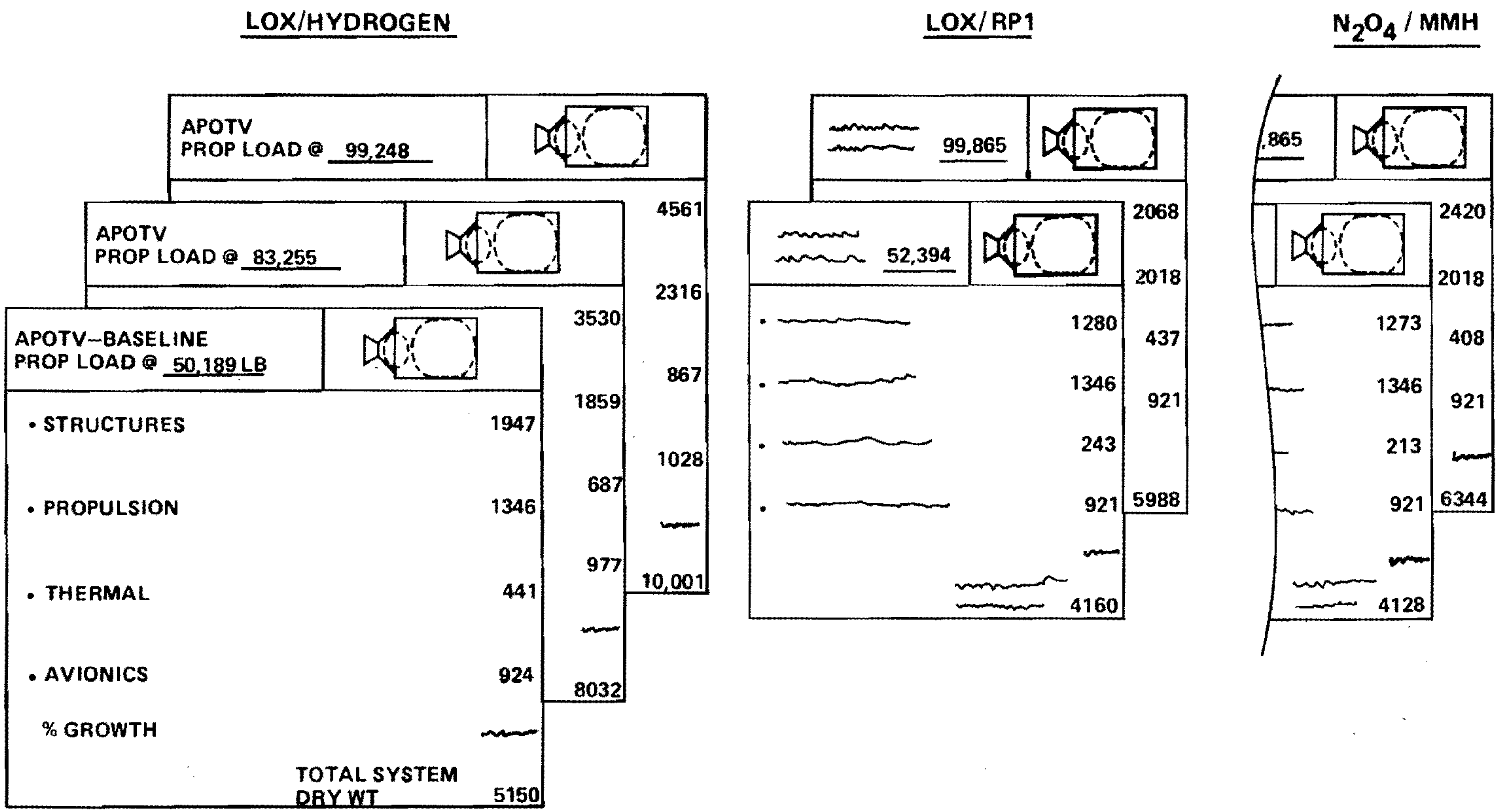


Figure 73. All propulsive orbital transfer vehicle weights (APOTV).

● VEHICLES FOR USE WITH SHUTTLES CAPABLE OF CARRYING 65 TO 125K POUNDS

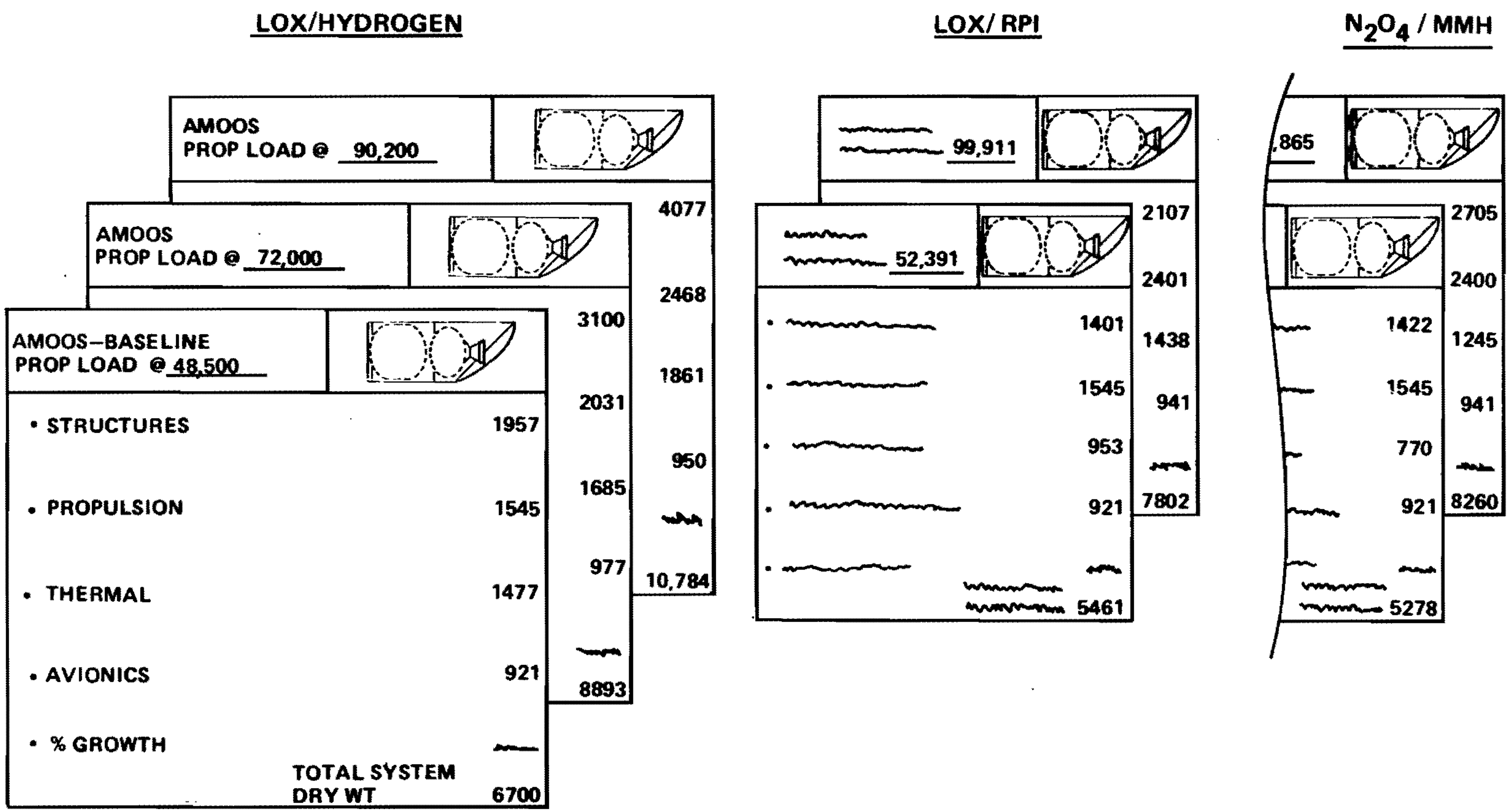
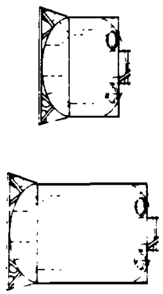


Figure 74. Aeromaneuvering orbit to orbit stage weights (AMOOS).

MANNED SYSTEM WEIGHT ANALYSIS

TRANSFER MODULES



4 MAN SORTIE WEIGHT REQUIRED

7 DAY MISSION

ITEM	WEIGHT
STRUCTURES	1598
CREW FURNISHING	325
CREW EQUIPMENT	1470
ELECTRICITY	935
CABIN PRESSURIZATION	130
CONTROLS (RCS)	60
EXPENDABLES	340
10% GROWTH	486
TOTAL	5344

MISSION	TOTAL
14 DAY MISSION	7874
21 DAY MISSION	8978
30 DAY MISSION	10,251

CREW TRANSFER

CREW SIZE	VOL (FTS)	WEIGHT (LB)
4	585	4062
12 *	1033	10,500

*REF LMSC 1977

4 MAN SORTIE VOLUME (CUFT.)

7 DAYS: STRUCTURE, CREW SYSTEM, ECLSS, ELECTRICAL

	7 DAYS	14 DAYS	21 DAYS	30 DAYS
Total	1008	1223	1414	1630

4 MAN SORTIE MISSION

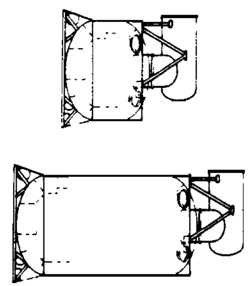


Figure 75. Weights for manned systems.

H. OTV Flight Profiles

Simplified mission flight profiles for the APOTV and AMOOS concepts are shown in Figures 76 and 77. The profiles shown are for single Shuttle stage operations. The principal difference in the profiles of the APOTV and AMOOS occur when the vehicles are returning to Earth. The APOTV performs a propulsive retromaneuver, and the AMOOS enters and maneuvers in the atmosphere using an ablative heat shield to brake the vehicle. It is this maneuver that gives the AMOOS a significant performance advantage. The maneuver reduces the AMOOS velocity requirements by over 7000 ft/sec.

The OTV flight profile will have a significant effect on the stage subsystem requirements. Previous studies in this area addressed different mission parameters than are currently envisioned. The determination, analysis, and selection of the OTV mission profile are issues which should be given high priority in the near future.

I. OTV Performance Capabilities

Performance calculations were made for lox/hydrogen, lox/RP, N_2O_4/MMH, and expendable solid motor concepts. The staging effects, i.e., single stage, dual stage, or drop tank plus stage, were also investigated. Staging effects for the lox/hydrogen APOTV and AMOOS concepts are shown in Figure 45. A 100 000 lb Shuttle payload capability was assumed for this analysis. It should be noted that all dual stage and drop tank configurations exceed the 60 ft cargo bay length.

Dual staging of the lox/hydrogen APOTV improves the APOTV concept performance by approximately 40 percent. Dual staging improves the lox/hydrogen AMOOS by approximately 16 percent. The APOTV dual stage performance is approximately equal to the AMOOS single stage. The lox/hydrogen drop tank cases are approximately 15 to 20 percent better than the dual stage cases. In violation of the total reusability/recoverability rule, the drop tanks were expended. Drop tank concepts probably do not warrant further consideration. Dual staging with lox/hydrogen in the same Shuttle requires a cargo bay length greater than 60 ft, and the additional burden on the Shuttle would probably be greater than the advantage gained by this type dual staging.

Single stage OTV performance comparisons for the 65 000, 100 000, and 125 000 lb Shuttle payload capabilities are shown in Figure 43. A comparison of single and dual Shuttle performance using lox/hydrogen OTV's with 65 000 and 100 000 lb Shuttle capabilities are shown in Figure 46.

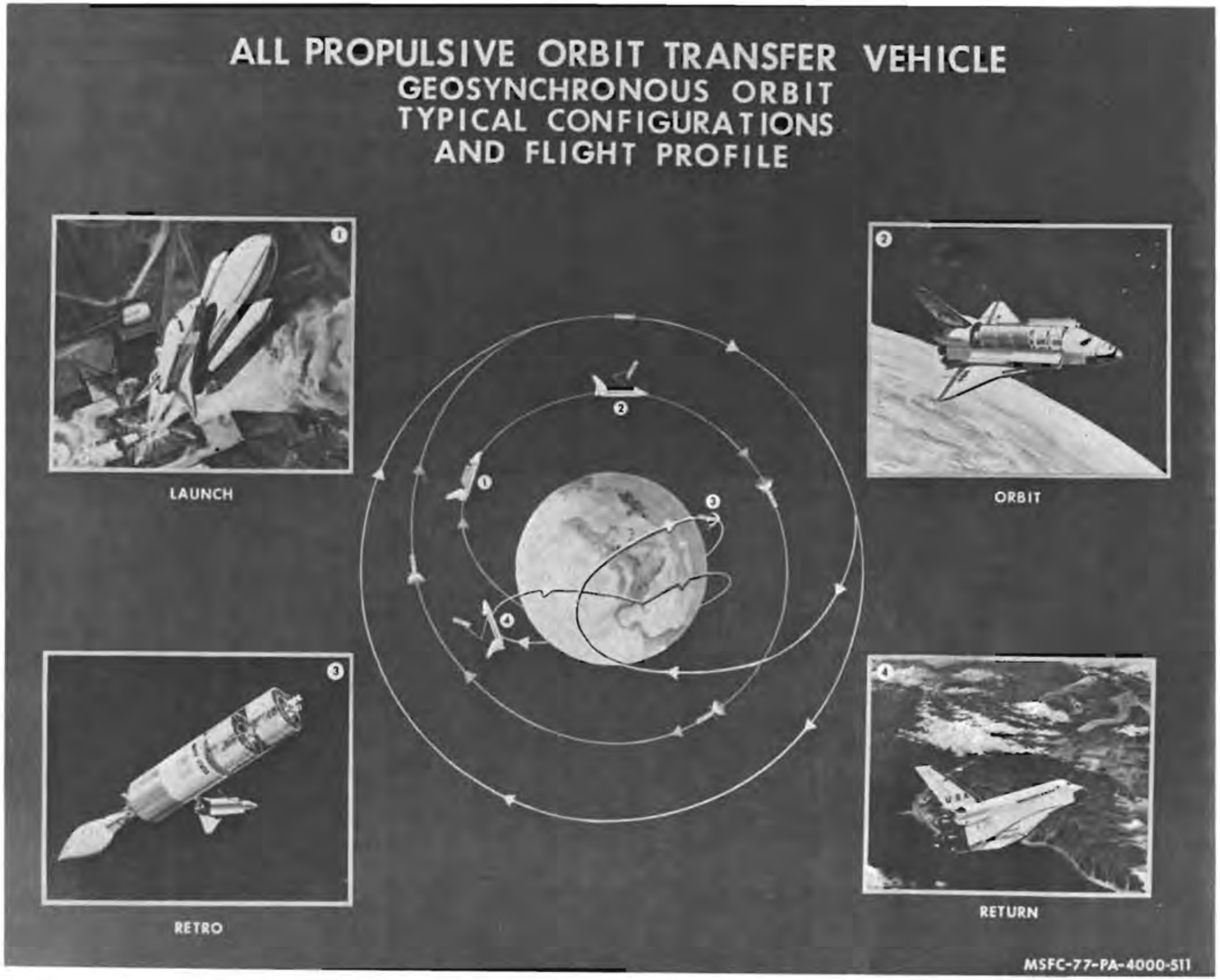


Figure 76. All propulsive orbit transfer vehicle geosynchronous orbit typical configurations and flight profile.

Figure 77. Aeromaneuvering orbit transfer vehicle geosynchronous orbit typical configurations and flight profile.

Figure 47 depicts the range of performance capabilities possible when a combination solid and lox/hydrogen AMOOS is used to transfer very large payloads. The possibility of using this type concept for very large assembled payloads is an issue which warrants further consideration.

J. Shuttle Cargo Bay Length Issues

The physical matching of payloads plus OTV in the Shuttle cargo bay is probably the most important issue addressed in this study. This problem involves not only the OTV and required OTV performance capability, but it also affects the Shuttle evolution, payload design, and OTV engine requirements.

Neither the APOTV nor the AMOOS has problems with the 65 000 lb Shuttle; however, both have problems as Shuttle capability increases. The payload delivery case seems to be the OTV application where cargo bay length gives more problems. However, round trip missions usually require more propellants than delivery only missions (Fig. 51).

If the OTV is to be standard for delivery and round trip missions, the OTV must be designed for round trip missions. The study indicates that the lox/hydrogen OTV tanks should probably be sized for engine operations at a 7:1 mixture ratio for round trip missions. Due to increased hydrogen boiloff for long mission duration, engine operation at a somewhat higher mixture ratio may be desirable for the 30 day sortie mission but would not affect tank sizing. Delivery missions would then be operated at a 6:1 mixture ratio. Highest possible I_{sp} at 6:1 also helps the situation because the higher I_{sp} requires less total propellant for a given start weight. A bonus for higher I_{sp} is a reduction in total transportation cost and a lowering of the needed Shuttle capability to facilitate a particular payload capability. An engine which is optimized for OTV is probably warranted.

Figure 55 shows the relationship of the OTV and payload in the Shuttle cargo bay.

Analysis indicates that a minimum of approximately 24 ft of cargo bay length is required to accommodate the delivery and round trip payloads required. If a 2 ft design margin is allowed, only approximately a 34 ft length remains when a 60 ft cargo bay length restraint is used.

The specific payload capability requirement dictates a need for a minimum Shuttle capability of approximately 100 000 lb payload for the AMOOS concept used in the single Shuttle launch case. To have room in a 60 ft long cargo bay for the AMOOS and for the payload, it is necessary that a very short AMOOS be used.

The APOTV concept in the single Shuttle launch case presents the same cargo bay length problem for delivery at approximately 125 000 lb Shuttle capability. However, the APOTV cannot provide the round trip capability required with the 125 000 lb single Shuttle capability.

For most cases, past OTV designs used single bulkheads with rather conventional elliptical bulkheads and are probably unacceptable.

