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PERFORMANCE OF RECOVERABLE SINGLE AND MULTIPLE SPACE TUGS FOR MISSIONS BEYOND EARTH ESCAPE

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PERFORMANCE OF RECOVERABLE SINGLE AND MULTIPLE SPACE TUGS FOR MISSIONS BEYOND EARTH ESCAPE

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ABSTRACT

A recoverable Space Tug launched by the Space Shuttle can provide the required post-orbital propulsion needed for placement of unmanned satellites. The Space Tug will also be used to launch interplanetary spacecraft from low earth orbit. This study summarizes the performance of single and multiple Space Tugs (in tandem) for launching spacecraft beyond earth escape. Trajectories are developed that allow recovery of the Tugs whenever practical. The effects of important Tug and trajectory parameters on performance are presented. It is concluded that a single Tug can inject spacecraft to Mars or Venus and still be recovered. The use of several Tugs in tandem can provide a significant increase in capability over the use of a single Tug. The more difficult missions involve a mix of recovered and expended Tugs.

INTRODUCTION

The Space Shuttle is planned to be operational by the end of 1979 and will launch not only manned NASA missions but essentially all unmanned spacecraft as well. The Space Shuttle will have a payload capability of 65,000 pounds for a due East launch into a low earth orbit. However, this payload capability falls off rapidly as the mission energy is increased. Review of typical long range mission plans indicates that most unmanned spacecraft or satellite deployment missions will require additional post-orbital propulsion, beyond what the Space Shuttle can provide. Long range NASA plans include the eventual development of a reusable Space Tug to provide the required post-orbital propulsion. The Space Shuttle will carry the Space Tug and payload to low earth orbit in its cargo bay. The Tug and payload are then deployed, and the Tug will inject the payload to its mission destination. In most cases sufficient propellant will be left in the Tug so that after injecting the payload, it can return to low earth orbit. Following rendezvous with the Space Shuttle, the Tug is returned to Earth for refurbishment and reuse.

The principal design mission for the Space Tug is the geostationary mission (synchronous equatorial orbit). This is logical since perhaps half the expected Tug missions will be to geostationary orbit, and it is essential that the Tug be able to accomplish this mission in a recoverable mode. The Tug is to have the capability of not only

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delivering payloads to geostationary orbit but also the capability of retrieving payloads when required. For planning purposes it has been specified that the Space Tug should have a design goal of being able to "round trip" a 3000 pound payload for the geostationary mission. Most Tug design studies to date have been directed primarily at defining the performance and system implications underlying this goal.

Since the Space Shuttle/Tug system will be used to launch interplanetary spacecraft, it would also be desirable to be able to recover the Tug after injecting spacecraft to energies beyond earth escape. The feasibility and system implications of achieving this capability have received less study. The optimization of round trip Tug trajectories for missions beyond earth escape is developed in reference 1. The purpose of this paper is to summarize and extend the results of reference 1. Also, since some future planetary missions will exceed the capability of a single recoverable Tug, the performance and mission characteristics associated with the use of an assembly of multiple Tugs to do the more difficult planetary missions will be discussed.

SPACE TUG ASSUMPTIONS

The Tug performance for this study is based on a single stage configuration, using oxygen-hydrogen propellants and having the capability of performing a round trip mission to the geostationary orbit with a 3000 pound payload. It should be recognized, however, that other Tug configurations are also under study. The performance assumptions for this study are summarized in Table I.

TABLE I

PERFORMANCE ASSUMPTIONS

Assumed	
Space Shuttle 100 N.MI. due East capability (lb)	65,000
Space Shuttle Tug and payload support weight (lb)	3,000
Space Shuttle deployed payload capability (lb)	62,000
Space Tug main engine specific impulse (sec)	470
Round trip geostationary payload (lb)	3,000
Flight performance Reserve (% of delta V)	2
Derived	
Required Space Tug stage mass fraction	0.892
Space Tug usable propellant capacity (lb)	52,640
Tug empty weight (lb)	6,360

The Space Shuttle is assumed to have a low earth orbit payload capability of 65,000 pounds which is a Space Shuttle specification. For convenience, the staging orbit in this study is assumed to be 100 N. MI. The best staging orbit altitude has not been established and will probably be mission dependent. A certain amount of Space Tug to Space Shuttle interface structure and equipment will have to be installed in the orbiter and is chargeable to Shuttle payload. This equipment, which stays with the orbiter, is arbitrarily assumed to weigh 3000 pounds in this study, allowing a deployed payload weight (including the Tug and spacecraft) of 62,000 pounds. The Space Tug is assumed to have a new, high performance main engine with a specific impulse of 470 seconds. As mentioned earlier, the specified mission for the Tug is to perform a round trip geostationary mission carrying a 3000 pound payload up and back. A flight performance reserve equivalent to 2 percent of the total mission delta V was used in the performance calculations. Using the assumed Tug gross weight and 470 second specific impulse, the required stage mass fraction to perform the 3000 pound round trip mission is .892. The stage mass fraction has the usual definition - the ratio of usable propellant weight to stage propellant plus empty weight. The associated Tug propellant and empty weights are 52,640 and 6,360 pounds respectively. The Tug performance characteristics summarized in Table I were used as the basis for studying the earth escape missions. It should be recognized that the stage mass fraction of .892 was not based on a design study but derived as being required to achieve the design mission. Also, in a detailed mission simulation, specific account should be taken of all non-impulse expendables such as engine start-up and shut down losses, boil-off, leakage, etc., rather than averaging these effects in to the stage mass fraction. However, the assumptions presented in Table I are adequate for the purpose of this exploratory study.

PERFORMANCE OF A SINGLE SPACE TUG

General performance - Using the assumptions of Table I, the general performance of a single Space Tug is summarized in figure 1. The data are ideal in that it was assumed that the required mission velocities (both outbound and return) could be imparted impulsively by the Tug, ignoring the fact that the Tug will have a finite burn time. The gravity losses and other mission constraints imposed by a finite Tug thrust level, while not serious for earth orbit missions, can be significant for earth escape missions as will be discussed later.

Achievable payload is shown as a function of the mission delta V which the Tug has to provide. Several typical Tug missions are indicated on the abscissa. As would be expected, maximum mission capability is achieved by using all the Tug propellant to inject the payload and expending the Tug (solid curve). The broken curves of figure 1 show mission performance where sufficient propellant is left in the Tug so that it can return to the Shuttle. In these cases, the Tug supplies the mission delta V twice, once in delivering the payload to the required mission delta V and again in returning to the Shuttle. Three cases are shown (1) a delivery mission where the Tug delivers the payload to the required mission delta V and only the Tug returns to the Shuttle, (2) a retrieval mission where the Tug goes out without a payload and retrieves a payload, and (3) a round trip mission where the Tug both delivers and retrieves equal payload weights.

