A Comparison of Two OTVs

A Summary Report

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NASA/USRA Advanced Design Program
June 1988 Summer Conference

(NASA-CR-184696) TWO DESIGNS FOR AN ORBITAL TRANSFER VEHICLE: A COMPARISON OF TWO OTVs Summary Report (Virginia Univ.) 19 p N89-20175
CSCL 22B Unclas
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Key Abbreviations

CCM	Crew Command Module
ECLSS	Environmental Control and Life Support System
EPS	Electrical Power System
EVA	Extravehicular Activity
EVAM	EVA Module
GEO	Geosynchronous Orbit
GNC	Guidance, Navigation, and Control
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
MMU	Manned Manuevering Unit
OTV	Orbit Transfer Vehicle
RCS	Reaction Control System

Introduction

For a Low Earth orbit to Geosynchronous orbit mission scenario, it can be shown that both a chemically propelled, aerobraked OTV, and the high-thrust, nuclear OTV use approximately 50% less propellant than a comparable, chemical OTV. At the University of Virginia, two teams worked on designs for these types of OTVs. One group formed WWSR Inc. and worked on the aerobraked OTV or what it called Project Orion. The other group, named MOVERS, collaborated on the design for the nuclear engine OTV. This report will briefly review the nature of their work and the specifics. In this introduction, there will be a summary of these propellant systems and the dollar savings. It will also highlight the strengths and weaknesses of each OTV concept.

The dollar savings made possible with either the Project Orion OTV or the MOVERS OTV are significant. For the 15,000 pound payload, roundtrip mission, the Project Orion OTV required 132,000 pounds of propellant, and the MOVERS OTV, 121,000 pounds. An OTV which only employs a chemical engine would require approximately 250,000 pounds of propellant. If a launch cost of $2500/pound is assumed, the propellant savings made possible by using an aerobrake and a chemical engine result in a saving of $236 million dollars. The use of a high- thrust nuclear engine results in slightly greater dollar saving of $250 million dollars.

An assessment of potential savings is incomplete without addressing the associated development costs. Both aerobrake and high- thrust nuclear engine technologies are in approximately the same stage of development; and it is anticipated that development costs would be approximately equal.

Although both OTV concepts result in significant dollar savings, there are nonetheless a number of important distinctions between the two concepts.

The first distinstion is a subtle one, and becomes apparent by looking at the weight summaries of the two crafts and the propellant requirements for the LEO-

GEO mission. In short, the MOVERS' high-thrust nuclear OTV is able to deliver more dry mass to GEO at a smaller cost than the WWSR's aerobraked, chemical OTV. Indeed, the MOVERS' vehicle delivers and extra 21,100 pounds (or 9,510 pounds after accounting the fact that the nuclear propulsion system weighs 11,590 pounds more than the aerobraked, chemical system) of dry mass to GEO and back to LEO using 4.9% less propellant than WWSR's craft. Note that in this case, "dry mass" refers to the weight of the cargo as well as the entire structure of the unfueled system.

The weight difference between the two propulsion systems is the crucial detail. As the dry mass of the spacecraft increases, the relative significance of the weight difference decreases--making the nuclear OTV increasingly more efficient in its use of propellant than the chemical OTV. For smaller spacecrafts, the weight difference in the propulsion systems become increasingly important. However, when light cargo or unloaded missions are considered, the chemical OTV becomes more efficient in its use of propellant than the nuclear OTV.

Implicit in the preceeding discussion is the assumption that both types of OTV's can handle heavier payloads. The MOVERS OTV, for example, could easily handle and Earth-Moon mission with a requirement to deliver and return an 80,000 pound payload by simply adding extra tankage along its boom. The addition of tankage to the Project Orion OTV is problematic. Aerodynamic passes require that the vehicle be compact, and that the center of gravity be accurately known. This does not mean that the Project Orion OTV could not handle the larger payloads. It would just be much more difficult for such a mission to be accomplished.

Although it may be more complicated to reconfigure the Project Orion OTV to handle the heavier lunar payloads, the demanding requirements of aerobraking do give the craft the structural integrity to possibly handle a lunar landing. In lunar orbit, the Project Orion OTV might simply replace aerobraking shield with orbiting lunar legs. This exciting possibility requires further research. In any case, this is simply not an option available to the MOVERS' OTV.

