THE TRANSPORTATION DEPOT— AN ORBITING VEHICLE SUPPORT FACILITY

Martin J. Kaszubowski[1] and J. Kirk Ayers

Aerospace Division
PRC Systems Services
Hampton VA 23666

This paper describes the details of an effort to produce conceptual designs for an orbiting platform, called a transportation depot, to handle assembly and processing of lunar, martian, and related vehicles. High-level requirements for such a facility were established, and several concepts were developed to meet those requirements. By showing that the critical rigid-body momentum characteristics of each concept are similar to those of the dual-keel space station, some insight was gained about the controllability and utility of this type of facility. Finally, several general observations were made that highlight the advantages and disadvantages of particular design features.

INTRODUCTION

Events of the last few years, including the Challenger disaster, reorganization of the space station program, and the usual funding problems for NASA, have shown the need for new goals in the national space program. Establishment of a permanently manned lunar base and a manned mission to Mars are the two goals most often cited as ways to reinvigorate this country's space program and reestablish our leadership in space-based operations.

Nearly every scenario that has been proposed for lunar bases and missions to Mars make extensive use of low-Earth-orbit (LEO) facilities, such as the space station, for assembly and maintenance of vehicles, storing of propellant, and temporary crew billeting. For both the Mars and lunar missions, however, the level and duration of support that is necessary poses potential problems for currently planned space station science and materials processing activities. There is, in fact, a fundamental conflict between activities that require a quiescent environment, such as microgravity research or high-precision astronomical measurements, and those activities, such as vehicle processing, that produce potentially large dynamic disturbances. This is not to say, of course, that the two types of activities are hopelessly incompatible. It simply means that if the two types of activities are present on the same facility, either the science and microgravity activities will be forced to deal with a less than ideal environment or the vehicle support activities will have to be curtailed to avoid disturbing those more sensitive users. The obvious solution is to separate as many conflicting activities as possible by either moving the sensitive users to a coorbiting facility, or developing a facility specifically for the needs of lunar and Mars mission support.

In recent months the space station office at NASA Langley has sponsored wide-ranging lunar base and Mars mission system analysis studies. These studies have shown, among many other things, that the current space station design is capable of supporting vehicle processing, but that the necessary modifications would adversely impact both the astronomical viewing and the microgravity environment to the point where it would be highly desirable to separate those sensitive users from the vehicle support facilities. This paper describes results of attempts to develop requirements and preliminary concepts for an LEO facility, called a transportation depot, to support assembly and maintenance of vehicles for lunar and Mars missions. Future studies will refine the concepts, develop growth scenarios, and perhaps consider the implications of the opposite alternative—developing a separate science and microgravity research facility.

VEHICLE ACCOMMODATION OPTIONS

The lunar and Mars missions envisioned for the next century are unlike any other planned space activity in that the mass and size of the vehicles, propellant, and support facilities are orders of magnitude greater than anything previously proposed for attachment to the space station. Furthermore, the length of time over which space station support is needed will make it impossible for other users to avoid dealing with the disturbances that are produced. For example, space station support for the lunar base described in *Weidman et al.* (1987) begins in the middle of the next decade and continues well into the next century, with a typical on-orbit mass of vehicles, propellant, and support equipment totaling nearly 300,000 kg (660,000 lbm). In contrast, the entire dual-keel station mass is only 209,000 kg (460,000 lbm). Similarly, the Mars mission described in *Cirillo et al.* (1988) entails a decade or more of support with, at one point, an on-orbit mass of 1,112,000 kg (2,448,000 lbm) over and above that of the station. As shown in the studies referenced, the magnitude and duration of support for lunar and Mars missions will make it very difficult to produce conditions acceptable for the needs of science and materials-processing users. It is clear, then, that despite the ability of the current station design to accommodate such missions, in the interests of satisfying the needs of as many users as possible, it is necessary to explore other options.

Table 1 shows a matrix of options that have, in some form or other, been considered in attempts to determine the most appropriate scheme for developing a usable LEO infrastructure. They represent various combinations of locations in LEO for potentially conflicting activities. The following definitions describe

---

[1] Now at National Research Council, 2101 Constitution Avenue, Washington DC 20418

TABLE 1. Low Earth orbit infrastructure options.

	Location in LEO			
Option	Vehicle Support Facilities	Propellant Storage	Vehicle Support Crew	Sensitive Users
Station based	Station	Station	Station	Station
Station based w/PTF	Station	PTF	Station	Station
Mantended transportation depot	Depot	Depot	Station	Station
Mantended depot w/PTF	Depot	PTF	Station	Station
Manned transportation depot	Depot	Depot	Depot	Station
Manned depot w/PTF	Depot	PTF	Depot	Station
Science emphasis	Station	Station	Station	Science Platform

the nomenclature used for these activities and the various facilities on which they might be located.

1. Vehicle support facilities are the hangar, tools, robotics, etc. needed to assemble, refurbish, and check out vehicles.
2. Propellant storage refers to facilities such as tanks, pumps, utilities, and robotics support for storing and handling propellant.
3. The vehicle support crew is the crew needed to assemble, refurbish, and check out Mars and lunar vehicles.
4. Sensitive users are experiments or processes that would be greatly affected by field-of-view blockage or by disturbances to the microgravity environment.
5. A propellant tank farm (PTF) is a coorbiting facility for storage and transfer of propellant.
6. "Mantended" means that a crew transfers to a facility for a given work shift and then returns to permanent quarters on a different facility.
7. A transportation depot is a coorbiting facility designed specifically to meet the needs of vehicle preparation and maintenance.
8. A science platform is a coorbiting facility designed to meet the field of view and microgravity requirements that cannot be met in the vicinity of vehicle support activities.

Each option shown in Table 1 has advantages and disadvantages associated with how well contrasting requirements are met. The first option is, in a sense, the default condition, where all activities are kept on the station. As discussed, this scenario is feasible but has adverse impacts on sensitive users. The second option has the advantage of separating crew and instruments from the potential danger and contamination of propellant, but does not alleviate blockage of field of view or disturbances to the microgravity environment.

The third option shown in Table 1 features all vehicle and propellant operations relocated away from the station onto a transportation depot. Options 4 through 6 extend this idea further by separating propellant and permanently manning the depot. These options have the advantage of maintaining a quiescent environment at the station, but disadvantages exist as well. Clearly, if the deposit is mantended, a scheme must be developed to transfer crew to and from the facility on a routine basis, involving added risk and potential loss of usable work time. For the permanently manned case, the potential risk to crew from propellant mishandling is the same as for the first option described, but moving propellant off the depot adds the complexity and expense of a third facility.

The last option shown on Table 1 brings the discussion full circle to maintaining the station as a base for vehicle operations while moving sensitive users to a separate facility. The obvious question here is, if science users were relocated, would it make sense to retain the dual-keel station configuration for vehicle support? The answer is almost certainly no. Rather, it would make sense to redesign the station for the specific purpose of supporting lunar and Mars missions, i.e., develop a transportation depot.