Examining the geostationary mission, the Tug can perform a round trip mission with a 3000 pound payload - as was specified. It can retrieve a payload of over 4000 pounds or deliver a payload (still recovering the Tug) of almost 8000 pounds. If higher delivery payloads are required, the Tug could be expended to achieve a maximum delivery capability of approximately 17,000 pounds. It should be noted that whenever the Tug is launched with a payload exceeding 3000 pounds, the Tug propellant has to be off-loaded to stay within the Space Shuttle maximum lifting capability of 65,000 pounds. This accounts for the superior performance of the retrieval mission at high payloads as shown in figure 1. At high payloads the Tug has to be severely off-loaded for both the expendable and recoverable delivery missions, whereas in the retrieval mission the Tug can still be launched with a full propellant load.

Regarding missions beyond Earth escape, the recovered Tug can deliver significant payloads to Mars and Venus class missions whose delta V requirements lie between the earth escape and geostationary mission delta V requirements. Consequently, it is of interest to examine the feasibility of actually returning a Tug from these post earth escape trajectories.

Characteristics of trajectories for a single recoverable Space Tug for missions beyond earth escape - The ideal strategy for injecting payloads to velocities beyond earth escape with a recoverable Tug would be to impart the required velocity to the payload impulsively (instantly), separate the payload, and then impulsively remove this velocity from the Tug. In this case the Tug would never leave the low earth orbit and maximum mission performance would be achieved. (As a general rule-of-thumb, it is best to make all major delta V maneuvers at as low an altitude as possible for the type of missions considered in this study.) In addition, since the Tug (in this ideal case) never leaves the orbit of the Shuttle, the problem of subsequent rendezvous with the Shuttle is minimized. The ideal impulsive maneuver is not possible since the Tug will have a finite thrust level, but it will be used in the following discussion as a benchmark against which the real cases can be measured.

In the real case where the Tug has a finite thrust level, it is not practical to keep the Tug in the initial low earth (Shuttle) orbit, and the resultant trajectory is more complicated. This trajectory problem was formulated using the variational maximum principal (reference 1) and solutions were obtained using a digital computer. An illustration of an optimum trajectory is shown in figure 2. The job of the Tug is to inject the payload onto the required earth escape hyperbola. This is accomplished in the first main burn departing from the initial Shuttle orbit. With a finite thrust Tug, the main burn can be quite long, and the altitude at the end of the burn will be significantly higher than the initial starting altitude. For example, if the Tug had a thrust level of 20,000 pounds (which is in the upper range of thrust levels being considered for the Tug), the total Tug burn time is approximately 20 minutes, most of which is associated with the first main burn. At the end of the main burn the altitude has increased to typically 600 nautical miles. At this point the payload is separated from the Tug, and the Tug must be turned around in preparation for the return back to low earth orbit. In the meantime, the Tug is coasting even further from the Earth along the payload trajectory and could reach altitudes above 1000 nautical miles. Because of the high altitudes encountered at initiation of the return burn, it is relatively inefficient compared to the ideal case. The optimum solution is to minimize the amount of the return burn done at high altitude by doing it in two main parts, (1) a retro burn done as soon as possible after payload injection and (2) a subsequent circularization burn back into the Space Shuttle orbit. The retro burn removes velocity from the Tug, changing its trajectory from the escape hyperbola to a highly elliptical earth orbit with a perigee altitude close to the initial low earth orbit. The Tug then coasts around this elliptical transfer orbit to near perigee where it does the final burn into the low circular Shuttle orbit. The optimum trajectory generally includes a very small burn near apogee of the transfer orbit to adjust its perigee to the value desired for initiation of the final circularization burn.

In implementing the mission shown in figure 2, two constraints have to be placed on the optimum trajectory. First, the optimum solution would like to start the retro burn immediately following the main burn. Some time has to be specified to allow for separating the payload and turning the Tug around. This time will be referred to as the turn-around-time or TAT. The retro burn is essentially opposite to the velocity vector, and therefore the Tug has to be rotated approximately 180 degrees. This introduces another problem in that the exhaust plume during the retro burn is oriented in the direction of the separated spacecraft. The specified TAT may have to be lengthened to allow build up of sufficient separation distance between the Tug and payload so that the exhaust plume will not damage the spacecraft.

A constraint also has to be placed on the total Tug trip time from start of the Tug first main burn to return to the Shuttle orbit. This total-trip-time will be referred to as the TTT. The optimum solution tries to minimize the length of the relatively inefficient retro burn by leaving the Tug in a highly elliptical transfer orbit with an impractically long period. Consequently, the optimum trajectory has to be constrained to return the Tug to the Shuttle orbit within an acceptable total-trip-time (TTT).

<u>Effect of TAT and TTT constraints</u> - The effect of constraints on TAT and TTT for a recoverable Tug injecting a payload onto a typical Mars or Venus trajectory is shown in figures 3 and 4. Figure 3 shows the effect of the TAT on payload for a recoverable Tug with a thrust of 20,000 pounds and a TTT of 24 hours. The ideal capability (assuming all the maneuvers are impulsive and occur in low earth orbit) is 10,000 pounds. Even at zero turn-around-time the payload loss is almost 10 percent, due primarily to the finite thrust level. As expected, the payload loss increases with increasing values of TAT, since the retro burn has to be done further from Earth. The required turn-around-time has not been

established, but for the remainder of this study it is set at 3 minutes. This should allow sufficient time for turning the Tug around and initiating the retro burn. Also, if the payload were given a separation velocity of 10 feet per second immediately upon injection, this would provide a separation distance of 1800 feet to ease the plume impingement problem.

The effect of a constraint on the Tug total-trip-time for the same mission is shown in figure 4. Again, the recoverable Tug is assumed to have a thrust of 20,000 pounds, and the turn-around-time is 3 minutes. Best performance is obtained by going to an infinitely long trip time since this minimizes the length of the retro burn. (However, the payload loss compared to ideal impulsive would still be on the order of 10 percent - due primarily to the finite thrust level.) Fortunately, total-trip-times from 24 to 48 hours give close to the best performance achievable. These total-trip-times are well within the Space Tug capability which is specified to have up to a 6 day space staytime capability.

