Nuclear-Electric Reusable Orbital Transfer Vehicle

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To help determine the systems requirements for a 300-kWe space nuclear reactor power system, a mission and spacecraft have been examined that utilize electric propulsion supported by the nuclear reactor's power for multiple transfers of cargo between low Earth orbit (LEO) and geosynchronous Earth orbit (GEO). A propulsion system employing ion thrusters and xenon propellant was selected. Propellant and thrusters are replaced after each sortie to GEO. The mass of the orbital transfer vehicle (OTV), empty and dry, is 11,000 kg; nominal propellant load is 5000 kg. The OTV operates between a circular orbit at 925-km altitude, 28.5-deg inclination, and GEO. Cargo is brought to the OTV by Shuttle and an orbital maneuvering vehicle (OMV); the OTV then takes it to GEO. The OTV can also bring cargo back from GEO for transfer by OMV to the Shuttle. OTV propellant is resupplied, and the ion thrusters are replaced, by the OMV before each sortie to GEO. At the end of mission life, the OTV's electric propulsion is used to place it in a heliocentric orbit so that the reactor will not return to Earth. The nominal cargo capability to GEO is 6000 kg, with a transit time of 120 days; 1350 kg can be transferred in 90 days, and 14,300 kg in 240 days. These capabilities can be considerably increased by using separate Shuttle launches to bring up propellant and cargo or by changing to mercury propellant.

Introduction

THE SP-100 Project was established to develop and demonstrate feasibility of a class of space reactor power systems (SRPS) that produces tens of kilowatts to one megawatt of electrical power. To help determine systems requirements for the SRPS, a mission and spacecraft were examined that use electric propulsion with this class of nuclear reactor power to make many transfers of cargo between low Earth orbit (LEO) and geosynchronous Earth orbit (GEO). Aspects of the mission and spacecraft bearing on the power system were the primary objectives of this study. Another mission and spacecraft study concerning SP-100 is reported in Refs. 1 and 2.

Prior to the initiation of this study, 300 kWe (kilowatts electric) had been selected as the design power level for development and ground test of key portions of an SRPS. To maximize applicability of the study to the planned SP-100 effort, the power level for the spacecraft was assumed to be 300 kWe. (After the study was completed, the design level was changed to 100 kWe.)

Important mission requirements follow. The first two of these were suggested by Ref. 3.

1) The OTV shall perform 10 sorties between LEO and GEO, 8 of these carrying cargo from LEO to GEO, and 2 carrying cargo from GEO to LEO.

2) The transit time from LEO to GEO shall not exceed 120 days.

3) The cargo carried to GEO, and the propellant required for the OTV sortie, shall be within the capability of a single Shuttle Orbiter.

4) If an intermediate stage is needed between the Shuttle and the OTV, propellant for the intermediate stage shall be included in the single Shuttle payload mentioned.

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Spacecraft functional requirements included:

1) After deployment of flexible elements of the power system, the acceleration provided by the electric propulsion system is the maximum that must be withstood by the OTV.

2) Pointing accuracy shall be ± 5 deg.

3) Launch of all mission elements by the Shuttle is assumed. (Later, Titan 4 launch was also considered.)

Spacecraft Systems

Power

The power source is a fast-spectrum reactor fueled with UN and cooled with liquid lithium. A shield shadows the rest of the spacecraft from reactor radiation, and an extendable boom further reduces the dose. Lithium pumped from the reactor heats one end of a set of thermoelectric elements made of Si-Ge doped with GaP. Waste heat from the cold end of the thermoelectrics is removed by heat pipes and radiated to space. Electrical power produced by the thermoelectrics is conditioned and delivered to the rest of the spacecraft as constant-voltage dc.

The SRPS boom and main radiator fold to permit the system to fit within a 9-m-long portion of the Shuttle cargo bay or Titan 4 fairing. These deploy on command. The deployed length of the SRPS is about 25 m, and the width is about 20 m. The mass of the SRPS was estimated at 7400 kg, broken down as shown in Table 1. (More recent work suggests that it may not be possible to keep the SRPS mass this low.) The thermal radiation from the power system to the rest of the spacecraft is limited to 1 sun (1.4 kW/m^2). Reference 4 gives further description of the SRPS.