Another important distinction between the two OTV concepts has to do with the environmental impacts. The Project Orion OTV is perfectly safe to use in Low Earth orbits and can be easily docked at a space station. Ther are, though, a number of environmental concerns associated with the MOVERS OTV. The worst case scenario would be a misfired thrust vector which puts the craft on a trajectory into the Earth's atmosphere. Such a scenario would require the destruction of the reactor at high altitudes, and the incorporation of some sort of escape module for the crew into the design of the OTV. The destruction of the reactor in low Earth orbit has been shown to be safe for the human population on Earth. However, more research is required to better assess these risks.

The MOVERS' OTV also has difficulty in docking with the space station. The approaches to the station have to be handled carefully due to the residual gamma radiation being produced in the reactor. A preferred technique would be to dock the OTV at a docking station and then ferry the crew to the space station. It is important to note that such a docking station is currently being considered for even the chemical spacecraft which are going to the space station. However, even if the problem with residual radiation could somehow be managed, the size of MOVERS' OTV might pose a threat to the orbital stability of the Space Station if it were to hard dock. Because of the radiation and stability problems that the MOVERS' OTV could cause for the Space Station, Project Orion's OTV would perhaps be more suited for missions where hard docking to the Space Station would be required.

Before a nuclear powered OTV could be used, yet another environmental issue must be dealt with: the storage and disposal of spent reactor assemblies. These simply cannot be allowed to accumulate in Low Earth orbit. It may be possible to reprocess the fuel, store in orbit closer to the sun, or to bury it on the moon. However, this issue must be addressed.

Finally, the last point of comparison between the MOVERS OTV and the Project Orion OTV has to do with stresses to which the craft is exposed. The Project Orion OTV must endure the high temperatures and the aerodynamic forces associated with an aerobraking pass at very high Mach numbers, and this may limit the design life of the spacecraft.

Clearly, each type of craft has both its strengths and weaknesses. Both offer potential for enormous dollar savings. It should also be emphasized that neither technology is mutually exclusive. Indeed, for more ambitious manned missions into the solar system, both technologies could be used together to achieve enormous propellant savings. In fact, those savings could make such exciting missions possible.

In the following two sections of this report, there are summaries of the designs for WWSR's and MOVERS' OTVs. These summaries contain design specifications for each vehicle that were completed as of June 11, 1988. A more detailed analysis of these systems can be found in the final reports submitted by WWSR and MOVERS. These documents accompany this report.

Section 1

Project Orion

Abstract:

The goal of the Project Orion team was to submit a proposal for a chemically propelled, manned, orbital transfer vehicle (OTV) that would meet the criteria set forth by the National Commission on Space in Pioneering the Space Frontier (1986). The OTV will consist of modular components and be capable of transporting a crew of three and a 12 ton payload between the Space Station and geosynchronous orbit.

The following is a summary of the final report prepared by the Project Orion team. It contains estimates and designs completed as of June 11, 1988.

Mission Requirements:

The following are the mission requirements for Project Orion's scenario to be compared with that of MOVERS:

Mission Objectives: The OTV will leave the Space Station carrying components for an experiment assembly (payload, 15,000 lbm). Such an assembly may be used for SDI testing, but of course any payload is possible. The OTV will also carry provisions for a full crew of 3 for a 7 day mission. Five days on station will be anticipated for carrying out the experiments. Upon completion of the experiments,the OTV will return with the assembly to the Space Station.

Mission Profile: Following separation from the Space Station and subsequent systems checkout, the OTV performs a phasing orbit injection burn (PIB). The phasing orbit is designed to bring the OTV to the transfer orbit injection point at the proper time so it will arrive at the correct location in GEO. The transfer injection burn places the OTV in a Hohmann elliptical transfer to GEO, which lasts approximately five hours. Following circularization at GEO, the OTV can remain on station for five days to complete the required experiments.