Use of perigee propulsion - Figures 3 and 4 show that there can be significant payload losses for missions beyond Earth escape associated with the finite thrust level of the Space Tug. These losses can be reduced by utilizing a technique referred to as perigee propulsion. With perigee propulsion, the main burn which places the payload on its hyperbolic trajectory is broken into two parts. An illustration of perigee propulsion is shown in figure 5. In the first main burn, only part of the required mission energy is added to the payload and the burn is terminated while the Tug and payload are still below earth escape energy and in an elliptic earth orbit. The Tug and payload are allowed to coast around this orbit and upon approaching perigee, a second main burn provides the remainder of the required mission energy. The second main burn is accomplished just prior to reaching perigee after coasting around the first orbit. The payload is separated and the turn-around-time (TAT) coast takes place while passing through perigee. At this point the Tug is on the same escape hyperbola as the payload, and the Tug retro burn takes place after perigee passage putting it back into an elliptical earth orbit. The Tug coasts around this second orbit and performs the final circularization burn upon approaching perigee again.

The use of perigee propulsion reduces the losses associated with a finite thrust Tug since both the second part of the main burn and the retro burn are accomplished at lower altitudes (closer to perigee) than before. It introduces the complication of an additional burn and the necessity of orbiting the Earth in a highly elliptic orbit twice. However, even when total-trip-time (TAT) is constrained to reasonable values, the use of perigee propulsion can, in some cases, reduce performance losses substantially as will be shown. The use of perigee propulsion is not restricted to the case of a single recoverable Tug and can also be used on missions employing a single expendable Tug. It can be especially advantageous for missions using multiple Tugs as will be shown later.

Effect of Space Tug thrust level - The Space Tug main engine thrust level is the major factor affecting trajectory performance losses for missions beyond earth escape. As the Tug thrust level is increased, the trajectory or "gravity" losses decrease. On the other hand, engine weight and length increase. Consequently, in selecting a Tug thrust level to maximize mission performance it is necessary to strike a balance between trajectory losses and engine weight. In the next several figures this tradeoff will be examined for several typical Tug missions. The engine weight and performance data used for the tradeoff study are shown in figure 6. The data were taken from reference 2 and represent estimates for a new staged-combustion cycle, oxygen-hydrogen engine with a nozzle expansion ratio of 400. The engine weight data of figure 6 were used to modify the stage mass fraction and Tug empty weight shown in Table I. The slight variation in specific impulse with thrust level was also used.

It should be recognized that as thrust level is varied, the Tug empty weight will be influenced by more than just the engine weight. It would be expected that there would also be some variation, for example, in thrust structure and propellant system weight. Determination of the total effect of engine thrust on stage weight would necessitate carrying out Tug designs over a range of thrust levels, which was beyond the scope of this exploratory study. In this study only the engine weight change with thrust level was accounted for, since this would be the principal weight change. However, with this simplifying assumption the following results are somewhat biased in favor of the higher thrust levels.

Before discussing the effect of Tug thrust level on performance for missions beyond earth escape, it is important to consider the effect on geostationary mission performance. It is essential that the choice of a Tug thrust level not seriously compromise performance for the geostationary mission. The effect of Tug thrust level on geostationary mission performance for both payload delivery and round trip missions is shown in figure 7. In both cases, the Tug is recovered. The technique of perigee propulsion can also be applied to the geostationary mission by breaking the first burn into two parts. These results are indicated by the dashed curves. Considering the round trip mission without perigee propulsion first, best performance is obtained with a Tug thrust level in the neighborhood of 15,000 pounds. Thrust levels from 10,000 to 30,000 pounds can be selected without introducing a major penalty. Below 10,000 pounds thrust the gravity losses increase rapidly, whereas above 20,000 pounds the gravity losses become negligible, and the increasing engine weight decreases performance. Similar results are shown for the payload delivery mission. The reader should be cautioned that since only engine weight effects were included, the curves should probably drop off somewhat more steeply at higher thrust levels.

With perigee propulsion a slightly higher performance is achieved, and the best thrust levels shift to somewhat lower values. The performance benefits associated with perigee propulsion will be negated to some extent by losses associated with increased coast time and the requirement for an additional engine start up. These are expected to be small and were not assessed in this study. On balance, it does not appear that the rewards associated with perigee propulsion in comparison to the increased mission complexity warrant its regular use for the geostationary mission. Thus, the Tug thrust level should be selected based on the case without perigee propulsion.

In choosing a Tug thrust level, other factors in addition to mission performance need to be considered. Higher thrust levels lead to longer engine lengths which reduces the cargo bay volume available for payload. This introduces the need to optimize engine expansion ratio or consider the use of a retractable nozzle. Normally, it would be expected that smaller engines would have lower development costs. However, in the case of the high performance, high chamber pressure staged combustion engine, small engine sizes introduce increasingly difficult technology problems. The larger sizes should be easier and possibly cheaper to develop. Historically, there has been a desire to uprate operational engines to meet expanding mission needs. If the Space Shuttle capability were improved in later years, the Tug propellant capacity could be increased to match this growth. However, if a relatively low thrust Tug engine was developed, future stage weight growth would lead to a rapid increase in gravity losses. It is clearly beyond the scope of this paper to resolve these and other considerations regarding the choice of Tug thrust level. It does appear, however, that the competitive range of thrust levels for the geostationary mission will lie between 10,000 and 20,000 pounds, and it would be informative to consider other Tug mission applications before making a final selection.

The effect of thrust level on the performance of a recovered Tug delivering a payload onto a typical trajectory to Mars or Venus is shown in figure 8. Since the influence of TAT and TTT constraints on the choice of thrust level were not known, two sets of values are shown (1) an optimistic set with a TAT of one minute and a TTT of 48 hours and (2) a conservation set with a TAT of 6 minutes and a TTT of 12 hours. As can be seen from figure 8, the choice of TAT and TTT constraints directly affects the payload level, but the choice of Tug thrust level is relatively unaffected, especially without perigee propulsion. In general, the best thrust levels occur at values unacceptably high for a geostationary mission. However, a thrust level of 20,000 pounds will provide close to best performance. Payload losses increase below a thrust of 20,000 pounds and below 10,000 pounds, payload falls precipitously - even with perigee propulsion. Perigee propulsion only appears warranted if the Tug has a low thrust level.

Another interesting class of missions for the Space Tug is the injection of payloads to the outer planets such as Jupiter and Saturn. As was shown in figure 1, these missions cannot be accomplished by a single recoverable Tug since the mission delta V is too high. The Tug has to be expended. The effect of thrust level on the performance for a typical outer planet mission is shown in figure 9. Since the Tug is expended, there are no TAT or TTT constraints for this mission. With no perigee propulsion, the best thrust levels occur at values unacceptably high for the geostationary mission. With a thrust level of 20,000 pounds there is a noticeable payload loss, and at a thrust of 10,000 pounds the payload loss is unacceptable. For this mission, the use of perigee propulsion appears more attractive than before. With perigee propulsion a thrust level of 20,000 pounds gives close to best performance. At 10,000 pounds thrust there is a noticeable payload loss, and below 10,000 pounds the losses increase markedly.

