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NUCLEAR REACTOR POWER FOR AN ELECTRICALLY POWERED ORBITAL TRANSFER VEHICLE

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Abstract

To help determine the systems requirements for a 300-kWe space nuclear reactor power system, a mission and spacecraft have been examined which utilize electric propulsion and this nuclear reactor 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 5,000 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 trip 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 produce electrical power in the less than 100 kW to 1 MW range. To help determine systems requirements for the SRPS, a mission and spacecraft were examined which utilize this class of nuclear reactor power and electric propulsion 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. The study was carried out by the Systems Design Audit Team of the SP-100 Project. Details are contained in Ref. 1. Another mission and spacecraft study concerning SP-100 is reported in Ref. 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, 300 kWe was assumed as the power level for the spacecraft. (After the study was completed, the design level was changed to 100 kWe.)

Important mission requirements were:

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

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 angle accuracy shall be ±5 deg.
(3) Launch of all mission elements by the Shuttle is assumed. (Titan 4 launch was later 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. Pumped lithium 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 mass of the SRPS is 7400 kg, broken down as shown in Table 1.

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 Complementary Expendable Launch Vehicle (CELV) fairing. They deploy on command. The deployed length of the SRPS is about 25 m and width about 20 m. The thermal radiation from the power system to the rest of the spacecraft is limited to 1 sun (1.4 kW/m^2). The SRPS is described in Ref. 3.

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	5,990	
TOTAL, with Propellant and Cargo		21,850

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. Ion thrusters and xenon propellant were selected. Alternatives considered were resistojets, arcjets, and ion thrusters with mercury propellant. 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. Mercury ion thrusters would provide somewhat better performance than xenon, but there are possible Shuttle safety and environmental issues associated with using mercury.

The characteristics assumed for electric propulsion included a minimum I_{sp} with xenon of 29,400 N-s/kg (3000 lbf-s/lbm) and a lifetime of 5000 hours for ion thrusters. This necessitates replacement of the thrusters after each sortie to GEO.

Other Systems

The spacecraft mission module contains communications, command, data handling, and 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 orbit geometries are inappropriate for satellite-satellite communication.

Table 2. Electric Propulsion Characteristics Assumed (Time Period: 1995–2000)

Arc Jets					
Propellant	NH_3	H_2			
I_{sp}, lbf/lbm-s	1,000	1,500			
Engine input power, kW	100	100			
Efficiency, PPU	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*	1.4	1.4			
Lifetime, h	1,000	1,000			
Ion Thrusters					
Propellant	Xe	Xe	Xe	Hg	Hg
Engine size, cm	50	50	50	50	50
I_{sp}, lbf/lbm-s	3,000	3,684	4,710	3,330	4,260
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 (including thruster)	100	120	170	120	170
PPU specific mass, kg/kW*	2.7	2.2	1.7	2.3	1.8**
Lifetime, h	5,000	5,000	5,000	5,000	5,000

Notes: Provide redundant engines, enough to cover failure of at least 10% for arc jets and 20% for ion thrusters. Except for a maximum of 1 engine on-axis, engines shall be in sets that balance thrust. Assume that if 1 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.

*kW for specific mass are input kW to PPU.

**For values at intermediate I_{sp}, use quadratic interpolation.

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.

Horizon and sun sensors are used for attitude control. Attitude control torque is provided by control moment gyros. These are unloaded by interaction with the Earth's magnetic field and by gimbaling or throttling of the propulsion thrusters. Attitude changes will be relatively slow.

Configuration

Three candidate OTV configurations (Fig. 1a,b,c) were evaluated. In one (Fig. 1a), propulsion thrust is perpendicular to the boom of the power system. 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 furthest from the reactor, and adjacent to the cargo bay. These configurations differ primarily in how the cargo is loaded in the OTV cargo bay, 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) would be preferred.

