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ORBIT DESIGN FOR A SPACE AMBULANCE VEHICLE

WALTER C. NELSON

ABSTRACT

A variety of rendezvous maneuvers are examined between space stations in geocentric orbits at altitudes ranging between 200 kilometers and geosynchronous altitude. Minimum times to complete rendezvous are studied for purposes of expediting crew patient transfer to an orbiting Medical Base Station (MBS). Stabilization of trauma and definitive care can be provided on the MBS for serious medical/surgical problems occurring during the course of space operations on some Space Station (SS) with less medical care capability remote from the MBS. The MBS to which the crew patient is to be transferred is assumed to incorporate the most advanced medical care capabilities in space. In the continuing exploration of space this MBS is regarded as a major element of a base station from which other satellite space stations will be operating. The rendezvous maneuvers examined are also applicable to healthy crew transfers and unmanned transfers between space stations in the year 2000 era when multiple space stations are planned to be operating, although with these types of transfers a minimum time constraint may not be applicable.

The vehicle to be used for crew patient transfers to the MBS will be referred to in this paper as a Space Ambulance Vehicle (SAV). The SAV is assumed to utilize two velocity impulses to complete rendezvous maneuvers between a SS and the MBS - one accelerating impulse when departing the SS and a second decelerating impulse prior to docking with the MBS. The velocity increments required for a SAV to execute a wide class of coplanar orbit transfers are examined between earth stations in orbits extending to geosynchronous altitude. In general these impulse velocity
increments will combine the propulsion requirements associated with coplanar orbit transfers and propulsion requirements associated with orbit plane changes accompanying most rendezvous maneuvers.

The conditions under which large expenditures of propulsive energy become a requirement for either coplanar transfers or orbit plane changes are described. Rendezvous maneuvers leading to requirements for four stage rocket designs are described. While such designs are not recommended to be pursued, it is felt that the examination of a wide spectrum of rendezvous scenarios will aid in establishing a class of achievable rendezvous scenarios for the year 2000.

Hohmann transfer orbits are not discussed in this paper because the constraints associated with their application to the design problems considered in this paper are too restrictive. Hohmann transfer orbits are generally thought of as one half of an elliptical orbit which is cotangential to two circular orbits of different altitudes. One of these circular orbits would correspond to the orbit of the MBS and the other to the orbit of some other SS. The elliptical orbit segment would be traversed by an SAV. Hohmann transfer orbits are minimum energy transfer orbits. Implicit in their application, however, is a waiting period, called the synodic period, during which the MBS and SS assume the appropriate relative positions to allow initiation of the Hohmann transfer. The more nearly the MBS and SS circular orbits are to the same altitude, the longer the synodic period. Clearly there can be no Hohmann transfer between space stations at the same altitude.

Recommendations are made relative to the planning of space operations which will aid in reducing both time and propulsive energy for rendezvous maneuvers should the necessity for crew patient transfer develop.

When the minimum time for crew patient transfer is not a requirement, it is described how low energy rendezvous maneuvers can be executed with arbitrarily low expenditures of propulsive energy.
A suggestion is offered to use throttleable engines when transferring a crew patient whose trauma, such as a spinal cord or head injury, could be exacerbated by excessive acceleration of the crew patient carrier vehicle.
Introduction

A scenario and sequence of events is introduced leading to establishing a need to rendezvous a seriously injured crew member of a space station with another space station incorporating the most advanced medical care facility in space. Returning the injured crew patient to earth for treatment is precluded from consideration because the objective of this paper is to evaluate a wide variety of rendezvous scenarios including the accompanying propulsion requirements. Terminology and vocabulary is introduced to facilitate the discussion. The initial scenario centers on the subject space stations moving in the same low earth orbit. Following the description of the orbit mechanics which lead to crew patient transfers in low earth orbit, the altitude of the subject space stations is progressively increased to geosynchronous altitudes. Every rendezvous maneuver requires at least two velocity increments, one to initiate the maneuver and one to complete the maneuver. For each of the space station scenarios described the associated rendezvous velocity increments are presented.

