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SPACE TUG AEROBRAKING STUDY

VOLUME I OF II

EXECUTIVE SUMMARY VOLUME

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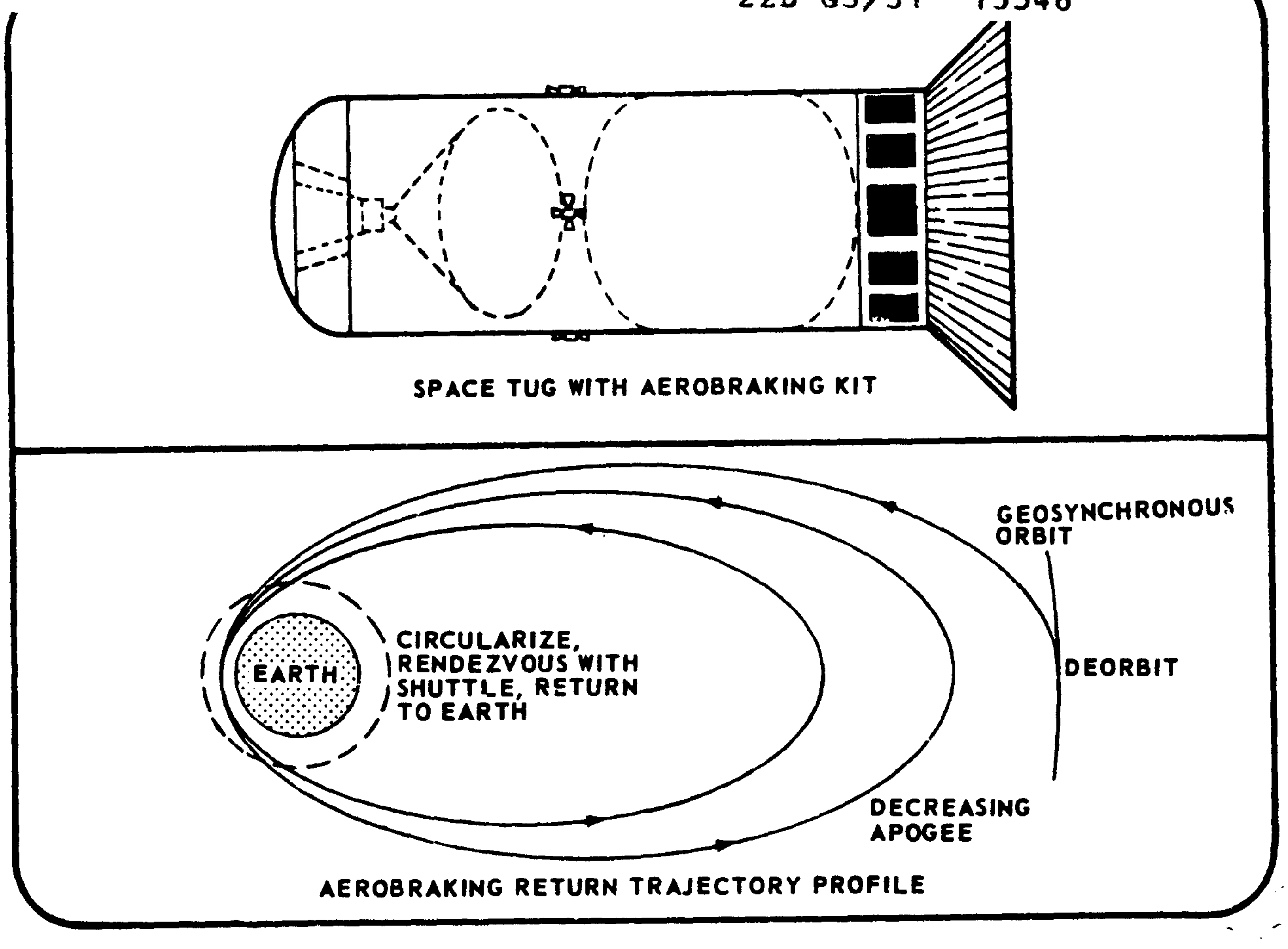