For a single Space Tug it can be concluded that thrust levels in the range from 10,000 to 20,000 pounds are of interest for the geostationary mission and that missions beyond earth escape would favor a choice closer to the upper end of this range.

PERFORMANCE OF MULTIPLE SPACE TUGS

As has been shown, the single Space Tug (either reusable or expendable) provides a substantial capability for future planetary missions. However, planetary missions have and will be proposed that require more than this capability. This is especially true for missions that require propulsion after earth departure such as planet orbiters, comet and asteroid rendezvous, and sample return missions. In these cases, the payload weight injected onto an earth departure trajectory by the Tug includes not only the science payload but the weight of the deep space propulsion as well. One approach to providing the required increase in earth departure weight is to consider the use of multiple Space Tugs. Multiple Space Shuttle launches would be used to place several Space Tugs in low earth orbit along with the mission payload. The Tugs would rendezvous in orbit and be assembled into a larger vehicle.

The proposal is to assemble the Tugs into a tandem vehicle as shown in figure 10. Each Tug would be launched to orbit by a separate Space Shuttle launch. The payload would be launched along with the upper Tug, or in the case of very heavy or voluminous payloads, it could be launched separately. Since the baseline Tug is to have the capability of rendezvous, docking and retrieving payloads, the Tugs will have the inherent capability of rendezvous and docking with each other to form the tandem vehicle. In performing the mission, the Tug stages will burn sequentially, and each stage, if it is to be recovered, will return on its own. The use of a tandem arrangement will minimize the required Tug modifications. Once assembled, vehicle axial loads are due only to the Tug engine thrust and are no higher than in the single Tug case. Since the assembled vehicle only operates outside the atmosphere where disturbances are small, engine gimbal angle requirements and the associated vehicle bending moments should be low. The Tug stage structure should be unaffected except for provision of interstage adapters and relocation of the docking equipment. Each stage navigates from the start of the mission, but guidance would not be enabled until the stage below was jettisoned. This approach should minimize the amount of overall vehicle astrionics integration. A brief study has recently been completed, examining the Tug modifications required for the tandem vehicle (reference 3). This preliminary study indicated that the tandem arrangement was feasible, and the Tug modifications were relatively minor.

Cost assumptions - In examining the performance of a multiple Tug vehicle, a large number of options are possible. The number of Tugs in the vehicle can be varied. The individual Tugs can be expended or recovered, and the payload can be launched to orbit separately or along with one of the Tugs. These options lead to a large number of competing vehicle possibilities on an overall performance plot similar to figure 1. For the mission planner, the option of greatest interest is the vehicle that can deliver his payload to the required mission energy at the lowest transportation cost. In the following discussion, example costs will be assigned in an effort to present performance data for only the more interesting vehicle combinations. The example costs used in this study are as follows:

1. Each Space Shuttle launch is assumed to cost 10 million dollars. This is close to the current NASA estimate of the recurring cost per Shuttle flight.
2. Each recovered Space Tug is assumed to cost one million dollars for stage operations and refurbishment. This cost has not been firmly established but is expected to be relatively low.
3. Each expended Space Tug is assumed to cost 15 million dollars, primarily for replacement of a Tug in the vehicle inventory. The recurring cost of a new Tug has also not been firmly established, and the 15 million dollars is used as an example. The real problem here is that it is not clear that the entire cost of a new Tug should be charged against the mission on which it is expended. If the Tug had been previously used a number of times in a recovered mode, part of the Tug acquisition cost could have been amortized against the recoverable flights. To illustrate this possibility, data are also presented where the cost charged for expending a Tug is arbitrarily taken at 5 million dollars.

Ideal performance of multiple Space Tugs - Using the Tug performance assumptions of Table I and the cost assumptions just discussed, the performance of multiple Space Tugs in a tandem arrangement is summarized in figures 11 and 12. The performance is based on ideal, impulsive maneuvers, and effect of finite Tug thrust levels and mission constraints will be discussed later. The assumptions for figures 11 and 12 are the same except for the cost charged for an expended Tug, which is taken as 15 million dollars for figure 11 and 5 million dollars for figure 12. Consider figure 11 first. The most cost effective vehicle for each region on the map is indicated by the coding shown. The first digit shows the number of Shuttle flights required to launch the Tugs and payload. The second digit indicates the number of expended Tugs in the assembled vehicle and the third digit the number of recovered Tugs. For example, the (2, 1, 1) code indicates that two Shuttle launches are used to place two Tugs and the payload in orbit. One Tug will be expended and one recovered. Whenever a mix of recovered and expended Tugs is used, the recovered Tugs are the lower stages (burned first), and the expended Tugs are the upper stages since this is the optimum arrangement. Whenever the number of Shuttle launches exceeds the number of Tugs, for example (2, 0, 1), this implies that the payload is brought up in a separate Shuttle launch. This mode is effective only at the higher payload weights. Otherwise, the payload is brought up with the uppermost Tug which necessitates propellant off-loading whenever the payload exceeds 3000 pounds.

The two digit number following the vehicle coding is the total recurring transportation cost per launch. For example, the (3, 1, 2) configuration of figure 11 has a 47 million dollar launch cost - 30 million for three Shuttle launches, 15 million for one expended Tug and 2 million for two recovered Tugs. In all cases, it is assumed that a recovered Tug is brought back to Earth with one of the Shuttles used to launch the Tugs and payload. No additional Shuttle cost is charged for returning a Tug.

Examining the geostationary mission on figure 11, the single recoverable Tug (1, 0, 1) can deliver close to 8000 pounds as was discussed earlier. Launching the payload separately (2, 0, 1) increases the payload to about 11,000 pounds, but at the cost of another Shuttle launch. More impressively, two Shuttle flights with two recoverable Tugs (2, 0, 2) can increase the delivered payload to about 24,000 pounds, assuming there is adequate cargo bay volume for a Tug and this payload weight. If a third Shuttle launch is used to bring up the payload (3, 0, 2), even higher values of delivered payload can be achieved. A single expendable Tug (1, 1, 0) could be used to deliver about 17,000 pounds to geostationary orbit, but with the cost assumptions of figure 11, this would be more expensive than using the (2, 0, 2).

