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Autonomous Propulsion System Requirements for Placement of an STS External Tank in Low Earth Orbit

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William C. Stone
and
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Abstract

This paper discusses the findings of an extensive series of computer simulations carried out at the National Institute of Standards and Technology to investigate the requirements for powered flight of the external tank through the thermosphere following separation from the Shuttle orbiter at main engine cutoff (MECO). The object of the investigation was to determine the minimum thrust and fuel requirements for an autonomous exterior propulsion package attached to the external tank in order to avoid re-entry on the critical first orbit, and to place the tank in a short term stable orbit from which customary orbit maintenance procedures may be carried out. Descriptions are given for the differential equations of motion, and the atmospheric drag and propulsion models used in the solution.

Introduction

Significant interest has developed during the past two years for the on-orbit utilization of the external tank for the Space Shuttle, that is, the U.S. Space Transportation System (STS). The external tank is currently the only non-reusable component of the STS. On a nominal "standard insertion" launch these tanks, which carry cryogenic oxygen and hydrogen to fuel the three main shuttle engines, reach approximately 98% of orbital velocity at an altitude of about 105 kilometers, after which they separate from the orbiter and are left to re-enter the earth's atmosphere. Each tank measures 8.4 m in diameter by 46.5 m in length and contains an enclosed volume of 2069 cubic meters which is structurally capable of handling internal pressures necessary for human habitation. Potential commercial uses of these tanks in space include, among others, low-cost manned orbital workshops and man-tended manufacturing platforms [Sophron 1984]; fuel storage depots [Arnold, 1983]; and as building blocks for low-cost lunar spacecraft [King, 1989]. Although it is possible on most missions for the Space Shuttle to take the external tank into orbit [NASA, 1988], this has not yet been attempted for several reasons. First, the shuttle cargo bay payload capacity (already a premium) or the maximum mission altitude would generally have to be reduced to accommodate the increased amount of propellant needed to boost the external tank to orbit. Secondly, after achieving orbit, safety issues arise relating to the control of the tank in the vicinity of a manned orbital vehicle (i.e. the Shuttle orbiter), and in particular to the question of uncontrolled random re-entry ("Skylab Syndrome").

Because of these concerns it is desirable to consider the development of an economical means for autonomous placement of the tanks in long term stable orbits following the current separation sequence of the tank from the Shuttle orbiter.

Because of the potentially high payoff, in terms of enhanced on-orbit capability at vastly reduced cost, to U.S. companies seeking to conduct business in space, the National Institute of Standards and Technology has undertaken a research program to resolve the engineering questions relating to the placement, stabilization, and pressurization of Space Shuttle external tanks in low earth orbit. In this paper we discuss the requirements for powered flight of the external tank through the thermosphere following separation from the Shuttle orbiter at main engine cutoff (MECO).

For the reader who is not familiar with shuttle operations, reference to Figure 1 will be of use. This shows a typical time sequence from launch to orbit for the STS for what is known as a "Nominal (or Standard) Insertion" mission, which is by far the most difficult case to solve in terms of propulsion requirements for an external tank. The methods which will be subsequently described apply equally well to "Direct Insertion" missions [see NASA, 1988]. In both cases solid rocket booster staging occurs approximately 2 minutes into launch, after which the orbiter and external tank continue to a predefined altitude of approximately 105 kilometers. There main engine cutoff (MECO) occurs and the external tank is jettisoned. On a Nominal Insertion launch the external tank will then trace an elliptical orbit with an apogee altitude of approximately 159 kilometers and a

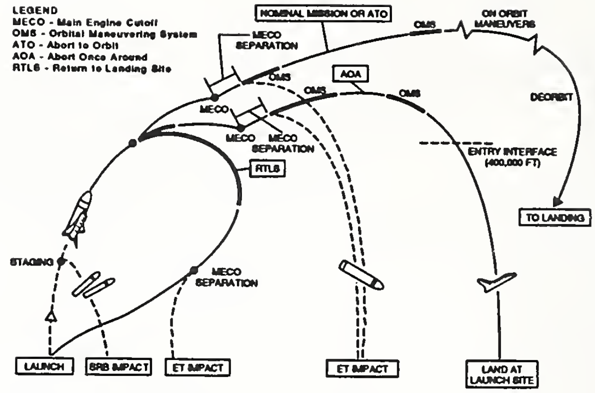

Figure 1: Standard Space Shuttle Launch Scenarios

perigee altitude of about 7 kilometers. It is generally recognized that a spacecraft which descends into the atmosphere below an altitude of approximately 70 kilometers will shortly re-enter and burn up, unless specific steps are taken to increase its tangential velocity. For the external tank this point is reached approximately 45 minutes beyond MECO, after which atmospheric drag increases exponentially, leading to the destruction of the tank. Of particular interest, then, is the determination of the minimum thrust and fuel required to avoid re-entry of the external tank during the critical first orbit.