The above discussion is not meant to show that any one of the options is the definitive answer to optimizing the LEO infrastructure for the next century. It is meant, rather to establish the concept of a transportation depot as a viable means of supporting lunar and Mars missions, while maintaining a suitable environment for users with more stringent requirements. The remainder of this paper focuses on the development and analysis of various transportation depot designs as represented by the third option shown in Table 1. This option, the man-tended transportation depot, can be upgraded to a permanently manned configuration, and many of its critical features remain essentially the same whether or not propellant tanks are attached. Thus, it represents a good basis for study.

APPROACH

The work described in this paper proceeded along two lines. First, a list of high-level design requirements was established, and three depot concepts were developed and evaluated against those requirements. Second, a quantitative analysis was performed that determined mass properties and flight mode attitudes for each concept. In this way the feasibility of each concept was evaluated and, more importantly, some generalizations were made about how to improve future designs.

HIGH-LEVEL DESIGN REQUIREMENTS

Design requirements were established from which the three depot concepts were developed. First, it was found necessary that the design provide (1) volume to accommodate vehicles and support equipment; (2) docking facilities to accommodate the OMV and shuttle; and (3) a pressurized command center for controlling/watching EVA and robotic activities. The depot should have expansion capability and provide room for propellant tanks and support equipment. Also, the robotic and EVA should have access to the vehicle and propellant tanks. The facility must provide for simple vehicle separation. The vehicle should separate from the depot along the velocity vector or negative radius vector, and there must be room to avoid any collisions. Orbital decay parameters must not interfere with separation. The vehicle, EVA crew, and propellant must be protected from micrometeoroid impact and as much volume as possible must be enclosed to provide for containment of debris. The EVA crew and propellant must have thermal protection, and solar dynamic power, GN&C, C&T, and RCS systems must be provided. Finally, the design must assure controllability of all phases of vehicle assembly while minimizing control system size and complexity.

TRANSPORTATION DEPOT CONCEPTS

Three concepts for a man-tended transportation depot were developed based on the design features listed above. An attempt was made to develop concepts that differed in their overall approach, yet still incorporated the desirable features. For example, to assure sufficient access to the vehicle throughout all stages of assembly, a good deal of surrounding truss structure was included in each concept; the differences lay in how much of the vehicle can be enclosed, and how easily robotic arms can get to the center of the vehicle while attached to the structure.

A word should also be said about the rationale behind the total size of the depot structures and the sizing of the propellant tanks that are attached. As will be seen, each concept was made large enough to accommodate a fully assembled piloted Mars vehicle stack as described in *Cirillo et al.* (1988). This meant that approximately 45,000 cm of volume was provided just for the vehicle. A typical lunar vehicle stack is somewhat smaller and so would be accommodated as well. The propellant most often proposed for lunar and Mars vehicles is a mixture of liquid oxygen (LOX) and liquid hydrogen (LH_2). It was decided that the depot should accommodate the maximum amount of LOX/LH_2 needed for the Mars Sprint mission described in *Cirillo et al.* (1988), and so nearly 800,000 kg of propellant can be stored on the depot concepts developed here. This is, of course, more than adequate for lunar mission support, since each lunar sortie requires only about 91,000 kg (200,000 lbm) of propellant. However, since lunar sorties occur six or seven times a year in most scenarios, the amount of propellant needed for multiple sorties or possible rescue missions would likely be two or three times that needed for a single sortie.

Liquid oxygen/liquid hydrogen propellant is generally proposed for lunar and Mars vehicles because of its relatively high specific impulse and because it is hoped that by mining O on the lunar surface, the overall cost of propulsion can be reduced. The great disadvantage is that storing such massive amounts of propellant on the depot applies significant demands on its control system. For example, every time a lunar or Mars vehicle leaves from the depot, a change in the total mass of the system of hundreds of thousands of kilograms results. In order to minimize the complexity of the control system, then, it is desirable to minimize the mass property changes by keeping the propellant distributed around the structure and loading it into the vehicle in a way that keeps the location of the center of mass (CM) relatively constant. Thus, all three depot concepts have three LOX tanks and seven LH_2 tanks distributed in various ways around the truss structure, rather than a single large tank for each. Also, one tank was included on each concept for the hydrazine propellant used by the orbital maneuvering vehicle (OMV). Suffice it to say, then, that while LOX/LH_2 propellant can be accommodated on the depot, development of alternate (i.e., less massive) propellants would help reduce the complexity of the control system and provide greater flexibility in design.

The mass balance of the depot is also affected by the configuration of the lunar or Mars vehicle. Since nearly all scenarios show multistage vehicles that leave LEO together but return at different times, the implication is that at different times during the mission there may be any number of pieces of the complete vehicle stack attached within the depot. This raises the question of how best to attach the vehicles within the depot structure to maintain a stable connection, provide adequate EVA and robotic access, maintain mass balance, and yet not hinder the eventual egress of the vehicle. This is particularly important for lunar vehicles, because the frequency of their arrival and departure makes simplicity and flexibility essential. Two schemes have been proposed. First, a series of deployable/retractable truss structures could be developed and distributed along the length of the vehicle to provide attachment points, as well as a convenient scaffolding for EVA and robotic access. Second, stiff cable could extend between the vehicle and the surrounding truss to provide stability and still allow simple movement of vehicles into, out of, and within the enclosed volume.

Finally, it should be noted that wherever possible, current space station hardware designs were used for the depot concepts; the truss bays are 5 m square, the solar dynamic power, alpha joints, and RCS systems are the same as those found on the station, and the command center and docking ports were derived directly from station nodes and modules. This was meant not only to explore the flexibility of those designs, but also to point out that the experience gained building the station is directly applicable to assembly and maintenance of the depot.

The following sections give brief descriptions of the three depot concepts developed in this study.

The Open-Box Concept

The open-box concept shown in Fig. 1 is the first of the three concepts developed. It features truss sections arranged into a rectangular box that completely encloses the vehicle during all stages of assembly. The box is open on the front, rear, and top faces, but blocked by a cross piece on each side and bottom. Robotic access to the vehicle is via the cross pieces, while the vehicle and associated hardware enter or leave via the front, rear, or top. It is probable that the entire box would be enclosed with impact and thermal protection and debris-containing material that would be drawn back to provide space for vehicle egress. The command center is placed at the top of the box overlooking the vehicle, and the attached docking port and airlock extend out into the flight path. This placement allows adequate viewing of the vehicle, with room for docking the shuttle or OMV and, at the same time, separates the crew from the propellant.

The open box is 12 truss bays long, 9 bays high, and 9 bays wide. Since each truss bay is 5 m square, the outside dimensions of the open box are 60 × 45 × 45 m, the inside dimensions are 50 × 35 × 35 m and the total inside volume 61,250 cu m (2,163,000 cu ft).

Figure 1 shows a standard right-handed body axis system where the positive X axis extends nominally in the direction of the velocity vector, and the positive Z axis extends toward Earth. For convenience in modeling, the origin was placed at approximately the centroid of the starboard face. The concepts described and shown in the next sections have different origin locations but, of course, maintain the same right-handed orientation.