When the orbits of the space stations are not in the same plane, additional increments of velocity are required to execute rendezvous maneuvers. The formula for calculating velocity increments to effect orbit plane changes is presented.

Finally, the basic mechanics of propulsion system design is presented. Propulsion system designs are presented which are sufficient to accommodate some extreme requirements in terms of coplanar rendezvous maneuvers and/or some extreme orbit plane changes.

Some recommendations for further study efforts are offered and some conclusions are developed pertaining to anticipated space medical rescue operations in the year 2000 era.
LOW EARTH ORBITS

Consider initially a Space Station (SS) orbiting the earth at 200 kilometers altitude in which a crew member becomes ill or sustains injury. Because capabilities for treatment of the crew patient within the SS where illness or injury occur are deemed insufficient, it is concluded that (1) the crew patient's condition is too serious to evacuate directly to earth or (2) a vehicle for return to earth is not available and therefore, the crew patient must be transferred to an orbiting Medical Base Station (MBS) which currently incorporates the most advanced medical care capabilities in space. Assume also the SS and the MBS are in coplanar* orbits at the same altitude and the means exist using a Space Ambulance Vehicle (SAV) for transferring the crew patient to the MBS. Given these circumstances a primary consideration will be to complete the transfer in the shortest possible time and a secondary consideration will be to perform the transfer with a minimum acceleration stress to the crew patient and a minimum expenditure of propulsive energy.

Referring to Figure 1, suppose a crew member of a SS sustains trauma when the SS is located at Point A in its orbit. The SS is assumed to incorporate limited medical treatment capability. A period of time follows during which the SS moves from A to B and during which diagnosis is made and after consultation communications develop with a co-orbiting MBS which incorporates the most advanced medical capabilities in space. A decision is then made to transfer the crew patient to the MBS for further definitive treatment, since it has been determined that to return him to earth is not feasible. Another period of time follows during which the SS moves from B to C and during which preparations are completed to transfer the crew patient to the MBS. During this period it is assumed the crew patient condition is stabilized for orbit transfer. Corresponding to the A, B and C locations of the SS are the 1, 2 and 3 locations of the co-orbiting MBS. At point C the rendezvous operation is initiated assuming the necessary tracking, communications and computations of the rendezvous maneuvers have been completed. Thrust is applied to the SAV imparting to it the velocity impulse which brings the crew patient to the orbiting MBS.

*coplanar - the SS and MBS orbits are in the same plane
FIGURE 1 — RENDEZVOUS SCENARIO
Note the intervals A-B and B-C are indicated on Figure 1 to be fractions of one orbit period. These intervals could be shorter or much longer. Factors relating to the duration of these intervals include the specific character of the crew patient trauma, the capabilities aboard the SS for trauma diagnosis and treatment, the time consumed during communications with the MBS for aiding diagnosis and decision making, the capabilities aboard the MBS for rendering treatment to the crew patient, the time required to stow the crew patient in the SAV and the time required to ready the SAV with enroute patient care capability for departure from the SS.

In relation to readying the SAV for departure from the SS, a new engineering capability requirement can be identified. Both SS and MBS must be continuously tracked and their orbits continuously updated to permit design of the SAV transfer orbit including the magnitude and duration of the departing and docking rendezvous thrust levels (velocity impulses). The condition of the crew patient must also be continuously communicated to the MBS. It is presumed the tracking instrumentation and computational capabilities are contained aboard the MBS and SS with the aid of any Tracking Data Relay Satellite Systems (TDRSSs) which may be operational in the 2000 era.