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After the experiments are completed, an injection burn places the OTV in a GEO-LEO transfer orbit that will take it through the Earth's atmosphere. The first aerobraking pass, dipping the OTV to a height of 85 kilometers above the Earth, lasts only five minutes and leaves the vehicle in an intermediate orbit. Based on the results of the first pass, correction burns take the OTV through the atmosphere a second time. This time the maneuver lasts about 11 minutes and places the OTV in an orbit that can be circularized at LEO by a small propulsive burn.

<u>Configuration:</u> This mission will require the use of 6 sets of propellant tanks containing LO2, and LH2, EVAM, and CCM.

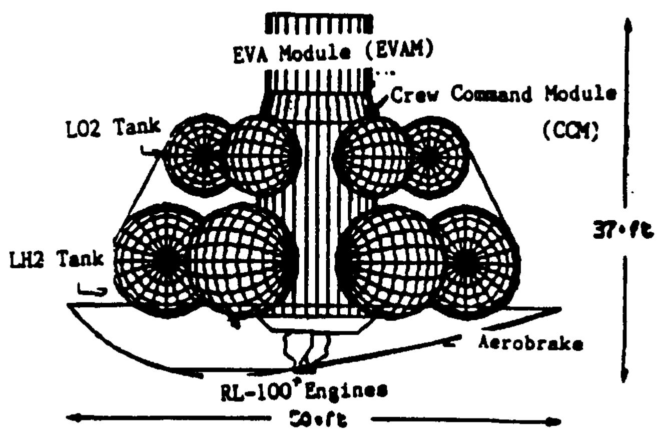

Figure 1-1: Orion OTV Configuration

Weight Estimates:

System	Weight (lbm)
Dry Weight	
ECLSS	2,500
Fuel Tanks and Supporting Structure	3,660
Engine System	1,050
CCM, EVAM, and Components	13,260
Aerobrake	2,800
Electronics	980
EPS	1,730
RCS	3,250
MMU	1,280
Crew	510
Total	31,125
Wet Weight (15,000 pound payload, LEO-GEO option):	
Propellant	132,000 (127474 lbm used 4526 lbm reserve)
Payload	15,000
Total	178,125

Design:

To complete the above mission, as well as our ˜Pworst case scenario" (see Project Orion's final report), several systems needed to be integrated. Each posed unique problems. The aerobrake required that the OTV be compact and symmetrical. The chemical propulsion system required that the OTV be light-weight. Being able to support manned-missions required redundant failsafe systems. Major trade-offs were demanded between redundacy and weight in order to maximize performance. What follows is a brief description of some of the primary systems of the OTV.

Aerobrake: The design of the OTV is based on a raked sphere cone configuration. This design has a blunt nose configuration, similar to but not the same as the Apollo space capsule. Several factors led to the selection of the

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configuration. The most immportant is its low ballistic coefficient (10 lb/ft^2) which makes it ideal for high altitude maneuvering where heating effects are small.

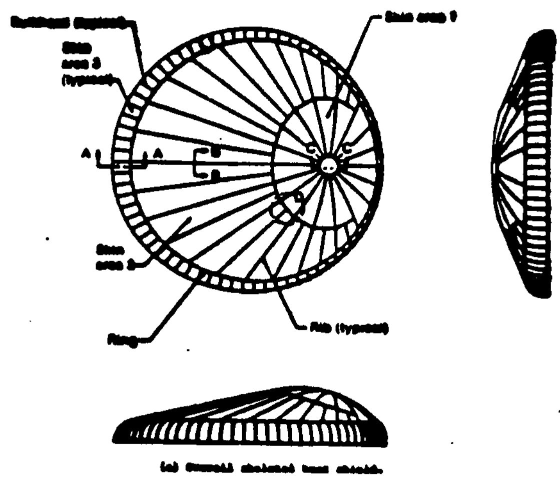

Figure 3-2: The Rake Sphere-Cone Aerobrake

The aerobrake is 50 ft. in diameter. This provides a cone of protection from atmospheric heating large enough to fully envelope the OTV and payload. The structure consists of aircraft-type aluminum skin, stringer, rib, and frame construction. The skin is covered with high-temperature, reusable, surface insulation similar to that used on the Space Shuttle. This material consists of sintered silica fibers reinforced with silicon fibers and are bonded to the skin with a thin layer of RTV-560 adhesive and NOMEX felt pad.