Regarding planetary missions, consider as an example a 5000 pound spacecraft. The single recoverable Tug can deliver the 5000 pound spacecraft to a delta V of about 15,000 feet per second. The next step would be to use two recoverable Tugs in tandem (2, 0, 2) which can deliver the 5000 pound spacecraft to a delta V of over 19,000 feet per second. Beyond this delta V, it becomes too difficult to recover the uppermost Tug, and the best approach is to use a single expendable Tug (1, 1, 0) out to a delta V of 25,000 feet per second. Beyond this, the (2, 1, 1) or (3, 1, 2) configuration can be used to deliver the 5000 pound spacecraft to delta V's of almost 33,000 or 37,000 feet per second, respectively. To cite a specific mission, the (1, 1, 0) configuration can inject a 3000 pound payload onto a 3 year trip to Saturn. This would be adequate for a flyby mission but marginal for an orbiter where the spacecraft weight has to include the planetary retro propulsion. The (2, 1, 1) configuration will allow a spacecraft weight of over 9000 pounds and the (3, 1, 2) a spacecraft weight of over 14,000 pounds.

If the cost charged for the expended Space Tug is changed from 15 million dollars (figure 11) to 5 million dollars (figure 12), the performance of a given vehicle configuration is, of course, unaffected. However, the choice of a most cost effective vehicle configuration at any given point on the performance map can be affected - as can be seen by comparing figures 11 and 12. In figure 12, for example, the use of a (1, 1, 0) configuration is preferred over the (2, 0, 2) since its cost is now lower. In either case, figures 11 and 12 show that the use of multiple Tugs can substantially increase the long range potential of the Space Shuttle Tug system for performing future unmanned missions.

The use of multiple Tugs necessitates multiple Shuttle launches over a period of days. Also, some of the Shuttles will have to wait in low earth orbit while the Tugs are assembled and for return of the recoverable Tugs. These operational problems were examined briefly in reference 3. Based on this preliminary study, the use of multiple Tugs up to the (3, 1, 2) configuration appeared feasible.

Effect of a finite Tug thrust level - Figures 11 and 12 presented the ideal impulsive performance of multiple Tug vehicles. This performance is optimistic since no account was taken of the effects of finite Tug thrust levels and real trajectory constraints. These effects have been studied for most of the vehicle combinations shown, but for brevity only the results for two of the more interesting cases will be discussed. In the following discussion the recovered Tug total trip times (TTT) are limited to 48 hours and the turn-around time (TAT) is set at 3 minutes.

The most complicated trajectory is associated with the (3, 1, 2) configuration using perigee propulsion. An illustration of this trajectory is shown in figure 13. For reference, a sketch of the (3, 1, 2) vehicle is also shown on the figure. The vehicle is assembled in the Shuttle circular parking orbit. Phase 1 is the main burn of the first Tug stage. At the end of phase 1, the vehicle is still in an elliptic orbit, since with the weight of two Tugs on top, the first Tug main burn cannot reach earth escape. The vehicle coasts to apogee along coast phase 2 during which the first Tug stage is separated from the vehicle. The first Tug stage does a small perigee correction maneuver in propulsion phase 3 which is near apogee. The first Tug stage then descends to perigee along coast phase 4 and does a final circularization burn back into the Shuttle orbit in propulsion phase 5.

In the meantime the remainder of the vehicle has also coasted to apogee along coast phase 2. If perigee propulsion were not used, stages 2 and 3 would have been fired as soon as possible after the end of propulsion phase 1. In the perigee propulsion case, however, the vehicle is allowed to coast to apogee along coast phase 2 and back down to perigee along coast phase 6. This permits the subsequent propulsion phases to be done nearer perigee. Upon approaching perigee, the second Tug stage does its main burn in propulsion phase 7. At this point, the vehicle has been accelerated to beyond earth escape energy. The second Tug stage is separated from the vehicle and turned around during the TAT coast phase 8. The second Tug stage does its retro maneuver during propulsion phase 9. It coasts to apogee along coast phase 10 and near apogee does a small perigee correction maneuver in propulsion phase 11. The second Tug stage then coasts to perigee along coast phase 12 and does a circularization burn back into the Shuttle orbit in propulsion phase 13. In the meantime, the expendable Tug stage 3 injects the spacecraft onto its hyperbolic trajectory during propulsion phase 14. This followed the TAT coast 8 during which stage 2 was separated. It should be noted that for clarity, many of the propulsion phases are shown further from Earth, in figure 13, than is actually the case (especially phases 7, 8, 9 and 14). The other vehicle combinations discussed earlier use similar, although generally less complicated trajectories.

A specific example of the effects of a finite thrust level is shown in figure 14. The results are for the (2, 1, 1) vehicle at a delta V of 28,000 feet per second which is typical for a three year trip to Saturn. The engine weight penalties as discussed earlier and shown in figure 6 were used. Best performance is obtained at thrust levels near 50,000 pounds which is unacceptable for the geostationary mission (figure 7). Even at a 20,000 pound thrust level, the losses are significant without perigee propulsion. With perigee propulsion, a thrust level of 20,000 pounds gives reasonable performance.

Using the 20,000 pound thrust level, the entire performance curve for the (2, 1, 1) vehicle is shown in figure 15. Consider the results for a 3 year trip to Saturn (delta V of 28,000 feet per second). The ideal impulsive performance is just over 9000 pounds. With a thrust of 20,000 pounds and including real trajectory constraints, the payload loss is about 40 percent. If perigee propulsion is used, the payload loss from ideal is about 15 percent. A similar comparison for the (3, 1, 2) vehicle is shown in figure 16. Here, the payload loss for a 3 year Saturn mission is almost 50 percent if perigee propulsion is not used. With perigee propulsion, the payload loss in comparison to ideal performance is about 25 percent. For lower energy missions, the losses are less severe on a percentage basis.

These results demonstrate that trajectories can be designed to recover Tugs from a multiple Tug vehicle used for missions beyond earth escape. However, performance losses can be high unless a relatively high thrust Tug engine is used. The use of perigee propulsion can cut the losses in half for many cases without imposing unrealistic requirements on the Tug design. One further qualification has to be placed on the results presented. Due to the perturbing effects of the earth's oblateness, the orbit of the waiting Shuttle will precess about 8 degrees per day. The recovered Tugs, since they spend most of their mission time at higher altitudes, will precess at a much slower rate. What this means is that the Shuttle orbiter and recovered Tugs will not stay in the same orbit plane. This introduces the requirement for some out-of-plane maneuvering in returning the Tugs to the Shuttle with a resulting loss in performance. Analysis of this problem is quite complicated and needs to be done on a mission by mission basis. This problem is currently being studied.