Orbital Dynamics

For the purposes of solving the problem described above, it is sufficient to consider the problem of orbital mechanics in two dimensions, as shown in Figure 2. Perturbations due to the asphericity of the earth are not considered. Given an initial set of conditions such as the altitude of the external tank at MECO, the altitude at apogee, and the altitude at perigee [as provided in NASA, 1988], it is possible to determine both the location and velocity of the tank from orbital mechanics as follows:

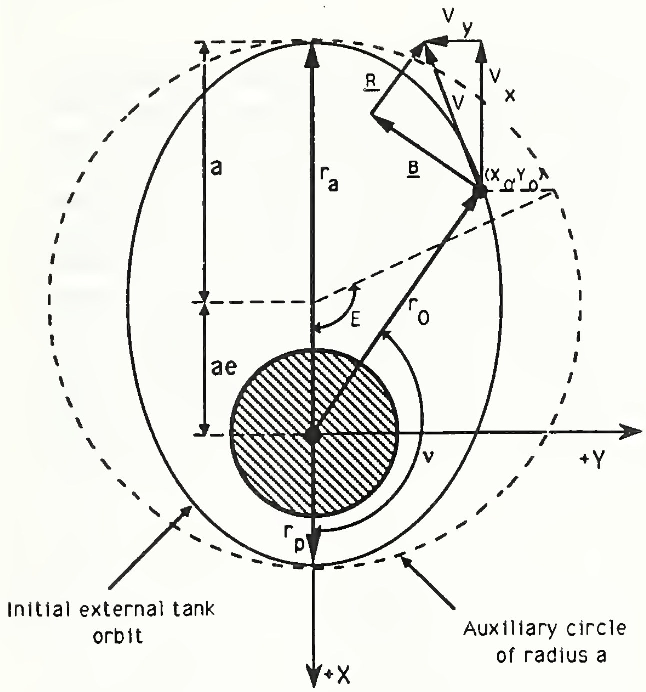

Figure 2: Orbital Mechanics Variables for External Tank Motion

First, the orbital radii at MECO (r_0), apogee (r_a), and perigee (r_p) are determined by adding 6378 km (the average radius of the earth) to the respective altitude figures already given. The orbit is described by an ellipse with a semi-major axis length, a, given by:

$$a = \frac{r_a + r_p}{2} \tag{1}$$

The eccentricity, e, for this orbit is given by:

$$e = \frac{r_a}{a} - 1 \tag{2}$$

The eccentric anomaly, E, in radians, measured counterclockwise from the positive X-axis (see Figure 2), is given by:

$$E = \cos^{-1}\left[\frac{a - r_0}{ae}\right] \tag{3}$$

At this point it is convenient to establish a cartesian coordinate system which can be used to describe both the position and velocity components of the external tank. The positive X-axis, with an origin at the center of the earth, is arbitrarily chosen to be parallel to the semi-major axis of the initial orbit ellipse in the direction of perigee. The initial tank coordinates at MECO are given by:

$$X_0 = a(\cos(E) - e) \tag{4}$$

$$Y_0 = a\sqrt{(1-e^2)}\ \sin(E) \tag{5}$$

The determination of the initial cartesian velocity components, V_{x0} and V_{y0}, begins with the calculation of the velocity components parallel and perpendicular to the initial radius vector r_0. These are, respectively:

$$\underline{R} = \frac{\sqrt{\mu a}\ e\sin(E)}{r_0} \tag{6}$$

$$\underline{B} = \frac{\sqrt{\mu a\,(1-e^2)}}{r_0} \tag{7}$$

Where μ = 398600 $Km^3/second^2$, and is the gravitational parameter for a spacecraft in near earth orbit. The true anomaly, ν, represents the counterclockwise angle, in radians, from the positive X-axis to the radius vector r_0 in Figure 2. The sine and cosine of the true anomaly are given by:

$$\cos(\nu) = \frac{a(\cos(E) - e)}{r_0} \quad (8)$$

$$\sin(\nu) = \frac{a\sqrt{(1-e^2)}\ \sin(E)}{r_0} \quad (9)$$

Using equations 6 through 9 the initial cartesian velocity components may be recovered directly as:

$$V_{x0} = \underline{R}\ \cos(\nu) - \underline{B}\ \sin(\nu) \quad (10)$$

$$V_{y0} = \underline{R}\ \sin(\nu) + \underline{B}\ \cos(\nu) \quad (11)$$

The velocity magnitude at any time may be determined as:

$$V = \sqrt{V_x^{\,2} + V_y^{\,2}} \quad (12)$$

And the proportional fractions of the velocity at any time in the X and Y directions are given by:

$$\tau_x = \frac{V_x}{V} \quad (13)$$

$$\tau_y = \frac{V_y}{V} \quad (14)$$

Perturbing Accelerations

During the critical post-MECO period, the external tank will be acted upon by two disturbing forces which in turn produce perturbing accelerations which must be accounted for in the differential equations describing the motion of the tank. These disturbing forces are aerodynamic drag and the thrust produced by the propulsion package. Disturbing forces typically included in long duration orbital lifetime calculations, such as solar radiation pressure, represent second order effects for spacecraft at altitudes below 500 kilometers and are therefore not considered in this analysis. The aerodynamic deceleration per unit mass is given by:

$$T_a = -\frac{C_d\ A_d\ \rho\ V^2}{2m} \quad (15)$$

where:

C_d = drag coefficient, taken as 2.0 for the external tank, a dimensionless quantity.

A_d = projected drag area perpendicular to the velocity vector, in square meters.

ρ = atmospheric density in kg/m^3.

m = mass of the empty external tank plus any residual hydrogen and oxygen following MECO, plus the weight of any external propellants (which vary with time as the ΔV motor is fired), storage vessels, and propulsion hardware, in kg.