Propulsion

Electric propulsion characteristics used in the study were limited to those considered to provide low or moderate developmental risk for the 1995 time period. They are summarized in Tables 2 and 3. The alternatives considered were resistojets, arcjets, and ion thrusters. It was found that the performance of resistojets and ammonia arcjets was too low to bring any cargo to GEO within the mission constraints of a single Shuttle launch for cargo and propellants. With hydrogen arcjets, the Shuttle cargo bay would be almost filled by the hydrogen tank, leaving inadequate room for the cargo meant for GEO. Also, current NASA policy does not permit large quantities of hydrogen in the Shuttle payload bay. Mercury ion thrusters would provide somewhat better performance than xenon, but there are possible Shuttle safety and environmental issues associated with using mercury. Accordingly, ion thrusters and xenon propellant were selected.

A specific impulse between 20,000 and 25,000 N-s/kg (2000 and 2500 lbf-s/lbm) was found to be optimum for 120-day maximum transit time to GEO. Higher specific impulse is undesirable because the corresponding low thrust leads to excessive transit time. There is a problem at the present state of the art in getting sufficiently low I_{sp} with ion propulsion while maintaining good efficiency. The characteristics assumed for electric propulsion included a minimum I_{sp} of 29,400 N-s/kg (3000 lbf-s/lbm) with xenon and a lifetime of 5000 h for ion thrusters. This lifetime necessitates replacement of the thrusters after each sortie to GEO.

Cargo Compartment

The OTV includes a compartment to hold its cargo. This was provided, rather than an end attachment for the cargo, primarily to maximize compatibility of the cargo interface with that for the Shuttle. The cargo compartment can be open, framed by structural members, or closed to provide temperature control for the cargo and to shield it from contamination by the thruster exhaust (which contains metal eroded from the thruster electrodes).

The cargo compartment is 4.5 m in diameter, the same as the Shuttle cargo bay, and its length is 20 m, compared to 18.3 m for the Shuttle cargo bay. These dimensions were chosen to provide room for any cargo that can be carried by the Shuttle along with an orbital maneuvering vehicle (OMV) to be used for operations in GEO. The OTV cargo compartment folds to fit in the Shuttle for launch.

Attitude Control

Inertial gyros are the principal attitude control sensors. They are calibrated against horizon and sun sensors. Attitude control torque is provided by control moment gyros. These are unloaded by interaction with the Earth's magnetic field and by gimbaling or selective firing of the propulsion thrusters.

Other Systems

The spacecraft mission module contains communications, command, and data handling, as well as the attitude control equipment. Small low-gain and medium-gain antennas are provided. Communication is via TDRSS or another satellite when the OTV is relatively low, direct to Earth when the spacecraft is high.

Configuration

Three candidate OTV configurations (Fig. 1a–1c) were evaluated. In one configuration, propulsion thrust is perpendicular to the power system boom (Fig. 1a). This necessitates a very long boom extension to position the center of gravity properly. As a result, the power cable length, mass, and losses are excessive. The other two configurations (Figs. 1b and 1c) place the thrust vector along the boom. They have the propulsion system at the end of the spacecraft farthest from the reactor and adjacent to the cargo compartment. These configurations differ primarily in how the cargo is loaded in the OTV cargo compartment, from the side or from aft. Side loading (Fig. 1c) was selected to maximize commonality of cargo interfaces with those used in the Shuttle. If, however, Titan 4 is to be used to launch the cargo going to GEO, commonality with the Titan cargo interface is more important, and the aft-loading OTV configuration (Fig. 1b) is preferable.

Note that an external attachment to the cargo, in place of the cargo compartment, would be undesirable with either of the configurations in Figs. 1b and 1c. Putting the cargo outboard of the thrusters, at the end of the OTV farthest from the reactor, would either place it in the thruster exhaust or, if the thrust

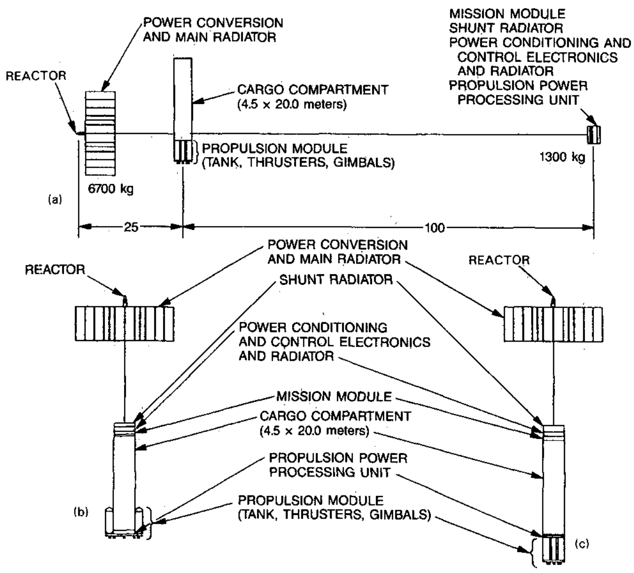

Fig. 1 Orbital transfer vehicle candidate configurations.