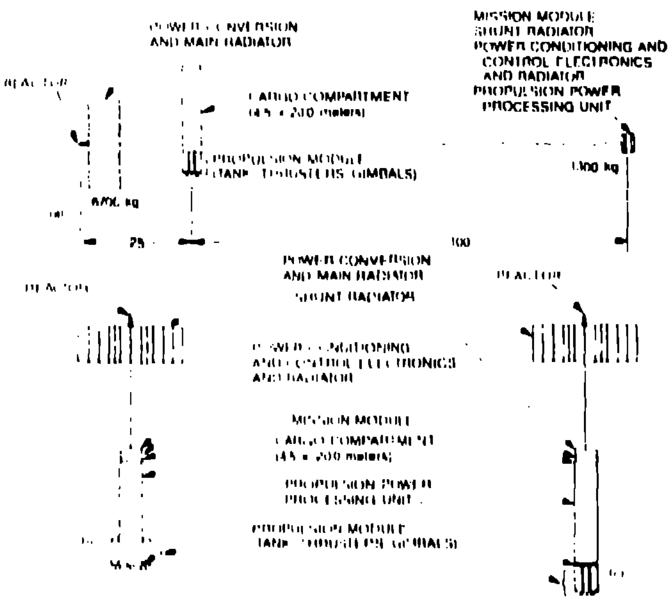

Fig. 1 Orbital Transfer Vehicle Candidate Configurations

The selected configuration is 50 m long when deployed (Fig. 2). Its cargo bay is 4.5 m in diameter, the same as the Shuttle cargo bay, and its length is 20 m, as 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, plus an Orbital Maneuvering Vehicle (OMV), to be used for operations in GEO. The OTV cargo bay structure folds to fit in the Shuttle for launch. The OTV mass, empty and dry, is 11,000 kg; Table 1 gives a breakdown. 5000 kg of xenon propellant are normally carried for a sortie to GEO.

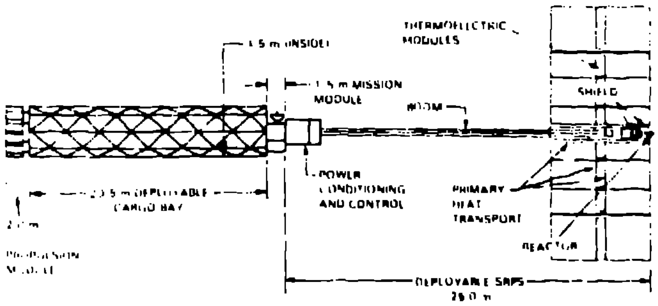

Fig. 2 Orbital Transfer Vehicle Details

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 in its operating orbit and, subsequently, to bring cargo, propellant, and replacement thrusters to the OTV. Expendable stages and an OMV were considered. The OMV was chosen because it can also be used to install and remove cargo, refuel the OTV, replace thrusters, and provide other needed functions.

Twelve scenarios were considered for placing the OTV in operational orbit and then transferring cargo between Earth and GEO. 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 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 bay deploys on radio command. Extra vehicular activity (EVA) is used to install stabilizers in the cargo bay structure and place a thermal blanket around the bay. The OMV then takes the OTV to 925 km, 28.5 deg. The SRPS boom is deployed and the SRPS is started. During the start-up 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 replaced by the OMV. Table 4 gives a mass breakdown for the various Shuttle payloads.