Having predicated 200 kilometer altitude circular orbits for the MBS and SS, the SAV cannot move into a lower altitude orbit to effect completion of the rendezvous maneuver because this implies reentering the earth's atmosphere. It follows that the only method for bringing the SAV and MBS together is to increase the orbit period of the SAV. This means the dimensions of the SAV orbit must increase. An apogee altitude is pre-selected and thrust is applied to the SAV at Point C, so that it will return to Point C precisely at the time of arrival of the MBS. Referring again to Figure 1, the SAV moves from C to D along an elongated (elliptical) orbit while the MBS moves through a fractional orbit from 3 to 4 followed by another complete orbit revolution. The rendezvous is completed when the SAV arrives back at point D simultaneously with the arrival of the MBS at point 4. Following application of the retro velocity impulse to the SAV, docking with the MBS takes place and the crew
patient is moved into the MBS for further treatment. By then the MBS medical staff is fully aware of the crew patient's condition including any changes which may have developed enroute. The MBS medical facility is fully prepared to receive the crew patient and administer required treatment.

The following is an example which quantifies the steps just described. The initial orbit altitude of the SS and MBS is 200 km with the MBS on the exact opposite side of the orbit from where the first rendezvous velocity impulse is applied to the SAV - i.e., point C, Figure 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular orbit speed @ 200 km altitude</td>
<td>7784.2 m/s</td>
</tr>
<tr>
<td>and orbit period</td>
<td>88.5 minutes</td>
</tr>
<tr>
<td>Initial rendezvous velocity impulse</td>
<td>873 m/s</td>
</tr>
<tr>
<td>providing an orbit period of 1.5x88.5</td>
<td>132.7 minutes</td>
</tr>
<tr>
<td>and apogee altitude</td>
<td>4282 km</td>
</tr>
<tr>
<td>Final rendezvous velocity impulse</td>
<td>873 m/s</td>
</tr>
</tbody>
</table>

Two hours and 12.7 minutes is the earliest possible time following application of the initial rendezvous impulse for rendering treatment to the crew patient at the MBS. Referring to Figure 1, the elapsed time between points A and D will be \((x + 132.7)\) minutes where \(x\) is the time duration between points A and C and 132.7 minutes is the time duration between points C and D. The total velocity increment needed to execute this rendezvous maneuver is \(2 \times 873 = 1746\) m/s.

If treatment for the injured crew is not time critical, great savings of propulsive energy can be achieved. This could be accomplished simply by extending the time from the start to completion of rendezvous in integral multiples of the MBS orbit period. A velocity impulse is applied to the SAV which increases its orbit period by some small amount. The geometry of the orbit becomes elliptical, the apogee altitude becoming correspondingly greater than the circular orbit altitude of the MBS. The cumulative difference in orbit periods of the SAV and MBS is chosen
so that after a specified number of orbit revolutions the SAV and MBS meet at point D where a velocity impulse equal and opposite to the initial rendezvous impulse is applied to the SAV. Corresponding to the previous example, if the rendezvous elapsed time is extended to 100.5 revolutions (6.176 days) of the MBS, the propulsion system needs to provide only 26.0 m/s total or 13.0 m/s at the beginning and at the end of the rendezvous maneuver. Apogee altitude of the SAV transfer orbit is 244 kilometers. In this case the enroute medical care capability requirements for the SAV would increase to take care of the crew patient for 6.176 days in contrast to the earliest possible rendezvous time of two hours and 12.7 minutes.

NEAR EARTH ORBITS

As the altitude of the MBS increases, the option for a SAV to use a "catch up" orbit for rendezvous is presented. This permits the SAV to move to perigee before completing the rendezvous maneuver with the MBS. An important consideration, however, is that the altitude of perigee should be above the sensible atmosphere to prevent imposing a velocity loss on the SAV causing it to reenter.