An issue for future design is to utilize nestled/common bulkheads and very low profile bulkheads.

Figure 26 shows the type unique AMOOS design which is necessary to utilize a 100 000 lb Shuttle payload capability.

Figure 54 shows a comparison of the APOTV and AMOOS length problems with conventional and unique design concepts. Also shown are the Shuttle capabilities, which can be practically utilized, and the resulting OTV capabilities, which are possible with the 60 ft cargo bay length restraint. The OTV concepts used for this calculation will be difficult to realize, and a list of other issues which can be addressed and which may make the OTV design somewhat easier are shown.

K. Mission Model Capture

Captures for the Nominal Program and Low Program Options were studied for the 65 000 and 100 000 lb Shuttle payload capabilities. The APOTV and AMOOS concepts were compared. To meet capability requirements, single and dual Shuttle launches are required for the 65 000 lb Shuttle case. For the 100 000 lb Shuttle case, single launches are required by the AMOOS and dual launches are required by the APOTV. Also, for the AMOOS with the 100 000 lb Shuttle, crew supplies for a 90 day mission are carried on the same flight as the four-man crew transfer module. The results of the analysis are summarized in Figure 57.

The launches per year required with a 65 000 lb Shuttle capability run very high. With a 100 000 lb Shuttle capability, the launch rates become more reasonable.

The APOTV concept always requires 40 to 45 percent more launches than the AMOOS concept. Also the AMOOS accommodates the total Nominal Program with only a few more launches than required by the APOTV to accommodate the Low Program Option.

Perhaps the most important issue here is that with a 100 000 lb Shuttle payload capability, the AMOOS can reasonably accommodate either program option and can do so with single direct launches. The latter assumes that large payloads are assembled in synchronous orbit at the maximum delivery payload capability for a single launch. Shuttle/AMOOS with a 100 000 lb Shuttle capability delivers approximately 21 000 to 22 000 lb.

L. Program Costs and Schedules

OTV program schedules and costs are not summarized here. The reader should refer to the Program Costs and Schedule Section. An STS cost summary for the program options, using the APOTV and AMOOS with the 65 000 and 100 000 lb Shuttle capabilities, is shown in Figure 78.

M. APOTV/AMOOS Design Comparison

The APOTV and AMOOS concepts have been compared from a design point of view. The APOTV design is rather straightforward with the AMOOS being quite complex. There are general and subsystems differences associated with the two concepts (Tables 39 and 40).

As can be seen, more problems are encountered by AMOOS than APOTV. However, no "show stoppers" are envisioned for either concept. Whether or not the difference in required effort is warranted may be seen on the Performance Capability Comparison for lox/hydrogen OTV's shown in Figure 67. The major issue associated with OTV selection appears to be the round trip payload capability required to perform four-man sortie missions with one Shuttle launch.

N. Comparison of the Options

Lox/hydrogen propellant OTV options seem to offer the most attractive possibilities to meet the future orbit transfer needs. A comparison of the options studied are shown here.

Figures 69 and 70 summarized the OTV capabilities with the payload requirements referenced thereon. Figure 71 shows the ability of each of the single and dual Shuttle OTV options to meet the orbit transfer capability requirements.

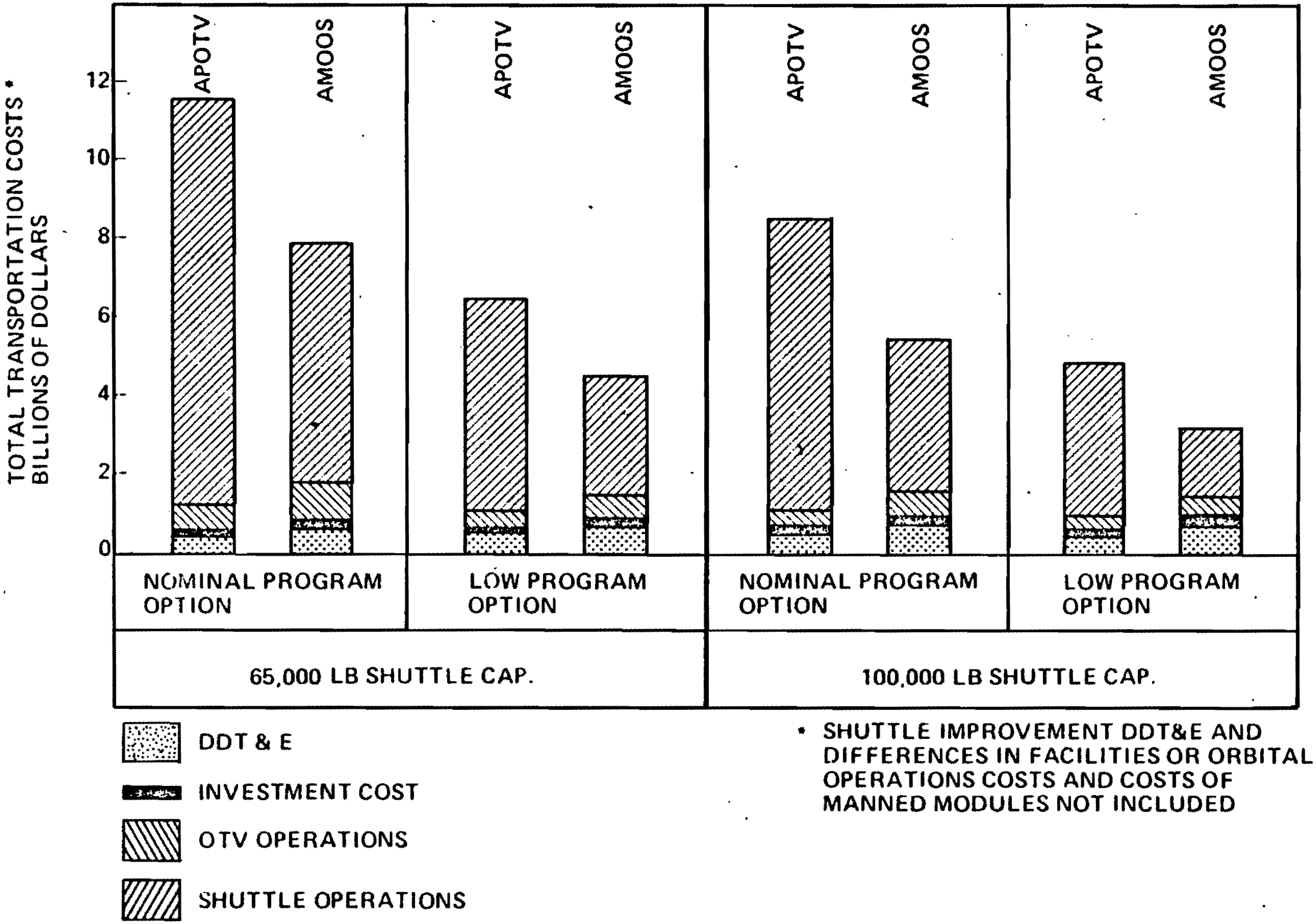


Figure 78. STS cost summary (1976 dollars).

TABLE 39. APOTV/AMOOS DESIGN COMPARISON (GENERAL)

• No "show-stoppers" for either concept • Concept maturity/depth of understanding is comparable for Pre-Phase A and portions of Phase A — thereafter AMOOS understanding is lacking. While certain portions of APOTV definition is applicable to AMOOS the following is needed for AMOOS: — Internal arrangement — Detail design of structural closures, ablative shield with associated aerodynamic/aerothermal analysis and refurbishment, autonomous navigation and protection of communication systems etc. during the atmospheric maneuver. • AMOOS requires extensive wind tunnel testing (3400 hr estimated for total program). • Due to the character of current OTV requirements, large portions of previous OTV definition is now somewhat outdated.

As shown, neither the APOTV nor AMOOS concepts can meet the orbit transfer needs with a single 65 000 lb Shuttle launch. With dual launches, the 65 000 lb Shuttle/APOTV offers marginal capability to meet the needs while the AMOOS can meet the need. APOTV and AMOOS fail to meet the large assembly payload need with any options over the 65 000 to 125 000 lb range of Shuttle capability.

The APOTV with a single Shuttle also fails to meet the transfer capability need with the 100 000 and 125 000 lb Shuttle capabilities. The AMOOS marginally meets the need with 100 000 lb single Shuttle capability and is quite adequate for 125 000 lb Shuttle capability. It should be remembered that for the Shuttle/AMOOS 100 000 lb Shuttle case, the 60 ft cargo bay is adequate while the 125 000 lb Shuttle requires a cargo bay length exceeding 60 ft.

The dual Shuttle APOTV and AMOOS meet the transfer needs if 100 000 lb, or more, Shuttle capability is available.

TABLE 40. APOTV/AMOOS DESIGN COMPARISON (SUBSYSTEMS)

- Propulsion
  - Main engines are similar
  - AMOOS requires large RCS ($\approx$200 lbf thrusters)

- Structures
  - APOTV very sensitive to dry weight — simple structural configuration
  - AMOOS is less sensitive to dry weight — complex structural configuration — experiences both cryogenic temperature and hot environments (during aeromaneuver)

- Thermal/Thermal Control
  - APOTV is simple
  - AMOOS requires more tank insulation — requires heat shield (Viking material proposed) — wide range of thermal environment
  - Tank insulation for 30 day sortie mission is issue for both concepts.

- Guidance, Navigation, and Control
  - Problems are similar for all maneuvers prior to Earth return
  - At Earth return

    APOTV has only 15 n.mi. constraint on Orbiter compatible rendezvous orbit

    AMOOS has 2 n.mi. constraint on atmospheric entry corridor prior to constraint for Orbiter compatible rendezvous orbit
  - AMOOS requires additional 5000 words software for aeromaneuvering guidance.
  - AMOOS has less than 45 min for update prior to orbit phasing maneuver to prevent atmospheric entry

- Communications and Data Management
  - AMOOS requires antenna deployment (ports) and thermal protection
  - AMOOS has plasma sheath problems (if communication is required during the atmospheric maneuver)

The 100 000 lb Shuttle/AMOOS option appears to be the minimum single Shuttle launch system size which can meet the orbit transfer capability need. Limitations, capabilities, and cargo bay loading configurations for this case are summarized in Figure 27. This type data for the other options shown here and in the main body of the report are issues requiring further study.

O. Technology Requirements

Technology development for the OTV has been underway for several years. Some efforts have been specifically for the OTV while in some cases technology development in other programs is shared. A listing of the activities underway or completed by MSFC are shown in Table 38. Additional technology development needs are also shown in Table 38. It can be noted that these primarily address the problems associated with the AMOOS.

P. OTV Program Options

Four OTV options have been identified; two of these options are for the APOTV concept and two are for the AMOOS concept. For each concept, an option using the 65 000 lb Shuttle capability and the improved 100 000 lb Shuttle capability was identified. These options are described and summarized in Tables 41 through 44 with qualifications for each.

Following are the major issues relating to OTV:

1. Whether an OTV can be justified depends on the need for manned missions beyond low Earth orbit.

2. With a 65 000 lb Shuttle capability, dual Shuttle launches will be needed to perform sortie missions. With the APOTV concept, the sortie mission will be limited to 14 days because of the payload capability of the dual stage system.

3. With a 100 000 lb Shuttle capability, the total number of launches is reduced by 28 to 35 percent for APOTV and AMOOS, respectively, when compared to the 65 000 lb Shuttle capability.

4. The AMOOS concept with, or leading to, a 100 000 lb Shuttle capability offers:

TABLE 41. OTV/STS EVOLUTION — CURRENT SHUTTLE (USING APOTV CONCEPT — GEO MISSIONS)

STEP 1	STEP 2
• Develop APOTV for — 65 000 lb Shuttle Capability — Semiconventional Design[a] for Dual Stage Operation	• Improve Shuttle to — 125 000 lb Capability — Cargo Bay Length TBD[e]
• Capability — Single Stage/Shuttle $\approx$ 6000 lb Delivery $\approx$ 2000 lb Round Trip } [b] — Dual Stage/Shuttle $\approx$ 21 000 lb Delivery $\approx$ 8 000 lb Round Trip[d] } [c]	• Improve OTV to match — 125 000 lb Capability — Unique Design for Dual Stage Operation • Capability Optional — Single Stage/Shuttle $\approx$ 17 000 lb Delivery $\approx$ 6 000 lb Round Trip } [b] — Dual Stage/Shuttle $\approx$ 58 000 lb Delivery $\approx$ 18 000 lb Round Trip } [c]

a. No length problem with 60 ft cargo bay.

b. Will cause load factor penalty.

c. One-half of each payload must be carried on each Shuttle.

d. Very marginal for 14 day sortie mission with 500 lb equipment.

e. Depends on need to keep load factor high on crew transfer and dual-stage delivery missions.

TABLE 42. OTV/STS EVOLUTION — IMPROVED SHUTTLE (USING APOTV CONCEPT — GEO MISSIONS)

STEP 1	STEP 2
• Improve Shuttle to[a] — 100 000 lb Capability — 60 ft Cargo Bay	• Improve Shuttle to — 125 000 lb Capability — Cargo Bay Length TBD } d
• Develop APOTV to Match — 100 000 lb Shuttle Capability — Semiconventional/Unique Design for Dual-Stage Operation	• Improve OTV to Match — 125 000 lb Shuttle Capability — Unique Design for Dual-Stage Operation
• Capability — Single Stage/Shuttle ≈ 2000 lb Delivery ≈ 4200 lb Round Trip } b — Dual Stage/Shuttle ≈ 48 000 lb Delivery ≈ 13 000 lb Round Trip } c	• Capability — Single Stage/Shuttle ≈ 17 000 lb Delivery ≈ 6 000 lb Round Trip } b — Dual Stage/Shuttle ≈ 58 000 lb Delivery ≈ 18 000 lb Round Trip

a. No length problem with 60 ft Cargo Bay.

b. Will cause Shuttle load factor penalty.

c. Marginal for 30-day, 4-man sortie mission.

d. TBD — Depends on need to keep load factor high on crew transfer and dual-stage delivery missions.

TABLE 43. OTV/STS EVOLUTION — CURRENT SHUTTLE (USING AMOOS CONCEPT — GEO MISSIONS)

STEP 1	STEP 2
• Develop AMOOS — For 65 000 lb Shuttle — Design Conventional, Unique, or in Between for Single Stage Operation • Capability[a] — Single Stage/Shuttle ≈ 13 000 lb Delivery ≈ 7 000 lb Round Trip — Dual Stage/Shuttle ≈ 30 000 lb Delivery ≈ 16 000 lb Round Trip	• Improve Shuttle[b] — 125 000 lb Capability — Cargo Bay Length (TBD) • Improve OTV to Match — 125 000 lb Shuttle Capability — Unique (Short) Design for Single Stage Operation • Capability — Single Stage/Shuttle ≈ 27 500 lb Delivery ≈ 17 000 lb Round Trip[c] Optional — Dual Stage/Shuttle ≈ 68 000 lb Delivery ≈ 37 000 lb Round Trip

a. No length problem, allowable payload length 24 to 32 ft, depending on type of design used for OTV.

b. Reduces transportation cost by approximately 50 percent.

c. Capability to transfer crew of 24.

TABLE 44. OTV/STS EVOLUTION — CURRENT SHUTTLE LEADING TO IMPROVED SHUTTLE (USING AMOOS CONCEPT — GEO MISSIONS)

STEP 1	STEP 1A	STEP 2
• Develop AMOOS — For 100 000 lb Shuttle Capability — Unique Design for Single Stage Operation • Fly Offloaded on 65 000 lb Shuttle • Capability[a] — Single Stage/Shuttle ≈ 11 000 lb Delivery ≈ 5 500 lb Round Trip — Dual Stage/Shuttle ≈ 26 000 lb Delivery ≈ 14 500 lb Round Trip	• Improve Shuttle to[b] — 100 000 lb Capability — 60 ft Cargo Bay • Develop AMOOS — For 100 000 lb Shuttle Capability — Unique Design for Single Stage Operation • Capability[c] — Single Stage/Shuttle ≈ 21 500 lb Delivery ≈ 12 750 lb Round Trip } d Optional — Dual Stage/Shuttle ≈ 52 000 lb Delivery ≈ 28 000 lb Round Trip } e	• Improve Shuttle to — 125 000 lb Capability — Cargo Bay Length (TBD) } f • Improve OTV to Match — 125 000 lb Shuttle Capability — Unique Design for Single Stage Operation • Capability — Single Stage/Shuttle ≈ 27 500 lb Delivery ≈ 17 000 lb Round Trip } g Optional — Dual Stage/Shuttle ≈ 68 000 lb Delivery ≈ 37 000 lb Round Trip

a. No length problem; however, payloads limited to 24 ft on each Shuttle.

b. Reduces transportation by about 40 to 45 percent.

c. Payload limited to 24 ft length.

d. OK for up to 21-day, 4-man sortie mission.

e. Length problem with some payloads.

f. Should reduce transportation cost.

g. Capability to transfer crew of 24.

- Single Shuttle launch of large elements and the man sortie missions
- Lowest cost for transportation
- Programmatic flexibility as to the time of introducing the improved Shuttle capability.

The selection of an OTV concept or the option to be used is not needed at this time. OTV planning and schedule considerations indicate that decisions on concept and option selection are needed in late FY-79. Other concepts or options may be identified in the meantime.

Q. OTV Activity Status/Future

The OTV activity status and near term future needs are summarized in Table 45. The future activity should primarily lead to better technical and programmatic definition of OTV and to acquire technology readiness in a timely manner.

XVII. RECOMMENDATIONS

Recommendations for future OTV efforts are as follows:

1. Key future system work to:
   - Current Shuttle capability leading to improved Shuttle (95 000 to 100 000 lb)
   - Sortie mission manned elements
   - Minimum length configurations.
2. Key OTV engine development to:
   - Short length concepts
   - Variable/high oxidizer-to-fuel mixture ratios
3. Key technology development efforts as identified.

TABLE 45. OTV ACTIVITY STATUS/FUTURE

At This Time

- This study has identified several Shuttle-type OTV concepts and related capability possibilities. Several conceptual approaches have been compared. Several issues related to the development of Shuttle and/or OTV capabilities have been identified. Major OTV technology needs are underway or have been identified.