The Prism Concept

Figure 2 shows the prism concept, which, like the open box, features truss sections that completely enclose the vehicle and can be covered with thermal and impact protection or debris

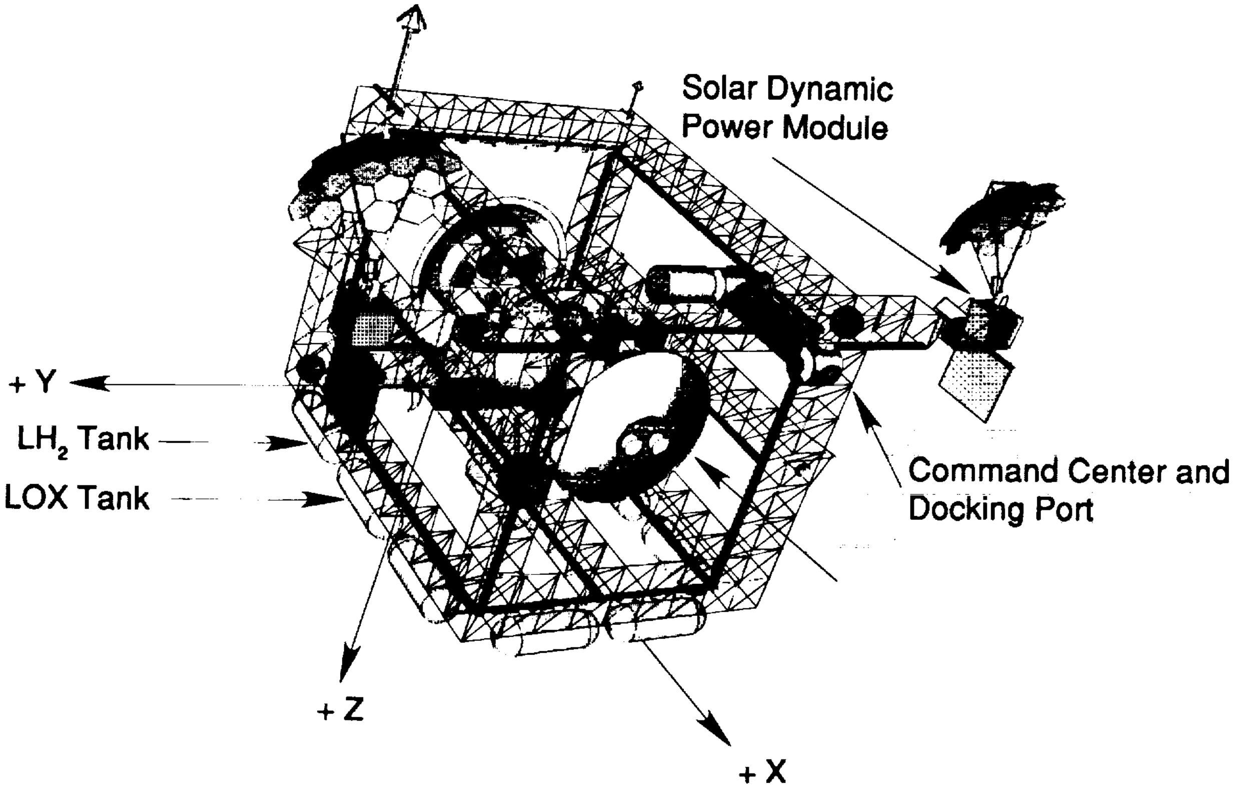

Fig. 1. The open-box concept.

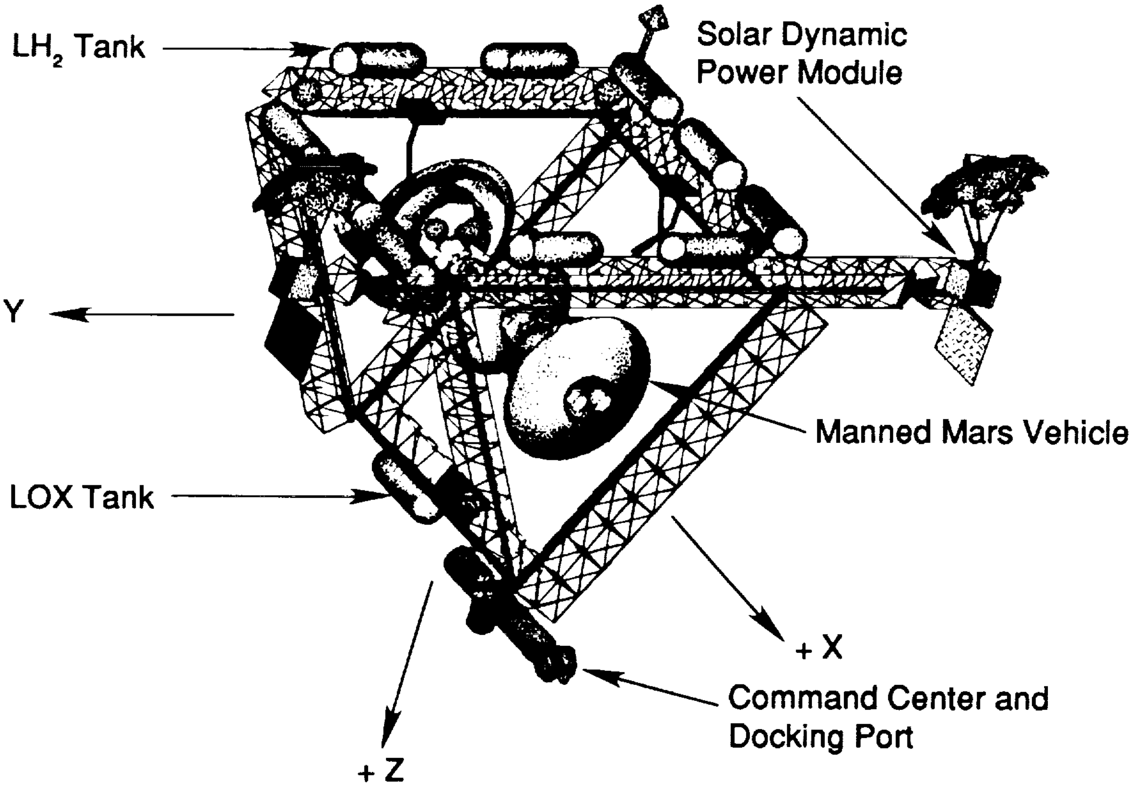

Fig. 2. The prism concept.

containment material. In this concept, however, the vehicle is enclosed by an equilateral triangular prism rather than a rectangular box. The advantages of this design are that the command center is placed with a slightly better view of the vehicle, and the triangular structure allows hardware to enter or leave through all five faces. A disadvantage is that the robotic arms have farther to reach to the center of the structure than on the open-box concept.