A few comments are in order regarding the above. Accurate closed form solutions are now available for external tank drag area for any given angle of attack (Stone and Witzgall, 1989). The minimum and maximum drag areas are 55.51 and 358.12 square meters for angles of attack of 0 and 90 degrees, respectively. The atmospheric density, ρ, used in this study is described by the National Standard Atmosphere (NOAA, 1976) for altitudes between 60 and 85 kilometers and by (Tobiska, 1989) for altitudes above 85 kilometers. Both the solar maximum and solar minimum conditions were considered in the analyses, since the atmospheric density may vary by as much as an order of magnitude during the 11 year solar cycle. Presently Solar Maximum is predicted to occur sometime in 1990 with Solar Minimum in 1997. These can represent real launch constraints if the mass of the external tank propulsion package is to be minimized.

It is assumed that a suitable attitude control system is provided which is capable of maintaining the longitudinal axis of the tank parallel to the velocity vector. This is essential to any practical application involving the tanks below an altitude of approximately 500 kilometers, since the drag area for a 90 degree angle of attack is nearly six and one half times that for the head-on configuration and would lead to premature re-entry. The thrust may be either positive or negative. The latter case applies specifically to the problem of de-orbiting the external tank, which is of considerable importance if the tank must be made to safely re-enter and land in a specific, uninhabited location on the earth's surface. The thrust acceleration (or deceleration) is given by:

$$T_f = \frac{F}{m} \tag{16}$$

where F is the thrust in Newtons of the propulsion system and m has units of kilograms. It should be noted that during an engine burn m is constantly changing since the propellant mass is decreasing. The overall spacecraft mass is thus given by:

$$m = M_{tank} + M_{fuel} - \frac{Ft}{I_{sp} g_0} \tag{17}$$

where:

M_{tank} = the structural mass of the external tank plus any residual cryogens (hydrogen and oxygen) not used for the propulsive maneuver, plus the structural weight of the propulsion module.

M_{fuel} = the mass of fuel <u>initially</u> available for use by the propulsion module.

t = the cumulative time of operation of the propulsion module at full rated thrust, in seconds.

I_{sp} = the Specific Impulse of the fuel used in the propulsion system, in seconds. Generally, the higher the value of I_{sp}, the higher the performance of the rocket motor. Gaseous hydrogen oxygen thrusters have an I_{sp} near 400s; solid rocket motors, about 200s.

g_0 = acceleration due to gravity at the earth's surface.

It should be noted that quantity

$$M_{fuel} - \frac{Ft}{I_{sp} g_0} \tag{18}$$

represents the usable fuel reserve. In the results described below it is assumed that once the motor is fired, it will continue firing until the fuel reserve allotted for the initial burn is expended, after which the tank will coast until further authority to fire at some later time is received. In the analysis the value of T_f is set to zero when equation (18) reaches zero. This is distinctly different from Hohmann Transfer theory (Kaplan, 1981), which assumes all velocity change to occur instantaneously. For a system having a very low thrust level and a large quantity of available fuel, the burn arc, or arc angle of an orbit through which the motor is firing, can be significant. Numerical integration, therefore, is the only means of accurately tracing the resulting motion of the tank. It should be noted that the location of ΔV burn initiation will also significantly affect the path of the tank, and the available time in orbit.

The sum of equations 15 and 16 gives the cumulative perturbing acceleration acting upon the external tank:

$$T = T_f - T_a \qquad (19)$$

Differential Equations of Motion

The motion of the external tank in two dimensions can be completely described by four differential equations, two containing derivatives of the velocity components V_x and V_y and two containing derivatives of the position vectors X and Y, as follows:

$$\frac{dV_x}{dt} = -\frac{\mu}{r^3} X + \tau_x T \qquad (20)$$

$$\frac{dV_y}{dt} = -\frac{\mu}{r^3} Y + \tau_y T \qquad (21)$$

$$\frac{dX}{dt} = V_x \qquad (22)$$

$$\frac{dY}{dt} = V_y \qquad (22)$$

The initial conditions for the above system are given in equations 4,5,10, and 11. The solution was carried out using single precision arithmetic on a Convex C-120 computer using the **SDRIV** numerical integration package (Kahaner, 1979) as an internal subroutine in the main program, **ET_ORBIT**, which consisted of 12,000 lines of Fortran 77 code. Single precision accuracy was determined through simulation to be adequate for the results reported below, which represent a relatively brief time on orbit. Off-the-shelf software, which operates in double precision, presently exists for long duration orbital lifetime calculations but these do not permit examination of powered flight.

Results

The objective of this study was to determine the smallest values for the propulsion system thrust and fuel mass required to avoid re-entry for a period sufficient to permit subsequent orbital optimization burns. For the sake of limiting computational time, the required orbital duration for a "successful" boost was set to 30 orbits, or approximately 2 days. During this time the propulsion system will be required to carry out an additional series of burns in order to boost the tank to a parking orbit with sufficient altitude to allow for storage periods of up to 30 years, depending upon the desired use. One recent study (NASA, 1988) has indicated that such a long term parking orbit would have an altitude in the vicinity of 500 kilometers.