What is Needed Next

- Development of detailed OTV mission scenarios
  - — Operational Requirements
  - — Functional Requirements

  } Leading to subsystems requirements

- Definition of probable OTV program evolution and concepts
- Definition of manned sortie modules and crew transfer modules
- Technology development as outlined.

APPENDIX A

A SUMMARY OF THE DEVELOPMENT STATUS OF CHEMICAL ENGINE SYSTEMS UNDER CONSIDERATION FOR THE ORBITAL TRANSFER SYSTEM (OTS) (NOVEMBER 1976)

Development Status of Chemical Engine Systems Under Consideration for the Orbital Transfer System (OTS)

Engine System	Estimated Time[1] Of Availability
1. RL10A3-3	Present
2. RL10 Category IIB	1985
3. RL10 Category IV	1985
4. Advanced Space Engine	1985
5. Orbit Maneuvering Engine	1985
6. Solid Rocket Motor	1985
7. Storable Propellant High Pressure Engines	1985
8. Space Shuttle Main Engine	1980
9. Plug Cluster Concept	1985
10. Aerospike Engine Concept	1985

1. RL10A3-3

The 15 000 lb thrust RL10A3-3 lox/hydrogen engine is the current production engine for the Centaur upper stage which is being flown on Atlas and Titan III launch vehicles. The present production run is for 14 engines and will terminate in February 1977. A proposal by the contractor, Pratt & Whitney, has recently been submitted to NASA-LeRC for an additional six engine production run (with an option for four more engines) for NASA-committed Centaur launches through 1980. The last of these engines will be delivered around August 1978 for integration into the stage. The Pratt & Whitney program technical manager foresees a possible additional small production run to accommodate the phase-in Shuttle transition period. Thus, the best projection for RL10 availability is late 1978 or possibly through 1980, depending on the NASA launch schedule utilizing expendable vehicles. The RL10A3-3 has an excellent reliability record and is the best performing engine currently operational; however, its technology base is approximately 1958 state-of-the-art. I_{sp} is 444 sec at a nozzle expansion ratio of 57:1. Engine mixture ratio is 5:1, and the engine utilizes an expander cycle turbopump power drive.

1. Assuming FY-79 Funding

2. RL10 Category IIB

The 15 000 lb thrust RL10 Category IIB is the baseline engine assumed for the MSFC Baseline Space Tug (1974) and is well characterized as the result of a Pratt & Whitney MSFC funded study conducted in 1973. (Technology level is mid-1960's.) This improved engine is derived from the current operational engine and can be made available with present technology and no advances in the state-of-the-art. To increase the I_{sp} from 444 to 456.4 sec, the injector has been reoptimized to operate at a 6:1 propellant mixture ratio and the nozzle expansion ratio increased to 205:1. The engine is configured with a two-position nozzle with the primary section recontoured for better performance. Further increases in I_{sp} can be achieved by increasing the nozzle expansion ratio beyond 205:1 to a practical maximum of 262:1 (I_{sp} = 459 sec). The chamber pressure is 400 psia (same as the current production model), and the engine operates in the same expander cycle.

3. RL10 Category IV

The 15 000 lb thrust RL10 Category IV engine represents the best performance available from the expander power cycle. It is a new engine design but does not require significant advance in technology and, therefore, is considered current state-of-the-art. Chamber pressure is increased to 915 psia, and nozzle expansion ratio on the order of 400:1 is achievable. At the maximum expansion ratio, I_{sp} is 470 sec at a propellant mixture ratio of 6:1. This engine is also defined in the 1973 Pratt & Whitney report, but is not as well characterized as the Category II engine.

4. Advanced Space Engine

The 20 000 lb thrust ASE is a staged-combustion cycle engine operating at chamber pressures on the order of 2000 psia. These characteristics result in a high performance engine with some weight and envelope advantages. I_{sp} is nominally 470 sec for operation at a 6:1 mixture ratio. Major components and subsystems have been designed and developed by Rocketdyne under NASA-LeRC contracts since the early 1970's. This engine is well characterized and was selected for the main engine system of the Space Tug defined by the Preliminary Design Office in 1972. (Engine thrust was set at 10 000 lbf.) Hardware items fabricated to date include the igniter, preburner, high pressure oxygen and hydrogen turbopumps, combustion section, and upper nozzle section. Combustor firing tests have been made in addition to laboratory testing of the other hardware items and a combined preburner and regeneratively cooled thrust chamber assembly test is scheduled for this month. Although this engine would be considered a new development item, the technology level is early to mid-1970's. If continued, the present modest level of NASA-LeRC funding should eventually lead to hardware development appropriate for all-up engine demonstration testing around 1980.

5. Orbital Maneuvering Engine

A candidate Earth-storable propellant engine system for the OTS is one derived from the Shuttle 6000 lb thrust Orbit Maneuvering Engine (OME). The fundamental design considerations for long service life, multiple starts, and reusability are fully compatible with OTV requirements. Significant modifications would be required for OTV application; however, these would not represent advances in the state-of-the-art. The most prominent of these modifications would be to change from pressure-fed to pump-fed operation and to increase the engine thrust to a more desirable level. The propellant mixture ratio (N_2O_4/MMH) would be increased from 1.65:1 to 2:1 for improved performance and the nozzle expansion ratio increased from 55:1 for the same reason. These changes would constitute a new engine based on existing technology. The various options for OME derivative engines were explored by the Aerojet Liquid Rocket Company under MSFC-funded studies and documented in 1974 in support of the Storable Space Tug Study. The I_{sp} range is 330 to 335 sec, depending on the cycle, chamber pressure, expansion ratio, propellant mixture, etc.

6. Solid Rocket Motor

Solid propellant motor manufacturers profess to have developed highly sophisticated computer programs that can predict with a high degree of accuracy in a relatively short time the motor design needed when given a set of requirements. This is exemplified in the IUS program which is using state-of-the-art components and scheduled to be operational by 1980. The case proposed is filament wound with Kevlar, a high-strength low-density fiber, that will maximize stage mass fraction. Over 200 cases have been made for the Trident and MX (advanced Minuteman) programs, and the industry at large has confidence in its ability to work with this relatively new material.

Carbon-carbon nozzles are being touted as the nozzle material to use for space application because with several limited duration firings no visible signs of erosion have been noticed. In the IUS program, carbon-carbon and a more conventional ablative type backup nozzle are to be made and tested. After these tests, a comparison will be made to determine which of the two materials will be used in the IUS motors. It is expected that the carbon-carbon nozzle will give better performance by 2 to 3 sec, resulting in a higher delivered I_{sp}. Although the nozzle is gimbaled, this is not a new technology item.

Minimum development time for a new state-of-the-art motor is on the order of 2.5 years depending on the long lead-time items, the amount of trade studies imposed, and the number of test/qualification motors required of the program.

The maximum vacuum I_{sp} expected in the foreseeable future is approximately 300 sec for Class 2 propellants.

7. Storable Propellant High Pressure Engines

Parametric and design analysis of several high pressure storable propellant engine concepts in the 6000 to 20 000 lb thrust range were studied by Aerojet Liquid Rocket Company, under contract from MSFC, in 1973. Gas generator and staged-combustion cycle engines were investigated, with all engines using nitrogen tetroxide (N_2O_4) as the oxidizer and monomethyl hydrazine (MMH) as the fuel. Both types of engines were regeneratively and film cooled with MMH. Maximum chamber pressure is on the order of 1000 psia.

The gas generator cycle engines are equipped with turbopump assemblies driven by exhaust products from N_2O_4/MMH gas generators. The turbine exhaust gases are then ducted into the main nozzle downstream of the throat or into small auxiliary nozzles. The staged-combustion engines are equipped with turbopump assemblies driven by hot gases produced in N_2O_4/MMH preburners. These exhaust gases are then fed directly into the main combustion chamber.

These storable-propellant high-pressure engines produce I_{sp} ranging from 335 to 349 sec, depending upon engine thrust, nozzle expansion ratio, chamber pressure, percent fuel used for film cooling (i.e., allowable chamber wall temperature), and overall engine propellant mixture ratio.

8. Space Shuttle Main Engine

The 470 000 lb thrust Space Shuttle Main Engine (SSME) is a staged combustion cycle engine operating at chamber pressures on the order of 3000 psia. The high thrust of the engine precludes its use for earlier (and smaller) elements of the OTS. However, there is a potential application for later (and larger) OTV's. Nominal vacuum I_{sp} is 455 sec. The SSME will be operational in 1979, barring serious difficulties in qualification testing. Technology level is considered to be early to mid-1970's. The engine as configured for the Shuttle has no extendable/retractable nozzle, but is throttable over a range of 50 to 109 percent of the rated thrust level.

9. Plug Cluster Concept

A potentially attractive alternative to using conventional bell nozzle engines is the grouping of multiple small engines in a "plug cluster" geometry. For OTS application, we have selected a lox/hydrogen engine of 1500 lb thrust arranged in a circular fashion around an aerodynamically designed central nozzle section to reduce overall stage length. The individual nozzle expansion ratio is 40:1; however, when appropriately arranged in the plug cluster geometry, the collective expansion ratio is 400:1 resulting in an effective I_{sp} of 466 sec. The number of individual engine modules may be varied to adjust the total thrust as desired. The nominal propellant mixture ratio is approximately 6:1. The operation of the plug cluster is necessarily sensitive to geometrical arrangement. For performance and stage conceptual layout purposes, the geometric relationships as they are presently theorized have been defined. The radius which defines the circle circumscribing the cluster of individual engines is determined by selecting the desired performance level (effective expansion ratio) and the desired total thrust (number of engine modules) and by specifying the throat diameter of the individual engine. From this, the geometry of the central nozzle section is determined. The individual nozzles are canted slightly inward to direct the exhaust product flow along the central nozzle cone surface.

The plug cluster is also an attractive concept for booster stages. By clustering engines such as the SSME or Space Shuttle Booster Engine (SSBE) around a central plug, altitude compensation is achieved which increases the average I_{sp} (over a boost trajectory) approximately 6 percent when compared to bell nozzle engines not used in a plug cluster arrangement. The plug cluster concept also has a potential for propulsion system/stage structure integration which could result in a decrease in stage inert weight. HLLV boosters (Class IV) using the plug cluster concept have been conceptually designed in-house.

The plug cluster design is presently undergoing conceptual evaluation by Aerojet (System Design) and Rocketdyne (Cold Flow Testing) and, therefore, must be considered only as theoretically attractive at this time, pending feasibility analyses and the usual demonstration testing. Funding is through NASA-LeRC.

10. Aerospike Engine Concept (OTS - 1985)

The current proposed baseline Aerospike engine for upper stages would operate on lox/hydrogen propellants in an expander cycle at a chamber pressure of 1000 psia, producing a thrust of 25 000 lb and a vacuum I_{sp} of 470 sec at an expansion ratio of 200:1 and a mixture ratio of 5:1. From analytical studies, it appears that the Aerospike engine is weight competitive with bell nozzle engines; however, a complete flight weight engine (i.e., turbopumps, valves, chamber, and nozzle) has not been built and successfully tested at this time. The major advantage of the Aerospike engine is the potential to achieve high performance in a shorter length than achievable with a bell nozzle engine of the same thrust. The shorter engine length would therefore result in a shorter overall stage length. Rocketdyne has been investigating the toroidal chamber Aerospike engine, applicable to upper stages, since the early 1970's. The present effort is a successor program to an earlier AFRPL fluorine/hydrogen demonstration program that terminated with destruction of the test article and facilities during an attempted demonstration hot firing. A demonstration lox/hydrogen 25 000 lbf thrust chamber/nozzle was initially built and tested by Rocketdyne under contract from AFRPL. This test program was discontinued by AFRPL in 1975 because of an oxygen cooling leak during a test firing which resulted in major damage to the Aerospike chamber and nozzle. In January 1976, NASA/LeRC took over the Aerospike program by initiating a contract with Rocketdyne to repair this test article (chamber and nozzle) and to test fire it again. After attempting unsuccessfully to repair the test article, NASA/LeRC has decided to discontinue the effort because new hardware could be required which is out of the scope and funding level of the contract. It appears unlikely that funding will be available to continue this program in the foreseeable future.

APPENDIX B

SUPPORTING STUDY DATA NOT COVERED BY THE NARRATIVE

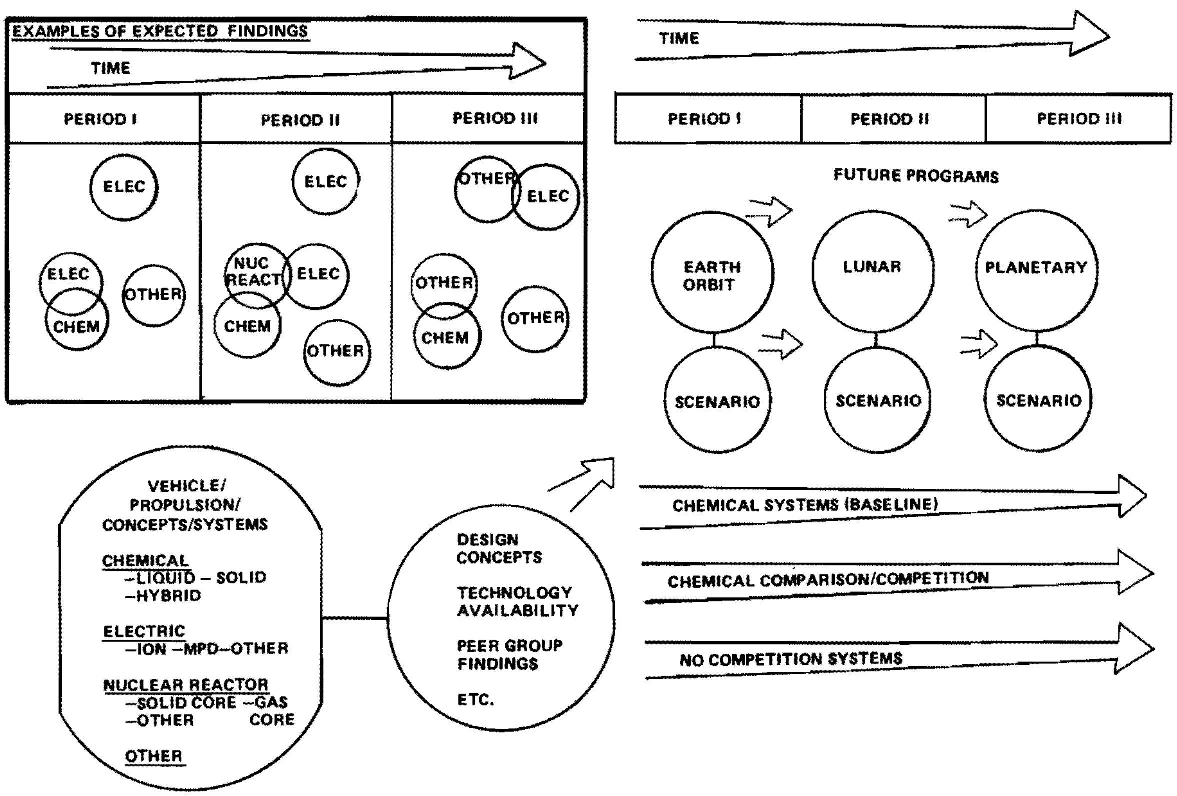
THE STUDY APPROACH — FUTURE OTV CONSIDERATIONS

The chart shows graphically how each concept will be treated.

A selection made in Period I will have effect on happenings in Period II and/or Period III. If a need during Period III is identified, selections to be made in Period I and Period II must be made with consideration to the need.

Some concepts may have large, general applicability. Other concepts may have only limited, specific applicability. Some concepts may be competitive with other concepts, and some concepts may have no competition in specific applications.

Findings may also be expected to discover or illuminate particular needs at some specific time.



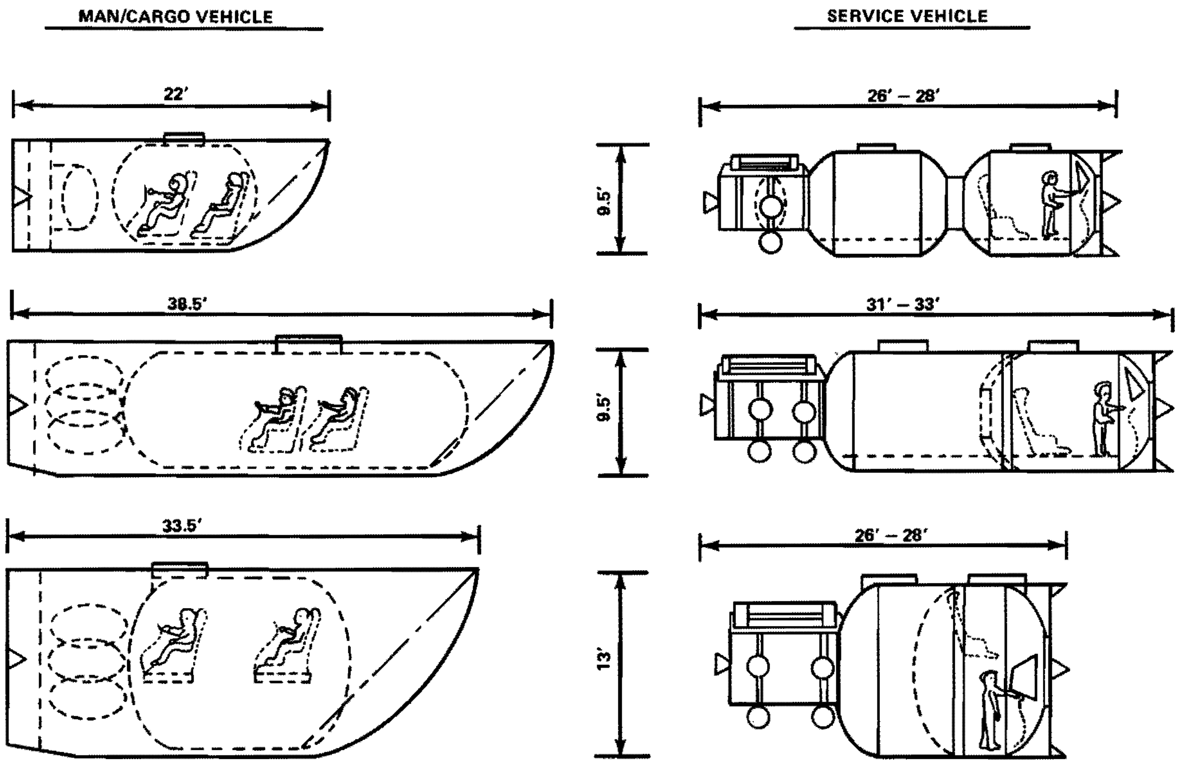
SERVICE VEHICLES DERIVED FROM MAN/CARGO VEHICLES

Shown are service vehicles which can be derived from man/cargo vehicles used with the AMOOS.