The triangular section of the prism is 11 bays (55 m) on each side, and the structure as a whole is 11 bays long. Thus, its inside volume is approximately 59,000 cu m (2,080,000 cu ft), slightly less than that of the open box. Another important feature is that the propellant tanks are distributed around the top of the prism to keep propellant away from the command center, except that to maintain mass balance, one LOX tank was located on the lower apex. As shown on the figure, the origin of the body fixed-coordinate system is in the center of the volume.

Readers who are familiar with the history of NASA's space station program will immediately recognize the similarity between the prism concept and an earlier proposed station configuration called the Delta (*Woodcock*, 1986). Early in the program it was thought that the control problems associated with structural flexibility were greater than those associated with rigid body dynamics and the Delta was developed to provide a very stiff platform to reduce the flexible body demands on the control system. However, later studies showed that by increasing the size of the truss bays, the overall flexibility could be reduced to the point that control of rigid body momentum buildup was the dominant issue. This, among other things, eventually led to the adoption of the dual keel as the baseline station configuration.

There are, fortunately, some significant differences between the prism and the Delta, so it should not be thought that the same configuration is being recycled. Most notably, the Delta was to fly "inertially" (always oriented the same with respect to the sun), while the prism, like all the concepts described here, flies "Earth pointing" (with the same apex always pointing toward the Earth). This orientation is possible because the prism uses solar dynamic collectors for power generation, while the Delta used photovoltaic (PV) arrays attached to one side of the structure. Since the Delta was thus forced to fly with the PV side always facing the sun, it was also forced to deal with a constantly changing orientation with respect to Earth, and the corresponding changes in the aerodynamic and gravity gradient forces made it difficult to control.

The Open-Platform Concept

The open-platform concept shown on Fig. 3 was derived somewhat from the dual-keel space station configuration, though obviously the inner transverse boom was removed and the keels were rearranged to provide access to the vehicle. In this concept the major advantage is that the command center and docking port

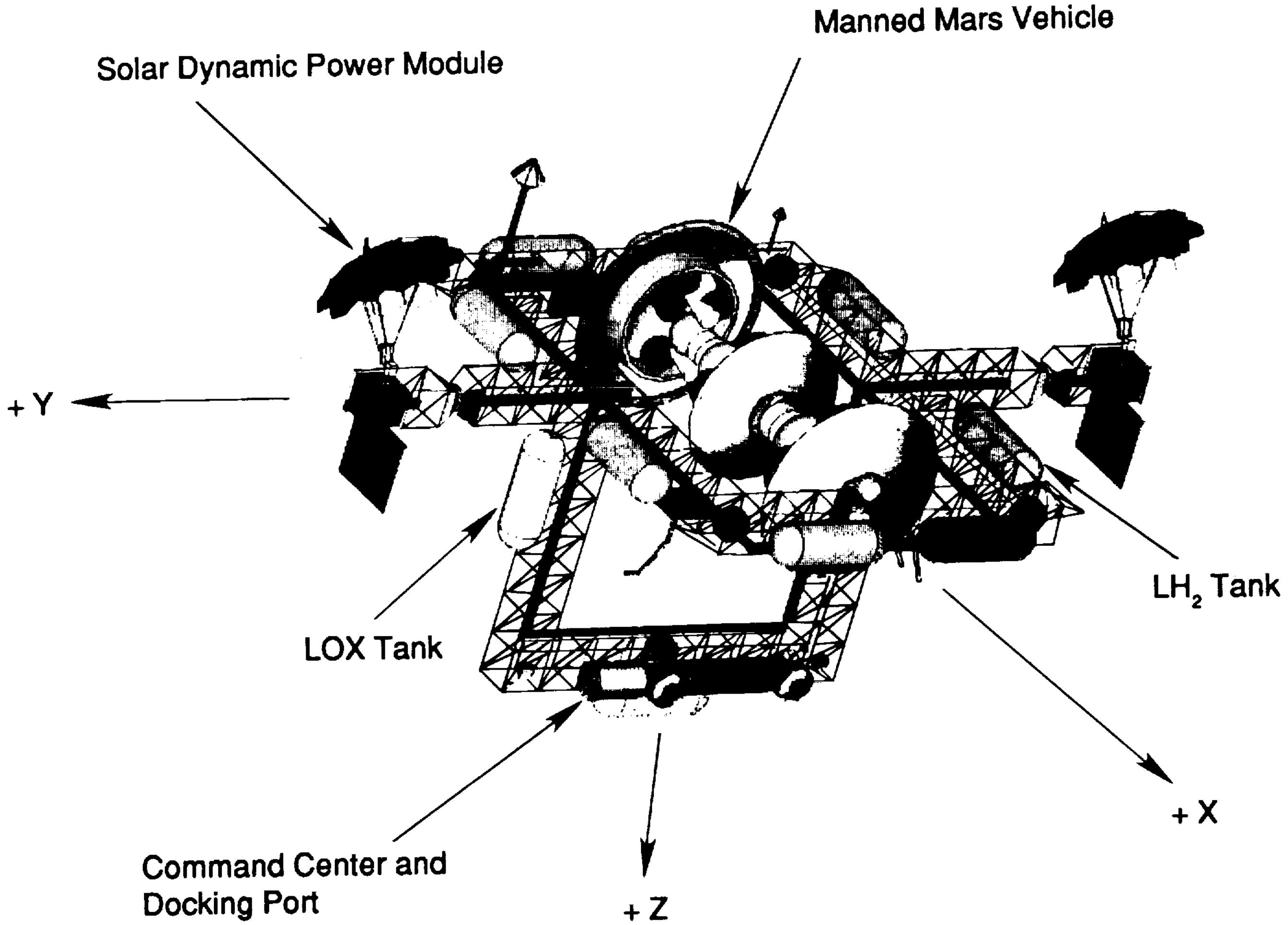

Fig. 3. The open-platform concept.

are placed such that maximum visual access to the vehicle is obtained. Disadvantages are that robotic access is reduced, and the vehicle cannot be completely enclosed for thermal and impact protection or debris containment.

The rectangle, or platform, that surrounds the vehicle is 12 bays long (60 m) and 9 bays wide (45 m). The lower keels, which connect the platform with the lower boom, are 8 bays long (40 m). These dimensions provide adequate room for both the Mars vehicle shown and the lunar vehicles that are generally proposed. The origin of the body fixed-coordinate system is shown in the center of the platform.

The velocity vector of the open platform is such that for the shuttle or OMV to dock at the docking port it must travel under the lunar or Mars vehicle and the surrounding structure. This is certainly possible, but for safety reasons it is not the most desirable scheme. Also, for balancing reasons, the open-platform concept has one LOX tank on the lower boom near the command center.

Table 2 lists the estimated mass of each component of the three depot concepts. The only difference in the total mass of each concept lies in their amount of truss structure and utility trays. As stated above, all components are copies or derivatives of current space station components, except in the case of the propellant tanks, where the masses were derived from previous studies of cryogenic propellant storage. Table 3 shows mass properties derived from the analytical models of the three concepts. The total mass of each concept shown in Table 2 corresponds approximately to the second configuration of each concept in Table 3, which includes tanks but no propellant.