SPACE TUG WITH AEROBRAKING KIT

AEROBRAKING RETURN TRAJECTORY PROFILE

**PREPARED UNDER
CONTRACT NAS8-27501**

BY THE BOEING COMPANY
AEROSPACE GROUP
HUNTSVILLE, ALABAMA

D5-17142

FINAL REPORT

SPACE TUG AEROBRAKING STUDY

VOLUME I OF II
EXECUTIVE SUMMARY VOLUME

PREPARED BY: Charles J Corso
C. J. CORSO

Ch Eyer
C. L. EYER

APPROVED BY: J. W. ALLEN
J. W. ALLEN

Joseph W Monroe
JOSEPH W. MONROE

PREPARED UNDER CONTRACT NAS8-27501
FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

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THE BOEING COMPANY
SATURN/APOLLO/SKYLAB DIVISION
HUNTSVILLE, ALABAMA

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ABSTRACT

The feasibility and practicality of employing an aerobraking trajectory for return of the reuseable Space Tug from geosynchronous orbit was investigated. The aerobraking return trajectory modes employ transfer ellipses from high orbits which have low perigee altitudes wherein the earth's sensible atmosphere provides drag to reduce the Tug return delta velocity requirements and thus decrease the required return trip propulsive energy. Aerodynamics, aerothermodynamics, trajectories, guidance and control, configuration concepts, materials, weights and performance were considered. Sensitivities to trajectory uncertainties, atmospheric anomalies and re-entry environments were determined. New technology requirements and future studies required to further enhance the aerobraking potential were identified.

KEY WORDS

Space Tug

Aerobraking

Return trajectories

Synchronous missions

Orbit-to-Orbit Shuttle (OOS)

Earth-to-Orbit Shuttle (EOS)

Space Tug Kits

Flare Concepts

Heat Shield Concepts

Propulsion Modules

Astrionics modules

Aerodynamic drag

FOREWORD

This Executive Summary is one of two volumes presenting the results of a study to investigate the feasibility of an aerobraking trajectory mode for return of the reuseable Space Tug from geosynchronous and other high energy earth orbits. The accompanying technical volume, Volume II, presents in detail, the study results. This study was accomplished by The Boeing Company at its Huntsville facility for the NASA Marshall Space Flight Center, Huntsville, Alabama. The NASA/MSFC Technical Monitor was Thomas W. Barrett, Advanced Systems Analysis Office, Vehicle Systems Group. Subcontractor to The Boeing Company for the navigational requirements inpacts on the astrionics module was the International Business Machine Corporation/Huntsville Facility.

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1.0 INTRODUCTION

This report describes the results of a feasibility analysis study of an aerobraking trajectory mode for the reusable Space Tug to reduce its propulsive (delta velocity) requirements for return from high energy earth orbits to a low earth parking orbit. The aerobraking mode for return from equatorial geosynchronous orbit is illustrated and compared to a conventional (propulsive braking) return mode in Figure 1.0.0.0-1. Note that the propulsive return delta velocity required for the aerobraking mode is between 5700 and 8050 feet per second less than that required for a conventional propulsive return mode. This reduction will decrease the required Space Tug weights, dimensions, and costs as compared to a conventional Tug used in a single Shuttle/single Tug mode. For accomplishment of high energy earth orbital missions, therefore, launch and subsequent retrieval of the Space Tug, its payload and other mission components with a single Space Shuttle flight may become practical.

1.1 BACKGROUND

Prior studies (References 1 through 5) have shown the need for a Space Tug to supplement the Space Shuttle and thereby increase the Shuttle's mission capability and versatility. A Space Tug must operate in conjunction with the Space Shuttle for accomplishment of a variety of missions such as higher energy earth orbital missions; translunar, lunar and lunar landing missions; and planetary missions. Of specific interest is the application of a reusable Space Tug for the placement of unmanned payloads in high earth orbits (up to and including equatorial geosynchronous).

Using conventional trajectory modes, a reusable Space tug cannot accomplish this high energy geosynchronous placement mission unless the Tug size is large and the mass fraction is high. The former solution (size) is prohibited by the Space Shuttle payload capacity while the latter solution (mass fraction) will necessitate advanced state-of-the-art low weight technology and improved engine performance (specific impulse increases to 470 seconds) with their attendant higher development risk and cost. Even larger and/or higher performance Tug configurations will be required for geosynchronous missions wherein a payload is placed in orbit and a similar payload is recovered and returned to low earth orbit (round trip missions).

When the required Space Tug size and/or weight exceeds the Space Shuttle payload capability, multiple Shuttle launches will be required for individual mission accomplishment, e.g., a large partially fueled single stage Tug could be launched with one Space Shuttle and the remaining fuel and the payload delivered to orbit by a second Shuttle layout. This would require orbital propellant transfer and orbital assembly of the payload to the Tug. Another alternative would be to use a tandem staged Tug wherein one Shuttle launch would carry up one Tug stage and a second Shuttle launch would carry the second Tug stage plus payload. This mode would require orbital assembly but would not require propellant transfer.