Figure 2 shows a spectrum of "catch up" transfer orbits extending out to geosynchronous altitudes. These transfer orbits were assumed to be initiated from the SS with the SS and MBS co-orbiting at the same altitude. After the SAV initiates the rendezvous maneuver from the SS, the maneuver is completed when the SAV returns to the MBS altitude. The geocentric angle traversed by the SAV is 180° and in each case the perigee of the transfer orbit was chosen to be 200 kilometers. During this period of time the MBS traverses a geocentric angle which when subtracted from 180° provides the maximum lead angle, $\theta$, which permits successful achievement of these high energy rendezvous maneuvers. This is referred to as the "latest early" rendezvous maneuver for the SAV. "Early" refers to the SAV traversing a geocentric angle of 180° or less to complete rendezvous. "Latest" refers to the maximum geocentric separation of the SS and MBS which permits the SAV to complete the rendezvous maneuver after traversing a geocentric angle of 180°.
FIGURE 2 — SPECTRUM OF "LATEST EARLY" RENDEZVOUS ORBITS
As the altitude of the SS and MBS increase, the magnitude of the angle, $\delta$, increases. Figure 3 shows $\delta$ increasing from 0 degrees when the SS and MBS are at 200 km altitude to 160° when the SS and MBS are at geosynchronous altitude. With the SS and MBS at 200 kilometers altitude, the only technique available for achieving rendezvous is for the SAV to move to apogee before closing on the MBS. But with the SS and MBS at the geosynchronous altitude the MBS can lead the SS as much as 160° and the SAV has sufficient opportunity to achieve an early rendezvous.

In all the cases depicted in Figure 2, the "latest early" rendezvous is completed in 80 minutes or less. Figure 3, shows the elapsed time corresponding to the Figure 2 rendezvous maneuvers to extend from 45 to 80 minutes. These short intercept times are accompanied by substantial costs in terms of propulsive energy. For the particular example shown on Figure 2 when the SS and MBS are at geosynchronous altitude, the SAV requires a total velocity impulse of 33,278 m/s ($2 \times 16,639$ m/s) to complete the rendezvous maneuver.

It should be noted the data in Figure 3 presents the maximum velocity increment required for the SAV corresponding to the maximum allowable geocentric separation of the SS and MBS. Lower velocity increments are required for the SAV as the initial geocentric separation of the SS and MBS is decreased. Also, the elapsed time for the complete rendezvous maneuver will be correspondingly shorter.

**MBS and SS at Different Altitudes**

In general it cannot be expected that a given SS and the MBS will be conducting operations at the same altitude. Consequently the data in Figure 3 is a limited presentation of SAV rendezvous parameters. Without presenting quantitative information it will be described how the results of the data in Figure 3 can be extended.
FIGURE 3 - "LATEST EARLY" RENDEZVOUS REQUIREMENTS
In reference to Figure 4, a SAV based at a SS in orbit at an altitude greater than that of the MBS may initiate a rendezvous maneuver with the MBS from point A. It will be presumed that the SAV moves through the 200 km perigee altitude to complete the rendezvous. During the approach to perigee the SAV will pass through the altitude of the MBS corresponding to point B. The subsequent orbit segment will correspond precisely to one of the spectrum of orbits depicted in Figure 2.

It is clear that the elapsed time for the SAV to move from A to B is equal to the elapsed time for the MBS to move from point 1 to point 2 along its orbit. Also, point 2 on the MBS orbit is chosen to correspond to the geocentric lead angle for the "latest early" interception at point 3 and/or point C. Finally, the velocity impulse applied to the SAV at point A, will be lower than the impulse requirement shown on Figure 3 because the starting altitude was chosen to be higher.

Similarly, in reference to Figure 5, a SAV based at a SS in orbit at an altitude lower than that of the MBS may initiate a rendezvous maneuver with the MBS from point B. The corresponding location of the MBS on its orbit is point 3. The elapsed times between A and B on the orbit of the SS and between points 2 and 3 of the MBS orbit are equal. And again the rendezvous is completed at point 4 and/or point C. The SAV orbit segment, B-C, will correspond precisely to one of the spectrum of orbits depicted in Figure 2. Also point 3 on the MBS orbit is chosen to correspond to the geocentric lead angle for the "latest early" interception at point 4 as if the SAV had initiated rendezvous from point 1. Finally, the velocity impulse applied to the SAV at point B will be greater than the impulse requirement shown on Figure 3 because the starting altitude was chosen to be lower.