To accommodate extravehicular activity, a second compartment is included. The second compartment serves as an airlock and cargo for the service vehicle.

A solar array and the necessary power conditioning equipment are added to extend the service vehicles' independent operating time.

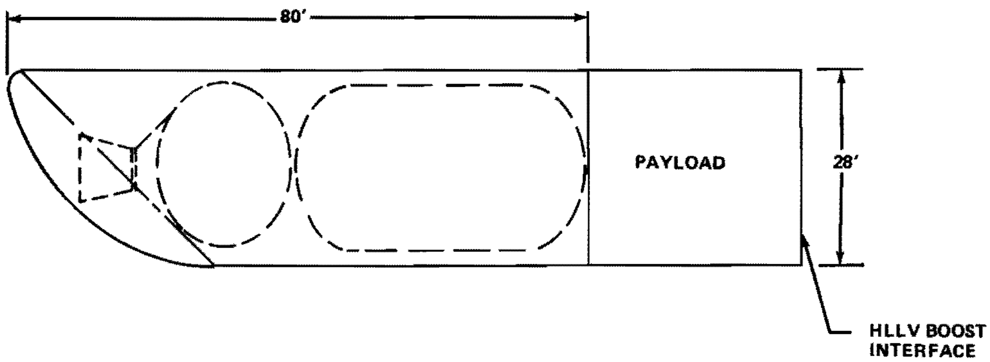
It may be necessary to add radiation shielding around the cabin/control compartment to reduce radiation exposure by the crew.



AMOOS FOR HLLV

The configuration shown reflects a possible final stage of an HLLV based on the aeromaneuvering concept for reentry deceleration. The configuration was sized for 375 000 lb of lox/hydrogen at a mixture ratio of 6:1. The diameter selected was arbitrary except for giving a reasonable length to diameter ratio. The reentry thermal protection system would require return through the atmosphere for eventual recovery. The payload compartment is assumed to be an integral part of the configuration so as to make the payload carrier reusable.

LO_2 / LH_2 AMOOS, HLLV CLASS, GROUND RETURN

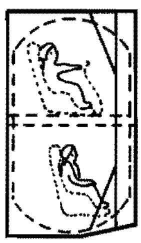


375,000 LBS PROPELLANT
6:1 MIXTURE RATIO
HI PC ENGINE, F = 75,000 LBS, ϵ = 400:1

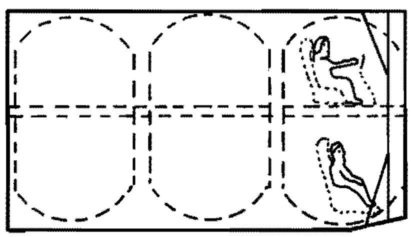
ALTERNATE CREW/CARGO MODULE CONCEPT FOR 65K TO 125K SHUTTLE (AMOOS OR APOTV)

Alternate crew/cargo module concepts may be necessary to reduce cargo bay and orbital hangar requirements. Shown here is a concept which has evolved during the in-house OTS studies. The concept is applicable to AMOOS and APOTV.

Although not illustrated here, the AMRS could be berthed in a similar fashion. The same is true for service vehicle.

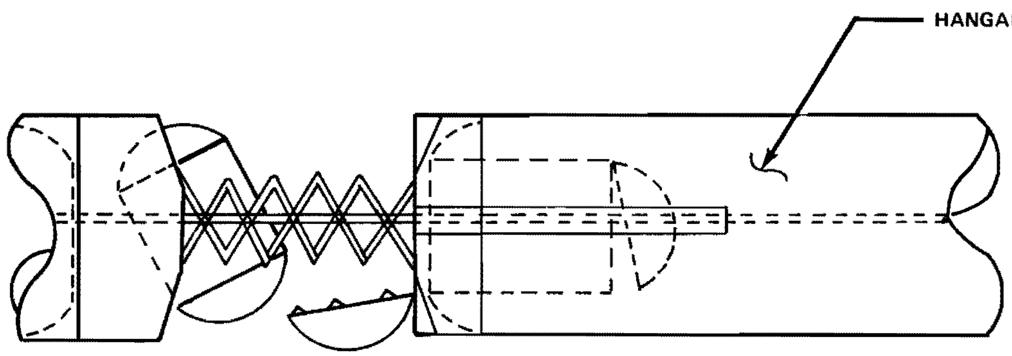


SINGLE UNIT



MULTIPLE UNITS

NOTE: USAGE OF THE BASIC MODULE FOR CREW OR CARGO CAN BE OPTIONAL.

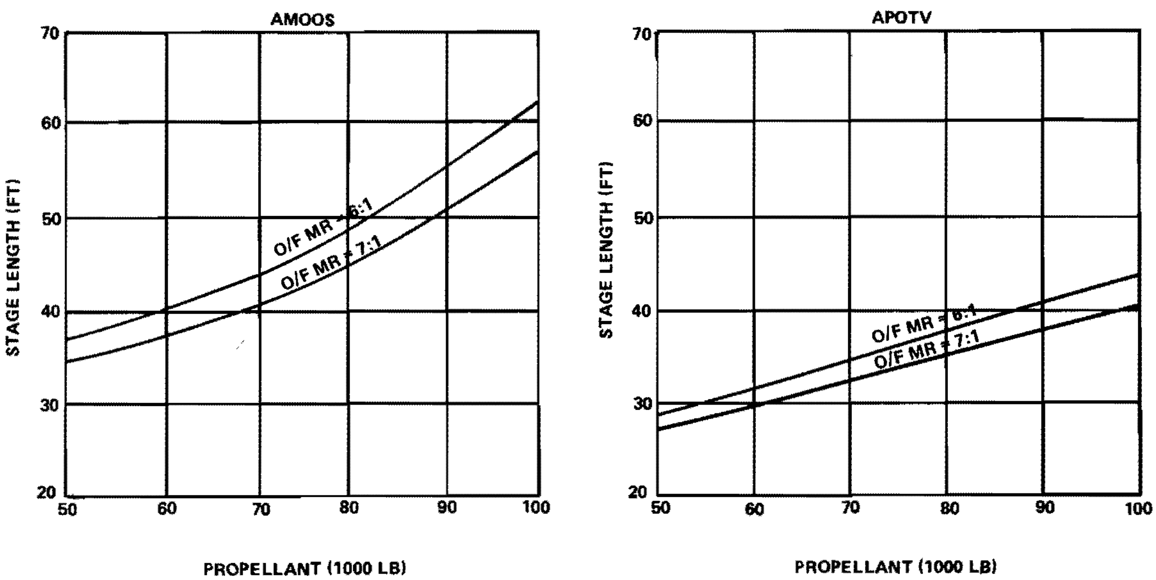


TRANSFER TO HANGAR

AMOOS AND APOTV STAGE LENGTH VERSUS PROPELLANT LOADING (15 ft CARGO BAY DIAMETER)

The graph reflects studies of sizing both the AMOOS and APOTV for compatibility with a 15 ft diameter cargo bay using two lox/hydrogen mixture ratios. The lengths shown are total including retracted nozzles on the Hi P_c engines. A constant thrust to weight of 0.15 was used in engine sizing.

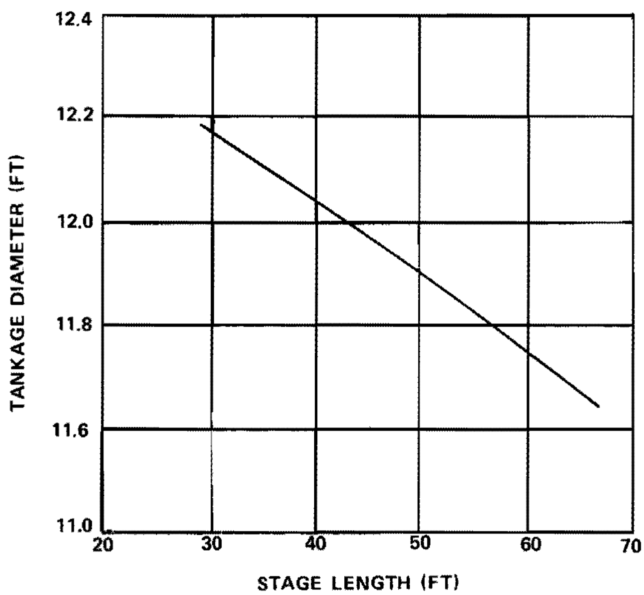
The APOTV slope is essentially straight because tank diameter is fixed, and length is primarily associated with the propellant capacity. In sizing the AMOOS stages, a nonlinear curve results as a result of the approach used in tank sizing. The larger configurations result in decreased tank diameters which, in turn, increase tank length.



NOTE: O/F REFERS TO THE OXIDIZER/FUEL AVERAGE MIXTURE RATIO USED BY THE ENGINE

AMOOS TANKAGE DIAMETER VERSUS STAGE LENGTH
(15 ft CARGO BAY DIAMETER)

The curve reflects several data points derived in the study of different length configurations. The larger stage lengths result in smaller tank diameters because of the required external shape of the AMOOS. An iterative process was used to derive the required tank diameter for clearance at the minimum applicable external diameter using the criteria stated on the graph.



NOTES:

AMOOS EXTERNAL SHAPE IS TAPERED AND ELLIPTICAL TO OBTAIN MANEUVERING CAPABILITY. TAPER IS ½ DEGREE HALF ANGLE AND ELLIPSE IS 0.9 RATIO. MAXIMUM DIAMETER IS 14.6 FT.

PAYLOAD WEIGHT VERSUS LOW EARTH ORBIT WEIGHT REQUIRED AND STAGE LENGTH (15 ft DIAMETER CARGO BAY)

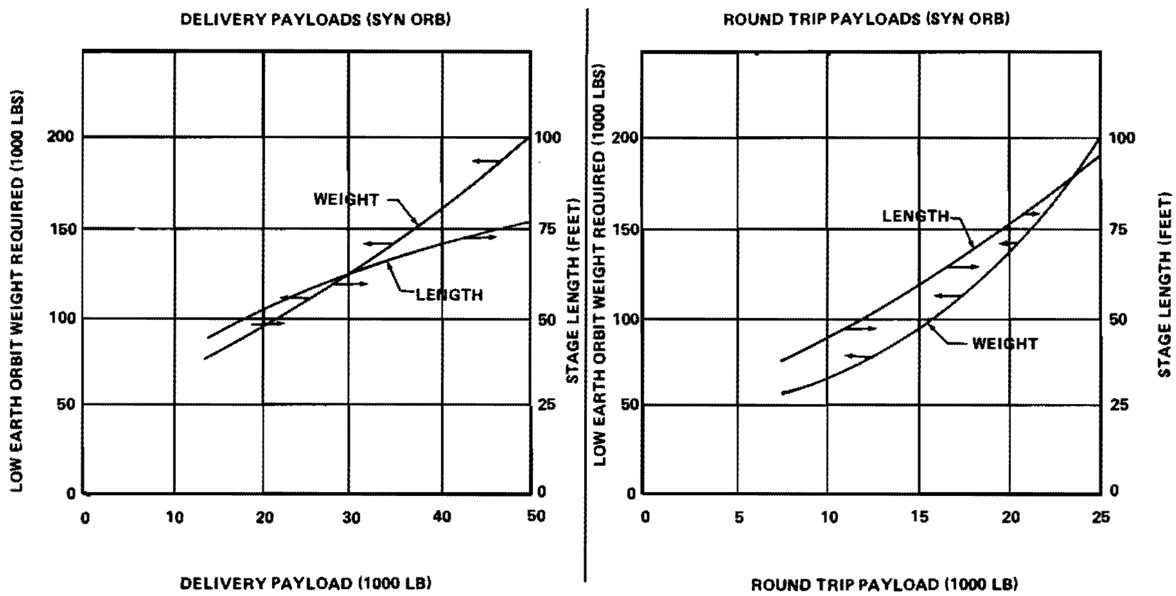
The charts show subject data for AMOOS and APOTV systems for single and dual stage applications.

For single stage applications the data show:

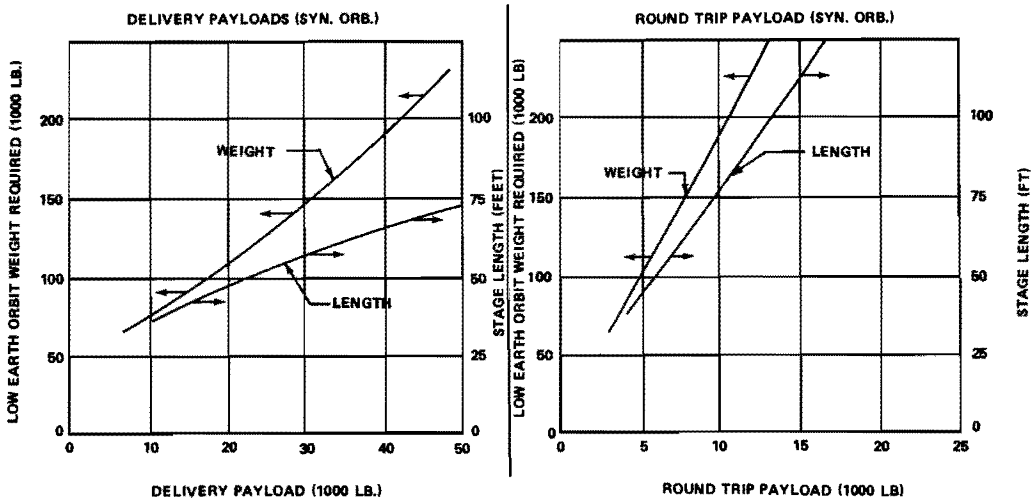
— For Delivery Only
APOTV weight requirements are higher, and stage lengths are approximately equal to AMOOS for equal payloads

— For Round Trip
AMOOS is much more favorable in weight and length for equal payloads

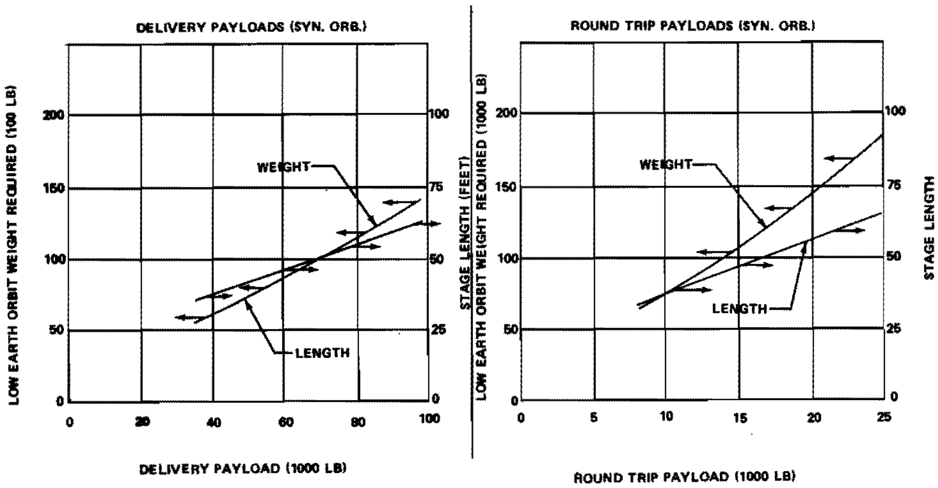
For dual stage application, the data show the same trend as for single applications with the differences somewhat lower.