ANALYSIS OF TRANSPORTATION DEPOT CONCEPTS

The following sections give the details of the analyses that were performed on the three transportation depot concepts described above. The first section describes a high-level systems analysis that evaluated each concept against the requirements that were established previously. The second describes the determination of the flight attitude and corresponding momentum buildup for each concept.

Systems Analysis

Each of the concepts described above was developed based on the established design requirements, but as the discussion shows, they do not perform equally well in all areas. Table 4 and the discussion that follows show how each of the concepts has been evaluated with respect to those requirements. The list of requirements that appears above was rearranged to produce nine important areas for the evaluation of the overall effectiveness of each concept. Each area was weighted according to its importance, and numerical rankings were given for each concept. The ranking received by each concept in each area was multiplied by that area's weighting factor to produce a score. Finally, the scores for each concept in each area were totaled to produce a numerical comparison of the effectiveness of each concept.

Naturally, the determination of the weighting factors and rankings was a highly subjective process. However, by outlining the rationale behind each, it is hoped that the total scores can be accepted as a valid comparison and, more important, provide a basis for development of more refined concepts. As more knowledge is gained about the characteristics of this type of structure, more precise evaluation techniques can be applied. In that sense, then, Table 4 provides a concise form for expressing the advantages and disadvantages of each of the concepts developed here.

TABLE 2. Component mass summary.

	Component Mass (kg)		
Component Name	Open Box	Prism	Open Platform
Airlock	2,014	2,014	2,014
Alpha joints	1,200	1,200	1,200
CMGs	1,567	1,567	1,567
Cupola	1,455	1,455	1,455
Docking adapters	1,000	1,000	1,000
Nodes (2)	9,091	9,091	9,091
Command center	31,523	31,523	31,523
MSC/transporter	4,909	4,909	4,909
RCS clusters	1,025	1,025	1,025
RCS propellant and tanks	6,364	6,364	6,364
SD power modules (2)	14,078	14,078	14,078
TDRSS and antenna	586	586	586
Tele. servicer (2)	2,381	2,381	2,381
11 propellant tanks	68,924	68,924	68,924
Attached hardware	12,980	12,980	12,980
2 depot radiators	3,670	3,670	3,670
Logistics	8,285	8,285	8,285
Truss	9,875	7,163	4,799
Utility trays	18,008	13,062	8,750
Total	198,900	191,300	184,600

Effectiveness of docking port/command center.

The placement of the command center and docking port is vital to the overall effectiveness of the depot, but because of the potential for telerobotic technology and the general flexibility of EVA, a less than optimum location can be tolerated. Thus, this area was given a weight of 4. The location of the command center on the open box was given a ranking of 2, since it may be blocked somewhat by the vehicle aeroshells. The prism and open platform command centers are in better locations, but as previously mentioned, docking to the open platform may entail some difficulty from passing below the vehicle.

Capability for expansion.

Capability for expansion is important for any space-based facility, but particularly one that hopes to provide a base for expanded human exploration. It is hoped, however, that the initial capabilities of the depot design will be sufficient for meeting the needs of lunar and Mars mission support. Thus, this area was rated an importance of 3. Each of the depot concepts has room for expansion, but the open box is capable of expanding in every direction. The prism can expand in each direction as well, but the added volume may be less useful due to the skewed nature of the triangular shape. The open platform could easily be modified into a structure resembling a box and then have greater capability for expansion.

Access to vehicle.

Without access to all parts of the vehicle during all phases of its construction and refurbishment, the depot would not be meeting its most basic goal. This area, then, has the highest importance. Access to the vehicle by EVA is essentially the same

TABLE 3. Analytical model mass properties.

	Center of Mass (M)			Inertia $(K_g \cdot M^2 \times 10^7)$					
Configuration (total mass)	X	Y	Z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
Phase II dual-keel space station (267,000 kg)	-3.5	-0.9	3.2	31.0	9.1	25.6	1.76	-1.54	-1.87
Open box (118,000 kg)	-3.1	-19.5	-12.2	8.0	8.8	9.7	0.02	-2.9	-0.08
Open box w/tanks (200,000 kg)	-12.0	-19.7	3.2	16.9	19.2	15.6	0.07	-6.7	-0.18
Open box w/propellant (1,030,000 kg)	-22.5	-20.0	20.7	46.4	39.5	49.7	0.33	-11.3	-0.32
Open box w/vehicle (1,190,000 kg)	-22.7	-20.0	17.9	53.1	49.9	53.9	0.33	-10.9	-0.32
Prism (107,000 kg)	-1.0	0.6	-61.1	22.3	18.6	9.1	0.1	0.78	-0.65
Prism w/tanks (190,000 kg)	-3.7	1.1	-45.1	37.9	31.3	15.2	0.15	-1.28	-0.57
Prism w/propellant (1,020,000 kg)	-7.0	1.6	-26.4	143.2	102.8	70.1	0.8	-13.2	-2.1
Prism w/vehicle (1,180,000 kg	-6.3	1.4	-25.0	145.4	108.9	74.8	0.69	-12.5	-2.4
Open platform (99,900 kg)	0.5	-1.8	20.8	7.9	3.9	6.5	-0.06	0.38	-2.2
Open platform w/tanks (183,000 kg)	-0.6	-0.9	18.5	13.2	7.5	11.5	-0.24	0.26	-5.5
Open platform w/propellant (1,010,000 kg)	-1.7	-0.26	17.6	65.2	36.6	56.4	-0.37	-0.50	-0.12
Open platform w/vehicle (1,180,000 kg)	-1.1	-0.2	15.1	70.2	45.5	60.9	-0.39	-1.6	-0.25

TABLE 4. Analysis of concepts.

		Open Box		Prism		Open Platform	
	Weight	Rank	Score	Rank	Score	Rank	Score
Effectiveness of docking port/command center	4	2	8	3	12	4	16
Capability for expansion	3	5	15	4	12	3	9
Access to vehicle	5	5	25	4	20	3	15
Access to propellant	4	4	16	4	16	3	12
Safety of propellant tank location	5	4	20	3	15	3	15
Impact protection	4	5	20	5	20	3	12
Debris containment	4	5	20	5	20	2	8
Thermal/radiation protection	3	5	15	5	15	3	9
Ease of vehicle separation	5	3	15	3	15	4	20
Total Score			154		145		116

Weight: 5 = very important; 1 = not important.
Rank: 5 = very good; 1 = poor.
Score = Weight × Rank.

for all concepts. Robots have considerably farther to reach on the prism than on the open box, and they may have difficulty reaching around the vehicle on the open platform.

Access on the prism could be improved considerably by building cross pieces between the front and back faces, similar to those on the open box. This would allow robots to travel much nearer the vehicle, but would close off two of the faces through which hardware can enter or leave the enclosed volume. Also, if the vehicles were attached to the structure by deployable/retractable truss sections, as mentioned previously, robotic access on both the prism and the open platform could be enhanced.