1.1 (Continued)

Utilization of aerodynamic drag for braking back into low earth orbit, however, offers a method of reducing the overall mission propulsive requirements and thereby reduces the mission complexities. With the aerobraking mode, synchronous missions can be accomplished (for all but the largest payloads) with a single stage reusable Space Tug deployed and retrieved with a single Shuttle flight. Thus, a simple, ground based Space Tug mode may be used. The resulting cost savings due to reduced Shuttle launches and reduced orbital operations will represent significantly lower overall costs for the space program.

1.2 COMPARISON OF CONVENTIONAL AND AEROBRAKING CAPABILITIES

The above observations relative to the conventional mode were verified by The Boeing Company and other contractors in the previous Tug studies. These previous studies identified Tug systems employing current (specific impulse of 460 seconds, mass fractions variable with stage size) and projected (1976) state-of-the-art. Representative geosynchronous mission performance data for these systems, as defined by the prior Boeing study (Reference 1), is shown in Figure 1.2.0.0-1. This figure shows that a single stage reusable Tug for placement of 7,000 pounds into synchronous orbit must weight on the order of 67,000 pounds (exclusive of the payload weight). Such placement missions with tandem staged reusable Tugs or with reusable Tugs with drop tanks will require Tug weights (exclusive of the payload weight) of 78,000 pounds or 73,000 pounds, respectively. For 3,000 pound payload retrieval missions or 3,000 pound round trip missions, the required weights for a reusable single stage Tug will be approximately 67,500 pounds or 73,000 pounds (exclusive of the payload weight), respectively. All of these required weights exceed the 65,000 pound Shuttle payload capability. As indicated, the use of the aerobraking return mode presents a way of reducing the Space Tug propulsion requirements so that the required Tug sizes will be compatible with the Shuttle payload capability.

It can readily be seen that the aerobraking mode offers the capability for mission accomplishment with a single Shuttle flight which cannot be provided by configurations employing the conventional mode (based on an Isp of 460 seconds and mass fractions between 0.876 and 0.904 depending on the stage size).

Studies have shown that to round trip 3,000 pounds of payload in an equatorial geosynchronous mission requires a Space Tug with a specific impulse of 470 seconds and a mass fraction of approximately 0.895. However, aerobraking makes it possible to accomplish this mission based on current technology (specific impulse 460 seconds and a mass fraction of 0.862). If the higher specific impulse and mass fraction are achieveable and used in conjunction with aerobraking, then approximately 6,500 pounds of payload could be round tripped in a geosynchronous mission.