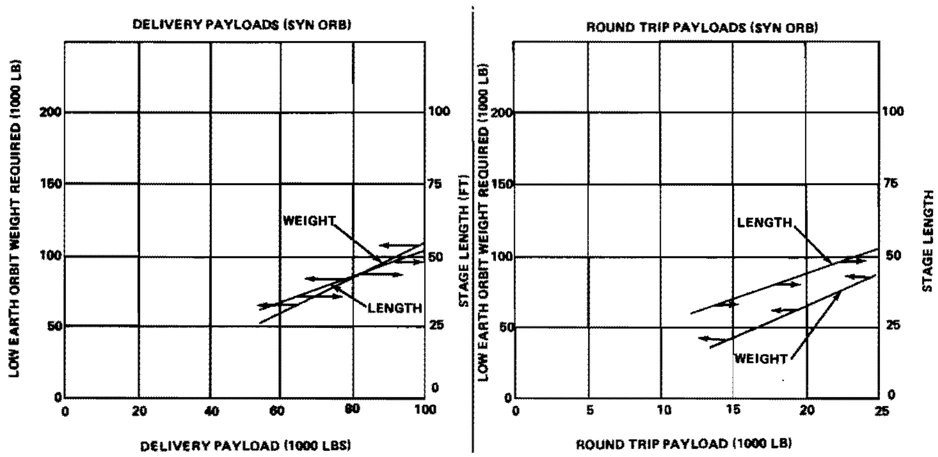
Single Stage (One Shuttle Launch) AMOOS



Single Stage (One Shuttle Launch) APOTV



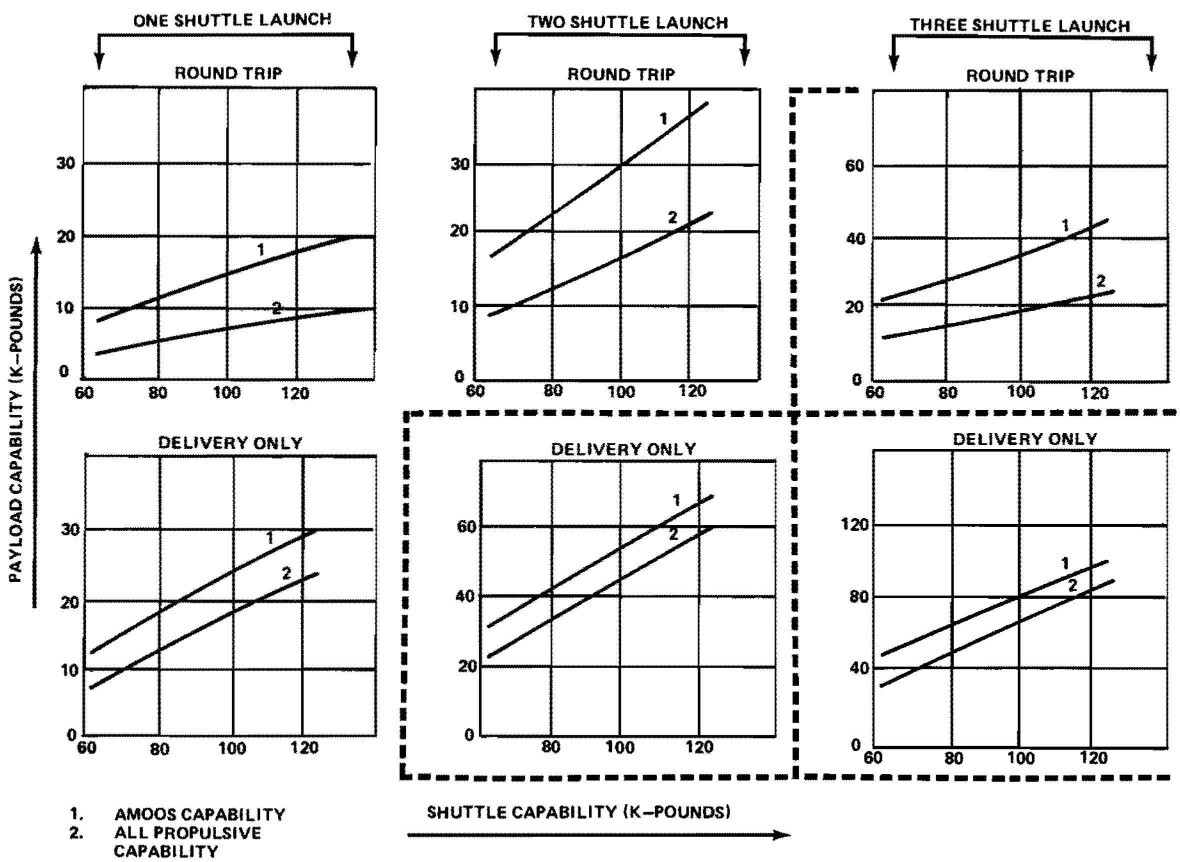
Dual Stage Amoos (Equal Stages)



Dual APOTV (Equal Stages)

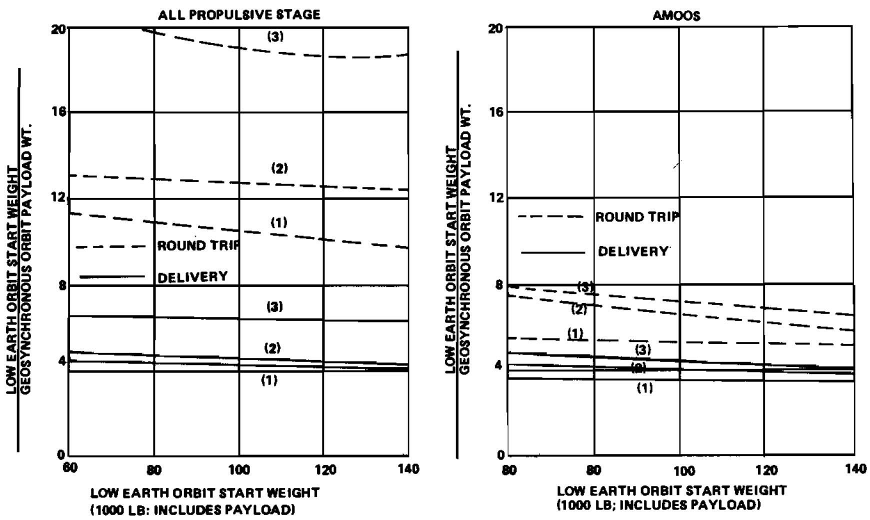
OTV CONCEPT COMPARISON AMOOS VERSUS APOTV
GEOSYNCHRONOUS ORBIT CAPABILITY

Geosynchronous orbit payload capability was developed for the AMOOS and APOTV systems as a function of Shuttle low Earth orbit capability of 65 000 to 125 000 lb. Payload delivery and payload round trip capability were derived for one, two, and three Shuttle launches. Two OTV's were employed on the second and third Shuttle launches. The payload delivery associated with an APOTV and a 65 000 lb Shuttle is approximately 8000 lb, and delivery associated with a 125 000 lb Shuttle is approximately 22 000 lb. Payload round trip capability associated with an APOTV and a 65 000 lb Shuttle is approximately 2800 lb, and round trip payload associated with a 125 000 lb Shuttle is approximately 8500 lb. Achieving the 10 000 to 20 000 lb round trip payload requires two Shuttle launches with two OTV stages having a Shuttle growth capability of 80 000 to 125 000 lb. Two Shuttle launches are also required to achieve the 50 000 to 70 000 lb payload delivery.



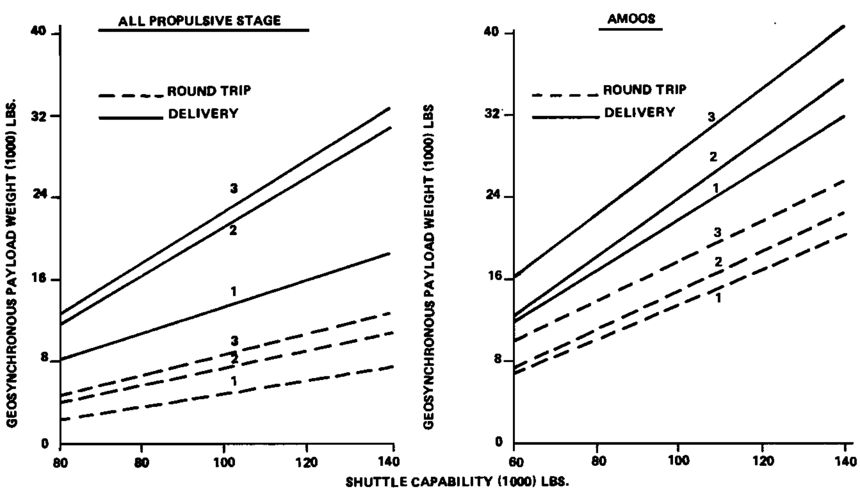
STAGING EFFECTS — OTV HIGH PERFORMANCE/LIQUID SYSTEMS

Analysis was conducted to determine the staging sensitivity on the APOTV and AMOOS system for geosynchronous payload delivery and payload round trip missions. Staging concepts of single stage, dual stage, and drop tank plus stage were considered. A 50 percent gain in payload capability can be realized by employing the drop tanks plus stage as compared to a single stage configuration APOTV system. However, the drop tanks are expended, and the on-orbit operation is more complex with the drop tanks; these points must be factored in to determine the real cost effectiveness of drop tank plus stage as compared to a single stage.



(1) DROP TANKS PLUS STAGE
(2) DUAL STAGES
(3) SINGLE STAGE

(1) SINGLE STAGE
(2) DUAL STAGE
(3) DROP TANK PLUS STAGE



OPERATION OF THE 125 000 SHUTTLE OTS IN 60 ft CARGO BAY — 65 000 SHUTTLE

It may be desirable to carry the crew and their orbit stay time interval supplies on a single flight. Also, it may be desirable to perform synchronous orbit sortie or geosynchronous Space Station assembly missions prior to the operation of a synchronous orbit Space Station. For either case, capability in excess of the 65 000 Shuttle/AMOOS (65 000 Shuttle concept) is required.

A solution to these problems may be to design the early system for a 125 000 Shuttle capability to be expected at a later time and for early usage operate the system in the 65 000 Shuttle. The system could be operated as shown or by some combination of Shuttle launching and orbital basing of AMRS, payloads, and lox.

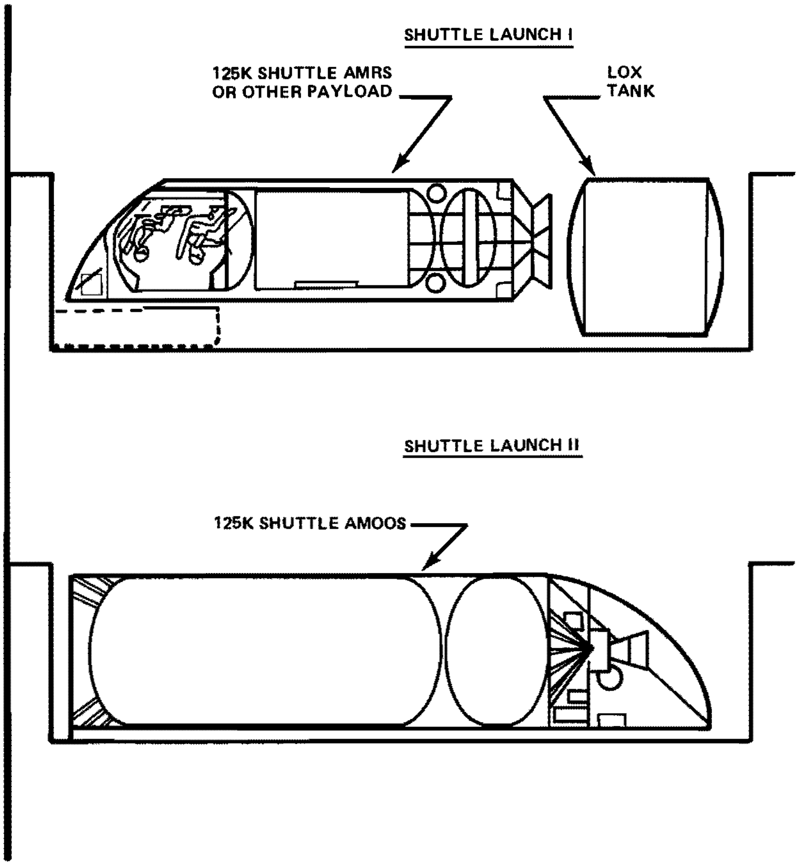
REQUIRES:

1. SIMULTANEOUS SHUTTLE LAUNCH-DUAL SHUTTLE OPERATIONS
2. LOX OFFLOADING IN AMOOS
3. LOX TRANSFER ON-ORBIT

CAPABILITY (DUAL LAUNCH):

ROUND TRIP
15,000 - 18,000 LB

DELIVERY ONLY
30,000 - 33,000 LB

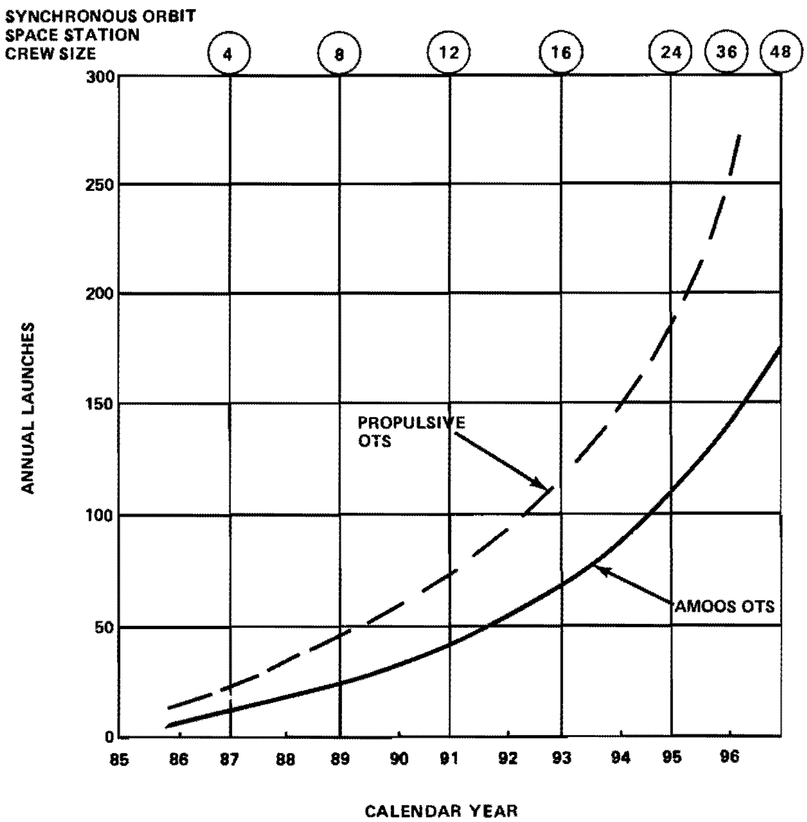


ANNUAL LAUNCH RATES COMPARISON OF ALL PROPULSIVE AND AMOOS OTS SYSTEMS USING 65K SHUTTLE

Mission Assumptions — The construction of a 12-man synchronous station by 1991 and the capability to construct one 12-man station each year after 1995. The assumptions represent the traffic for synchronous Earth orbit initiatives except hardware cargo deliveries for space power.

The AMOOS concept requires approximately 40 percent less transportation launches of the Space Shuttle. (The AMOOS normally round trips 2.5 to 3 times as much and delivers approximately 30 percent more.) The 40 percent trend is representative of the range of OTS capabilities being considered.

Note: The AMRS lifeboat was assumed for both OTS concepts.



BASIC ASSUMPTIONS

I EACH 4-PERSON STATION HAS
- –4 STATION MODULES AT 30 TO 35K LB.
- –1 SERVICE VEHICLE AT 12 TO 15K LB.
- –1 LIFEBOAT AT 12-15K LB.

II. CREW ROTATION AT 90 - DAY INTERVALS.

III. 4 EACH SUPPLY DELIVERY PER 4-MAN CREW AT 12 TO 15K LB.

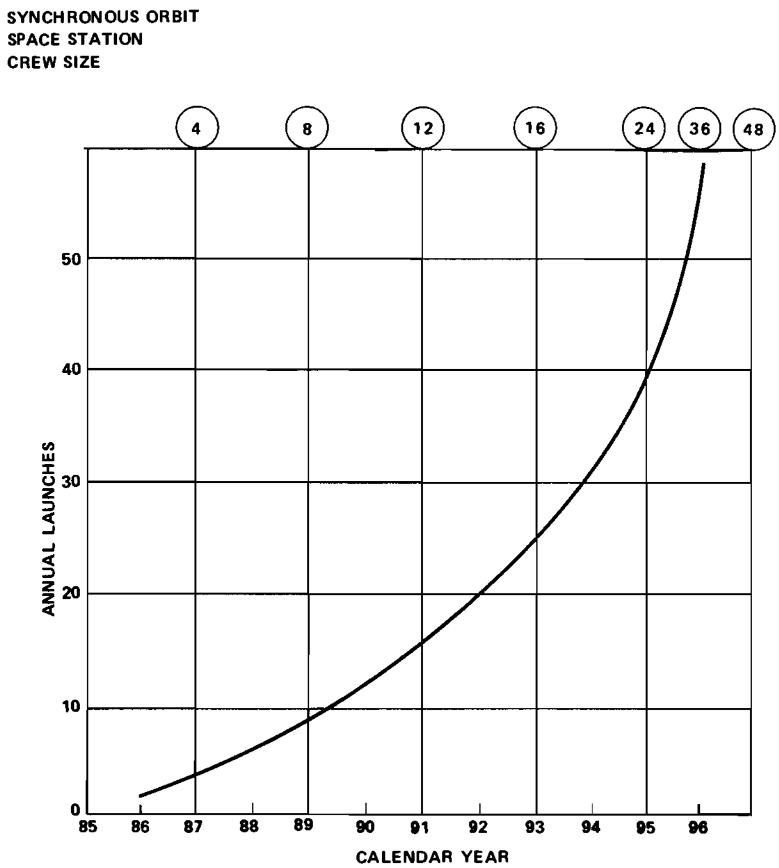
IV. 50,000 LB OF MISSION HARDWARE PER 4-MAN CREW PER YEAR IS ALSO DELIVERED.

NOTE: SIMULTANEOUS SHUTTLE LAUNCHES OR ORBITAL STORAGE OF CRYOGENIC STAGES IS REQUIRED FOR THIS CASE.

ANNUAL LAUNCH RATES FOR AMOOS WITH 125K SHUTTLE

Mission Assumptions — The construction of a 12-man synchronous station by 1991 and the capability to construct one 12-man station each year after 1995. The assumptions represent the traffic for synchronous Earth orbit initiatives except hardware cargo deliveries for space power.

A 4-man crew module with the crew supplies is used up to the time the HLLV is introduced. After HLLV introduction, the crew module is converted to a 12-man system and the crew supplies and all other cargo carried on the HLLV.



BASIC ASSUMPTIONS

I. EACH 4 – PERSON STATION HAS
- – 4 STATION MODULES AT 30 TO 35K LB.
- – 1 SERVICE VEHICLE AT 12 TO 15K LB.
- – 1 LIFEBOAT AT 12–15 K LB.