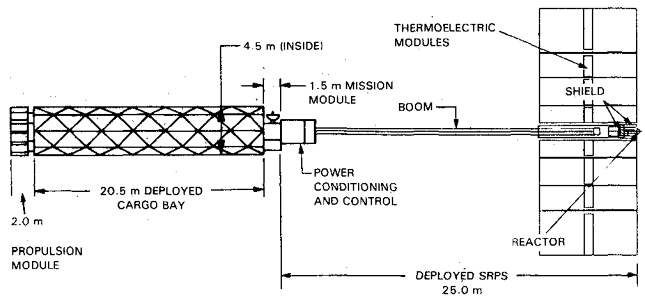

Fig. 2 Orbital transfer vehicle details.

Table 1 Spacecraft mass breakdown

	kg	kg
SRPS		
Reactor	1,650	
Shield	700	
Heat transport	1,450	
Power conversion	775	
Heat rejection	1,440	
System control, power conditioning and distribution	950	
Structure and mechanisms	420	
		7,385
Mission module		
Communications, command, attitude control	250	
		250
Cargo bay		
Structure	500	
Skin	110	
Cargo interface fixtures	100	
		710
Propulsion		
Electric propulsion	1,995	
Propellant tank	480	
		2,475
Total, dry and empty		10,820
Propellant (xenon)	5,040	
Total, with propellant, empty		15,860
Cargo		
Total, with propellant and cargo	5,990	21,850

direction were reversed, place the main radiator in the thruster exhaust.

The figures show a roll-out flat panel radiator for the SRPS. This radiator configuration is illustrative only. Pros and cons of various SRPS radiator configurations are discussed in Ref. 4.

The selected configuration is 50 m long when deployed (Fig. 2). The OTV mass, empty and dry, is 11,000 kg; Table 1 gives a breakdown. For a sortie to GEO, 5000 kg of xenon propellant are normally carried.

Dynamics

Preliminary examination indicates that the lowest natural structural frequency may be of the order of 1 Hz. This constrains the attitude control bandwidth and hence the rate of attitude change. The available torque also constrains the rate of attitude change. The electric thrusters provide a torque of only about 400 N-m. However, control moment gyros are available that provide 6500 N-m. With this torque and a simple control system, it will take about 1 h to make a 1-rad turn and stabilize.

The primary external torque on the OTV is the gravity gradient. The stable attitude under this torque is with the boom vertical. However, the control moment gyros provide more than enough torque to bring the vehicle to any desired attitude and hold it there.

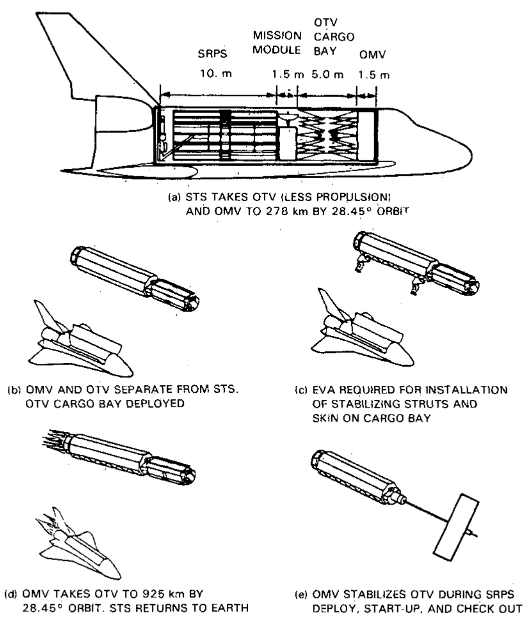

Fig. 3 Placing OTV in orbit, first Shuttle flight.