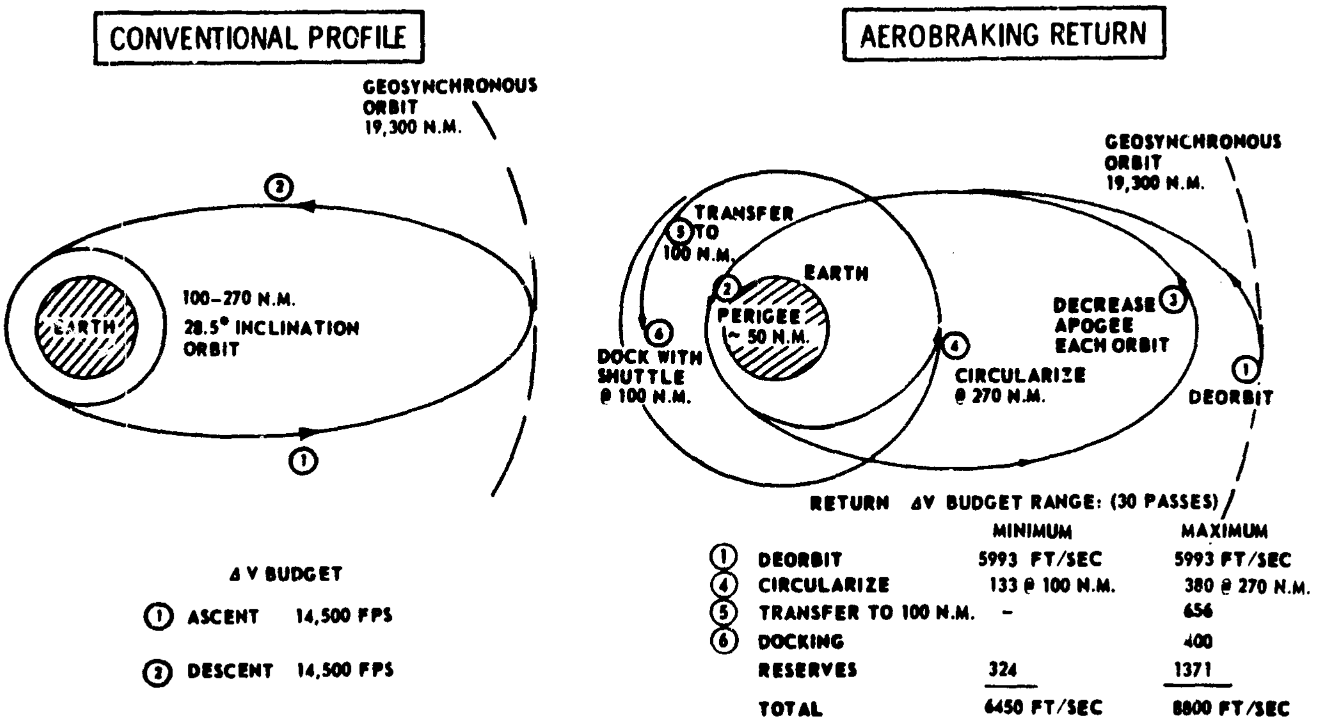


FIGURE 1.0.0.0-1: COMPARISON OF CONVENTIONAL AND AEROBRAKING TRAJECTORY PROFILES

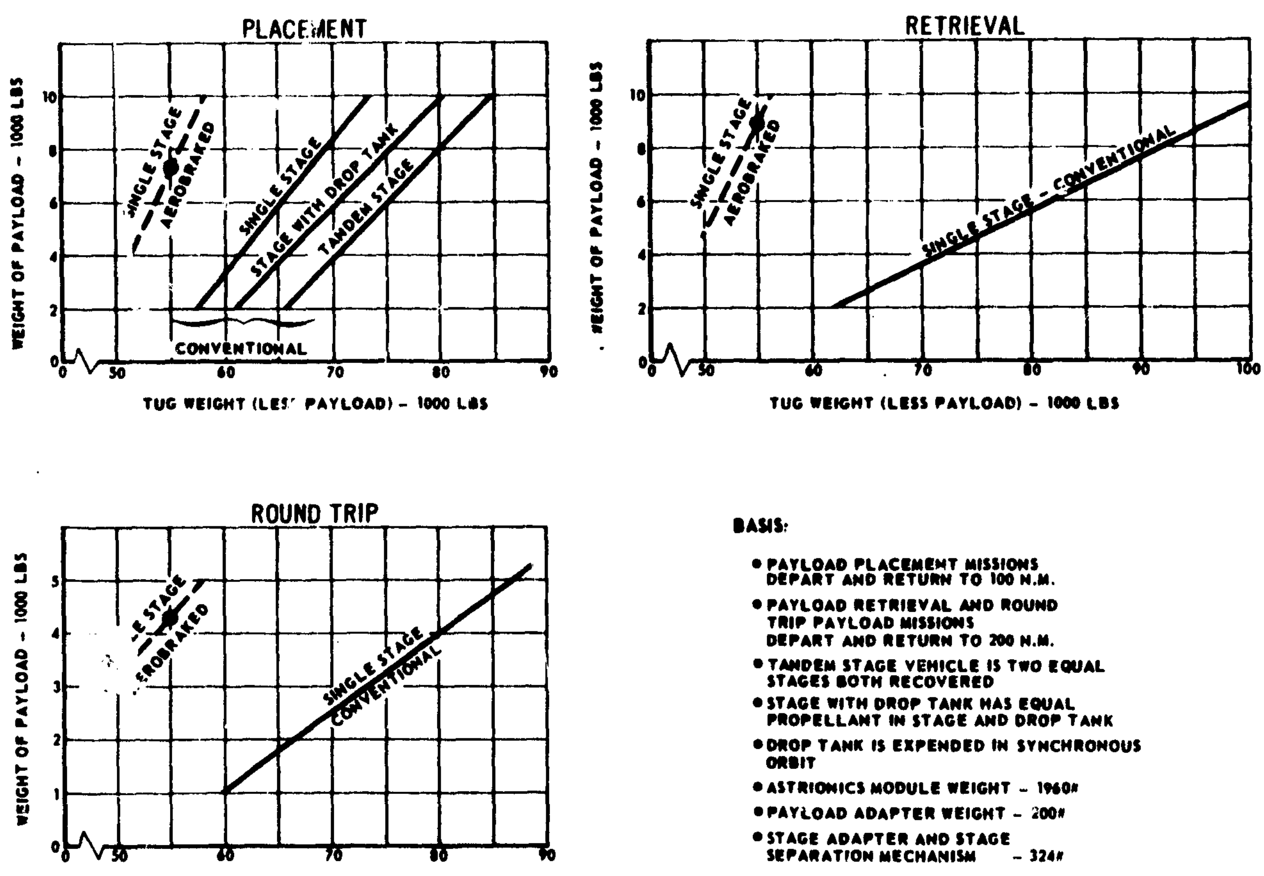


FIGURE 1.2.0.0-1: PAYLOAD CAPABILITY COMPARISON - AEROBRAKED VERSUS CONVENTIONAL TUG

2.0 SUMMARY

This study investigated the feasibility and practicality of the aerobraking mode for return trajectories of the Space Tug from geosynchronous orbit. Payloads weighing between 3000 and 4000 pounds can be carried in a round trip mode to and from equatorial geosynchronous orbit using a Space Tug weighing approximately 55,000 pounds. Payload capabilities for placement (only) or retrieval (only) missions will be approximately twice that of the round trip mission. As shown in Figure 2.0.0.0-1, this is sufficient payload capability for performance of 95% of the projected round trip geosynchronous missions in a mode wherein a single Shuttle flight can