Other Rendezvous Options

When the altitude of the MBS is sufficiently great to permit the SAV to utilize space at altitudes lower than that of the MBS to accomplish rendezvous, other transfer orbit options become available. Reference Figure 6. Here the SAV based at a SS co-orbiting the earth in the same
FIGURE 4 — RENDEZVOUS — SS ORBITING AT AN ALTITUDE GREATER THAN THE ALTITUDE OF THE MBS
FIGURE 5 – RENDEZVOUS — SS ORBITING AT AN ALTITUDE LESS THAN THE ALTITUDE OF THE MBS
orbit as the MBS, initiates the initial rendezvous impulse at point A. The SAV orbit is designed to move through perigee and return to point A at the same time the MBS arrives at point A. The second rendezvous impulse is applied to the SAV to circularize the orbit and permit docking with the MBS to follow.

The data in Figure 7 summarizes SAV rendezvous maneuver requirements for the SS and MBS co-orbiting at altitudes extending to geosynchronous altitude. The MBS and SS are assumed in each case to be at the same altitude with the SAV departing the SS and moving through a 200 km perigee altitude before completing the rendezvous maneuver. Constraining the perigee altitude to 200 km permits defining the maximum lead angle, $\delta$, the MBS may have relative to the SS for successful completion of the rendezvous maneuver.

For the case where the MBS and SS are co-orbiting at an altitude of 1.06 earth radii, the initial velocity impulse applied to the SAV reduces its 5504 m/s circular orbit speed to 4448 m/s i.e. $\Delta v = 1056$ m/s. The resultant perigee altitude is 200 km and the transfer orbit period is 205 minutes. The lead angle $\delta$ of the MBS is 65° and is the maximum lead angle the MBS may have to permit an interception using this type of rendezvous maneuver. If perigee of the transfer orbit is progressively raised the MBS lead angle decreases as does the velocity impulse needed to effect rendezvous.

When the time to rendezvous is extended as described, the energy to achieve rendezvous is correspondingly reduced. As described for low earth orbits, the time to complete rendezvous can be increased almost indefinitely. An important associated constraint is that the time to complete rendezvous increases in integral multiples of the MBS orbit period.

**Orbit Plane Changes**

In general rendezvous maneuvers require the rendezvous vehicle (SAV) to change motion from the orbit plane of the SS to motion in the orbit plane of the MBS. This change of orbit planes imposes a propulsion
FIGURE 6 — RENDEZVOUS — SAV MOVES TO PERIGEE AND TRAVERSES A COMPLETE ORBIT BEFORE DOCKING WITH MBS
FIGURE 7—RENNDEZVOUS REQUIREMENTS
requirement on the rendezvous vehicle over and above the requirements needed to execute coplanar orbit transfers. The magnitude of the requirement depends on the orbit velocity of the SS and the angle between the orbit planes of the SS and MBS.

Given in terms of a velocity increment, $\Delta v$, this propulsion requirement is provided by the following equation

$$\Delta v = 2v \sin \frac{\theta}{2}$$

where $v$ is in m/s and is the orbit velocity of the SS and $\theta$ in degrees is the angle between the SS and MBS orbit planes.

In general the orbit plane of the rendezvous vehicle (SAV) will be different than the orbit plane of the SS or MBS. Consequently, it will be necessary to apply velocity impulse components to the rendezvous vehicle when initiating and when completing rendezvous. See Figure 8. However, if the line of intersection of the SS and MBS orbit planes passes through the point where the initial rendezvous thrust application is applied, then the plane change component of thrust is applied at the same time as the first rendezvous thrust impulse. And if the line of intersection of the SS and MBS orbit planes passes through the point where the final rendezvous thrust application is applied, then the plane change component of thrust is applied at the same time as the final rendezvous thrust impulse. For either of these two examples a single velocity impulse is sufficient to effect the necessary plane change for rendezvous.

The potential propulsion penalties associated with rendezvous orbit plane modifications can be very large. This becomes evident if one considers a single MBS accommodating crew patient transfers from polar to equatorial orbits or visa versa. Even when rendezvous maneuvers are nearly coplanar, the sensitivity of propulsion system designs to small plane changes can be pronounced. A one degree change of plane in low earth orbit requires a velocity component of approximately 135 m/s. The preplanning of space operations which preclude or minimize requirements for orbit plane changes will likely be imposed on crew patient orbit
FIGURE 8 — ORBIT PLANE CHANGE DURING RENDEZVOUS
transfers. Determination of acceptable levels of orbit plane changes for medical rescue is worthy of further study.