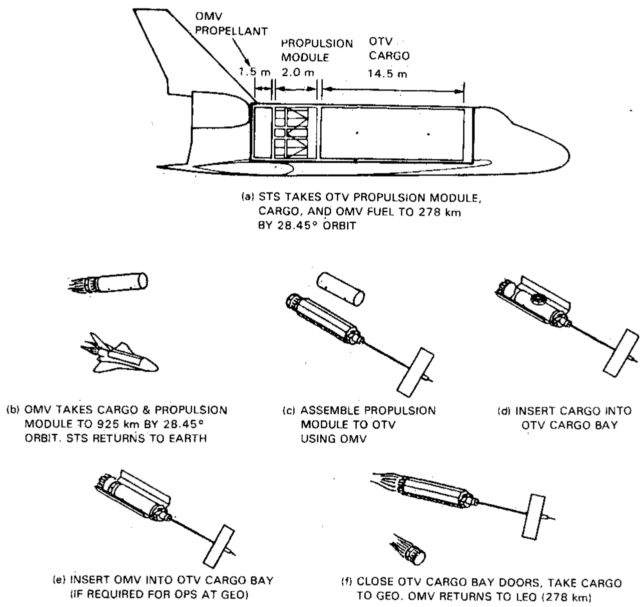

Fig. 4 Bringing cargo to GEO, second Shuttle flight. (In subsequent flights, Shuttle and OMV may bring up propellant and replacement thrusters for OTV, rather than complete propulsion module.)

Table 2 Electric propulsion characteristics assumed (time period: 1995–2000)

Arcjets					
Propellant	NH_3	H_2			
I_{sp}, lbf/lbm-s	1000	1500			
Engine input power, kW	100	100			
Efficiency, PPU[a]	0.96	0.96			
Efficiency, engine	0.45	0.54			
Thruster mass, kg	38.8	38.8			
Engine-associated mass, kg (including thruster)	150	150			
PPU specific mass, kg/kW[b]	1.4	1.4			
Lifetime, h	1000	1000			
Ion thrusters					
Propellant	Xe	Xe	Xe	Hg	Hg
Engine size, cm	50	50	50	50	50
I_{sp}, lbf/lbm-s	3000	3684	4710	3330	4260
Engine input power, kW	19	29	45	29	45
Efficiency, PPU	0.92	0.92	0.92	0.92	0.92
Efficiency, engine	0.65	0.75	0.79	0.77	0.80
Thruster mass, kg	20.4	20.4	20.4	20.4	20.4
Engine-associated mass, kg (incuding thruster)	100	120	170	120	170
PPU specific mass, kg/kW	2.7	2.2	1.7	2.3	1.8
Lifetime, h	5000	5000	5000	5000	5000

[a]PPU: Propulsion power-processing unit.
[b]kW for specific mass are input kw to PPU.
NOTES: Provide redundant engines, enough to cover failure of at least 10% for arcjets and 20% for ion thrusters. Except for a maximum of 1 engine on axis, engines will be in sets that balance thrust. Assume that if one engine fails, its set will be shut down and replaced by a redundant set. This may require increasing the number of redundant engines. Include engine-associated mass for the redundant engines.

Mission Profile

The OTV is operated only at altitudes of 925 km and above. This constraint was assumed to ensure an orbital lifetime of at least 300 years for decay of radioactivity if a spacecraft malfunction should occur. (A decision on operation of the reactor at lower altitudes is pending.)

The Shuttle cannot deliver substantial payloads to an altitude of 925 km. A chemical upper stage is needed to place the OTV into its operating orbit and, subsequently, to bring cargo, propellant, and replacement thrusters to the OTV. Expendable stages and an OMV were considered. Twelve scenarios were evaluated for placing the OTV in operational orbit and then transferring cargo between Earth and GEO. These differed in such characteristics as the lowest altitude to which the OTV is brought, the choice of upper stage for transfer between Shuttle and OTV orbits, the direction of cargo transfer (up or down), the vehicle employed to pick up cargo in orbit, and the use of Space Station. Criteria used to evaluate the scenarios included the resultant OTV performance, the number of Shuttle launches required, the orbital operations required, and nuclear safety.

The OMV was chosen for the upper stage because it also can be used to install and remove cargo, refuel the OTV, replace thrusters, and provide other needed functions. Transfer of cargo at the Space Station was found to be unattractive because the Shuttle can bring so little mass from Earth to the Space Station.

The selected scenario is as follows: An initial Shuttle flight launches the folded OTV, less propulsion, plus an attached OMV (Fig. 3). (The OTV propulsion module is not carried because of insufficient room in the Shuttle.) The OTV and OMV are placed in a circular orbit at 278-km altitude and 28.5-deg inclination. The OTV cargo compartment deploys on radio command. Extravehicular activity (EVA) is used to install stabilizers in the cargo compartment structure and place a thermal blanket around the compartment. The OMV then takes the OTV to 925 km, 28.5 deg. The SRPS boom is deployed, and the SRPS is started. During the startup sequence, SRPS coolants thaw, and the SRPS main radiator panels are deployed. The OMV returns to 278 km.