deploy and retrieve the Tug and its round trip payload. The aerobraking mode may also be applied to return from other high energy missions to provide larger payload capabilities than those possible with similar sized Tugs operating with conventional trajectory modes.

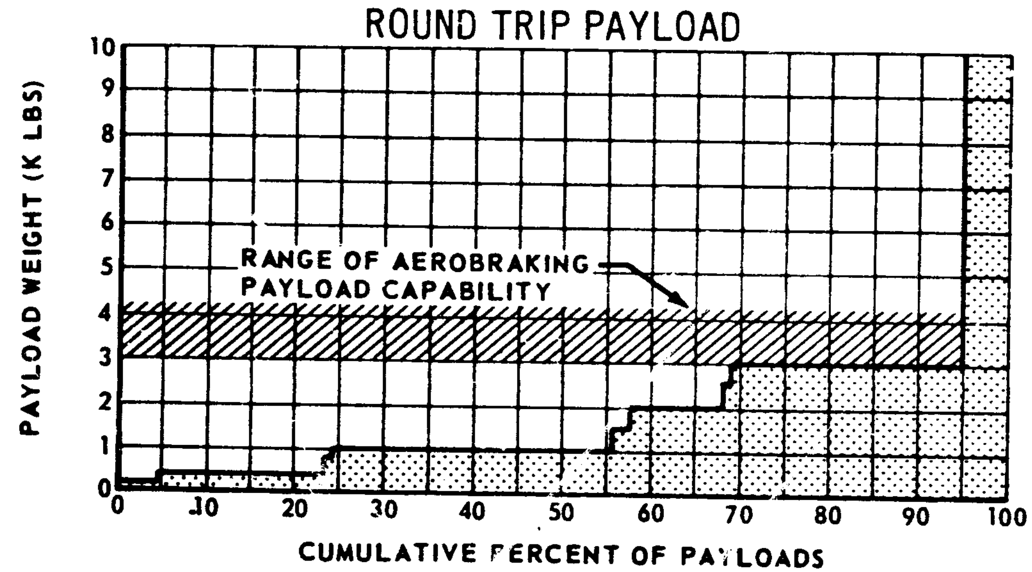
The primary approach for this study was to determine the round trip payload capability as a function of the return trip time (number of aerobraking passes) for each of six specified aerobraking adaptions to a baseline Space Tug configuration. A range of trajectory return times from less than one day to eleven days (2 to 60 passes) was analyzed. The impact of the various return times were related in terms of the weight of the additional structures, materials, subsystems and expendables required for thermal protection, increased drag, aerodynamic stability, guidance, control, and payload protection.