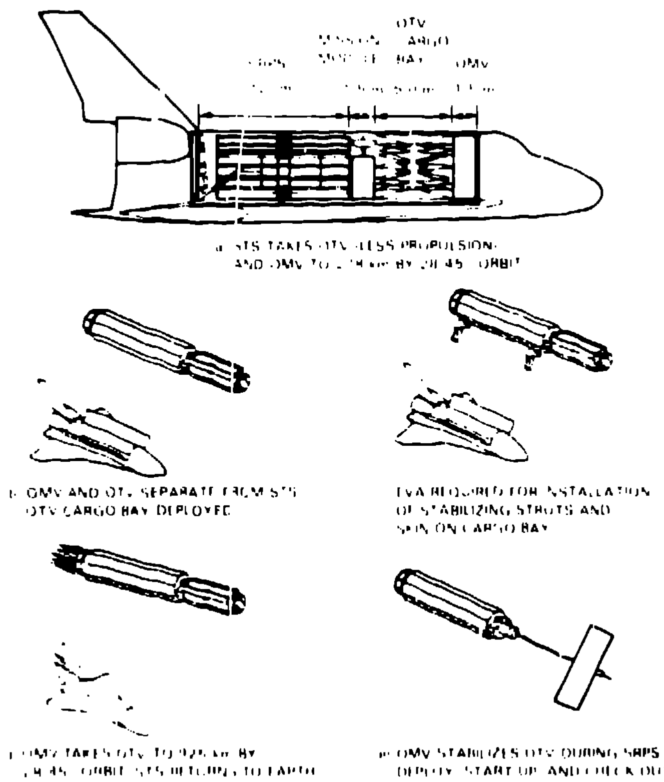

Fig. 3 Placing OTV in Orbit, First Shuttle Flight

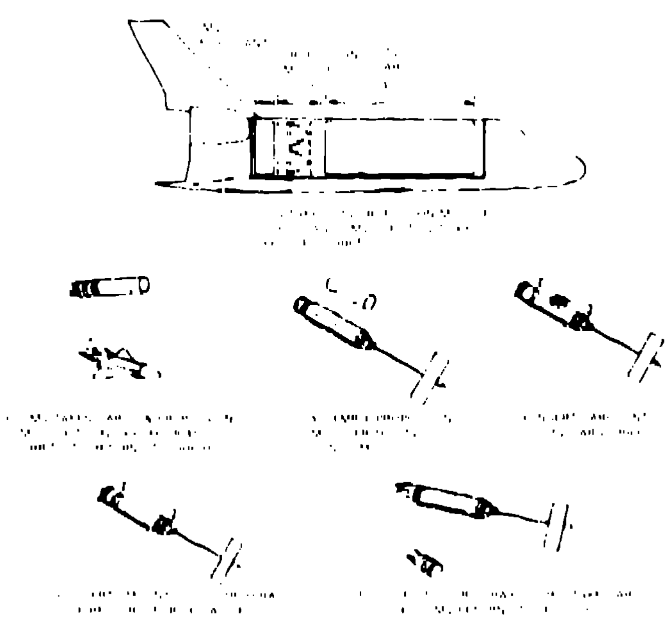

Fig. 4 Bringing Cargo to GEO, Second Shuttle Flight. (In subsequent flights, Shuttle and OMV may bring up propellant and replacement thrusters for OTV, rather than complete propulsion module.)

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 bay. The OTV takes the cargo down to 925 km, and an OMV then brings it to Shuttle orbit.

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. The old 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 bay 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 on-board 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. 3. The OMV, launched with it, is supported per the standard Shuttle/OMV interface. The OTV mission module and the folded OTV cargo bay 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.

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 Shuttle to the OTV and inserting it in the OTV cargo bay.
(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 bay, and subsequently transferring the cargo from the OTV at 925 km to Shuttle orbit.
(5) Bringing used propulsion tanks, thrusters, and propulson modules from the OTV back to the Shuttle for subsequent refurbishment and re-use.

Plans for the OMV call for a number of capabilities to be incorporated over a period of time (Ref. 4). Among the OMV capabilities needed for the OTV mission are:

(1) Resupply and transfer of expendable fluids; spacecraft servicing and module replacement, including placing cargo in the OTV cargo bay and removing cargo from it.
(2) Ability to operate in GEO.
(3) Ability to rendezvous and dock with the OTV while the OMV is carrying cargo.

Table 4. 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			
OMV initially at 278 km	90	1,350	3,100
OTV initially at 925 km	120	6,000 (Baseline)	8,400
Single shuttle launch for cargo, propellants, and thrusters	240	14,500	
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		
Two Shuttle launches	240	23,200	26,100
	360	28,500	
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.

(4) Ability to place itself in the OTV cargo bay and to remove itself from the bay.

Additional tankage beyond that planned for initial OMV capability will also be needed.

Environment and Payload Accomodations 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. The dose of ionizing radiation expected from the natural environment during this transfer, under average conditions, will be about 1×10^6 rad through 0.1 g/cm^2 of aluminum and 2×10^4 rad through 1 g/cm^2. An insulating blanket surrounding the cargo compartment of the OTV will protect OTV cargo from possible contamination by the thruster exhaust, and will provide passive temperature control. The OTV will also provide active heating or cooling as required. Any power needed by the cargo while it is attached to the OTV can be easily supplied. Communications between the cargo and ground will be provided via the OTV's communication links.

As mentioned above, the OTV cargo bay 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 by the cargo for mounting 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 bay 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

Performance of the selected OTV design is shown in Table 4. Also shown is 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 OTV propulsion module can be replaced in orbit with one incorporating mercury ion thrusters or ammonia arcjets, as desired.

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 years at full power, 10 years 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 years 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 fission products to decay if the spacecraft should fail during operation.
(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 of the low capability of the Shuttle to bring mass to the Space Station.
(4) The lifetime assumed for electric thrusters will necessitate frequent replacement of thrusters in orbit. Techniques which can be used by the OMV need to be developed for orbital replacement of thrusters, propellant, and/or the electric propulsion system.
(5) The design of the OTV should preferably provide full self-deployment in orbit without the need for manned assistance.
(6) Methods should be considered for retrieval of spinning or tumbling spacecraft by the OMV.

Acknowledgments

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