The second Shuttle launch brings up to 278 km the cargo to go to GEO, propellant for the OMV, and the OTV propulsion module (Fig. 4). The OMV takes the cargo and OTV propulsion module to 925 km and transfers them to the OTV. The OMV returns to 278 km. The OTV brings the cargo to GEO, places it there, and returns to 925 km. Subsequent flights are similar except that, instead of the OTV propulsion module, replacement OTV thrusters and propellant may be brought to the OTV. Propellant is transferred and thrusters are replaced by the OMV. Table 4 gives a mass breakdown for the various Shuttle payloads.

When cargo is to be brought down from GEO, the OTV carries an OMV to GEO. The OMV rendezvouses and docks with the cargo, then places it in the OTV cargo compartment. The OTV takes the cargo down to 925 km, and an OMV then brings it to Shuttle orbit.

Table 3 Tankage and plumbing mass relationships[a]

Propellant	Propellant mass, m_p kg	Tankage and plumbing mass, kg
NH_3	5,000–18,300	$120 + 0.173\, m_p + 2.28\, m_p^{2/3}$
NH_3	18,300–22,000	$1020 + 0.198\, m_p$
H_2	5,000–13,000	$610 + 0.493\, m_p$
Xe	5,000–22,000	$52 + 0.075\, m_p + 0.154\, m_p^{2/3}$
Hg	5,000–22,000	$150 + 0.020\, m_p$

[a]Data for NH_3, H_2, and Xe are from B. Palaszweski.

A Titan 4 could be used in place of Shuttle to launch the cargo, with some decrease in the mass that can be transferred to GEO. Worn-out OTV thrusters and empty propellant tanks could be jettisoned instead of being returned to Earth. Because of the EVA planned for installation of structural stabilizers, a Shuttle would be needed for the launch of the OTV itself unless a cargo compartment structure with self-deploying stabilizers can be designed.

At the end of mission, the OTV is disposed of by using its electric propulsion to take it to a heliocentric orbit. (Transfer from GEO to heliocentric orbit requires much less propellant than a return flight from GEO to LEO.) The reactor is then turned off by ground command, backed up by an onboard clock.

Interactions with Shuttle and Orbital Maneuvering Vehicle

Figures 3 and 4 show spacecraft elements stowed in the Shuttle Orbiter cargo bay. Structural support of the SRPS in the Shuttle bay is described in Ref. 4. The OMV, launched with it, is supported per the standard Shuttle/OMV interface. The OTV mission module and the folded OTV cargo compartment are between the SRPS and the OMV and are supported by them. The OTV propulsion module, carried on the second Shuttle launch, can be mounted to the Shuttle Orbiter bay keel and sills. The xenon propellant of the OTV will have to be vented or refrigerated while in the Shuttle.

Resupply of OTV propellant and replacement of OTV thrusters are carried out by the OMV. Propellant resupply may be handled either by tank-to-tank transfer or by replacing an entire plug-in tank. New thrusters can also be plugged in. Alternatively, the entire propulsion module can be removed and replaced; this may be simpler but it will increase the mass to be transferred from Earth to OTV.

Table 4 Mass breakdown of Shuttle payloads for OTV missions

Item	kg	kg
First Shuttle launch		
Orbital transfer vehicle (OTV)		
Space reactor power system	7,385	
Mission module	250	
Cargo bay	710	
Subtotal (OTV, less propulsion)		8,345
OTV airborne support equipment (ASE)		500
Orbital maneuvering vehicle (OMV)		
OMV, dry	2,700	
Propellant	3,180	
Subtotal, OMV		5,880
OMV ASE		90
Total		14,815
Second Shuttle launch		
Cargo (to be transferred to GEO)		4,250
OMV propellant		3,110
OMV propellant tank		260
OTV propellant		5,040
OTV propulsion system (dry)		2,470
ASE		910
Total		16,040
Subsequent Shuttle launches		
Cargo (to be transferred to GEO)		5,990
OMV propellant		3,110
OMV propellant tank		260
OTV propellant		5,040
OTV propellant tank		480
OTV replacement thrusters		250
ASE		910
Total		16,040

OTV features designed to facilitate integration with the OMV include: 1) adapters to permit docking and transmit structural loads during OMV propulsion; 2) an OTV propulsion module and, preferably, thrusters, designed for replacement by OMV; and (3) either an OTV propellant tank designed for replacement by OMV or provisions for tank-to-tank transfer of propellant from OMV to OTV.