SUMMARY AND CONCLUSIONS

The use of single and multiple Space Tugs for injecting spacecraft to missions beyond earth escape has been studied. A single recoverable Space Tug can be used to inject spacecraft to Mars or Venus. The use of two or three Space Tugs in tandem can greatly increase this capability. The more difficult missions require a mix of recovered and expended Tugs.

Trajectories are developed that allow recovery of the Tugs whenever practical. The resulting mission profiles will not, in general, place new design requirements on the Tug. Constraints will have to be placed on the turn-around-time and total-trip-time of Tugs to be recovered, but these do not appear to be serious. The principal Tug parameter affecting trajectory losses is the main engine thrust level. For the geostationary mission, which is the principal Tug design mission, best thrust levels are in the range of 10,000 to 20,000 pounds. The interplanetary missions, especially those using multiple Tugs, would favor a thrust level at the upper end of this range. In some cases the use of perigee propulsion is helpful in reducing the need for high thrust levels. In any event, many other factors in addition to mission performance have to be considered in selecting the Tug thrust level.

Precession of the Shuttle and Tug orbits, due to the Earth's oblateness, was not considered in this study and will require further study. These effects will complicate the recovery of Tugs and lead to additional performance losses not yet determined.

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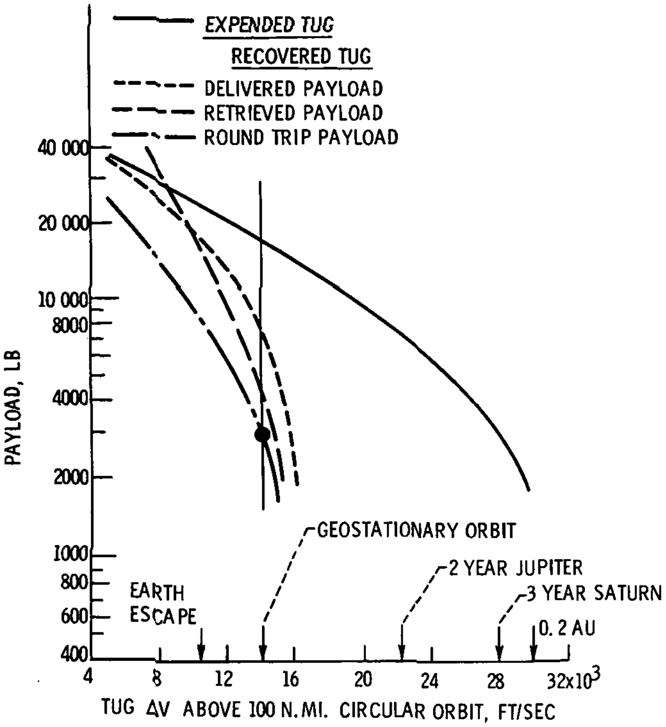

Figure 1. - Ideal impulsive performance of a single space Tug.

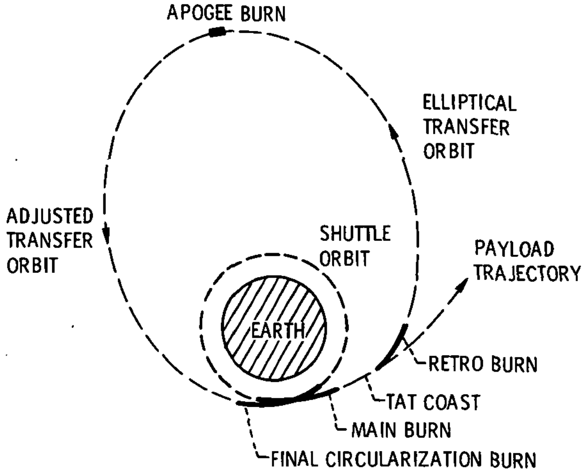

Figure 2. - Optimum recoverable Tug trajectory profile for a typical mission beyond Earth escape.

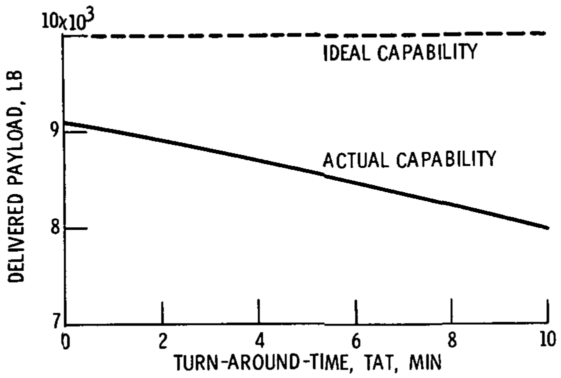

Figure 3. - Effect of turn-around-time on payload for a typical Mars or Venus class mission. Single recoverable Tug; Tug thrust, 20 000 lb; total-trip-time, 24 hours; mission delta V, 13 180 ft/sec.

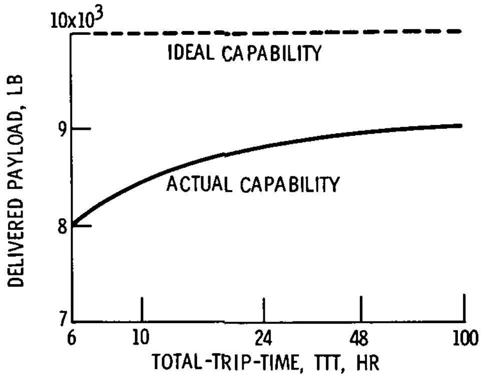

Figure 4. - Effect of total-trip-time on payload for a typical Mars or Venus class mission. Single recoverable Tug; Tug thrust, 20 000 lb; turn-around-time, 3 minutes; mission delta V, 13 180 ft/sec.

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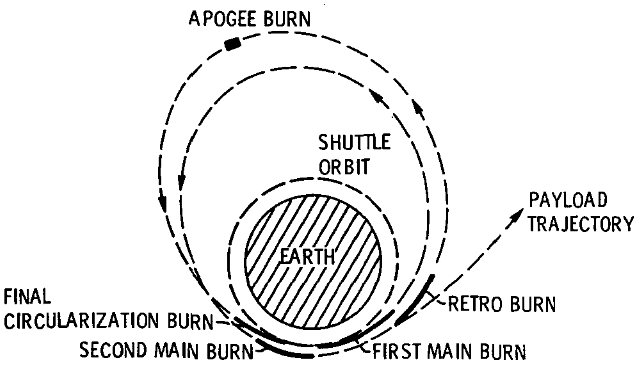

Figure 5. - Optimum recoverable Tug trajectory profile for a typical mission beyond Earth escape using perigee propulsion.