Access to propellant.

Since a great deal of the total vehicle support activity consists of replacing or refilling propellant tanks and maintaining storage and pumping apparatus, routine access to propellant areas is essential. Also, in the case of a spill, access must be simple and rapid to allow repairs to begin as quickly as possible. This area was weighted a 4 because, like the command center location, a less effective propellant handling scheme can be partially overcome by automation and expanded EVA.

All three concepts have adequate robotic access to propellant areas, but because the open box and the prism allow EVA access from inside the enclosed volume, they were ranked slightly higher. Clearly, the thermal, radiation, and impact protection provided by the enclosed volume should be taken advantage of wherever possible.

Safety of propellant tank location.

To maintain mass balance, the propellant tanks must be distributed around the depot structure. However, it is also important to have propellant near the vehicle to aid the fueling process, and because pumping it over great distances might increase the chances of a mishap. Of course, to ensure a safe haven in an emergency, as well as an uncontaminated base for repair operations, it is desirable to maintain as much distance as possible between the tanks and the command center. Since this is both an operations and a safety issue, it was weighted as high as possible. As stated before, the platform and prism have one LOX tank near the command center, and so they were rated slightly lower than the open-box concept.

Impact protection.

The importance of this area was rated at 4 out of 5 because the probability of impact damage increases with surface area, which Mars and lunar vehicles have in abundance, and with mission duration. Thus, over the decades of support for lunar and Mars missions, the potential for impact damage to unprotected vehicles and crew will be considerable. Clearly, the open box and the prism have a great advantage over the open platform in being able to cover the entire vehicle with impact protection.

Debris containment.

One of the many things that humans must learn to do in space is contain the loose material that results from routine operations, such as assembling or repairing spacecraft. This is on the same order of importance for the depot as providing impact protection, since every piece of orbiting debris is potentially damaging to the vehicle and crew. Again, the open-box and prism concepts have the advantage of completely enclosing the entire work and storage area, whereas on the open-platform concept the area can be, at best, only partially enclosed.

Thermal/radiation protection.

Both Mars and lunar mission support will require significant amounts of EVA for assembly and maintenance of vehicles. This makes it essential that external thermal and radiation protection be provided to augment that afforded by the EVA suit. Furthermore, due to the long duration of exposure to space that the vehicles will undergo, reduction of radiation and thermal cycling effects will enhance the reliability of the hardware. As before, the open-box and prism concepts have the advantage of enclosing the vehicle, work, and storage areas.

Ease of vehicle separation.

Separating the vehicle from the depot will be a complicated process regardless of the configuration of the depot. The disentangling of plumbing, utilities, and checkout equipment, the retracting of support structure or cables, and the danger of collision, make simplicity and reliability essential. Furthermore, should a failure happen such that the vehicle and depot were not able to be separated for a significant length of time, the impact on the mission would be severe. Thus, this process has been rated of equal importance with propellant safety and vehicle access.

There is a fundamental conflict between the two concepts that enclose the entire vehicle (open box and prism) and the one that does not (open platform). Enclosing the vehicle carries the advantages of enhanced protection, but at the same time complicates the separation process. In this area, then, the open platform is superior to the other two concepts due to the sparseness of the truss that surrounds the vehicle. It is vital, however, to consider the manner in which the vehicle separates from the depot. With the open-box and prism concepts, the vehicle may exit the enclosed volume through the front, back, or top faces, depending on orbital and plume impingement requirements. With these concepts, therefore, it is only necessary to assure that sufficient margin for clearance is allowed when sizing the vehicle and depot. With the open platform, the vehicle must separate vertically away from the depot, but only half the vehicle needs to clear the surrounding truss. The operational flexibility of the open platform is less than the other two concepts, but the danger of collision is reduced as well, and so it was rated slightly higher.

FLIGHT ATTITUDE ANALYSIS

A necessary step toward showing the viability of a large space structure design such as those described in this paper is to determine whether its configuration is controllable enough to provide a stable environment for on-orbit operations. A complete analysis would develop an attitude control/momentum management scheme for each stage of its assembly, as well as for as many operational configurations as possible, and couple flexible body effects with a control system design. *Heck et al.* (1985), *Woo et al.* (1986), *Robertson and Heck* (1987), and *Sutter et al.* (1987) describe how this level of analysis is being performed for the current space station design. For the purpose of this study, however, such an in-depth analysis would be premature. Instead, it was decided that by determining the key flight attitude characteristics for each transportation depot concept and comparing them to the corresponding values for the space station, the reasonableness of each design could be shown and indications could be made for future refinements. The following sections give a brief discussion of momentum management schemes, show how the depot attitude control requirements differ from those of the station, and give results of the analysis.

Approach and Modeling

An orbiting spacecraft is subject to a variety of environmental and operational effects that disturb its flight attitude. Environmental disturbances include forces due to aerodynamic drag, the difference in gravitational force due to the mass distribution (called gravity gradient forces), and forces due to solar radiation pressure. *NASA* (1969, 1971, 1986) details these effects. Operations such as relocating payloads, berthing and docking, and articulation of solar dynamic collectors, produce disturbances to the attitude of the spacecraft, as well as changes to its physical configuration and mass properties. Of course, changes in the physical characteristics of the spacecraft alter the aerodynamic, radiation pressure, and gravity gradient effects as well. The net result of these disturbances is a buildup of angular momentum that must somehow be dissipated to maintain the desired flight attitude.

If it were possible to instantaneously measure or predict environmental effects and calculate operational effects, it would be posssible to continuously correct the attitude of the spacecraft to maintain a net angular momentum of zero. Much like flying a plane or driving a car, whenever a disturbance was sensed, a corresponding correction would be made to maintain the desired attitude or direction. Unfortunately, due to imprecise knowledge of the aerodynamic and solar environment, and the difficulty with sensing disturbances, such a complete knowledge of the current state of the spacecraft is not achievable. Furthermore, continuous correction of attitude would require either constant use of expendable fuel, or some means to continuously change the aerodynamic and gravity gradient characteristics of the system. Such continuous correction would also be likely to disturb normal operations.

A more practical scheme is to allow some moderate amount of momentum to build up over a period of time and correct the attitude only when operational requirements allow. Unfortunately, if angular momentum is simply allowed to build up, the attitude of the spacecraft will change significantly over a period of time, changing viewing angles and seriously complicating C&T and protection systems. It is necessary, then, to provide a mechanism by which momentum can be stored within the spacecraft without disturbing its attitude or continuously making corrections. Of course, all the momentum that is stored must eventually be released in some way, and so periodic corrections must be made.

The scheme for maintaining momentum buildup in the current space station design involves the use of control moment gyros (CMGs) as a method of storing momentum. As the station passes through each orbit, a certain amount of angular momentum is built up and countered with torques produced by the CMGs. When the momentum buildup reaches a level near the CMGs torque-producing capacity, the station's reaction control system (RCS) jets are fired in a way that releases the built-up angular momentum and allows the CMGs to return to a lower level of torque. This process is called "desaturation" of the CMGs.