The OMV plays an essential role in the selected scenarios, serving as a "tender" to the OTV "ship." Key functions include: 1) initial transfer of the OTV from Shuttle orbit to its 925-km operational orbit; 2) bringing cargo from the Shuttle to the OTV and inserting it into the OTV cargo compartment; 3) bringing the OTV propulsion module, propellant, and replacement thrusters from the Shuttle to the OTV and attaching or transferring them to the OTV; 4) picking up cargo in GEO and placing it in the OTV cargo compartment; 5) transferring cargo, brought down from GEO, from the OTV at 925 km to Shuttle orbit; and 6) bringing used propulsion tanks, thrusters, and propulsion modules from the OTV back to the Shuttle for subsequent refurbishment and reuse.

Plans for the OMV call for a number of capabilities to be incorporated over a period of time.[5] Among the OMV capabilities needed for the OTV mission are: 1) resupply and transfer of expendable fluids; 2) spacecraft servicing and module replacement, including placing cargo in the OTV cargo compartment and removing cargo from it; 3) ability to operate in GEO; 4) ability to rendezvous and dock with the OTV while the OMV is carrying cargo; and 5) ability to place itself in the OTV cargo compartment and to remove itself from the compartment. Of these, items 1–3 are planned future capabilities of the OMV.[6,7] Capability 4 appears to be within initial planned capabilities though it has not been specifically called out. Capability 5 does not appear to have been examined in OMV plans.

Environment and Payload Accommodations on the OTV

The maximum radiation dose delivered to the cargo from the nuclear reactor during a 120-day orbital transfer will be less than 5×10^3 rad and 5×10^{11} neutrons/cm^2. During this transfer, the dose of ionizing radiation from the natural environment, when charged particle fluxes in the Earth's radiation belts are high, will be about 1×10^6 rad through 0.1 g/cm^2 of aluminum, 1×10^5 rad through 0.5 g/cm^2, 2×10^4 rad through 1 g/cm^2. An insulating blanket surrounding the cargo compartment of the OTV can protect OTV cargo from possible contamination by the thruster exhaust and provide passive temperature control. The OTV can also provide active heating or cooling as required. The OTV can easily supply any power needed by the cargo while it is attached to the OTV. Communi-