2.1 STUDY CONCLUSIONS

The conclusions reached in this study are, due to the limited study scope and time available, preliminary and provide trends rather than detailed data. However, the results present ample justification for the recommendation of further aerobraking study activity and technology programs. Many of the conclusions are subject to re-analysis as the aerobraking technique level of knowledge becomes comparable to conventional trajectory techniques and the on-going studies further define the Shuttle.

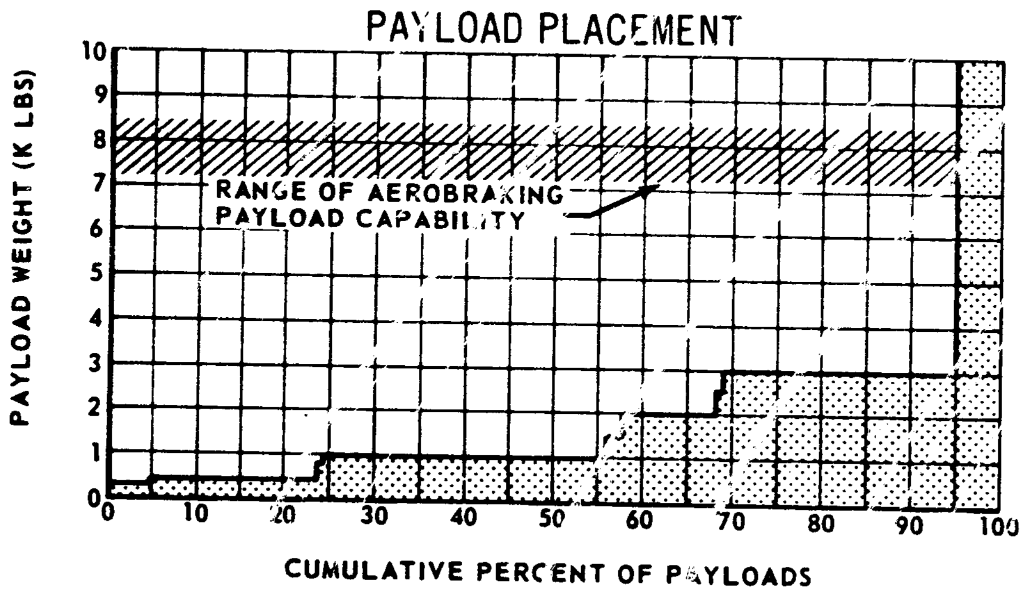
The general conclusions reached in the study are:

- o The aerobraking mode is feasible for the return of the Space Tug from geosynchronous and other high orbit missions.
- o The aerobraked Tug's payload capability is maximized by missions having 25 to 35 atmospheric passages during the aerobraking phase. This corresponds to total Tug geosynchronous mission time of from 4 to 7 days. A 5 day mission duration is within the on-orbit capability of the Shuttle and permits a single Shuttle/Tug to accomplish a mission.