RENDEZVOUS PROPULSION SYSTEMS

Rendezvous maneuvers are characterized by the application of two velocity increments to the rendezvous vehicle. The first increment initiates the SAV rendezvous maneuver and the second increment completes the rendezvous maneuver and permits docking the SAV with the MBS. Achieving these velocity increments for many of the rendezvous scenarios described earlier poses a formidable propulsion engineering task. Visualizing the scope of the propulsion engineering task is aided with the application of the basic rocket equation for a single stage rocket.

\[ v = -g \text{Isp} \ln (1-f) \]

where

- \( v \) is the velocity increment attainable by a single rocket stage - m/s.
- \( \text{Isp} \) is the specific impulse and its value depends on the chemical properties of the propellant and design of the rocket - kg seconds of thrust/kg of propellant.
- \( f \) is called the fuel ratio and it is the ratio of the total weight of rocket fuel to the total rocket weight including propellant, structure and payload.
- \( g \) is the acceleration of gravity - 9.8 m/s^2.

Chemical propulsion systems are capable of providing specific impulse values of approximately 450 kilogram seconds of thrust per kilogram of propellant (e.g. liquid hydrogen and liquid oxygen). The fuel ratio, \( f \), is limited because it always takes a certain proportion of structure to contain a given quantity of fuel. Values in the neighborhood of 0.9 are still moderately difficult to achieve, the actual limit depending on whether the propellant is liquid or solid, the flight loads and other environmental conditions to be withstood, size of the rocket etc..
Consequently, single stage rockets are limited in the magnitude of the velocity increment they can impart to a payload. Given a specific impulse of 450 kg sec/kg and a fuel ratio of $f = 0.9$, this increment is approximately 10,000 m/s. Maintaining the specific impulse and reducing the fuel ratio to $f = 0.8$ the velocity increment is approximately 7,000 m/s. Notice these limits are independent of variation in design and hold in principle for any size rocket.

Multistage vehicles are required for rendezvous when the total required velocity increment exceeds the capability of a single stage vehicle. It follows that rendezvous maneuvers requiring up to 20,000 m/s (e.g. 10,000 m/s initiating and 10,000 m/s completing) require a 2 stage vehicle. Maneuvers requiring 20,000 m/s to 40,000 m/s require a 4 stage vehicle. Table 1 illustrates the development of the weight fractions for each stage of a 4 stage vehicle. The physical size of the total vehicle depends directly on the size of the SAV. Note also that the burnout weight of a given stage is distributed between the unexpended upper stages and the final stage structure. This weight distribution ratio was taken to be 1.0.

If the design weight of the SAV is to be 1000 kilograms, the total weight of a 4 stage rendezvous vehicle with a fuel ratio of 0.9, $I_{sp} = 450$ kg sec/kg and capable of providing a velocity increment of approximately 40,000 m/s would be 160,000,000 kilograms which would include 151,578,000 kilograms of propellant.

Similarly, if the design weight of the SAV is to be 1000 kilograms, the total weight of a 4 stage rendezvous vehicle with a fuel ratio of 0.8, $I_{sp} = 450$ kg sec/kg and capable of providing a velocity increment of approximately 28,000 m/s would be 10,000,000 kilograms which would include 8,888,000 kilograms of propellant.

The foregoing examples provide an indication of the complexity in terms of propulsion system design and operational utilization of multistage vehicles associated with implementing many of the rendezvous options presented earlier in this paper. Other ways of providing in orbit medical rescue will likely be developed. They are expected to be based on
Table 1 Examples of Allocation of Mass Components in a 4 Stage Rocket
preplanning of space operations which will preclude the need for
multistage propulsion systems

Rendezvous propulsion requirements can be limited by the use of a single
restartable engine factored into a core SAV. Determination of the
propulsion performance limits of such a system is worthy of further
investigation.