Control during the aerobraking maneuver is assured by symmetrical design of OTV components, rotating the OTV by firing the RCS system thus obtaining a timed average lift over drag ratio, and pumping propellant between tanks to achieve a predetermined position for the center of gravity before entering the atmosphere. Calculations done by the design team have shown that two passes through the atmosphere will be necessary to minimize heating effects and ensure safety by allowing intermediate correction maneuvers.

Engine System: The propulsion system selected by the Project Orion team was the RL-100 engine currently being designed by Pratt & Whitney. Two engines were deemed necessary to provide redundancy. Using two engines ensures a reliability of 99.6% over an expected lifespan of 25 missions. The RL-100 was selected over other engines because of its high reliability, high thrust, and low weight. The RL-100 uses LH2 for its fuel and LO2 for its oxidizer. Suspending metallic aluminum in the hydrogen will boost the specific impulse of the system to 502 seconds and thus lower propellant requirements. The total expected thrust of the system is 15,000 lb. Even if one engine should fail during the mission, the other engine will have ample thrust to return the OTV to the space station. The engines nozzles will extended through the aerobrake during firing. During aerobraking the nozzles will be retracted so that they are flush with the aerobrake.

The fuel system consists of six pairs of spherical 2029 aluminum alloy tanks containing LO2 and LH2. The LO2 tanks are 8.4 ft in diameter and hold 18856 lb LO2; LH2 tanks are 11.6 ft in diameter and hold 3144 lb LH2. The tanks are pressurized to 7 psia in order to reduce structural loading. Pairs of tanks can easily be disconnected from the structure so that extra weight can be eliminated for missions that do not require maximum propellant. Two main pumps feed propellant to the engines. Six auxiliary pumps are used to control the position of the c.g. of the OTV. Bleed off from the tanks is used for tank pressurization, EPS, or ECLSS.

CCM and EVAM: The modules are semimonocoque 2090 aluminum structures stiffened with ring frames and skin singers. The CCM, which is 22 ft long and 12 ft wide, contains various control, power, and life-support systems as well as crew quarters for three people. The cabin will be pressurized to 14.7 psia with a mixture of nitrogen and oxygen similiar to Earth's atmosphere. The EVAM, which is 8 ft long and 10 ft wide, will house 2 MMUs and tools needed for various missions. It will be evacuated at all times but contains an airlock which allows access to the CCM as well as space. A robot arm similar to the one used on the Space Shuttle, along with a satellite berthing ring, are externally mounted to the EVAM and will be used for satellite servicing

Power, Control and Life-Support Systems: Most of these systems will be similiar to those used on the Space Shuttle. The EPS will consist of two hydrogen-oxygen fuel cells and one bipolar nickel-hydrogen battery for back-up. ECLSS consists of an atmospheric revitalization system, freon/water cooled thermal control system, and appropriate systems for food preparation and hygiene. GNC will utilize the planned Global Positioning System as well as on board systems. RCS consist of 36 hydrazine fueled jets placed in 8 stations. Data management will be controlled by three IBM 1750A avionic system computers.

Cost Estimates:

The estimated cost to construct and deploy the first OTV is estimated as being $1.09 billion. $800 million will be needed for construction and subsystem components. $250 million will be needed for research and development. Most of this money will be needed for developing the aerobrake and software for the computer system. $40 million will be needed for transporting the OTV on the Space Shuttle and deploying it at the Space Station.

Conclusions and Recommendations:

There is still a considerable amount of research that needs to be completed before the Project Orion team will be fully content with its design. The current design consists of modular components - propellant tanks, CCM, EVAM, and engines - and can easily be adapted for many missions other than the one illustrated in this summary. The Project Orion team feels confident that with a few minor changes the OTV could be used for lunar missions. Possible missions include retrieving a payload in orbit or landing on the Moon. The possibility of Project Orion's OTV being capable of completing such ambitious missions truly makes it a transfer vehicle for the 21st century.

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Section 2

The MOVERS Orbital Transfer Vehicle

Abstract:

The objective of the MOVERS design team was to explore the potential of a high-thrust nuclear, orbital transfer vehicle.