To solve the differential equations, certain additional initial conditions must be specified such as the spacecraft mass (structural mass and residual fuel not available for propulsion), the ΔV burn initiation point, the aerodynamic drag model (which includes the specification of solar maximum or minimum and the angle of attack), and the specific impulse, I_{sp}, of the propellant. It may be appreciated that no single optimum design will exist for all users, owing to the availability of an appropriate launch window, safety considerations which may affect where a ΔV burn may be initiated, and budget constraints which may limit a smaller company to consideration of a lower performance propulsion package. The results presented below, therefore, cover a wide spectrum of variables which present a range of options to the user.

Apogee Burn

From an analytical point of view, a propulsive maneuver may be initiated at any time following separation from the shuttle (MECO). From a practical point of view, a minimum separation distance must be allowed between the shuttle orbiter and the external tank in order to maintain safety for the orbiter and its crew. Thus one insertion scenario for the external tank would consist of firing the exterior propulsion package as soon after MECO as safety permits. The alternative would be to allow the tank to coast to its initial apogee (approximately 159 km vs 105 km at MECO) before initiating the burn. This would be the location of choice for a conventional boost intended to raise the perigee altitude.

The apogee-boost case represents the most conservative opportunity for placement of an external tank in orbit at minimum cost. "Conservative" in this context refers to the lack of sensitivity of the resulting motion of the tank to errors in the thrust magnitude and direction. Other scenarios discussed below can be more efficient, but at the price of sensitivity to propulsion system thrust level and attitude vector alignment variations. Figures 3 and 4 show families of curves in which the X-axis represents ΔV motor thrust and the Y-axis represents the time until re-entry in hours. An ascending curve which has been terminated at 43 hours indicates that the tank is still in orbit, and has therefore undergone a successful boost. The mass of the vehicle has been assumed to be 74,000 lbm (33,596 kg), which includes a 5,000 lbm (2,270 kg) budget for residual cryogens in the liquid hydrogen (LH_2) and liquid oxygen (LO_2) tanks and support structures for the propulsion package. This can be considered representative of the vehicle mass during most missions although the residual cryogen mass can be substantially higher, depending on the particular mission. The effect of changing vehicle mass is discussed below. The vehicle mass does not include the fuel used by the propulsion system, which is accounted for separately in the calculations since it is a dynamic quantity. An I_{sp} of 400 seconds (oxygen/hydrogen) has been assumed; the performance for different values of specific impulse is subsequently discussed.

Both figures 3 and 4 indicate that a threshold value of approximately 400 lbf (1800 N) exists for the thrust level necessary to achieve orbit regardless of the amount of fuel available or the prevailing solar flux. This threshold can be viewed as the aerodynamic drag compensation thrust. From an engineering standpoint it will be necessary to

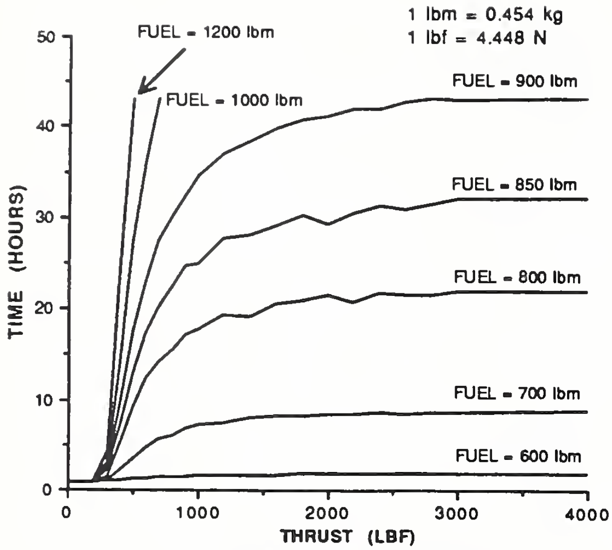

Figure 3: TIME IN ORBIT VS. ENGINE THRUST
Vehicle Mass = 74,000 lbm
ISP = 400 s, Burn at apogee
Solar minimum, Angle of attack = 0^{o}

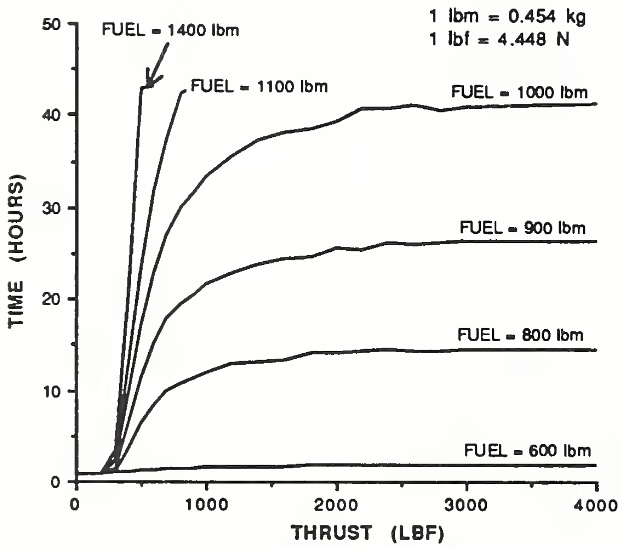

Figure 4: TIME IN ORBIT VS. ENGINE THRUST
Vehicle Mass = 74,000 lbm
ISP = 400 s, Burn at apogee
Solar maximum, Angle of attack = 0^{o}

have sufficient reserve thrust to ensure attainment of orbit despite any problems which might arise, for example in the pointing accuracy of the reaction control system or a decrease in engine performance. A reasonable value of thrust would appear to be approximately 1000 lbf (4450 N). Such a thrust level could be obtained from a variety of off-the-shelf components and is in the range of the larger reaction control units presently employed on the space shuttle orbiter.