Throttleable Engines

It may be necessary to limit the acceleration applied to the SAV (and to
the crew patient) at the beginning and end of the rendezvous maneuver
depending on the nature of the crew patient's medical problems. Spinal
cord and/or head injuries will most likely reduce the g's a victim can
tolerate without exacerbating the injury. In any event, the fact that
specific crew trauma which may occur in a Space Station cannot be
predetermined, imposes requirements on propulsion systems to be used for
transferring incapacitated crew patients. Throttleable engines may
satisfy these propulsion system requirements. In addition, they could
be used to execute the docking or berthing maneuvers required to
complete all rendezvous operations.

The use of throttleable engines implies a degrading effect on the
transfer orbit performance figures quoted in this paper. This happens
because the time required to obtain the velocity increments for
rendezvous can become long compared with the duration of the rendezvous
period. No attempt has been made here to quantify this performance
degradation.
Rendezvous Capabilities Using A Single Stage Vehicle

In the year 2000 it is not anticipated that a multistage SAV will be a practical consideration. Therefore, given a single stage SAV some performance capabilities will be examined in terms of the transfer orbit scenarios described in earlier section of this paper.

Assumed SAV Characteristics

- Single Stage 10,000 kg SAV consisting of:
  - 1,000 kg for crew carrier compartment
  - 1,000 kg for structure and engine
  - 8,000 kg for propellant - liquid hydrogen, liquid oxygen
- Fuel Ratio 0.8
- Specific impulse - 450 kg sec/kg
- Total \( \Delta v = 7000 \) m/sec
- Total cost = $33,609,076
  - SAV - 1000 kg at $10,200/kg
  - Structure and engine 1000 kg at $10,200/kg
  - Liquid Hydrogen - 889 kg at $ 3.57/kg
  - Liquid Oxygen - 7,111 kg at $ 0.83/kg
  - Cost of delivery to Orbit - 10,000 kg at $1320/kg

Total Cost $33,609,076

Orbit Plane Changing

Because the \( \Delta v \) capability is limited to 7000 m/s, this capability must be budgeted between coplanar maneuver requirements and the requirements associated with orbit plane changing.

Operating between a SS and an MB\( S \) in low earth orbit, a SAV with a total \( \Delta v \) capability of 7000 m/s can execute
a plane change of 53.4°. If such a maneuver were executed no $\Delta v$ capability would remain for executing any required coplanar portion of a rendezvous maneuver.

However, as the operational altitude of the SS and MBS increases, the plane changing capability of the SAV increases. At geosynchronous altitude circular orbit speed is 3071 m/s. It follows that a SAV at geosynchronous altitude with a $\Delta v$ capability of 7000 m/s could execute a plane change of 180° and have a surplus $\Delta v$ capability of approximately 850 m/s which could be used for coplanar rendezvous maneuvering.

Coplanar Maneuvering in Low Earth Orbit

The maximum $\Delta v$ needed to complete an early rendezvous is associated with the SS and MBS operating in the same 200 km altitude orbit. In this case the SAV must traverse an orbit of double the orbit period of the SS/MBS orbit. The magnitude of this $\Delta v$ requirement is 4768 m/s - 2384 m/s for initiating the maneuver and 2384 m/s for completing the maneuver. This leaves a balance of $(7000-4768) = 2232$ m/s which may be utilized for orbit plane changing. At 200 km altitude 2232 m/s can provide a plane change of 16.5°.

Coplanar Maneuvering in Near Earth Orbit

The maximum altitude at which a "latest early" rendezvous maneuver can be executed with a SAV having a total $\Delta v$ maneuver capability of 7000 m/s is 0.6 $\text{re}$. See Figure 3. At this altitude 3500 m/s would be utilized to initiate rendezvous and 3500 m/s would be utilized to complete rendezvous.
To execute this type of rendezvous maneuver in conjunction with an orbit plane change would require executing the maneuver from an altitude lower than 0.6 \( r_e \).