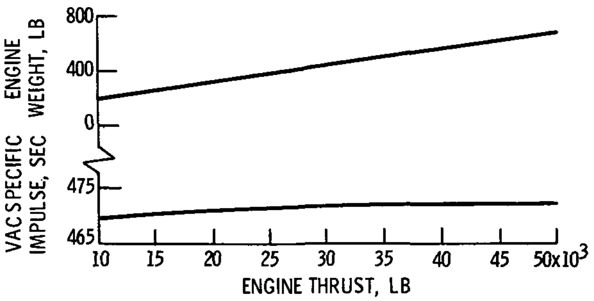

Figure 6. - Variation of engine weight and specific impulse with thrust level. Staged combustion cycle engine; nozzle expansion ratio, 400.

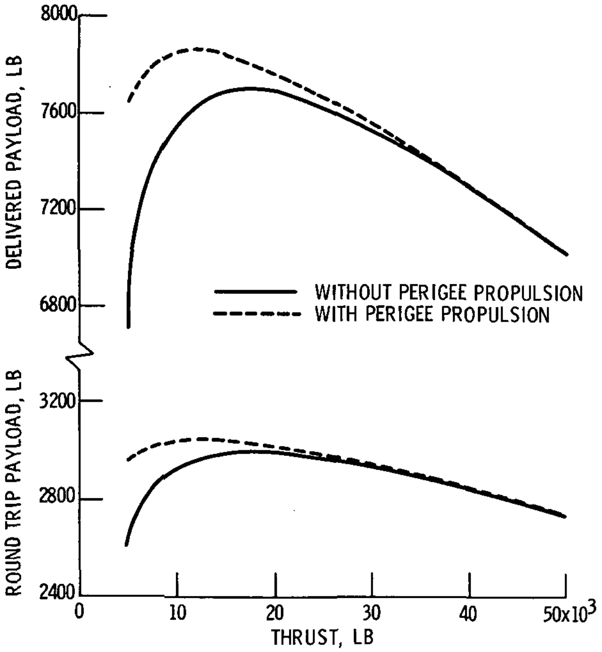

Figure 7. - Effect of Tug thrust level on geostationary mission performance. Recoverable Tug mission mode.

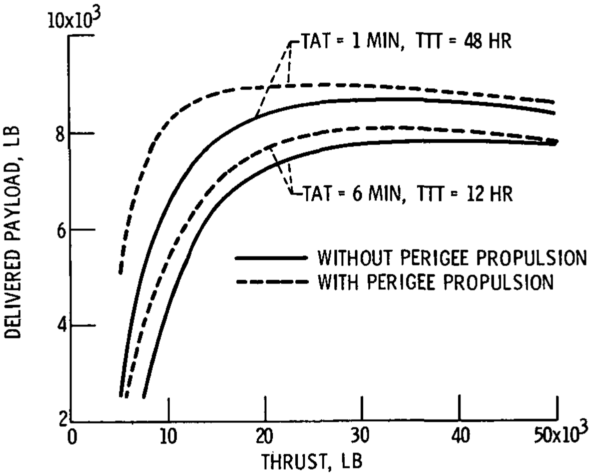

Figure 8. - Effect of Tug thrust level on a Mars or Venus class mission. Recoverable Tug mission mode; mission delta V, 13 450 ft/sec.

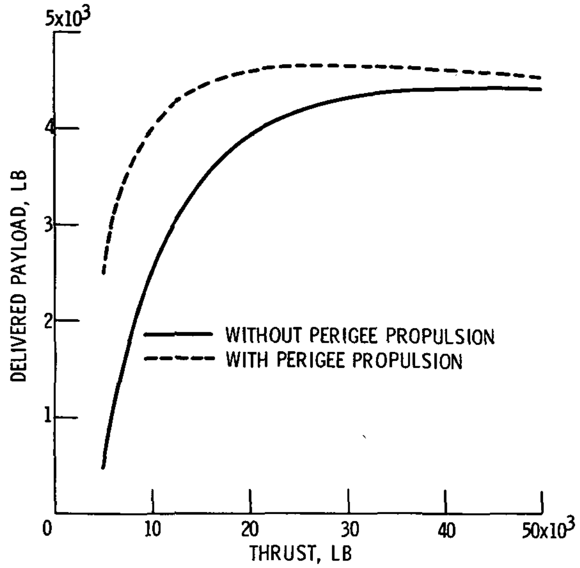

Figure 9. - Effect of Tug thrust level on an outer planet class mission. Expended Tug mission mode; mission delta V, 25 415 ft/sec.

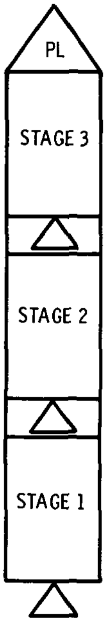

Figure 10. - Tandem multiple Tug configuration.

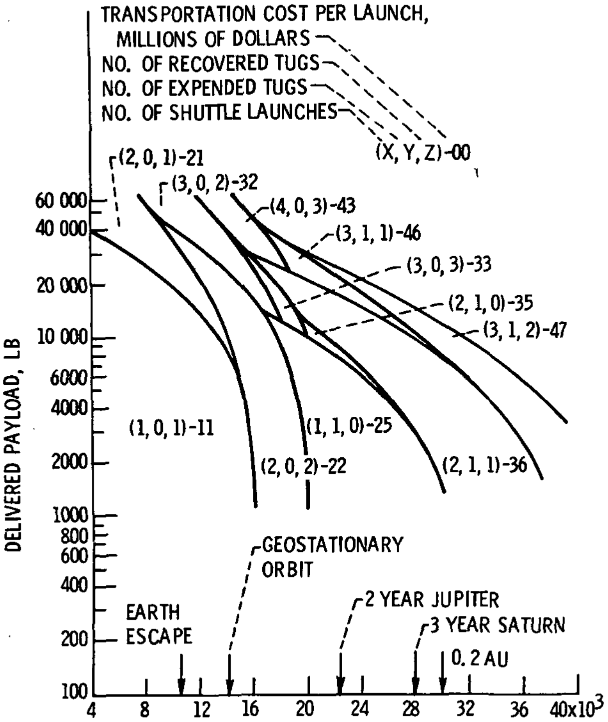

Figure 11. - Ideal impulsive performance of multiple space Tugs. Cost per Shuttle launch, $10 M; cost per recovered Tug, $1 M; cost per expended Tug, $15 M.