II. CREW ROTATION AT 90 – DAY INTERVALS.

III. 4 EACH SUPPLY DELIVERY PER 4–MAN CREW AT 12 TO 15K LB.

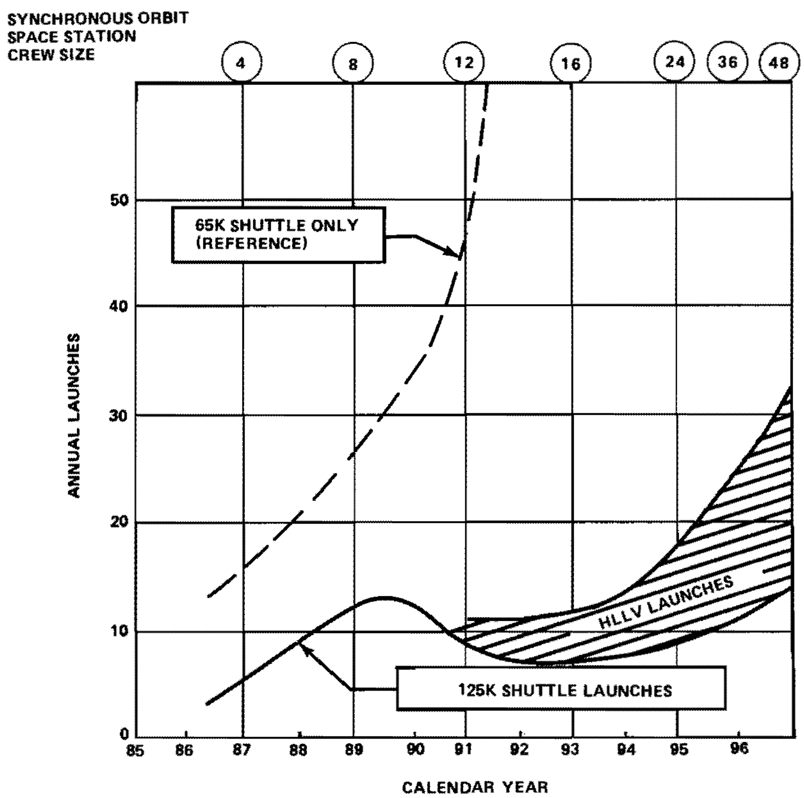
IV. 50,000 LB OF MISSION HARD– WARE PER 4 – MAN CREW PER YEAR IS ALSO DELIVERED.

NOTE: NO SIMULTANEOUS SHUTTLE LAUNCHES OR ORBITAL ASSEM- BLY IS REQUIRED. CARGO BAY LENGTH ABOUT 95 – 105 FT NEEDED.

ANNUAL LAUNCH RATES FOR AMOOS WITH 125K SHUTTLE AND HLLV AFTER 1991

Mission Assumptions — The construction of a 12-man synchronous station by 1991 and the capability to construct one 12-man station each year after 1995. The assumptions represent the traffic for synchronous Earth orbit initiatives except hardware cargo deliveries for space power.

A 4-man crew module with the crew supplies is used up to the time the HLLV is introduced. After HLLV introduction, the crew module is converted to a 12-man system and the crew supplies and all other cargo carried on the HLLV.



BASIC ASSUMPTIONS

I. EACH 4 - PERSON STATION HAS
   - 4 STATION MODULES AT 30 TO 35K LB.
   - 1 SERVICE VEHICLE AT 12 TO 15K LB.
   - 1 LIFEBOAT AT 12-15K LB.

II CREW ROTATION AT 90 - DAY INTERVALS.

III. 4 EACH SUPPLY DELIVERY PER 4 MAN CREW AT 12 TO 15K LB.

IV 50,000 LB OF MISSION HARDWARE PER 4-MAN CREW PER YEAR IS ALSO DELIVERED.

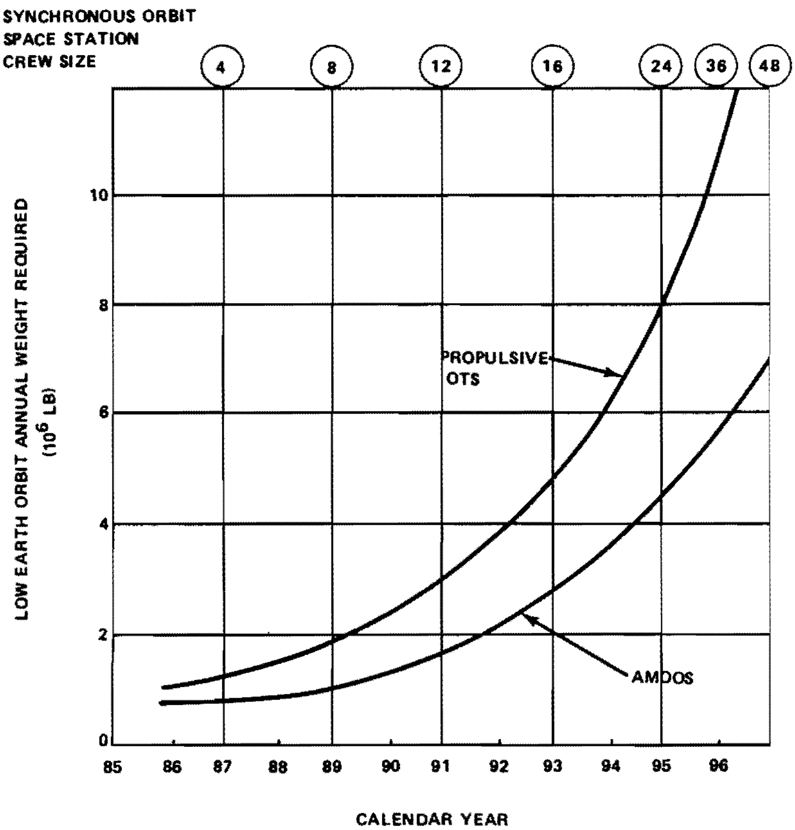
V. 4- MAN CREW MODULE UP TO 91- 12 - MAN CREW MODULE THEREAFTER.

IV. 125K SHUTTLE USED FOR SUPPLIES AND MISSION HARDWARE THRU 91 -- HLLV USED THEREAFTER

LOW EARTH ORBIT PAYLOAD REQUIRED FOR OTS OPERATION (ANNUAL RATE)

A comparison of the APOTV and the AMOOS in a scenario which has delivery and round trip payloads is shown.

The scenario used results in the capability to construct one 12-man station in synchronous orbit each year after 1995. Assumptions used in the calculations are given.



ASSUMPTIONS:

(1) FIVE STATION ELEMENTS AT 150,000 POUNDS FOR EACH FOUR MAN UNIT.

(2) FOUR MAN CREW TRANSFER ON SINGLE STAGE OTS.

(3) CREW ROTATION AT 90-DAY INTERVALS.

(4) ONE MANNED SORTIE FLIGHT FOR EACH FOUR MAN STATION CONSTRUCTION.

(5) 30,000 POUNDS OF CARGO NEEDED PER MAN PER YEAR.

(6) STATION ELEMENTS AND CARGO CARRIED ON MIXTURE OF SINGLE AND DUAL STAGE FLIGHTS.

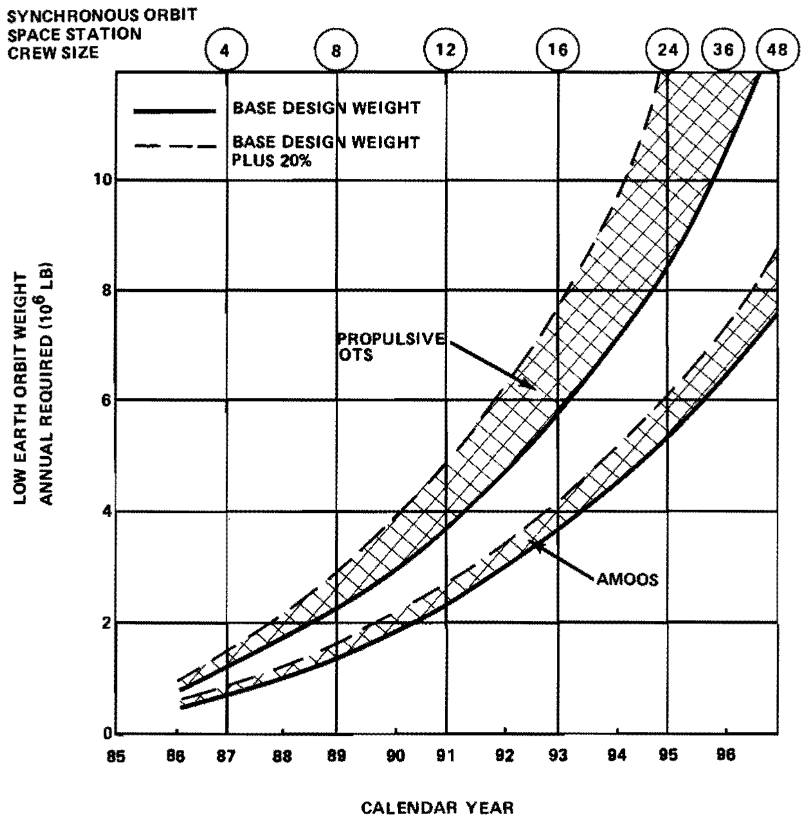
NOTE: RESULTS IN CAPABILITY TO BUILD ONE 12 MAN STATION PER YEAR BY 1995.

LOW EARTH ORBIT WEIGHT GROWTH REQUIRED BY A 20 PERCENT WEIGHT GROWTH ON OTS

Shown are the effects of OTS weight growth effects on low Earth orbit transportation in a scenario which requires delivery and round trip payloads.

The scenario results in the capability to construct one 12-man synchronous orbit station by 1995. Assumptions used in the calculation are shown.

Generally, a 20 percent weight growth on the APOTV increases requirements by 33 to 34 percent. A 20 percent weight growth on the AMOOS increases requirements by 16 to 17 percent.



ASSUMPTIONS:

(1) FIVE STATION ELEMENTS AT 150,000 POUNDS FOR EACH FOUR-MAN UNIT

(2) FOUR-MAN CREW TRANSFER ON SINGLE STAGE OTS

(3) SINGLE STAGE LAUNCHES ONLY

(4) CREW ROTATION AT 90-DAY INTERVALS

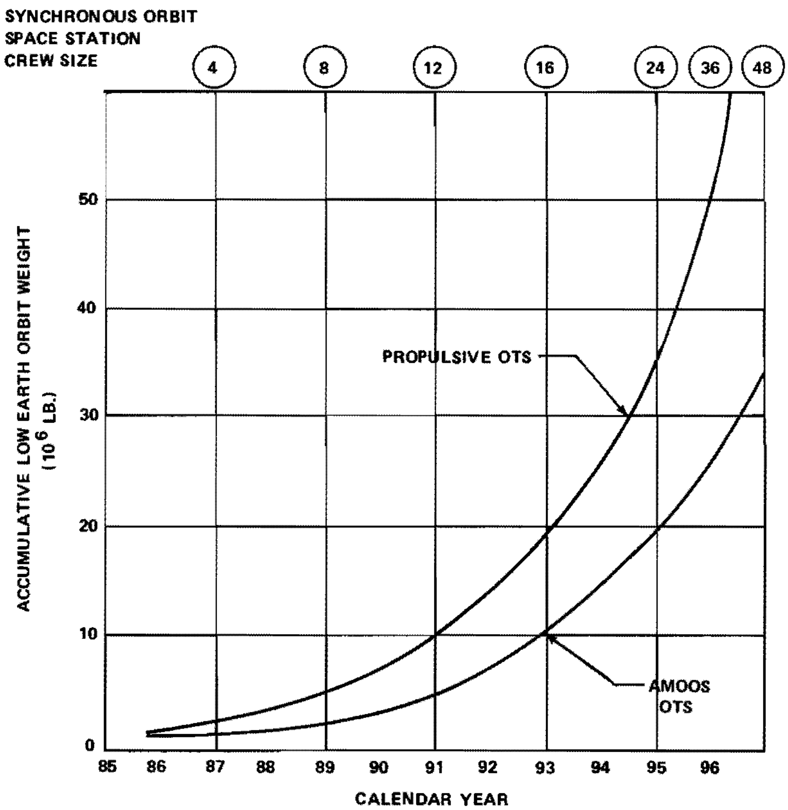
(5) 30,000 - LB OF CARGO NEEDED PER MAN PER YEAR

NOTE: RESULTS IN CAPABILITY TO BUILD ONE 12-MAN STATION PER YEAR BY 1995

ACCUMULATIVE LOW EARTH ORBIT WEIGHT REQUIRED FOR OTS OPERATION

Shown is a comparison of the APOTV and the AMOOS in a scenario which has delivery and round trip payloads.

The scenario results in the capability to construct one 12-man station in synchronous orbit each year after 1995. Assumptions used in the calculations are given.



ASSUMPTIONS:

(1) FIVE STATION ELEMENTS AT 150,000 POUNDS FOR EACH FOUR MAN UNIT.

(2) FOUR MAN CREW TRANSFER ON SINGLE STAGE OTS.

(3) CREW ROTATION AT 90–DAY INTERVALS.

(4) ONE MANNED SORTIE FLIGHT FOR EACH FOUR–MAN STATION CONSTRUCTION.

(5) 50,000 POUNDS OF CARGO NEEDED PER MAN PER YEAR.

(6) STATION ELEMENTS AND CARGO CARRIED ON MIXTURE OF SINGLE AND DUAL STAGE FLIGHTS.

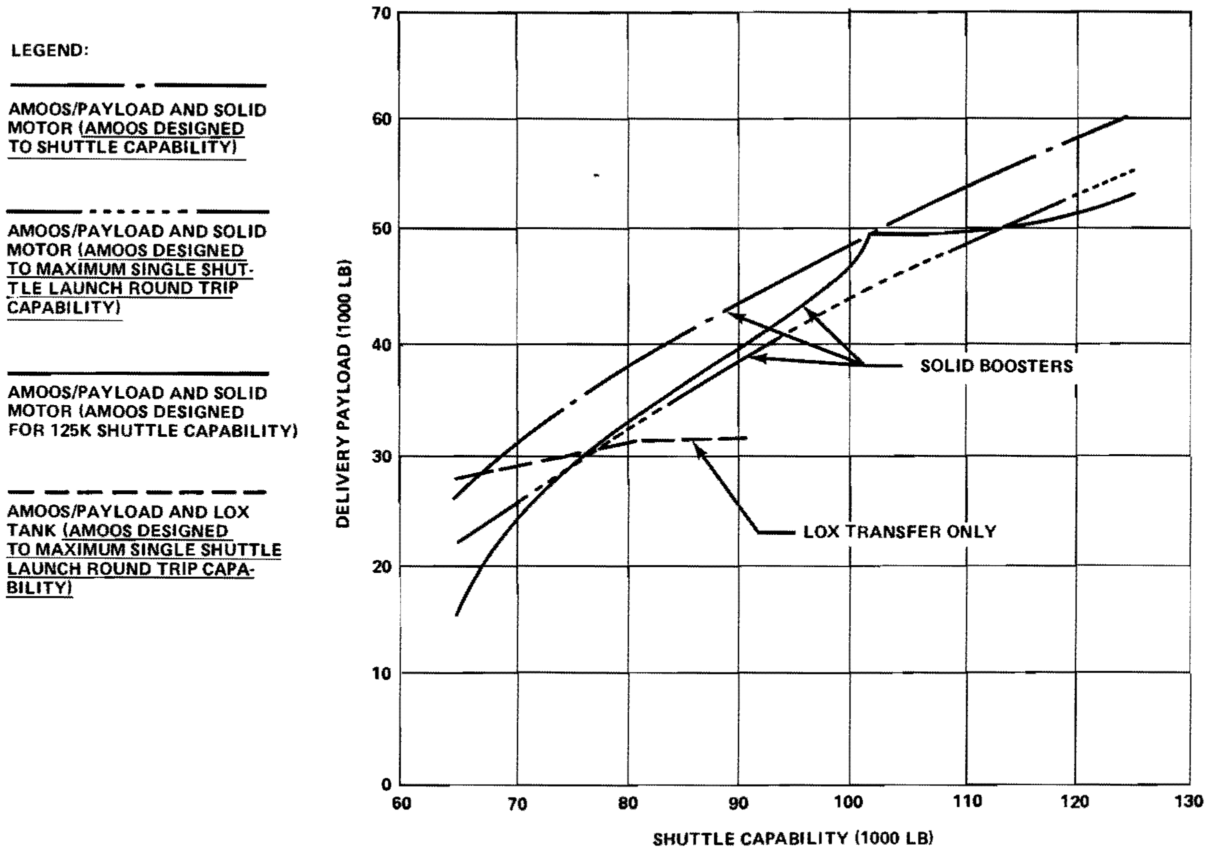
NOTE: RESULTS IN CAPABILITY TO BUILD ONE 12–MAN STATION PER YEAR BY 1995.

DUAL SHUTTLE LAUNCH AMOOS CONCEPTS
SOLID BOOST OR LOX TRANSFER

This chart was prepared to determine the trends to be expected as a result of the selection of various OTS concepts using dual launches with lox transfer or solid boost.

The significant points to be seen are the effects of Shuttle capability and the effects of the size selection of the OTV.

Low Earth orbit basing of certain OTV elements will also affect the issues being considered.

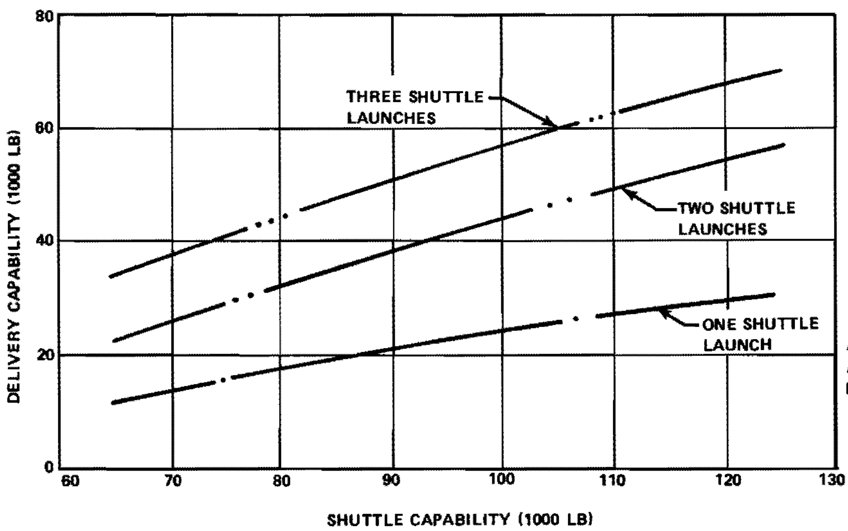


SUMMARY AMOOS — SOLID BOOST CAPABILITIES FOR SINGLE AND MULTIPLE SHUTTLE LAUNCHES

Shown here are summary data on the range of solid boosted AMOOS configurations being considered. The single launch AMOOS data are shown for reference.