Figures 3 and 4 indicate that in order to achieve an initial 40 hour period on orbit (during which additional altitude boost maneuvers would be carried out) a propulsion fuel budget of 1100 lbm (454 kg) is needed under solar maximum conditions. For an oxygen/ hydrogen thruster running a mixture mass ratio of 6:1 (oxidizer: propellant), this amounts to a storage requirement of only 374 liters LO_2 and 1023 liters LH_2.

MECO Burn

The apogee burn scenario described above was termed "conservative", because the time available on-orbit increases monotonically for increasing levels of thrust and amount of propellant. This is not the case when the burn is initiated close to MECO, as shown in figures 5 and 6. Here it is seen that the threshold thrust level to achieve orbit is approximately 200 lbf (900 N). However, there is wide variation in the time in orbit, depending upon the chosen thrust level and fuel mass. Furthermore, thrust levels above 500 lbf (2200 N) lead to significantly decreased time in orbit. The performance depicted in figures 5 and 6 can be better appreciated when one considers the following rule of thumb in conjunction with figure 2, which shows the initial orbit parameters for the external tank at MECO: an instantaneous thrust impulse at any point in an orbit will have the effect of raising the orbital altitude at a point 180 degrees opposite the point where the impulse was initiated. When low levels of thrust are applied continuously, the effect is generally to increase the orbital altitude at a point approximately 180 degrees opposite the center of the "burn arc". For the MECO burn scenario just described, high levels of thrust, combined with the relatively small quantities of fuel shown, represent nearly impulsive loading, which raises the initial orbital perigee only a small amount, compared with that for a smaller engine which burns over a much longer arc, indeed almost to initial apogee, before expending the same mass of fuel.

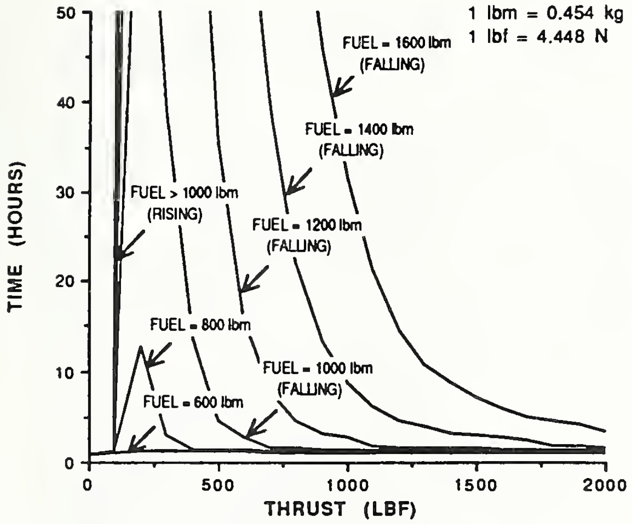

Figure 5: TIME IN ORBIT VS. ENGINE THRUST

Vehicle Mass = 74,000 lbm
ISP = 400 s, Burn at MECO
Solar minimum, Angle of attack = 0°

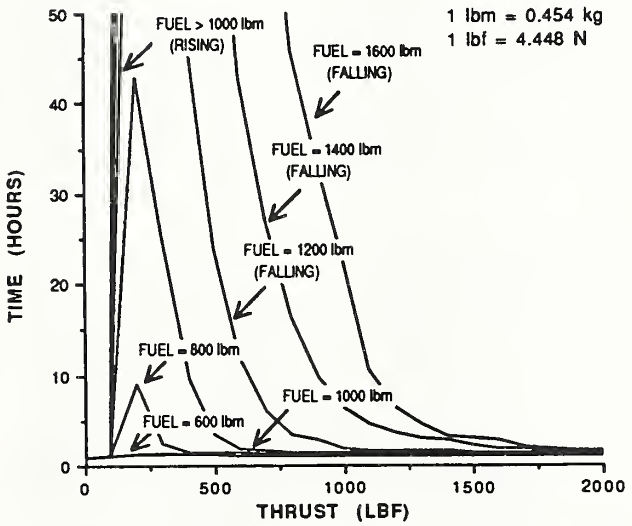

Figure 6: TIME IN ORBIT VS. ENGINE THRUST

Vehicle Mass = 74,000 lbm
ISP = 400 s, Burn at MECO
Solar maximum, Angle of attack = 0°

Despite the benefits indicated by figures 5 and 6, if one could achieve the peak performance shown, the MECO burn scenario represents a risky proposition, because minor variations in the level of thrust or drag would result in vastly reduced time in orbit.

Effect of Specific Impulse

So far, it has been assumed that oxygen/hydrogen thrusters (I_{sp}=400s) would be used to boost the external tank. Other propellants could be used with varying degrees of reduced performance. Bipropellants, such as Nitrogen Tetroxide (N_2O_4) and Mono Methyl Hydrazine (MMH) are non-cryogenic and have an I_{sp} of about 300 s. Solid rocket motors are available in a wide variety of thrust and duration levels and have I_{sp} values between 200-250s. Figures 7 and 8 show the effect of specific impulse on time in orbit for varying quantities of fuel mass. The thrust level, using the apogee burn scenario, has been set at 1000 lbf (4448 N). Figures 7 and 8 indicate that time in orbit is approximately proportional to I_{sp}. A solid rocket motor with twice the mass of the liquid propellant for the oxygen/ hydrogen engine would be needed to achieve the same time in orbit.

