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The Satellite Power System (SPS) program necessitates the transfer of significant cargo mass and personnel from low earth orbit (LEO) to geosynchronous earth orbit (GEO). The SPS transportation costs represent a major portion of program funding requirements and therefore require a most cost-effective approach toward LEO-GEO transfer.

Orbital transfer vehicle propulsion options include both chemical (COTV) and electrical (EOTV) options. The chemical options evaluated included single- and two-stage liquid oxygen/liquid hydrogen propulsive elements. The electric propulsion options considered alternate power sources (i.e., silicon or gallium aluminum arsenide solar arrays), propellant type (mercury, argon, cesium, etc.), low and high current density thrusters, methods of maintaining attitude hold during periods of shadow (chemical or electric), and programmatic impact of LEO-GEO trip time. The proposed EOTV construction method is similar to that of the SPS and, by the addition of a transmitting antenna, may serve as a demonstration or precursor satellite option.

The results of the studies to date have led to the tentative selection of a single-stage COTV for crew and priority cargo transfer (the COTV is refueled in GEO for return to LEO). The size of the propulsive element is dictated by the estimated crew transfer requirement. An EOTV concept is favored for cargo transfer because of the more favorable orbital burden factor over chemical systems. Although it is highly desirable to maintain a maximum degree of commonality between the SPS and EOTV, the gallium arsenide solar array is favored over the silicon array because of its self-annealing characteristics of radiation damage encountered during multiple transitions through the Van Allen radiation belt.

Transportation system operations are depicted in Figure 1. A heavy-lift launch vehicle (HLLV) delivers cargo and propellants to LEO, which are transferred to a dedicated EOTV by means of an intra-orbit transfer vehicle (IOTV) for subsequent transfer to GEO.

The Space Shuttle is used for crew transfer from earth to LEO. At the LEO base, the crew module is removed from the Shuttle cargo bay and mated to a COTV for transfer for GEO. Upon arrival at GEO, the SPS construction cargo is transferred from the EOTV to the SPS construction base by IOTV. The COTV with crew module docks to the construction base to effect crew transfer and COTV refueling for return flight to LEO. Crew consumables and resupply propellants are transported to GEO by the EOTV.

Transportation requirements are dominated by the vast quantity of materials to be transported to LEO and GEO (Figure 2). The average annual mass to orbit is in excess of 100 million kilograms, with over 100 personnel transfer flights per year.
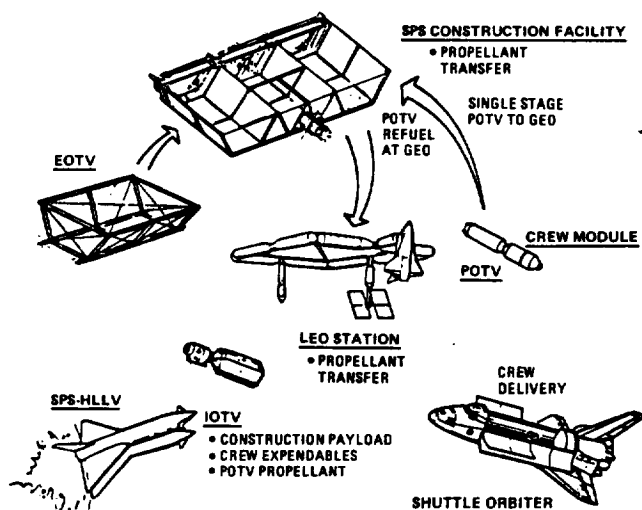

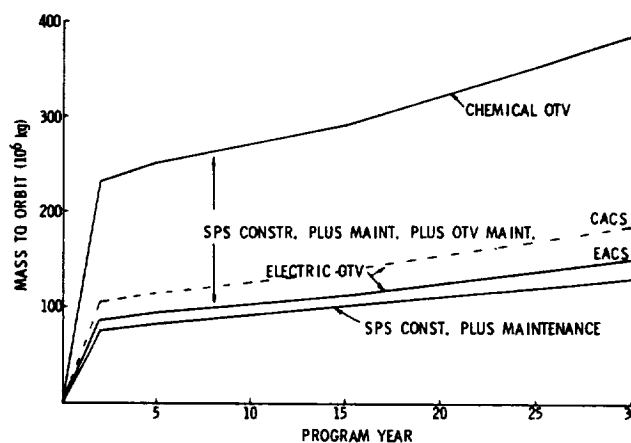Figure 1. Transportation System Orbital Operations

Figure 2. Orbital Mass Flow Requirement

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The personnel orbital transfer vehicle (POTV) uses a single-stage chemical propulsive element (COTV) to transport the crew module and its crew and passengers from LEO to GEO and return (Figure 3). Although significant propellant savings occur with this approach, as compared to a two-stage concept, the percentage of total mass is small when compared with satellite construction mass. However, the major impact is realized in the smaller propulsive stage size and the overall reduction in orbital operations requirements.