The momentum buildup is divided into two distinct components called "cyclic" and "secular." Cyclic momentum results from environmental forces that grow and then dissipate through an orbit such that the net buildup is approximately zero. This type of momentum buildup is important because, even though the net value is negligible, the peak value is generally so large that it greatly affects the size of momentum storage devices needed to maintain attitude. Secular momentum results from forces that vary in magnitude such that the net resulting momentum is nonzero. Values of secular momentum are generally lower than those for cyclic, but it is the secular component that must be dissipated periodically to avoid exceeding the capacity of the momentum storage system. The capacity of the momentum storage device needed, then, is determined by the maximum value of momentum buildup (the maximum sum of cyclic and secular momentum) experienced in an orbit. *Robertson and Heck* (1987) give a good discussion, as well as numerous examples, of how the secular and cyclic components combine to produce the total spacecraft momentum.

Along with the use of CMGs to store momentum, the space station makes use of the fact that since environmental forces are highly dependent on the flight attitude, it is generally possible to maintain an attitude that reduces their magnitude. Clearly, by maintaining an attitude that minimizes the magnitude of the environmental forces, the CMGs would need to store less angular momentum and be desaturated less often. This minimum torque attitude is expressed as three ordered Euler angles, called torque equilibrium angles (TEAs), which represent successive yaw, pitch, and roll rotations about the body axes. Before the rotations are executed, the body axes correspond to the local vertical local horizontal (LVLH) coordinate axes defined by the positive X axis along the veolocity vector, positive Z toward Earth along the nadir vector, and positive Y in the orbit plane to form a right-handed system.

A major advantage of the transportation depot concept is that by separating the vehicle processing activities from the sensitive users, the depot is released from requirements for astronomical and Earth viewing angles. Thus, while the space station must maintain a pitch angle of ±5° for viewing reasons, the depot is constraihed only by communications requirements and operational needs, such as vehicle separation. Also, since the depot need be only a moderately quiescent environment, the constraints on attitude correction are less stringent as well. On the other hand, the mass property changes mentioned several times above make it imperative that a flexible momentum management scheme with sufficient CMG capacity be provided.

The flight attitude analysis consisted of calculating TEAs and corresponding momentum buildups for 4 different configurations of each depot concept (12 configurations in all), where each configuration represents a different operational state. The first configuration was simply the depot without any propellant, tanks, or vehicle on board. Empty tanks were added for the second configuration, propellant was loaded into the tanks for the third, and finally a complete vehicle was included. In this way, it was possible to evaluate the effects of increasing and repositioning the total mass of the three depot concepts.

Solid models of each configuration were developed using the GEOMOD program developed by Structural Dynamics Research Corporation (SDRC), and the geometry and mass properties were then passed to the ARCD program described in *Heck et al.* (1985) and *Robertson and Heck* (1987). The ARCD program computes forces and moments needed to maintain a given attitude and calculates the momentum buildup about each axis in a single orbit. The calculations in ARCD include environmental effects as well as the effects due to articulating mechanisms such as solar dynamic collectors. The two software packages, GEOMOD and ARCD, are integrated under a single operating environment at NASA Langley called IDEAS[2] (*SDRC*, 1985), which also includes other SDRC- and NASA-developed software for structural, thermal, and controls analysis.

Flight Attitude Analysis Results

Table 5 contains the basic results of the flight attitude analysis of the depot concepts in each of the four configurations described above. The first three entries in Table 5 are the attitude angles for each configuration that minimize the amount of momentum built up in an orbit. These are the TEAs described above, where positive values for the angles ϕ, θ, and ψ represent positive rotations about the X, Y, and Z axes, respectively. Thus, if one were looking along the flight path, a positive ϕ would be characterized by a clockwise roll, θ by an upward pitch, and ψ by a left-to-right yaw.

The fourth entry in Table 5 is the resultant magnitude of the X, Y, and Z axis secular momentum buildups that correspond to the given TEAs. The fifth is the value of momentum buildup for the given attitude, which represents the greatest resultant of the cyclic and secular components in a single orbit. These two values are given because it is the secular component that needs to be dissipated periodically, while the maximum value provides a good measure of the size of momentum storage device needed. In a broader sense, then, the maximum value expresses the overall difficulty of maintaining the given attitude and thus is a convenient means for comparing concepts.

Before discussing the results in detail, a few things should be mentioned. First, the dominant momentum value generally occurs about the pitch axis, but in some cases the value about the roll or yaw axis is larger. This is why the resultant magnitude is given, with the implication that it is necessary to provide significant momentum storage and dissipation along all three axes. Second, these values are very sensitive to small changes in attitude. For example, the maximum momentum buildup for the open box and the prism increase by two orders of magnitude with only a 5° change in θ. This implies that to provide margin for maneuvering and reboosting, a significantly larger storage device would be needed. The open platform is slightly less sensitive than the open box and prism, but still would require a greater capacity than indicated by the maximum value shown. Also shown in Table 5 are results for the dual-keel space station design. These values are subject to the same argument, but since the station will not experience the same degree of mass property changes, it will not need to change its attitude as drastically or as often as the depot.

TABLE 5. Flight attitude characteristics.

Configuration	Torque Equilibrium Angles (Degrees)			Momentum Buildup (Nt-M-Sec)	
	ϕ (X)	θ (Y)	ψ (Z)	Secular	Maximum
Phase II dual-keel space station	0.2	3.0	0.6	1,500	3,050
Open box	1.3	-36.6	-2.6	467	5,800
Open box w/tanks	-1.45	-48.1	-2.0	674	4,740
Open box w/propellant	0.1	-41.4	-9.2	2,442	8,400
Open box w/vehicle	0.0	-44.4	-4.4	2,335	3,270
Prism	-4.0	-6.4	-4.0	3,441	10,870
Prism w/tanks	-2.1	2.2	0.9	1,841	6,130
Prism w/propellant	-3.8	10.1	0.1	1,440	3,360
Prism w/vehicle	-3.9	9.9	0.0	1,075	2,900
Open platform	5.0	-0.4	-1.0	1,750	6,470
Open platform w/tanks	4.9	1.8	-0.9	2,019	9,860
Open platform w/propellant	0.3	4.0	-0.7	442	2,880
Open platform w/vehicle	0.6	10.9	-0.7	616	5,380

Finally, it is interesting to note what the momentum buildup would be if the depot were to fly at a zero attitude (ϕ, θ, and ψ equal to zero). For the open box without tanks, propellant, or vehicle, the maximum value is 588,800 Nt-M-sec. The prism in the same configuration would have a maximum value of 313,800 Nt-M-sec, while the open platform would build up 128,400 Nt-M-sec. Clearly, a great deal is gained by flying at a mimimum torque attitude, but the precision required to maintain it, and the penalty for straying away from it must also be considered.