The following criteria were used in the design of the OTV. The OTV must be capable of delivering a 15,000 pound payload to geosynchronous orbit (GEO) from Low Earth Orbit (LEO). The craft must be able to sustain a crew of three for seven days, and support extra-vehicular activities (EVA). The basic spacecraft, moreover, should be adapatable to Earth-Moon missions with payloads as large as 80,000 pounds.

This section will outline the basic configuration of the MOVERS OTV. In addition, a sample mission profile will be described.

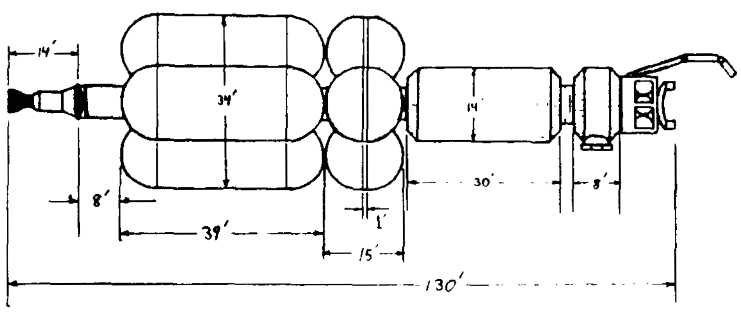

Figure 2-1: MOVERS OTV Design Configuration

Basic OTV Configuration:

Figure 2-1 is a diagram of the configuration for the MOVERS OTV. Looking from right to left, the configuration includes the satellite servicing system, the command module, the living quarters module, the eight propellant tanks, the reactor shield, the high thrust nuclear engine, and the exhaust nozzle. Table 2-1 is a listing of the weight estimates for the configurations.

Table 2-1

Weight Estimates for MOVERS OTV

Subsystem	Weight (lbm)
Dry Weight	
Habitation Module Interior (bulkheads, galley, etc.)	3,000
Command Module Interior (panels, chairs, etc.)	800
Power Systems and ECLSS	4,000
Reaction Control System	1,041
Avionics and Rendezvous Equipment	1,039
Satellite Serving (propellant and Hardware)	7,900
Nuclear Reactor and Engine	4,000
Reactor Shielding	8,500
Radiation Shielding and Skin	19,875
Tankage	6,600
TOTAL	56,775
Wet Weight (no payload, LEO-GEO option):	
Propellant	93,293
Total	150,068
Wet Weight (15000 pound payload, LEO-GEO option):	
Propellant	121,184
Payload	15,000
TOTAL	192,959

Description of OTV Subsystems:

In designing the OTV, the MOVERS design team studied the following subsystems extensively: avionics, crew systems, electrical power systems, environmental control and life support systems, navigation and orbital maneuvers, propulsion systems, reaction control systems, servicing systems, and structures.

Considerable trade-offs were encountered in preparing the design. This section briefly outlines the various sysystems which were ultimately chosen for the MOVERS OTV.

Avionics: State-of-the-art equipment, both hardware and software, were chosen for the OTV. New features of the computer system include bubble memory and electroluminescent screens, while all software will make use of Ada programming language.

Crew Systems: The crew compartment was designed to maximize privacy, and minimize crowding and sensory deprivation. The command module will house all of the command and control modules, as well as the spacesuits and other equipment needed for EVA operations.

Electrical Power and Environmental Control & Life Support: A chemical power production system was chosen to provide power for the OTV. It uses two hydrogen-oxygen fuel cells to produce the electrical power needed by the spacecraft. The environmental control and life support system is integrated with OTV's power production system. The craft will operate with a partially closed system. The system receives water, which is produced in the operation of the fuel cells, and regenerates waste carbon dioxide into elements which can be used again in the OTV's atmosphere.

Navigation: The OTV employs a combination of reliable instruments from the space shuttle such as IMU's and star trackers, and recently developed state-of-the-art equipment such as a Global Processing System (GPS) processor/receiver, and a laser docking system. In addition, a maneuver, termed the PIB maneuver, was devised to make it much easier to rendezvous with satellites in GEO.