Table 5 Performance simulation example

Propulsion type:[a]	Arcjet				Ion						
Propellant:[a]	NH_3	NH_3	H_2	H_2	Xe	Xe	Xe	Xe	Hg	Hg	Hg
I_{sp} (lb-s/lbm)[a]	1,000	1,100	1,500	1,800	2,220	3,000	3,684	4,710	2,010	3,330	4,260
Input power/engine, kW[a]	100	100	100	100	13	19	29	45	12	29	45
Thruster specific mass, kg/kW[a]	2.4	2.4	2.4	2.4	9.3	7.4	6.1	5.1	9.4	6.2	5.3
Mass of one thruster, kg[a]	240.0	240.0	240.0	240.0	120.9	140.6	176.9	229.5	112.8	179.8	238.5
Mass of redundant thrusters, kg[a]	980.0	980.0	1400.0	1820.0	377.0	267.9	226.2	1224.0	342.0	226.0	315.0
Power processing efficiency[a]	0.96	0.96	0.96	0.96	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Engine efficiency[a]	0.45	0.45	0.54	0.54	0.62	0.65	0.75	0.79	0.65	0.77	0.80
Overall propulsion system efficiency	0.43	0.43	0.52	0.52	0.57	0.60	0.69	0.73	0.60	0.71	0.74
Thruster life, h[a]	1,000	1,000	1,000	1,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Initial circular altitude, km[a]	925	925	925	925	925	925	925	925	925	925	925
Initial orbital inclination, deg[a]	28.45	28.45	28.45	28.45	28.45	28.45	28.45	28.45	28.45	28.45	28.45
Initial circular velocity, m/s	7,392	7,392	7,392	7,392	7,392	7,392	7,392	7,392	7,392	7,392	7,392
Destination circular altitude, km[a]	35,860	35,860	35,860	35,860	35,860	35,860	35,860	35,860	35,860	35,860	35,860
Destination orbital inclination, deg[a]	0	0	0	0	0	0	0	0	0	0	0
Destination circular velocity, m/s	3,074	3,074	3,074	3,074	3,074	3,074	3,074	3,074	3,074	3,074	3,074
Delta V, each leg, m/s	5,642	5,642	5,642	5,642	5,642	5,642	5,642	5,642	5,642	5,642	5,642
Mass, power system, kg	7,500	7,500	7,500	7,500	7,500	7,500	7,500	7,500	7,500	7,500	7,500
Number of engines needed	3.00	3.00	3.00	3.00	23.08	15.79	10.34	6.67	25.00	10.34	6.67
Integer number of engines	3	3	3	3	23	15	10	6	25	10	6
Net power to propulsion system, kW	300	300	300	300	299	285	290	270	300	290	270
Propellant flow, g/s	2.698	2.230	1.439	0.999	0.720	0.394	0.307	0.184	0.924	0.386	0.228
Propulsion dry mass, less struc. and tank., kg	1,700	1,700	2,120	2,540	3,158	2,377	1,995	2,601	3,162	2,024	1,746
OTV mass, less power and propulsion, kg[a]	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
OTV dry mass, less tankage, kg	10,200	10,200	10,620	11,040	11,658	10,877	10,495	11,101	11,662	10,524	10,246
Total mass delivered to initial orbit, kg[a]	20,029	20,029	20,029	20,029	20,029	20,029	20,029	20,029	20,029	20,029	20,029
Propellant mass for return leg, kg	13,150	11,171	9,756	7,333	3,734	2,427	1,856	1,488	3,997	2,037	1,516
Max. time for up leg, days[a]	120	120	120	120	120	120	120	120	120	120	120
Max. propellant mass, up leg, set by time, kg	27,976	23,120	14,920	10,361	7,470	4,088	3,183	1,909	9,585	3,999	2,364
Mass leaving initial orbit, kg	30,229	30,229	30,649	31,069	31,687	23,409	21,998	16,595	31,691	25,188	18,699
Max. propellant mass, up leg, set by delivery mass, kg	13,231	12,318	9,769	8,505	7,238	5,397	4,416	3,582	7,893	4,851	3,827
Propellant mass, up leg, kg	13,231	12,318	9,769	8,505	7,238	4,088	3,183	1,909	7,893	3,999	2,364
Mass tankage, kg	6,693	6,043	10,232	8,414	955	596	477	343	388	271	228
Mass required at initial orbit, kg	20,029	20,029	20,029	20,029	20,029	12,532	11,503	5,494	20,029	14,664	8,453
Time, up leg, days	56.76	63.93	78.57	98.50	116.28	120.00	120.00	120.00	98.81	120.00	120.00
Time, down leg, days	56.41	57.98	78.47	84.92	59.99	71.26	69.98	93.51	50.03	61.13	76.94
Payload capability, kg	0	0	0	0	8,102	5,421	5,987	1,755	7,752	8,357	4,346
Payload capability/(mass required at initial orbit)/(up time + down time), day$^{-1} \times 10^3$	0	0	0	0	2.295	2.262	2.740	1.496	2.600	3.146	2.610

[a]Input parameter.
NOTE: 300-kW power; one ground-based propellant tank; OMV on orbit at 278 km. Maximum transit time = 120 days. Single STS for payload and propellant.

Table 6 OTV performance summary

Design	Transit time, days	Cargo deliverable to GEO, kg: With xenon propellant	Cargo deliverable to GEO, kg: With mercury propellant
Selected design	90	1,350	3,100
OMV initially at 278 km	120	6,000 (baseline)	8,400
OTV initially at 925 km	240	14,500	
Single Shuttle launch for cargo, propellants, and thrusters			
I_{sp} limited to low to moderate risk			
Ion engine efficiency increased 5%	90	2,300	4,100
	120	7,200	9,700
Ion thruster lifetime increased from 5000 to 7000 h	240	14,700	
Low ion engine I_{sp} (high development risk for 1995)	90	2,750	5,600
	120	8,100	
Low I_{sp} and 2 propellant tanks, one discarded near GEO	90	3,800	
	120	8,200	
Low I_{sp} and 5% increase in engine efficiency	90	4,200	7,300
Low I_{sp} and two Shuttle launches	90		5,900
	120	8,900	
Two Shuttle launches	240	23,200	26,100
	360	28,500	2,900
Two Shuttle launches, hydrogen arcjets, high I_{sp} (high development risk for 1995)	240	2,900	

NOTE: Cargo masses for alternative designs are listed only if greater than those for the selected design and less ambitious alternatives, at a given transit time.

cation between the cargo and ground will be provided via the OTV's communication links.