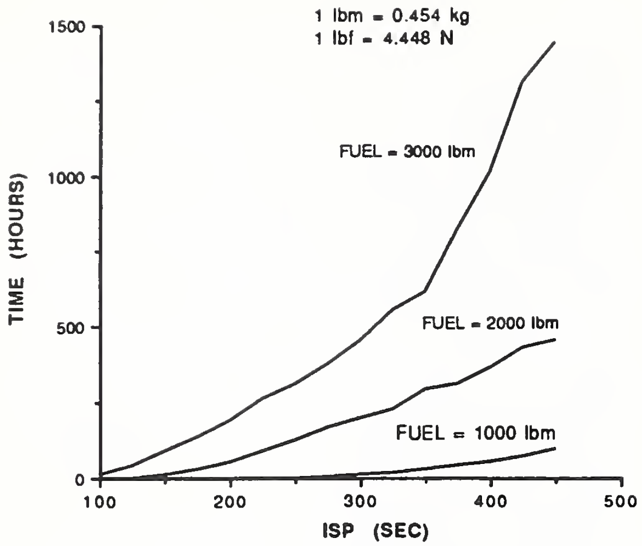

Figure 7: TIME IN ORBIT VS. SPECIFIC IMPULSE
Vehicle Mass = 74,000 lbm
Thrust = 1000 lbf, Burn at apogee
Solar minimum, Angle of attack = 0°

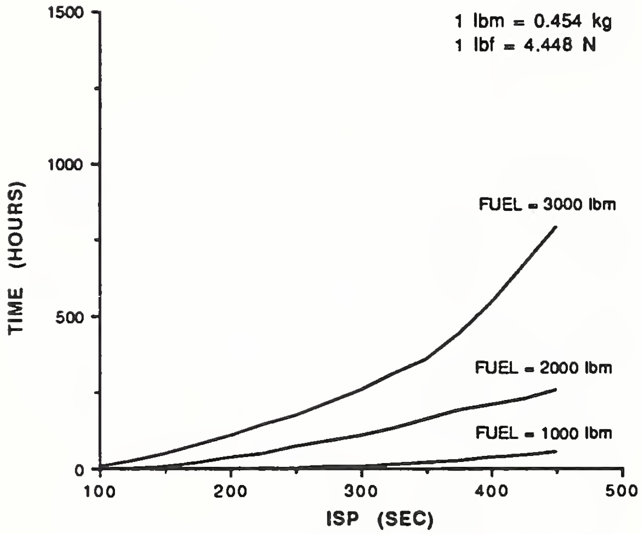

Figure 8: TIME IN ORBIT VS. SPECIFIC IMPULSE
Vehicle Mass = 74,000 lbm
Thrust = 1000 lbf, Burn at apogee
Solar maximum, Angle of attack = 0°

Effect of Spacecraft Mass

Figures 9 and 10 show the time in orbit for an external tank equipped with a 1000 lbf (4448 N) propulsion package as a function of overall vehicle mass (propellant mass for the indicated burn excluded). The important aspect of these figures is that while all curves show decreasing performance for increasing vehicle mass, the penalty for additional mass, in terms of time in orbit following the initial boost, is small. This indicates that additional payload mass could be

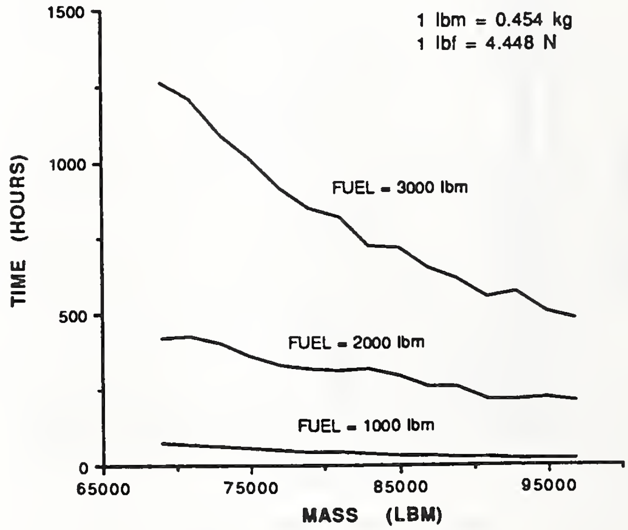

Figure 9: TIME IN ORBIT VS. VEHICLE MASS
Thrust = 1000 lbf
ISP = 400 s, Burn at apogee
Solar minimum, Angle of attack = 0°