BASIS:
- EOS CAPABILITY ~ H-33 ORBITER
- 287 GEOSYNCHRONOUS MISSIONS
- 30 PASS MISSIONS

CONCLUSIONS:
- 95% OF ALL GEOSYNCHRONOUS MISSIONS CAPTURED



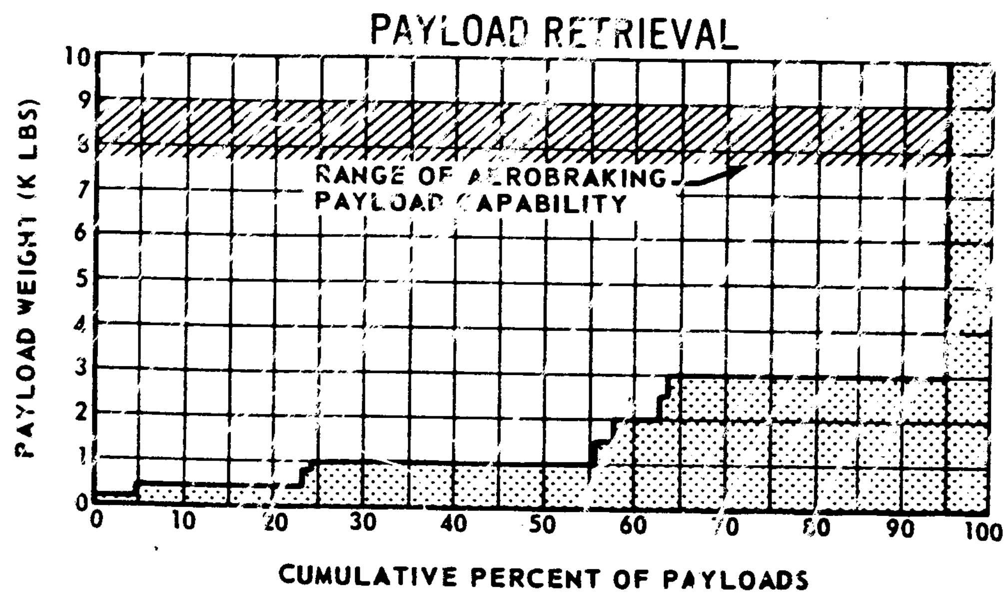


FIGURE 2.0.0.0-1: GEOSYNCHRONOUS PAYLOAD CAPABILITY OF AEROBRAKED TUG

2.1 (Continued)

- A one day return mission from geosynchronous orbit can be accomplished in from one to five passes. However, the thermal and pressure environments increase the structural requirements and result in significantly lower payload capability than the longer duration, maximum payload missions.

- The maximum geosynchronous payload capability of the aerobraked Tug can be obtained by optimizing the departure/recovery orbits and maximizing usage of the Shuttle for Shuttle/Tug interface operations.

- Comparing the required weights for aerobraked and conventional trajectory Tugs to accomplish comparable payload geosynchronous missions, the aerobraked Tug weight is approximately 55% (retrieval), 65% (round trip), or 80% (placement) that of the conventional Tug.

- The aerobraking kits for the Space Tug can be designed so that the aerobraked Tug will fit within the Shuttle's cargo bay. The aerobraking kits have a negligible scar weight impact on the conventional trajectory Tug. When the kits are removed, the Tug may be used for its lower energy missions with insignificant reduction in performance.

- Reducing the ballistic coefficient with a large flare or other large surface area drag devices will permit lower thermal and pressure loads at re-entry. Obtaining this large area, however, will reduce the weight available for payload and presents many design problems with packaging in the Shuttle cargo bay, deployment, retraction, astrionics visibility and payload rendezvous and docking to the Tug.

- In general, short duration aerobraking missions will require more complex designs of the aerobraking kit elements, and will require technology advances in materials to increase payload capabilities.

- A radiative heat shield is more desirable than the ablative heat shield as it is lower weight, reusable with minimal and/or no refurbishment and is less complex.

- The atmospheric anomalies may be overcome by trajectory correction techniques. The thermal effect was less than 100°F.

- The solar, lunar, and earth harmonics perturbations significantly impact the selection of the target perigee altitudes but have only minor impacts on thermal, aerodynamics, and control parameters. These effects are generally predictable and can be accounted for in pre-mission planning.