Note: Multiple launch data shown are very preliminary because the total conceptual design iteration was incomplete when multiple launch performance was calculated. The data are accurate only to 5 to 10 percent for the multiple launch concept.

The solid boost concepts, to date, have been considered only as competitors to liquid boost concepts. If low Earth orbit basing of some OTS elements is considered, more solid motor capability could be used and increase maximum delivery payload more.

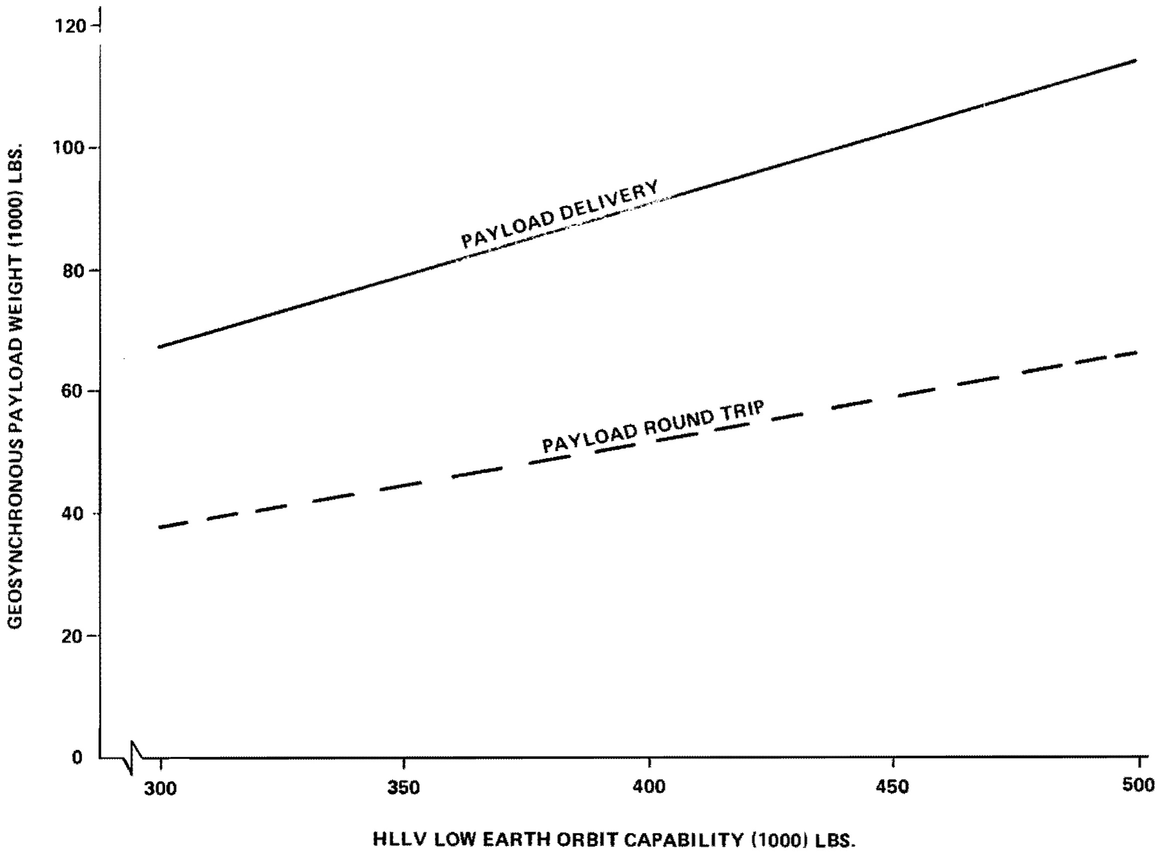


ASSUMPTION:
AMOOS SIZED FOR OPTIMUM PERFORMANCE WITH ONE SHUTTLE LAUNCH FOR EACH SHUTTLE.

NOTE:
THE THREE SHUTTLE LAUNCH CASE IS OPERATED WITH A VERY LOW LOAD FACTOR. — THE TWO SHUTTLE LAUNCH CASE SUFFERS ONLY A LOW LOAD FACTOR PENALTY.

AMOOS OTV GEOSYNCHRONOUS CAPABILITY BASED ON HLLV PAYLOAD TO LOW EARTH ORBIT

Geosynchronous payload weight as a function of HLLV low Earth orbit capability is depicted for an AMOOS system. The target OTV payload round trip (10 000 to 20 000 lb) capability can be realized with a 300 000 lb HLLV low Earth orbit capability. The AMOOS payload round trip capability is 38 000 to 65 000 lb for an HLLV capability of 300 000 to 500 000 lb, respectively. The geosynchronous OTV target delivery weight of 70 000 lb can be achieved by employing a 310 000 lb HLLV low Earth orbit capability. The AMOOS payload delivery capability is 67 000 to 114 000 lb for an HLLV capability of 300 000 to 500 000 lb, respectively.

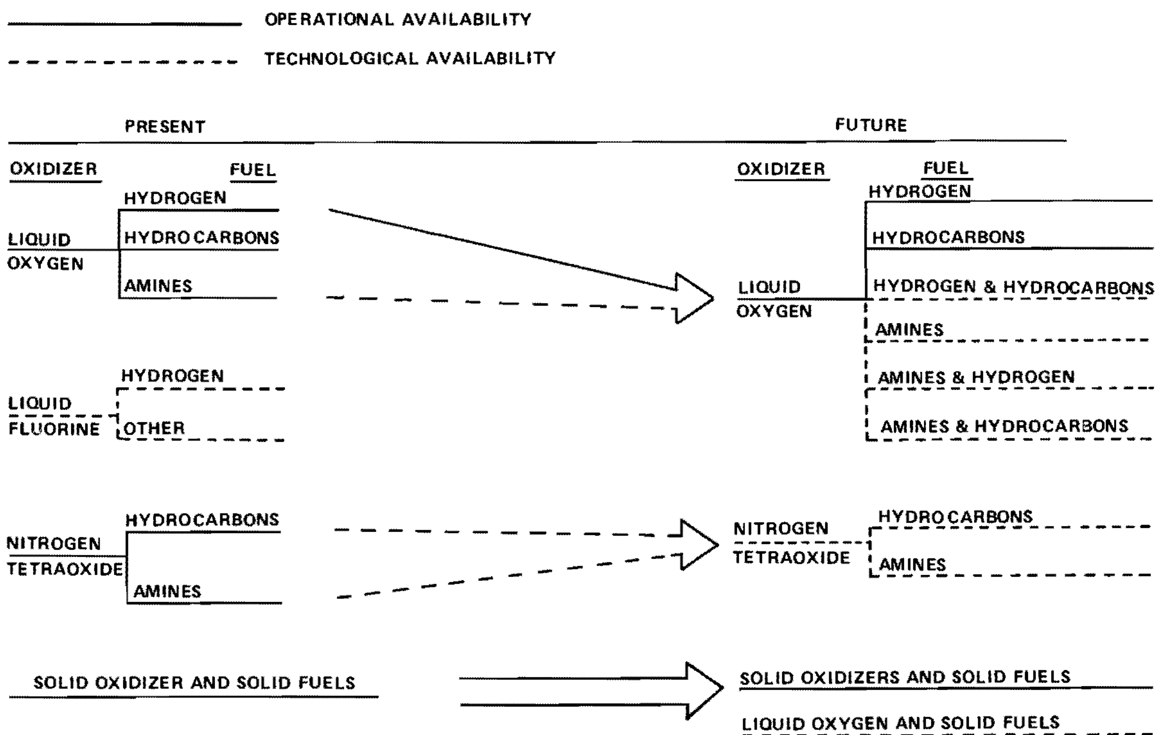


CHEMICAL PROPULSION SYSTEMS FOR OTV APPLICATIONS

Shown are present chemical propulsion capabilities and future requirements for OTV Main Engine applications. Chemical propulsion systems can (and probably will) be used to satisfy propulsion requirements for major Earth orbit programs and Lunar and Planetary resource development until well after the turn of the next century.

On the chart the solid lines (——) signify operational availability and the dash lines (----) signify technological availability.

The introduction of extra terrestrial oxidizers and perhaps fuel sources will be the paramount factor in the evaluating course of chemical propulsion in the future SPS. Oxidizer recovery from low load factor transportation system will also be a major course director. Solid propellant system will be used where very large stores of propellant are needed.

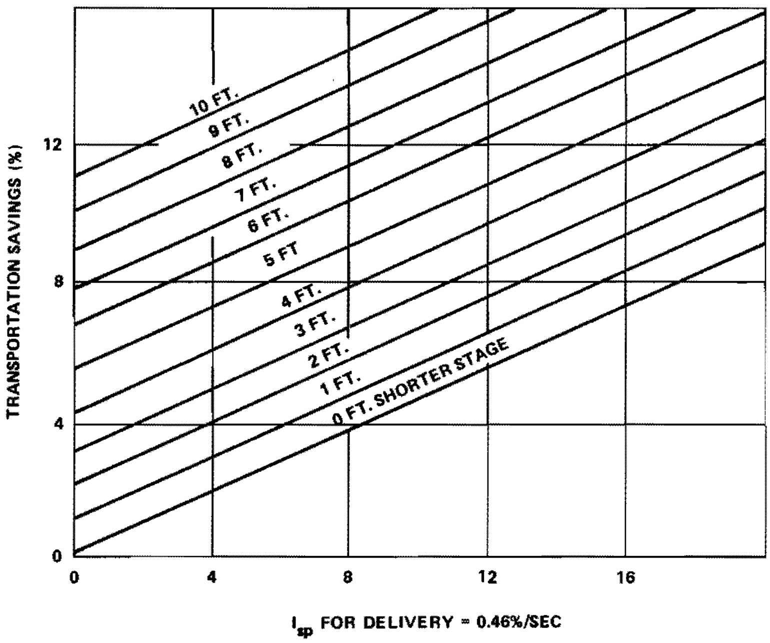


EFFECTS OF ENGINE PERFORMANCE AND STAGE LENGTH (AMOOS)

Shown here are the effects of engine performance and stage length for a given AMOOS type propulsion system. Transportation savings shown represent only savings in flights.

As noted, no savings in stage or engine system weight was included. It is expected that savings to be expected from these factors will also be positive and significant. It is also expected that the cost of building a unique short stage may be offset by savings in building longer cargo bays for lower stages.

Unique engines and unique stage designs are probably needed.



BASELINE DATA:

- TOTAL WEIGHT STAGE AND PAYLOAD = 63, 100 LB
- ROUND TRIP PAYLOAD = 8,000 LB
- DELIVERY PAYLOAD = 13,000 LB
- I_{sp} = 456 S
- STAGE WEIGHT = 6,500 LB

SENSITIVITIES:

- I_{sp} FOR ROUND TRIP = 0.57%/SEC
- I_{sp} INCREASE (SEC)
- STAGE LENGTH - 1.1%/FT

LENGTH FACTOR:

CARGO BAY WEIGHT IS ABOUT 685 LB/FT.

NOTE: NO SAVING FOR STAGE OR ENGINE SYSTEM WEIGHT REDUCTION IS INCLUDED. CASE SHOWN IS FOR DELIVERY ONLY.

EXAMPLE — TRADES TO BE MADE IN ENGINE SELECTION
(AMOOS CONFIGURATION — 80K SHUTTLE)

Shown here are example engine trades to be made for engine selection for OTV.

All baseline OTV stage data have been developed using the RL10-IIB engine system. Trades for engine selection will be compared against the RL10-IIB. In the example, cases involving a possible change in the RL10-IIB and introducing a new engine (ASE data used) are typical of trades to be made. Stage data have been parameterized to accommodate these trades.

It can be noted from the examples that interface transportation element (the Shuttle cargo bay in this instance) problems have significant effects on engine selection.

CHANGE TO BASELINE ENGINE

BASELINE ENGINE (RC10–IIB)

RET LENGTH	@ 55 IN.
I_{sp}	@ 456.5 SEC
WEIGHT	@ 442 LB.
ϵ	@ 200:1
MR	@ 6:1
PC	@ 400 PSI

NEW ENGINE (ASE)

RET LENGTH	@ 47 IN
I_{sp}	@ 471 SEC
WEIGHT	@ 310 LB.
ϵ	@ 400 S
MR	@ 6:1
PC	@ ≈ 1400 PSI

NEW ENGINE (ASE)

RET LENGTH	@ 48 IN.
I_{sp}	@ 464.5 SEC
WEIGHT	@ 320 LB
ϵ	@ 400
MR	@ 7:1
PC	@ 1400 PSI

EFFECTS ON TRANSPORTATION

	6:1	7:1
SHUTTLE/STAGE LENGTH	+0.6%	+2.8%
I_{sp}	+7.3%	+4.0%
ENG WEIGHT	+1.6%	+1.5%
NET RESULT	+9.5%	+8.3%

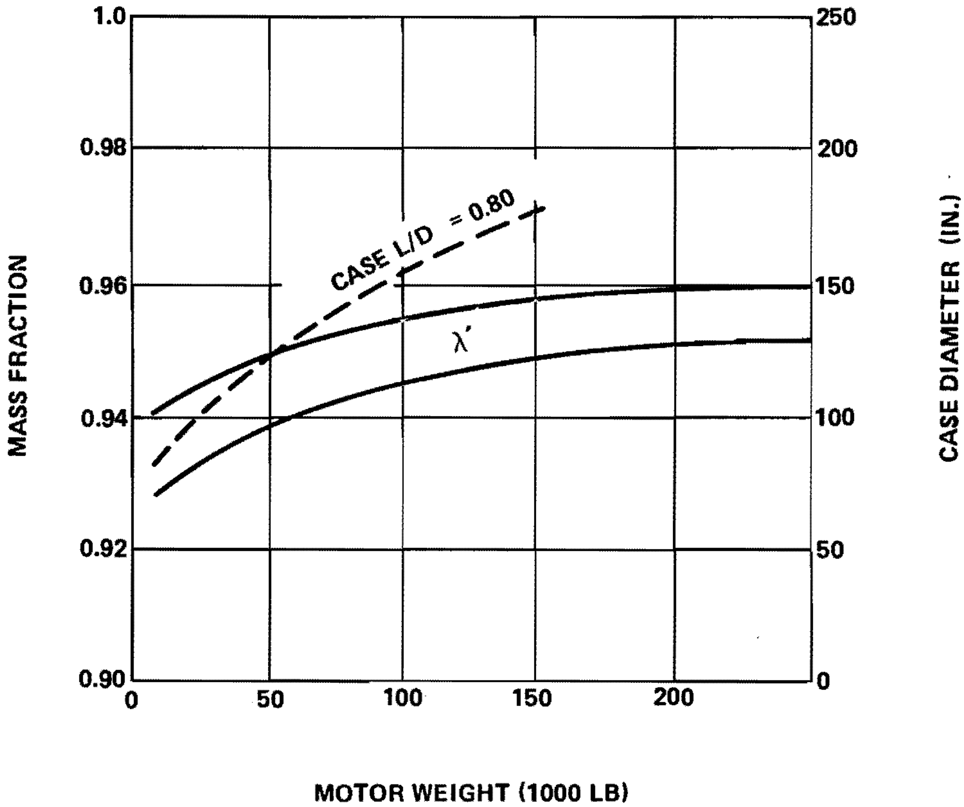
* REDUCE CARGO BAY LENGTH REQUIRED BY 3 TO 4 FEET.

CHART 2 OF 2

SOLID ROCKET MOTOR PARAMETER DATA

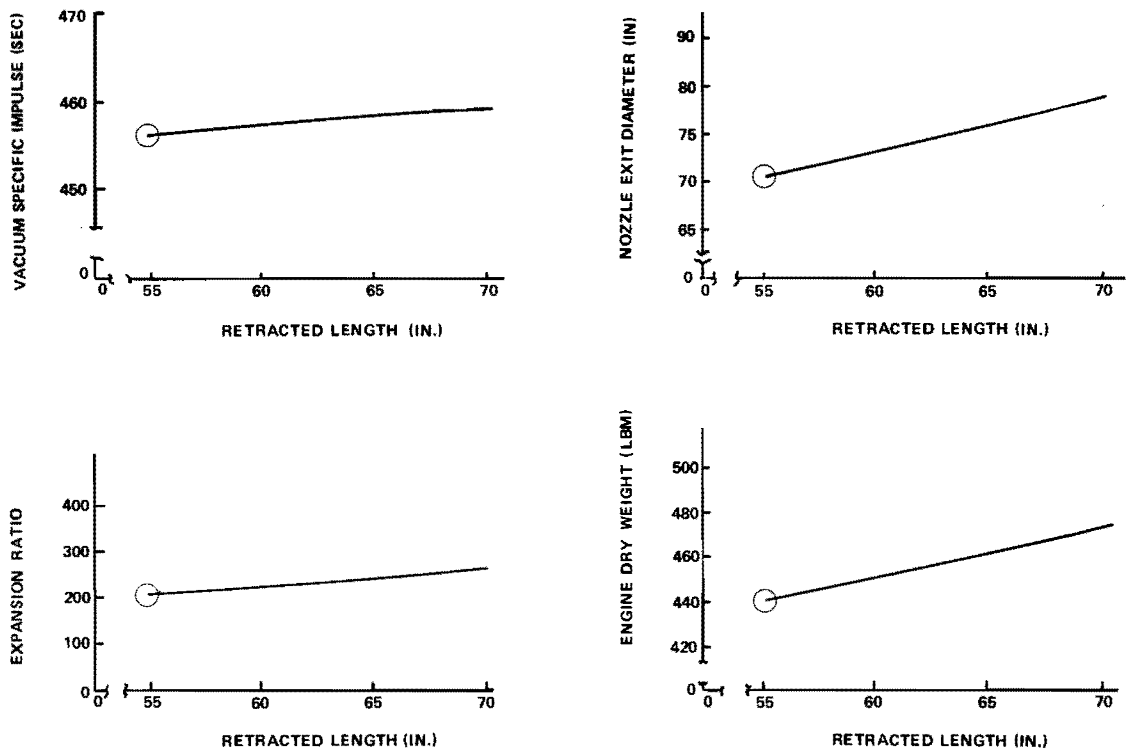
The two mass fraction curves represent current (bottom curve) state-of-the-art, and the top curve is an estimate of 1980 state-of-the-art. Both curves should be used with an I_{sp} of 300 sec. Solid propellant performance (I_{sp}) is currently at the upper limit.