Individual propellant tanks are indicated for the LO_2 and LH_2 in this configuration because of uncertainties at this time in attitude control requirements. With further study, it may be advantageous to provide a common bulkhead tank as in the case of the Saturn S-II stage and locate the ACS at the mating station of the POTV and personnel module or in the aft engine compartments—space permitting.

The POTV utilizes two advanced space engines (ASE), which are similar in operation to the Space Shuttle main engine. The engine is of high performance with a staged combustion cycle capable of idle-mode operation. The engine employs autogeneous pressurization and low inlet NPSH operation. A two-position nozzle is used to minimize packaging length requirements.

Since the POTV concept utilizes an on-orbit maintenance/refueling approach, an on-board system capable of identifying/correcting potential subsystem problems to minimize/eliminate on-orbit checkout operations is postulated.

The EOTV concept (Figure 4) is based on the same construction principles of the Rockwell reference satellite. The commonality of the structural configuration and construction processes with the satellite design is evident. The structural bay width of 700 m (solar array width of 650 m) is the same as that of the satellite. The structural bay length is reduced from 800 to 750 m for compatibility with the lower voltage requirement of the EOTV.

The solar array voltage must be as high as possible to reduce wiring weight penalties and to provide high thruster performance, yet power loss by current leakage through the surrounding plasma must be minimized. At the proposed LEO staging base, with very large solar arrays and high efficiency cells, an upper voltage limit of 2000 volts is postulated. These considerations lead to the selection of a two-bay configuration with structural dimensions of 700 m x 1500 m (solar blanket size 650 m x 1400 m) with a total power output of 309 mw (includes 6% line losses).

Primary assumptions in EOTV sizing are given in Table 1. The solar array weights are scaled from satellite weights and are summarized in Table 2.

Since GaAlAs solar cells are employed in this concept with a concentration ratio of 2 on the solar cell blanket, the resulting cell operating temperature of 125°C allows continuous self-annealing of the solar cells during transit through the Van Allen radiation belt.
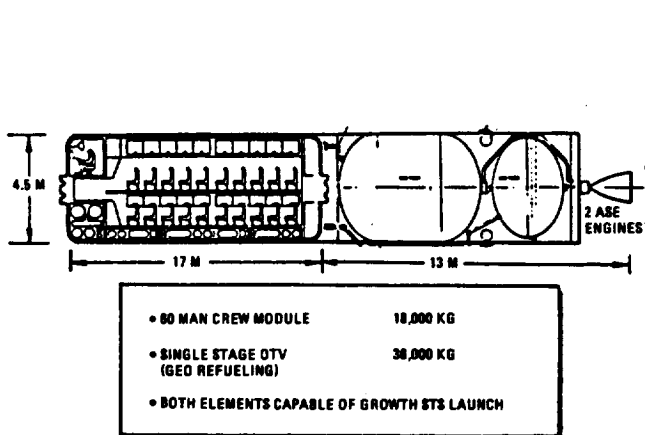
WEIGHT – KG X 10⁻⁶

EOTV DRY	0.758
PROPELLANT	0.848
PAYLOAD	6.860
TOTAL	8.468

Figure 3. Personnel Orbital Transfer Vehicle
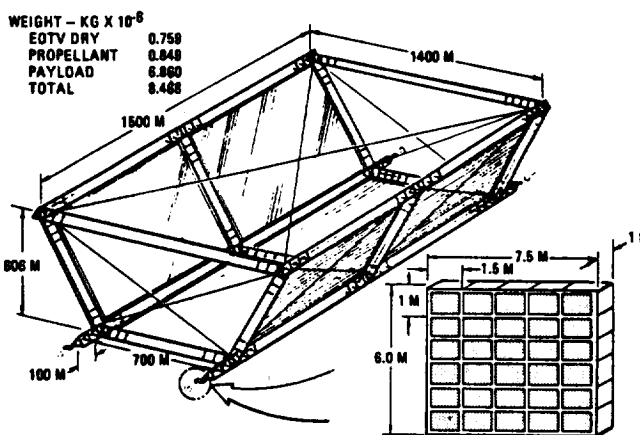
Figure 4. Electric Orbital Transfer Vehicle