Other Coplanar Maneuvering Options (Reference Figure 6)

The assumed SAV design is capable of executing all full orbit transfers between the SS and MBS regardless of the altitude at which these stations may be co-orbiting. Following the expenditure of the \( \Delta v \) capability needed to execute the coplanar portion of a given rendezvous maneuver substantial \( \Delta v \) margin will remain for orbit plane changing. For example, execution of a full orbit coplanar rendezvous between a SS and MBS co-orbiting at geosynchronous altitude requires a \( \Delta v \) expenditure of 3140 m/s. This leaves a \( \Delta v \) balance of 7000 - 3140 = 3860 m/s for orbit plane changing. The magnitude of the plane change 3860 m/s can produce at geosynchronous altitude is 77.7°.

Conclusions

- A minimum time approaching one orbit period (88.5 minutes) of the MBS exists in low earth orbit for the transfer of the SAV between the SS and MBS. Performing this rendezvous maneuver in a period of time approaching one orbit period of the MBS requires an arbitrarily small amount of propulsive energy.

- When the time for the SAV to complete transfer between the SS and MBS in low earth orbit approaches 2 orbit periods of the MBS (177 minutes) the propulsive energy required to execute the rendezvous is maximized (4768 m/s - initial impulse = 2384 m/s and final impulse = 2384 m/s).
o When the time for the SAV to complete transfer between the SS and MBS in low earth orbit is extended beyond 2 MBS orbit periods, the propulsive energy required for rendezvous can be progressively reduced to arbitrarily small levels.

o Because the specific character or severity of trauma suffered by SS crew members and the urgency of some specific treatment needed within a specific time cannot be predicted, a requirement for throttleable engines should be placed on the design of the SAV.

o Space Stations operating in the 2000 era should be capable of conducting operations independent of real time earth based assistance. The capabilities for performing communications, computations, command, control and tracking should be contained within the operating space stations with the aid of any Tracking and Data Relay Satellite Systems which may be operational. Included in these capabilities should be equipment which utilizes tracking data for orbit computations and ephemeris generation.

Tracking information should be utilized to generate all viable rendezvous options on a continuous basis to permit selecting the most desirable option for SAV transfer if a crew patient transfer requirement develops.

o As the altitude of the SS and MBS orbits increase, the time available for accomplishing rendezvous maneuvers in less than one orbit period of the MBS increases. The propulsion required for the "latest early" rendezvous is greater the greater the altitude of the SS and MBS orbits.

o If the opportunity is missed to accomplish rendezvous between the SS and MBS prior to the elapse of the "latest early" option, subsequent opportunities can be utilized by the SAV moving to apogee beyond the altitude of the MBS. Then the time to complete rendezvous will involve an integral multiple of the MBS orbit period. Associated
propulsion requirements will maximize when the SAV utilizes two orbit periods of the MBS to complete rendezvous. SAV propulsion requirements become arbitrarily small when the time to complete rendezvous approaches one MBS orbit period or when the SAV transfer time becomes indefinitely large in integral multiples of the MBS orbit period.

The SAV may also accomplish rendezvous by maintaining apogee at the altitude of the SS in which case the time for rendezvous is some fraction of the MBS orbit period. Associated velocity requirements are less than 3000 m/s for SS and MBS altitudes as great as geosynchronous altitude.

- The planning of space operations which pose the threat of injuring or incapacitating SS crew members should be accompanied with planning the ephemeris of the SS and MBS such that if rendezvous becomes a requirement that the SAV transfer operations are capable of being accomplished in a minimum time period with minimum propulsive energy.

- Rendezvous operations requiring orbit plane changes should be minimized. This can be accomplished by preplanning space operations which could lead to a need for medical rescue. This in turn minimizes the velocity increments needed for rendezvous maneuver plane changes and, therefore, minimizes the size of the SAV propulsion system.

- Rendezvous operations requiring velocity increments leading to a need for multistage propulsion systems should be avoided. This can be accomplished by the preplanning of space operations.