Propulsion: The MOVERS elected to employ nuclear power on the OTV in order to study to potential of this exciting new propulsion technology. A high-thrust, NERVA (Nuclear Engine for Rocket Vehicle Application) derivative engine was chosen. The engine, including the neutron/gamma shield, weighs 12,500 pounds, has a specific impulse of 880 seconds, and can deliver 30,000 pounds of thrust. For the LEO to GEO mission, these engines result in significant propellant savings over traditional chemical engines. These engines were also found to be very competitive with proposed, aerobraked, chemical systems. Environmental analysis indicated that the problems of catastrophic failures and the diffusion of radioactive particles though the fuel rods in low Earth orbits do not pose significant health hazards to the human population on Earth.

Reaction Control System (RCS): A supercritical hydrogen/oxygen RCS was chosen for the OTV. This system has a specific impulse of 410 seconds, which gave it the lowest wet mass of all the RCS systems considered for the OTV. This was an important design criterion given that the OTV's large moments of inertia mean that considerable RCS thrusting is necessary to obtain desired rotations and translations. The system was also chosen because the propellants are the same gases which are used in the fuel cells--thus minimizing the number of fluids which must be stored at the space station and on the OTV.

Tankage: The optimum configuration of propellant tanks for the OTV were three cylindrical, aluminum tanks. The tanks were made out of aluminum because alternative composite materials would tend to delaminate when exposed to the reactor's radiation and the ambient background radiation of space. The cylindrical shape was chosen because it maximized the amount of propellant which could be transported to the space station within the shuttle's cargo bay. Additionally, all tanks are shielded by the radiation shield. This is important because it minimizes cryogenic heating, and thus cryogenic boiloff.

Satellite Servicing: Three types of satellite servicing missions were identified: resupply of expendables such as attitude control system propellants and water; replacement of failed elements; and the upgrading of spacecraft systems to incorporate advances in technology. To capture satellites, a remote manipulating system (RMS) has been incorporated into the OTV design. A manned maneuvering unit is also included onboard the OTV. The satellite servicing station includes a berthing system to fascilitate the changeout of defective or obsolete satellite parts, and to affect fluid resupply.

Structures: The exterior skin of the OTV is an alluminum alloy. A thickness of 5 gms/cm^2 provides sufficient protection against background radiation. In thre event of a sudden solar flare, the OTV will be oriented such that the radiation shield will protect the crew from the flare.

Sample Mission:

April 24, 1996, telstar Satellite Repair

The OTV and crew are called upon to service a failing Telstar satellite. After preparing the OTV for departure, the crew performs an alignment orbit burn. The alignment orbit is used to position the OTV so that when it returns to its initial position it is correctly aligned to rendezvous with the target satellite in GEO. The dry mass of the OTV at the time of the first burn is 50,300 pounds, and 84,926 pound of propellant are onboard to complete the roundtrip. 2 hours and 11 minutes are required to complete the alignment orbit.

When the OTV returns to the initial departure point, a second transfer burn is performed to place the OTV into a Hohmann transfer for rendezvous. The time of flight for this Hohmann transfer orbit is 5 hours and 16 minutes. Once the OTV reaches its destination, a third burn is performed to put it is the same orbit as the Telstar satellite. At this point servicing begins. servicing takes 4.5 days.

To return to the space station the above sequence is essentially repeated in reverse. A burn is initiated to put the spacecraft into a Hohmann transfer orbit. Time of flight is again 5 hours and 16 minutes. Once the OTV reaches the space station's orbit, another burn is performed to put the craft in an alignment orbit, which will align it with the space station. The time of flight for the alignment orbit is 1 hour and 43 minutes. When the OTV returns to the point where the second burn was performed, it arrives there just as the Space Station gets there. A third burn is then performed to put the OTV in the space station's orbit. The total mission time is 5 days, 2 hours and 29 minutes.

Cost of an OTV:

5.09 billion dollars will be necessary to develop and build the first nuclear OTV. In addition,, it will cost $101 million to deliver the craft to the space station assuming a launch cost of $2000/pound.

Conclusions:

This report has outlined the basic components of the MOVERS design team's orbital transfer vehicle. The exciting aspect of this research is that it indicated that high-thrust, nuclear propulsion may be appropriate for OTV applications,and that further research is warranted.