As previously mentioned, the OTV cargo compartment size will match that of the Shuttle and will provide additional length to house an OMV. Structural interfacing for cargo will match the interfacing used for mounting the cargo in the Shuttle. (Alternatively, if cargo is to be brought up primarily by Titan 4, the interface will be designed to match that used for Titan 4.) Interface mechanisms and connectors will be provided in the OTV cargo compartment to permit receipt of the cargo from the OMV, including making electrical connections. These mechanisms will also permit release of the cargo on command, either to the OMV or as an unattached spacecraft.

Performance

Table 5 illustrates the performance calculation for a few cases of interest. Deviations of the points from a smooth curve are due to the discrete values of I_{sp} examined and the discrete steps necessary in the number of engines. Note that, for the cases in this table, the payload capability with arcjets is zero. Plotting results from this and similar calculations gave Fig. 5, the cargo capability to GEO as a function of transit time. Table 6 summarizes the performance of the selected design and the effect of various options in increasing performance. The nominal cargo capability to GEO is 6000 kg with a transit time of 120 days; 1350 kg can be transferred in 90 days, and 14,500 kg in 240 days. The capability can be increased to about 28,000 kg by using one Shuttle launch for the propellant and another for the cargo, and extending the allowable transfer time. For special missions the standard OTV propulsion module can be replaced in standard orbit with a module incorporating mercury ion thrusters or arcjets, as desired.

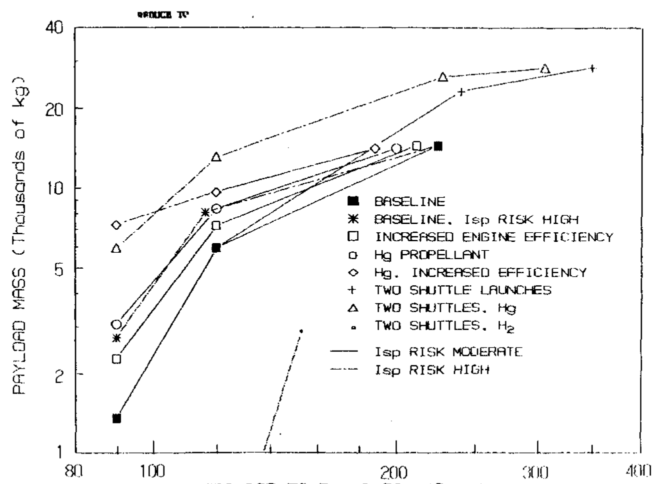

Fig. 5 OTV capability for transfer of payload to GEO, as a function of transit time.

Conclusions

Findings concerning the nuclear power system are:

1) The stowed length of the power system is a design driver for this mission.

2) To maximize the number of OTV sorties to GEO for a given burnup of reactor fuel, it should be possible to reduce reactor output to a low level for weeks or months. This would permit 14 OTV round-trips within the SRPS design limits of 7 yrs at full power, 10 yrs total life.

3) Placing the reactor in heliocentric orbit should be considered as one general method of disposing of it at end of mission.

Some findings relevant to the OTV mission are:

1) The minimum altitude to provide 300 yrs' orbital lifetime is about 900 km for the spacecraft envisaged in this study. It may be desirable to keep the operational OTV above this altitude to allow time for decay of fission products, minimizing the risk should the spacecraft fail during operation and re-enter inadvertently.

2) The OTV should be used with an OMV. The OMV is recommended as the means of bringing and transferring cargo, propellant, and replacement thrusters from Shuttle or Titan 4 to the OTV. When cargo is to be taken from GEO to LEO, the OTV should bring an OMV to GEO to retrieve the cargo and place it in the OTV.

3) Transfer of cargo at the Space Station is unattractive for this mission because the mass that a Shuttle can bring to the Space Station is low.

4) The lifetime assumed for electric thrusters will necessitate frequent replacement of thrusters in orbit. Techniques need to be developed for orbital replacement, using the OMV, of thrusters, propellant, and/or the electric propulsion system. Development of ion thrusters with greatly increased lifetime is desirable.

5) Ion thrusters with low specific impulse are needed to obtain short times for transit to GEO. Development of ion thrusters with good efficiency at specific impulse as low as 20,000 N-s/kg (2000 lbf-s/lbm) is desirable.

6) Preferably, the design of the OTV should provide full self-deployment in orbit without requiring manned assistance.

An open issue for the OTV mission is the safety of operating the reactor at the very low altitudes reachable by the Shuttle. Such operation is not part of the mission profile devised in this study. However, if safe operation at such low altitudes can be ensured, the mission profile could be simplified and costs reduced.

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