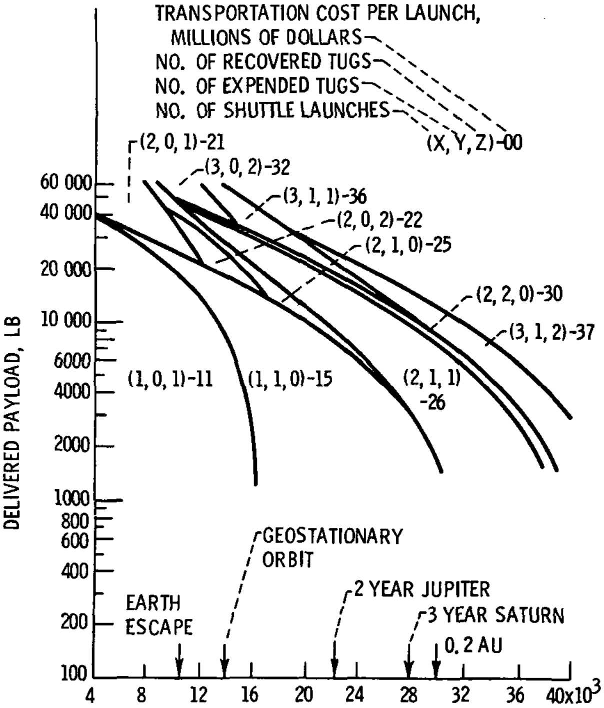

Figure 12. - Ideal impulsive performance of multiple space Tugs. Cost per Shuttle launch, $10 M; cost per recovered Tug, $1 M; cost per expended Tug, $5 M.

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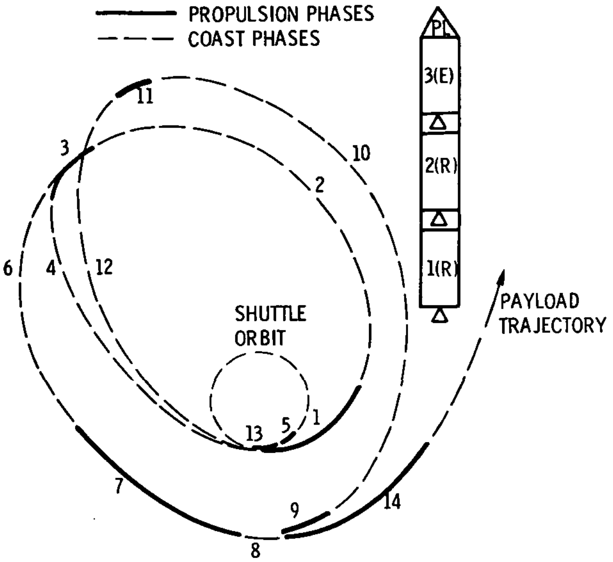

Figure 13. - Trajectory profile of the (3, 1, 2) vehicle with perigee propulsion.

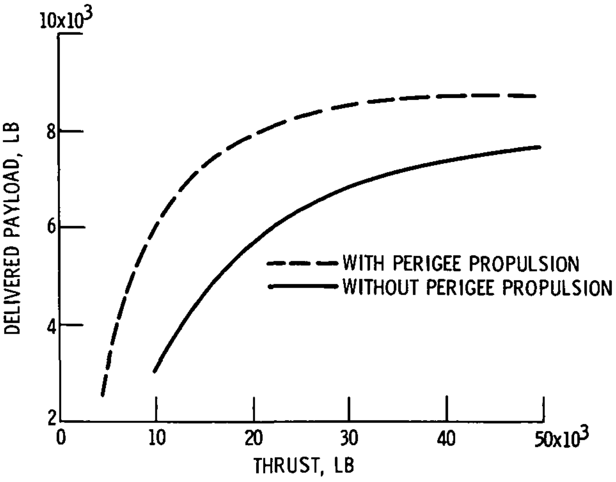

Figure 14. - Effect of thrust level on the (2, 1, 1) vehicle configuration for a typical outer planet mission. Delta V, 28 000 ft/sec; TAT, 3 minutes.

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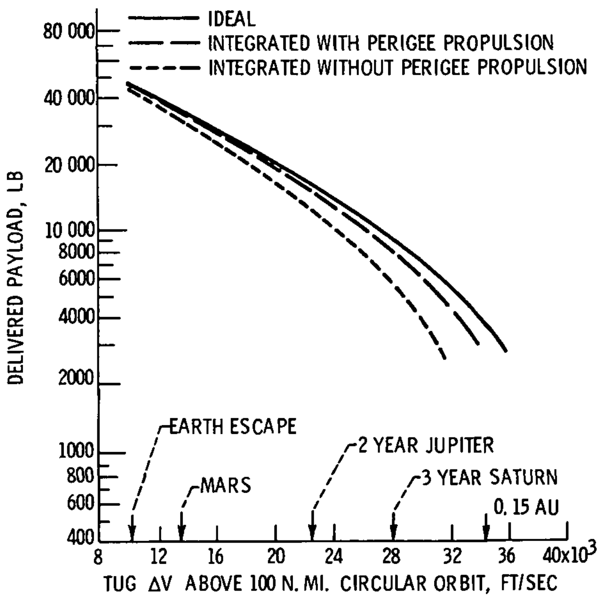

Figure 15. - Performance of the (2, 1, 1) tandem Tug configuration. Tug main engine thrust, 20 000 lb; TAT, 3 minutes.

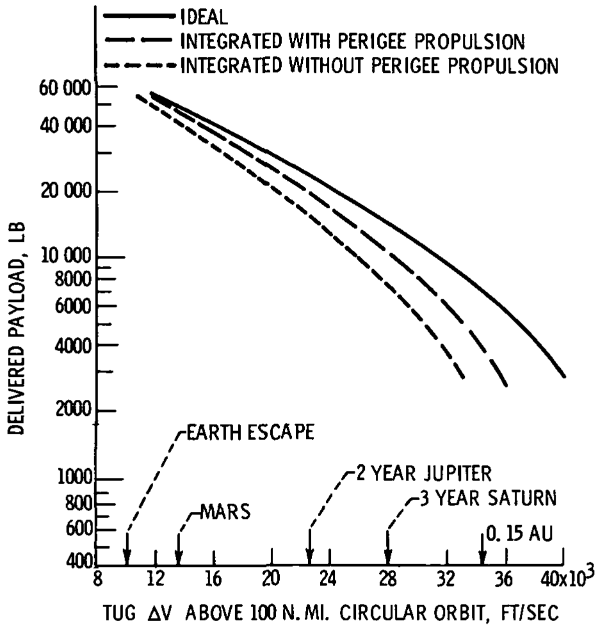

Figure 16. - Performance of the (3, 1, 2) tandem Tug configuration. Tug main engine thrust, 20 000 lb; TAT, 3 minutes; TTT, 48 hours.

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