The dotted curve shows the motor case diameter for a length-to-diameter ratio of 0:8. To get the total motor length, a nozzle length must be added.



ORBITAL TRANSFER SYSTEMS RL10 CATEGORY IIB ENGINE PERFORMANCE DATA

Additional data for the RL10-IIB engine were defined giving performance, weight, and geometry as a function of propellant mixture ratio. It should be noted that engine I_{sp} is near optimum at a propellant mixture ratio of approximately 5:1 and shifting the ratio to 6:1 or 7:1 results in significant degradation of performance as well as increasing engine size and weight. Two curves are presented for retracted-nozzle lengths of 55 and 70 in. For intermediate lengths data may be interpolated between the curves.

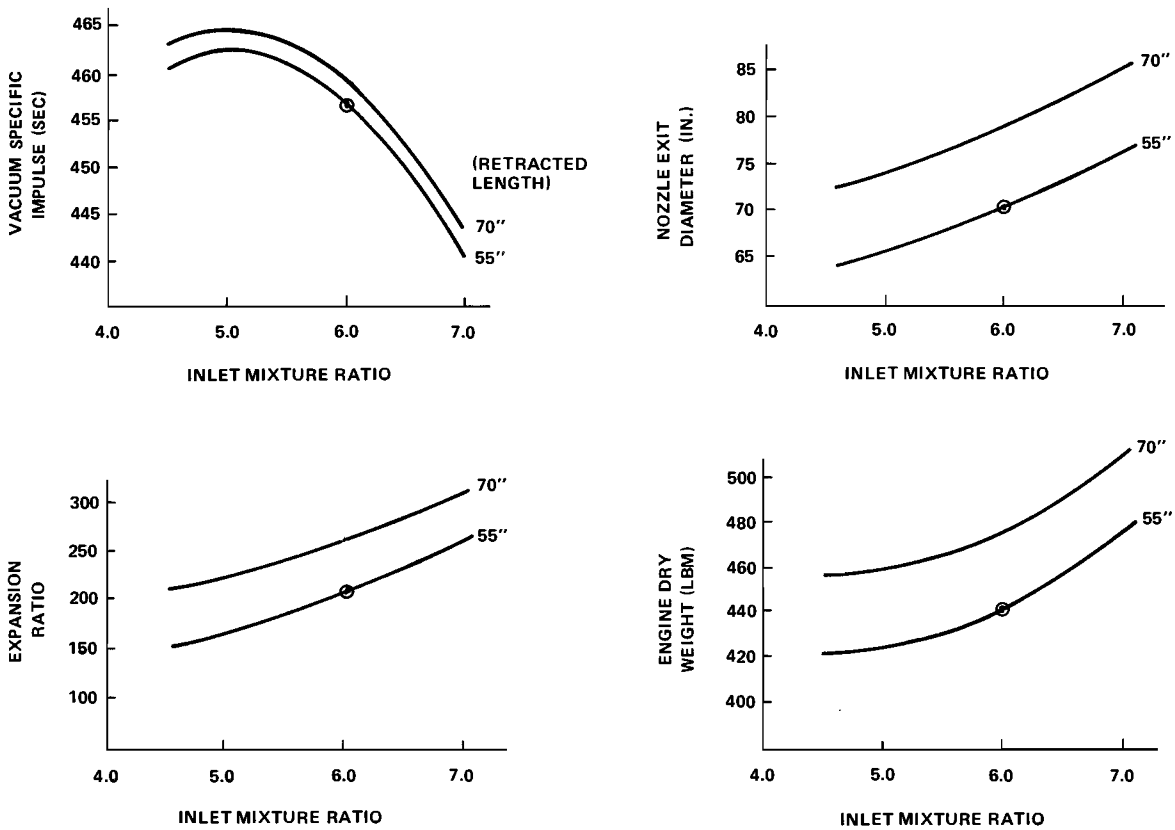


NOTE: RETRACTED LENGTH = 0.5 OVERALL LENGTH
(M. R. = 6/1)

ORBITAL TRANSFER SYSTEMS RL10 CATEGORY IIB ENGINE PERFORMANCE DATA

Serious consideration must be given to utilizing RL10-type lox/hydrogen engines for OTV application. In this case, engine thrust is held constant at 15 000 lbf resulting in engine thrust to gross weight ratios of 0.23, 0.15, and 0.12 for the three representative vehicles. For the RL10-II engine, performance (as measured by I_{sp}) is increased by increasing the nozzle expansion ratio.

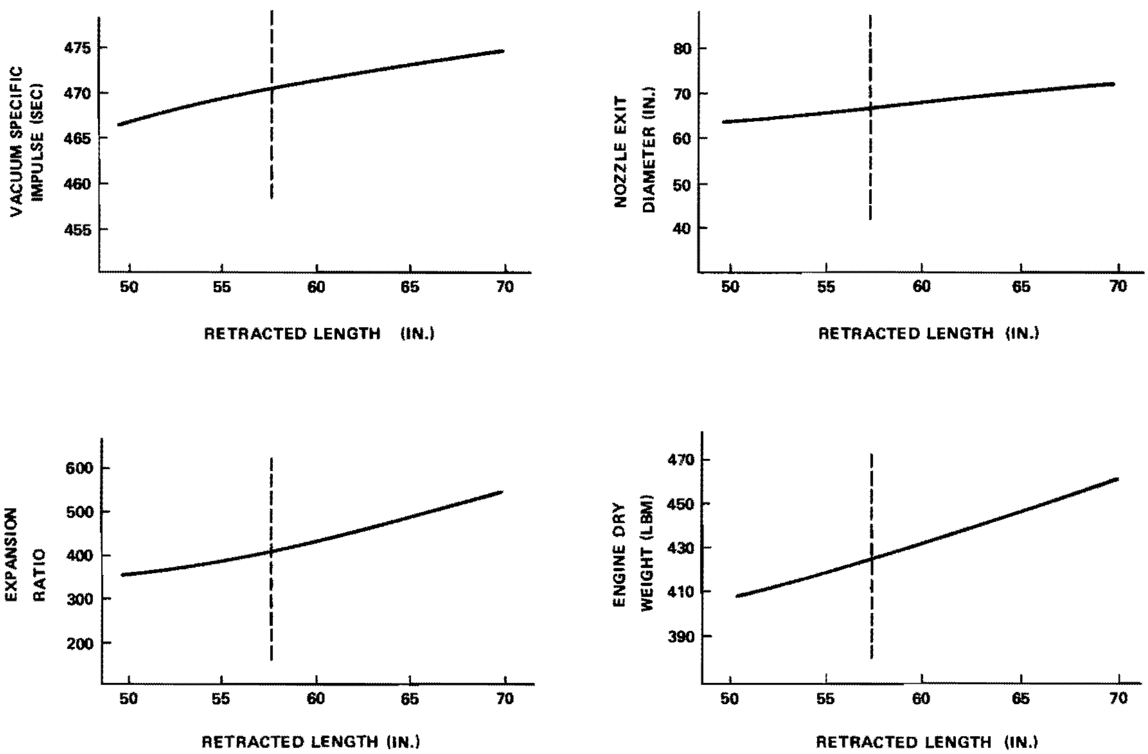
The data given are for a propellant mixture ratio of 6:1. As a reference point, the S&E baseline Space Tug engine performance is based on a retracted nozzle engine length of 55 in. with an expansion ratio of 205:1 and a corresponding I_{sp} of 456.5 sec.



NOTE: RETRACTED LENGTH = 0.5 OVERALL LENGTH

ORBITAL TRANSFER SYSTEM RL10 CATEGORY IV ENGINE PERFORMANCE DATA

Significant performance improvement is attainable by utilizing the RL10-IV engine for the OTV stages. Parametric data are given for an engine of 15 000 lbf at a propellant mixture ratio of 6:1. The dotted vertical lines on the chart represent the practical upper limit of approximately 470 sec I_{sp} for expander cycle engines.



NOTE: RETRACTED LENGTH = 0.5 OVERALL LENGTH MR= 6/1 F = 15,000 1bf

ORBITAL TRANSFER SYSTEM PLUG CLUSTER OPTION

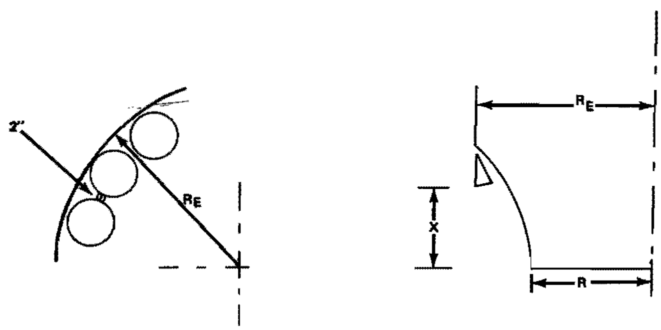
An attractive alternative to using conventional bell nozzle engines such as the ASE or RL10 is the grouping of multiple small engines in a "plug cluster" geometry. For OTS application, we have selected a lox/hydrogen engine of 1500 lb thrust arranged in a circular fashion around an aerodynamically designed nozzle cone for illustration. The individual nozzle expansion ratio is 40:1; however, when appropriately arranged in the plug cluster geometry, the collective expansion ratio is 400:1, resulting in an effective I_{sp} of 466 sec. The number of individual engine modules may be varied to adjust the total thrust as desired. The nominal propellant mixture ratio is 6:1.

The operation of the plug cluster is necessarily sensitive to geometrical arrangement. For performance and stage conceptual layout purposes, the geometric relationships as they are presently theorized have been defined. The radius, R_E, which defines the circle circumscribing the cluster of individual engines, is determined by selecting the desired performance level (effective expansion ratio) and the desired total thrust (number of engines), and by specifying the throat diameter of the individual engine. From this, the geometry of the central nozzle cone is determined by the relationships shown. Nominal separation of the individual engine nozzles is 2 in. For OTV application, the individual nozzles are canted slightly inward to direct exhaust product flow along the central nozzle cone surface.

The plug cluster design is presently undergoing conceptual evaluation and, therefore, must be considered only as theoretically attractive at this time, pending feasibility analysis and the usual demonstration testing.

PLUG CLUSTER PERFORMANCE DATA

- EACH ENGINE MODULE HAS 1500 LBF
- LOX/LH_2 PROPELLANTS
- INDIVIDUAL EXPANSION RATIO IS 40/1
- COLLECTIVE EXPANSION RATIO IS 400/1
- EFFECTIVE SPECIFIC IMPULSE IS 466 SEC
- MIXTURE RATIO – 6/1



$R/R_E = 0.7$

$X/R_E = 0.81$

$R_E = (\epsilon_{EFF} \cdot N \cdot D_t^2 / 4)^{1/2}$

WHERE: ϵ = EFFECTIVE EXPANSION RATIO

D_t = ENGINE THROAT DIAMETER

N = NUMBER OF ENGINES

ORBITAL TRANSFER SYSTEM ADVANCED SPACE ENGINE (ASE) OPTIONS FOR 65-125K lbm CLASS STAGES

Three point cases were selected to represent the OTV stages being considered: 65 000, 100 000, and 125 000 lbm gross weight vehicles. In each case it was desired to maintain the engine thrust to gross weight ratio at 0:15, resulting in engine thrusts of 9750, 15 000 and 18 750 lbf, respectively. For each of these engines, I_{sp}, weight, extended length, retracted length (where applicable), and nozzle exit diameter are defined. In addition, nozzle expansion ratios of 200:1 (fixed) and 400:1 (extendable/retractable) and propellant mixture ratios of 6:1 and 7:1 are parameterized.

ADVANCED SPACE ENGINE DATA FOR SELECTED POINT-DESIGNS

MR = 6/1

PAYLOAD - LBM	65,000		100,000		125,000	
THRUST - LBF	9,750		15,000		18,750	
P_c - PSIA	1,380		1,600		1,730	
	ϵ = 200	ϵ = 400	ϵ = 200	ϵ = 400	ϵ = 200	ϵ =400
I_{SP} –SEC	462	469	463.5	470	464	471
WEIGHT –LBM	170	200	230	260	260	310
LENGTH EXTENDED -IN	57	78	64	88	68	94
LENGTH RETRACTED –IN	N.A.	39	N.A.	44	N.A.	47
DIAMETER –IN	31	44	35	50	38	54

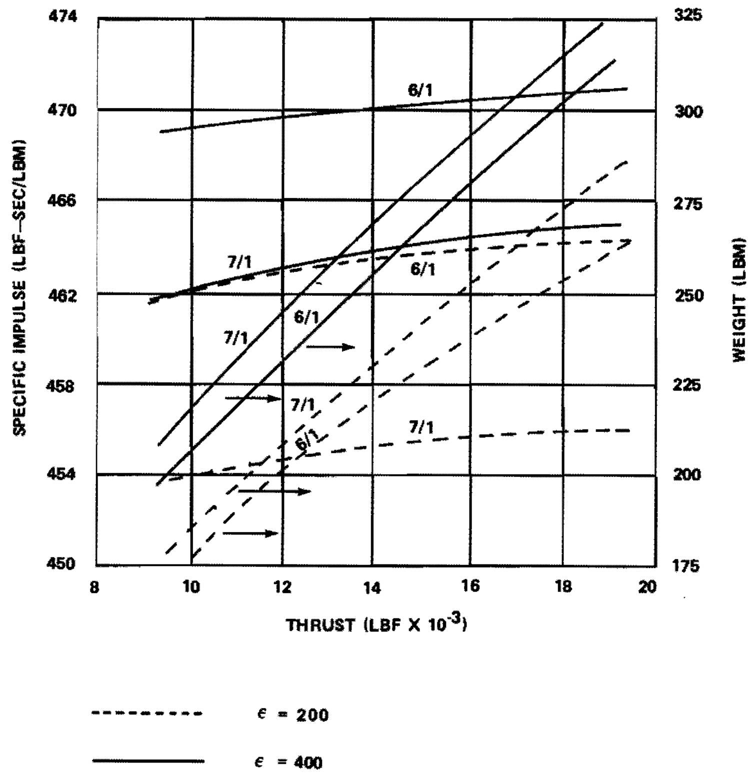
MR = 7/1

PAYLOAD - LBM	65,000		100,000		125,000	
THRUST - LBF	9,750		15,000		18,750	
P_c - PSIA	1,280		1,510		1,650	
	ϵ = 200	ϵ = 400	ϵ = 200	ϵ = 400	ϵ = 200	ϵ = 400
I_{SP} –SEC	454	462	455.5	464	456	464.5
WEIGHT –LB	180	210	240	280	280	320
LENGTH EXTENDED –IN	58	80	66	91	70	96
LENGTH RETRACTED –IN	N.A.	40	N.A.	46	N.A.	48
DIAMETER –IN	32	44	36	51	38	54

ORBITAL TRANSFER SYSTEM ADVANCED SPACE ENGINE (ASE) OPTIONS FOR 65-125K lbm CLASS STAGES

To examine the characteristics of OTV stages over the gross weight range of 65 000 to 125 000 lbm, parametric data were developed for ASE with thrust levels ranging from approximately 9000 to 20 000 lbf. Data are presented for nozzle expansion ratios of 200:1 and 400:1, with the assumptions that the 200:1 nozzle is fixed and the 400:1 nozzle is extendable/retractable. Data are presented with engine thrust on the abscissa of the graph and I_{sp} and weight on the left and right ordinate, respectively. Propellant mixture ratios of 6:1 and 7:1 are given, the former having superior engine performance.

These engines use cryogenic hydrogen and oxygen propellants and operate in a staged combustion power cycle. Chamber pressure is relatively high and increases with engine thrust.



ADVANCED SPACE ENGINE

- LOX/LH_2
- STAGED COMBUSTION CYCLE
- GIMBAL ANGLE ± 7°
- HIGH P_c
- ε = 200 FIXED NOZZLE
  ε = 400 EXTENDABLE/RETRACTABLE NOZZLE

APPENDIX C

OTV – MSFC STUDY PARTICIPANTS

OTV-MSFC STUDY PARTICIPANTS

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Norma Terrell	Secretary — Report Preparation	PD01	205/453-4160
Reba Kozub	Editorial Clerk — Report Preparation	PD01	205/453-4162

Principal Contributors

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Oliver Meredith	Design Analysis	PD23	205/453-3569
Archie Young	Performance Analysis	PD32	205/453-3479
James Thompson	Engine Systems	PD13	205/453-3228
James Sanders	Propulsion Systems	PD13	205/453-3229
Gene Whitaker	Costing Analysis	PP03	205/453-0467
Ken Turner	Schedule Analysis	PP02	205/453-3216
John Belcher	Operations/Capture Analysis	PD34	205/453-3936
Stephen Hall	Large Payload Capability Requirements	PD24	205/453-4196
Max Akridge	Concept Comparison/Evaluation	PD31	205/453-4721

Other Contributors

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Richard Kramer	Liquid Propulsion	PD13	205/453-3228
George Kearns	Solid Propulsion	PD13	205/453-3228
Carl Fritz	Thermal Evaluation	PD22	205/453-4263

APPROVAL

ORBIT TRANSFER SYSTEMS WITH EMPHASIS ON SHUTTLE APPLICATIONS – 1986-1991

By Program Development

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