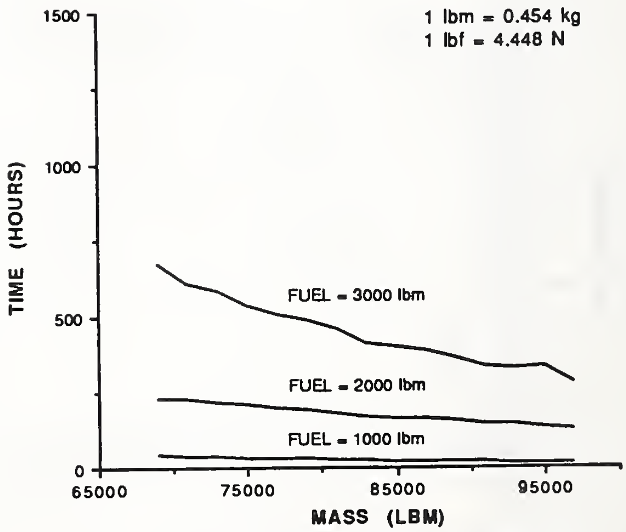

Figure 10: TIME IN ORBIT VS. VEHICLE MASS
Thrust = 1000 lbf
ISP = 400 s, Burn at apogee
Solar maximum, Angle of attack = 0°

taken to orbit by the external tank-- perhaps inside the hollow Intertank structure -- with no significant re-scaling of the exterior propulsion package; provided that the overall shuttle system payload capacity was under-manifested.

Overall Propellant Budget for Orbital Storage of External Tanks

It has been recommended that a suitable long term circular orbit storage altitude would be in the vicinity of 500 km [NASA, 1988]. If, as previously suggested, a 1100 lbm (500 kg) apogee burn is carried out by the tank propulsion system using a 1000 lbf (4450 N) hydrogen/oxygen engine, then the resulting orbit is as described in figure 11a. This orbit has an apogee altitude of 218.3 km and a perigee altitude of approximately 159 km. If no further action is taken to boost the tank to a higher orbit, or if no other orbit maintenance burns are carried out, then the orbit will progressively decay due to atmospheric drag, as shown in figure 11b, ultimately ending with the re-entry of the tank 56.5 hours (38.6 orbits) after the initial apogee burn. Clearly, it is advantageous to act early to boost the tank, as the apogee altitude decreases by a greater amount with each successive orbit.

An initial estimate of the additional fuel required to achieve a 500 km altitude circular orbit may be obtained using Hohmann transfer theory [Kaplan, 1981]. At least three additional burns are required for this maneuver. The first, a circularization burn carried out at the apogee altitude of 218.3 km, involves a velocity change of 18 m/s. The next burn, which may take place anywhere along the circular orbit, places the tank into a transfer ellipse with an apogee altitude of 500 km and a perigee altitude of 218.3 km. The third burn takes place at apogee of the transfer ellipse and results in the final 500 km altitude circular storage orbit. The combined velocity change for these two burns is 160 m/s. This, added to the initial circularization burn amounts to 178 m/s. The propellant mass required to achieve this change may be determined from the standard rocket equation as:

$$Q = m(1-e^{-\Delta V/I_{sp} g_0}) \qquad (23)$$

where:

Q = mass of propellant required.
ΔV = velocity change (m/s)

For a spacecraft mass of 74,000 lbm (33,596 kg) this velocity change requires 3285 lbm (1,491 kg) of propellant. Thus, the total post-MECO fuel budget comes to 4537 lbm (2059 kg) or, in terms of volumetric storage requirements, 54 cu.ft. (1542 liters) LO_2 and 149 cu.ft. (4219 liters) LH_2. This is, coincidentally, quite close to the estimates [NASA, 1988] of the minimum residual cryogens suitable for propulsion which remain in the tank following MECO. The calculations thus far have counted this as deadweight and have assumed that all propellants would be carried in exterior tanks which comprise the autonomous velocity change propulsion package. Effective utilization of residual cryogens would essentially eliminate any launch constraints which might exist due to Space Shuttle cargo bay manifesting. This paper has dealt solely with the subject of the initial boost requirements for placing external tanks in long term storage orbits. Other key facets of

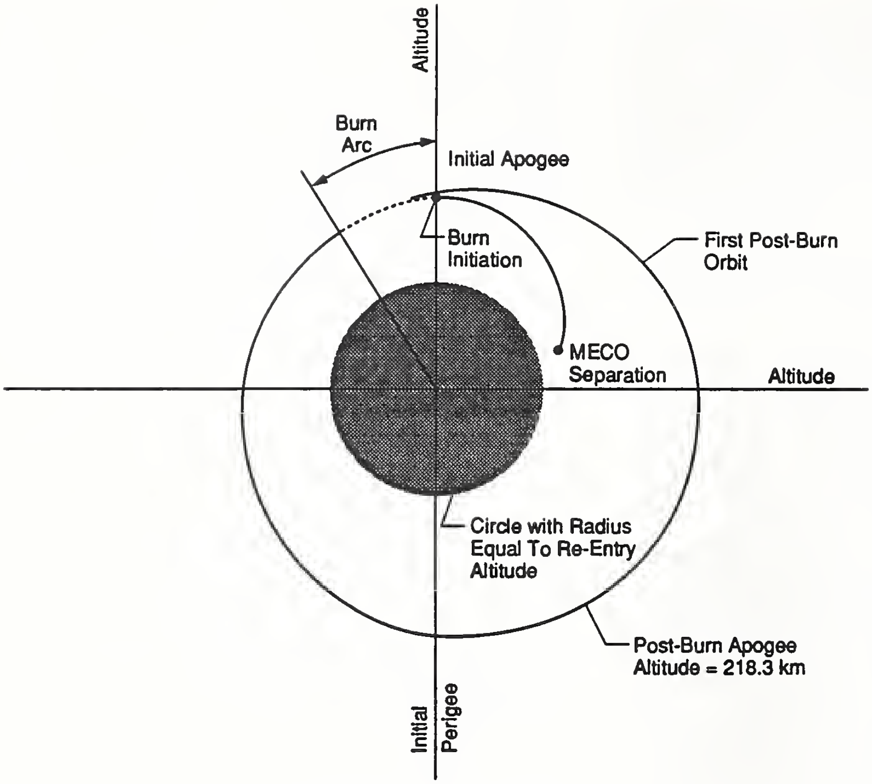

Figure 11a:

First Orbit Following Apogee Burn

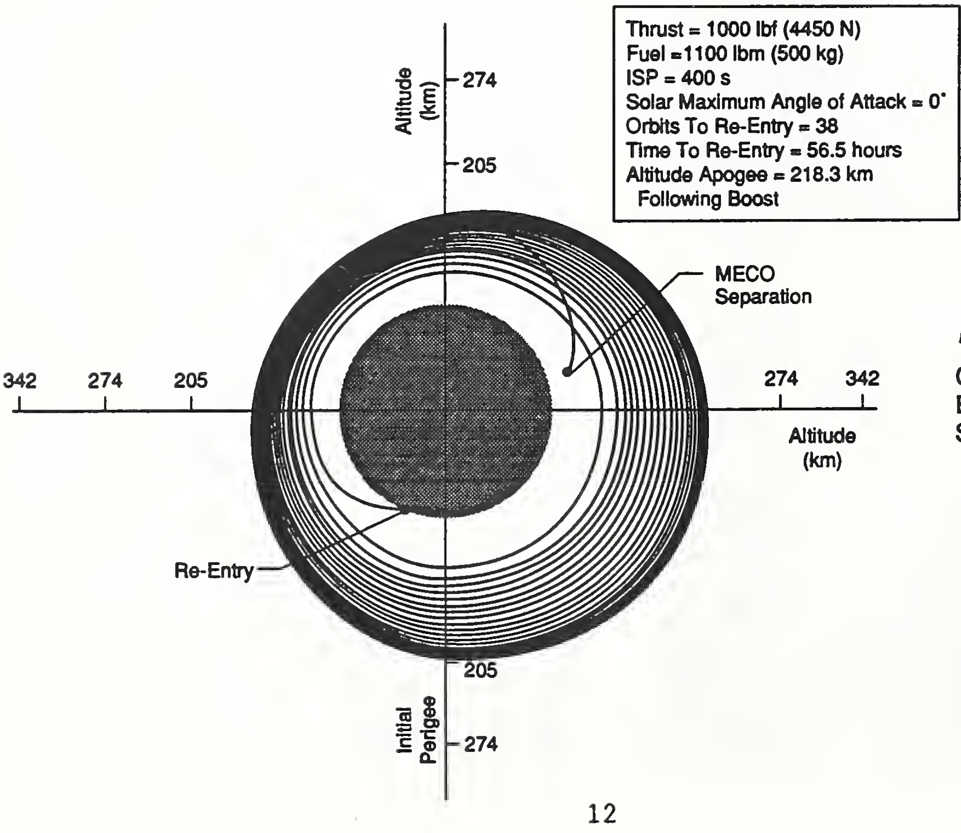

Figure 11b:

Complete Decay Trace For External Tank Following Single Apogee Burn the problem include orbit maintenance propellant budget determination and the assessment of an appropriate deboost system should the tank need to be brought down in a controlled fashion. These subjects will be discussed in future papers.

Conclusions:

On the basis of extensive numerical simulations it was calculated that the space shuttle external tank can be boosted to a short term stable orbit following standard MECO separation from the shuttle orbiter, and without any direct interaction nor detriment to orbiter performance. An exterior propulsion package for the external tank equipped with a minimum thrust capacity of 1000 lbf (4448 N), a propellant mass of 1100 lbm (500 kg), and an I_{sp} of 400s appears sufficient to achieve an initial time in orbit of nearly two days under solar maximum conditions, provided the burn is made at initial apogee and the angle of attack is maintained near zero degrees by an onboard attitude control system. It is assumed that additional velocity change burns will take place following the initial burn which will place the tank in a circular orbit between 400-500 km altitude for long term storage. Initial estimates of the total fuel required to achieve a 500 km circular storage orbit come to 4537 lbm (2059 kg) based upon Hohmann transfer theory following the initial apogee burn. All calculations assumed 5000 lbm (2270 kg) of residual cryogens in the external tank following MECO as <u>deadweight</u>. Recovery and use of these propellants by the exterior propulsion package would lead to a dramatic increase in the time in orbit above the values reported in this paper.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This paper discusses the findings of an extensive series of computer simulations carried out at the National Institute of Standards and Technology to investigate the requirements for powered flight of the external tank through the thermosphere following separation from the Shuttle orbiter at main engine cutoff (MECO). The object of the investigation was to determine the minimum thrust and fuel requirements for an autonomous exterior propulsion package attached to the external tank in order to avoid re-entry on the critical first orbit, and to place the tank in a short term stable orbit from which customary orbit maintenance procedures may be carried out. Descriptions are given for the differential equations of motion, and the atmospheric drag and propulsion models used in the equations.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

atmospheric drag; external tanks; orbital lifetime; orbital mechanics; propulsion requirements; Space Shuttle

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