205

Table 1. EOTV Sizing Assumptions	
Item	**Characteristics**
LEO altitude	487 km, 31.6° incl.
Orientation	Solar inertial
Launch opportunity	Anytime of year
ΔV requirement	5700 m/sec
Solar inertial attitude hold	During occultation only
Plume clearance	50°
Number of thrusters	Minimize
Spare thrusters (failures/thrust differential)	20%
Performance losses during thrusting	5%
ACS power requirement	Max occultation period
ACS propellant requirements	100% duty cycle
Weight growth allowance	25%

Table 2. EOTV Solar Array Weight Summary	
Item	**Weight (10^{-6} kg)**
Structure	0.051
Primary	(0.026)
Secondary	(0.025)
Mechanisms	0.004
Concentrators	0.033
Solar panels	0.229
Power distribution and controls	0.011
Maintenance provisions	0.003
Information management	0.002
Total	0.333

An all-electric thruster system was selected for attitude control during occultation periods to minimize propellant weight requirements (Figure 1). The power storage system was sized to accommodate maximum gravity gradient torques and occultation periods.

An excess of thrusters is included in each array to provide for potential failures, to permit higher thrust from active arrays when thrusting is limited or precluded from a specific array due to potential thruster exhaust impingement on the solar array, and to provide thrust differential as required for thrust vector/attitude control.

Having established the solar array operating voltage, the maximum thruster screen grid voltage is established, which in turn fixes propellant ion specific impulse. To assure adequate grid life for a minimum round-trip capability of approximately 4000 hours, a maximum beam current of 1000 amp/m² was selected. Based on the available power and a desire to maintain reasonable thruster size, the remaining thruster parameters are established. A rectangular thruster configuration (1 m x 1.5 m) is assumed. Primary thruster characteristics are summarized in Table 3.

Conventional power conditioners for ion bombardment thrusters regulate all supplies, serving as an interface between the power source (solar array) and the thrusters. Various direct-drive concepts have been proposed in which the primary (beam power)-thruster supply is obtained directly from the solar array power bus. This approach reduces power conditioner mass, power loss, and cost and improves system reliability. Solar cell temperature, efficiency, and output voltage variations will cause acceptable transients in beam voltage during thruster operation.

Based on the individual thruster power requirements and the available array power, 100 thrusters may be operated simultaneously. An additional 20 thrusters are added to provide the required thrust margin. The thrusters are arranged in 4 arrays of 30 thrusters each. The thruster array mass summary is presented in Table 4.

The EOTV performance is based on a 120-day trip time from LEO to GEO (obtained from trade studies). Knowing the propellant consumption rate of the thrusters and the thrusting time, the maximum propellant which can be consumed is determined, which in turn defines the payload capability. The vehicle also is sized to provide for the return to LEO of 10% of the LEO-to-GEO payload. The EOTV weight summary is presented in Table 5.

Since the EOTV solar array utilizes the same configuration, materials, and manufacturing processes as the satellite, common technology requirements are evident. The unique technology requirement is in the primary area of ion engine development. The key requirement is in large size (1.0 m x 1.5 m) high current density (1000 amp/m²) thruster demonstration.

Table 3. Argon Ion Thruster Characteristics

Item	Value
Maximum total voltage (V)	4405
Maximum operating temperature (°K)	1330
Screen grid voltage (V)	1880
Accelerator grid voltage (V)	-2525
Beam current (amp)	1500
Beam power (W)	2.82×10^6
Specific impulse (sec)	7963
Thrust (NW)	56.26

Table 4. Thruster Array Mass Summary

Item	Mass (kg)
Thrusters and structure	23,760
Conductors	5,920
Beams and gimbals	2,256
Power processing	1,550
Attitude reference system	1,000
Batteries and charger	154,500
Total	188,986

Table 5. EOTV Mass Summary

Item	Mass (10^{-6} kg)
Solar array	0.333
Thruster array (4)	0.189
Propellant tanks and distribution	0.085
EOTV (dry)	0.607
Growth (25%)	0.152
EOTV, total	0.759
Propellant	0.849
Main LEO-GEO	(0.655)
Main GEO-LEO	(0.130)
Attitude control	(0.064)
EOTV (wet), total	1.608
Payload	6.860
LEO departure	8.468
GEO arrival	7.789
GEO depature	1.603
LEO arrival	1.469