With the above in mind, it is immediately clear from Table 5 that the prism and the open platform exhibit much more favorable TEAs than the open box, while the momentum values are comparable. It would be desirable in future studies to investigate the performance of the box with impact or thermal material covering various faces. Blocking off the top or bottom, for instance, would likely alter the aerodynamic drag profiles in such a way as to reduce the pitch TEA.

Another interesting result that does not appear on Table 5 is that, because of its symmetry, the box has a minimum torque attitude at a high positive pitch angle. For example, the box without tanks, propellant, or vehicle can fly at a pitch angle of 52.3° with a maximum momentum value of 6500 Nt-M-sec. This, again, is because by not covering the top or sides, minimum frontal area of the configuration exists when a front edge blocks one of the rear edges. Thus, the minimum aerodynamic drag profile exists when the box is tilted so that a front-to-back diagonal aligns approximately with the velocity vector.

The prism and open platform are less symmetrical and so do not exhibit an alternate minimum torque attitude. It is important to note as well that the prism does not experience the same control difficulties as the Delta space station configuration described previously. In fact, the momentum requirements of the prism are not significantly more demanding than those of the other depot concepts or the dual-keel station, and it also maintains moderate TEAs.

The above analysis of depot concepts increases the feeling that this type of facility is feasible. By showing that the controllability requirements of a few very different configurations are comparable to those of the current station design, some confidence is gained that future designs will avoid significant difficulty.

RECOMMENDED FURTHER ANALYSIS

Throughout the high-level analysis described in this paper, several studies were identified by which the transportation depot concepts can be refined. The authors hope to continue the development and analysis of concepts to (1) verify controllability of the depot during various stages of vehicle assembly and for various amounts of stored propellant; (2) determine reactions to dynamic disturbances (modal excitation, structural loads, control systems interactions, etc.); (3) develop depot assembly timelines; (4) manifest depot hardware on ELV or shuttle; (5) determine resource requirements (power, logistics, etc.); and (6) develop growth scenarios for depot concepts. It is also hoped that time can be found to investigate the characteristics of other large-scale coorbiting facilities such as a science platform, a propellant tank farm, and an artificial-/variable-gravity facility.

GENERAL OBSERVATIONS

The following discussion summarizes several of the generalizations drawn from the analysis of the transportation depot concepts. As mentioned, not all the desirable design features listed as high-level requirements are compatible, and so it is important to identify conflicts and potential solutions wherever possible.

Large Enclosed Volumes

By enclosing the vehicle work areas, it is possible to provide better thermal, radiation, and impact protection, better debris containment, and generally better robotic and EVA access. However, it is important not to block viewing from the command center or somehow cut off the ability to enter or leave the volume in an emergency. Also, surrounding the vehicle with a great deal of truss or equipment makes for more complex separation of the vehicle from the depot.

Command Center Location

It is important that the command center be near the middle of the vehicle or high over one end to avoid blockage of view by the vehicle aeroshells. Also, by locating the command center inside an enclosed volume or very near a partially enclosed volume, it is possible to take advantage of extra thermal, radiation, and impact protection. In fact, the two concepts with large enclosable volumes, the open box and the prism, could both have the command center moved inside the volume while still attached to the docking port.

Propellant Tank Location

For both lunar base and Mars mission support, the largest mass on orbit at any given time is propellant. Because the location of the propellant mass greatly affects the depot's flight attitude (TEAs) and creates potential problems for the control system, it is vital that proper distribution of tanks be maintained. Furthermore, distributing tanks around the structure would reduce the effect of a localized spill, since only limited amounts of propellant would be released. However, this may require that propellant be pumped over great distances, thereby increasing the complexity of the pumping system and the probability that a spill would occur.

On-orbit Assembly of Depot

Assembly and integration experience gained on the space station is directly applicable to the assembly of the depot. In particular, techniques and timelines for the assembly of truss, integration of power modules and utilities, GN&C and C&T systems, robotic support, EVA/IVA procedures, maintenance and failure prediction, and the transfer and mating of payloads all will have been dealt with in detail during the assembly and test phase of the space station. Finally, assembly and checkout of the depot has a significant advantage in that the crew needed for the effort can be based on-station and transferred to the assembly area via OMVs.

CONCLUDING REMARKS

The transportation depot and other similar coorbiting facilities clearly represent the second generation of space stations and, as such, assume successful completion of currently planned facilities. In particular, the space station, the shuttle, heavy lift launch systems, and OMVs all play a part in the overall infrastructure needed to provide proper support for expanded human presence in space. The above discussions have established the viability of the transportation depot concept, but whether this type of facility is ever built is another matter altogether.

Ultimately, the decision to locate vehicle processing activities on a coorbiting facility rather than on the station requires a prioritization of national goals and, most likely, a compromise between conflicting requirements for science and exploration. The resolution of such conflicts is obviously well beyond the scope of this paper. However, it is clear that without a broad-based commitment from government, industry, and the public, ambitious projects such as lunar and planetary bases, and the facilities required for their success, can never become a reality. It is hoped that as NASA's Space Station Program and Office of Exploration proceed, such long-term goals continue to be articulated as being vital for the continued growth of the national space program.

Acknowledgments. This preliminary requirements definition and design effort was performed under contract NAS1-18000 directed by the Langley Research Center (LaRC). The authors appreciate the suggestions made by B. Pritchard and D. Weidman of the LaRC Space Station Office, W. Cirillo of PRC, and C. P. Llewellyn. Publication of this report does not constitute approval by NASA of findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

REFERENCES

Cirillo W. M., Ayers J. K., Kaszubowski M. J., Llewellyn C. P., Merideth B., and Weidman D. J. (1988) *Manned Mars Mission Accommodation—Sprint Mission.* NASA TM-100598.

Heck M. L., DeRyder L. J., and Orr L. H. (1985) *Articulated Space Station Controllability Assessment.* AIAA Paper 85-0024.

NASA (1969) *Spacecraft Gravitational Torques.* NASA SP-8024.

NASA (1971) *Spacecraft Aerodynamic Torques.* NASA SP-8058.

NASA (1986) *Natural Environment Definition for Design.* NASA, JSC30000, Appendix 3.1, Version 3.0.

Robertson B. P. and Heck M. L. (1987) *Spacecraft Attitude Control Momentum Requirements Analysis.* NASA CR-278219.

SDRC (1985) *IDEAS^2 User's Manual.* Structural Dynamics Research Corp., Cincinnati.

Sutter T. R., Cooper P. A., Young J. W., and McCutchen D. K. (1987) *Dynamic and Attitude Control Characteristics of an International Space Station.* AIAA Dynamics Specialist Conference, AIAA Paper 78-0931-CP.

Weidman D. J., Cirillo W. M., Llewellyn C. P., Kaszubowski M. J., and Kienlen E. M. (1987) *Space Station Accommodations for Lunar Base Elements—A Study.* NASA TM-100501.

Woo H. H., Morgan H. D., and Falangas E. T. (1986) *Momentum Management Concepts for a Space Station.* AIAA Paper 86-2047.

Woodcock G. R. (1986) *Space Stations and Platforms.* Orbit, New York. 232 pp.