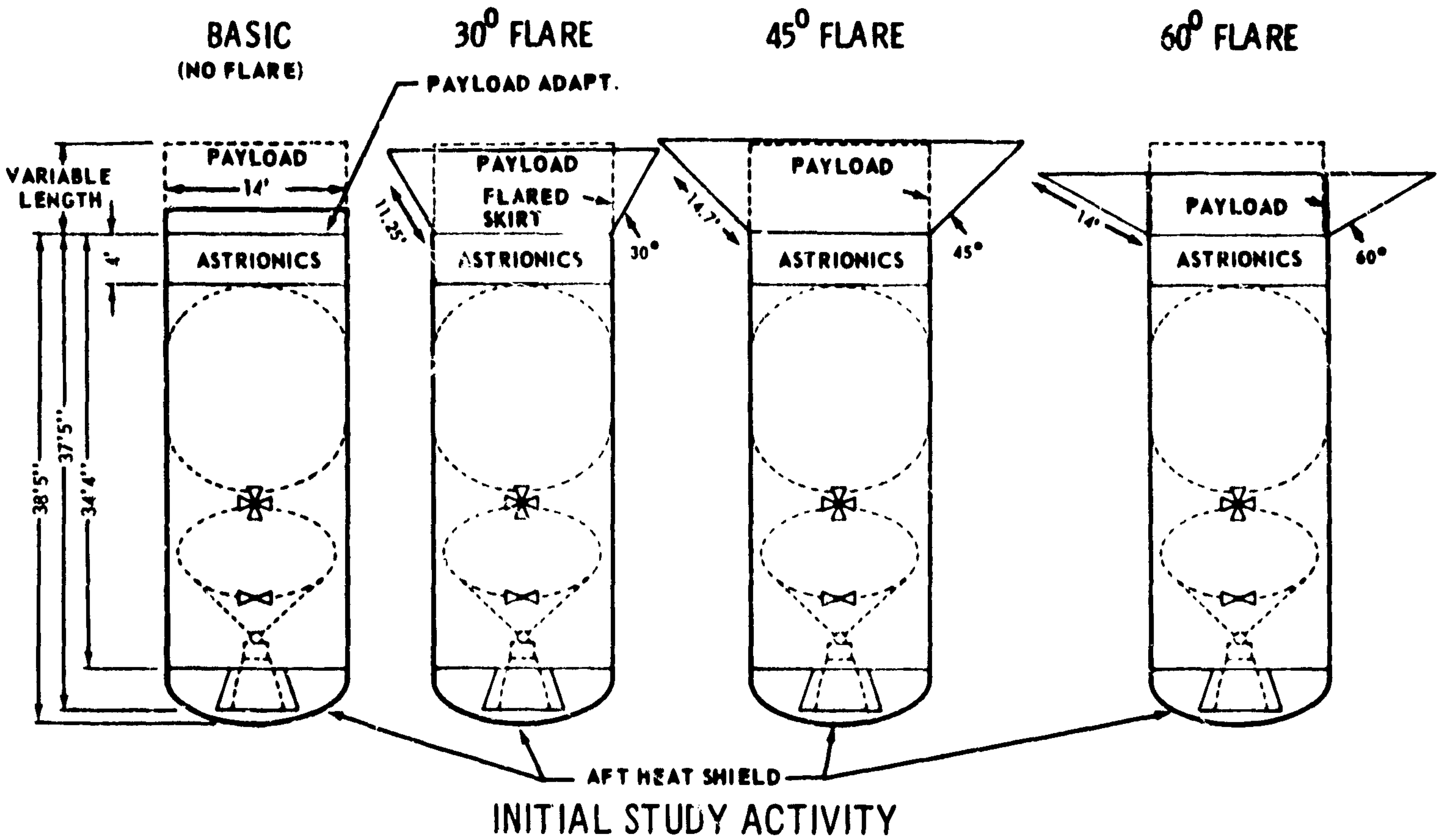
2.2 AEROBRAKING CONFIGURATIONS

To obtain a baseline Tug for this aerobraking study, the Space Tug configuration developed by The Boeing Company under the aforementioned previous NASA/MSFC study contract (Reference 1) was updated to conform to the current Shuttle payload capability. This baseline configuration was then modified for aerobraking using the criteria that the Tug with the aerobraking kit attached would be compatible with the Shuttle bay dimensional constraints.

This study limited its analysis to investigation of aerobraking with the propulsion module end of the vehicle entering the atmosphere first (aft end first). This approach offered several advantages. The highest heating loads will occur on the end of the vehicle entering the atmosphere first. The propulsion module aft end can much more readily be protected to withstand the resulting high temperatures than can the payload (which, by groundrule was restricted to a 300°F maximum temperature limit). The propulsion module will be partially protected from the heating environment by the insulation required for normal Tug operations so that only a limited amount of additional (heat shield and sidewall) insulation will be required for aerobraking. The payload first entry mode would necessitate large insulated payload adapters for payload protection. Thus, the aft end first mode appears to offer a lower weight and less complex heat shield system.

For the longer duration missions (lower thermal environment), a radiative hot structure designated as the aft heat shield was selected to cover the base of the propulsion module during aerobraking (and also during launch and retrieval of the Tug in the Space Shuttle). For the short duration missions (high thermal environment), an ablative insultion mounted atop a cold structure was used as the aft heat shield.

The six configurations shown in Figure 2.2.0.0-1 were specified for the aerobraking analyses of this study. The first configuration shown at the top of the figure is an adaptation of the baseline Tug wherein an aft end heat shield, sidewall thermal protection and a payload adapter have been added. This configuration, which has no aerodynamic flare (and which is identified as the basic configuration) will be statically unstable and will require the use of the reaction control system to provide the controlling moments. The other three configurations at the top of the figure also employ aft heat shields, sidewall insulation and the payload adapters but, in addition, have flares of various angles and lengths to provide static stability and increased drag. The flares are located aft of the astrionics module section of the vehicle to provide maximum stability. The three configurations shown in the bottom of Figure 2.2.0.0-1 illustrate the configurations investigated for the short duration missions. The first two configurations are similar to the basic Tug and flared configurations shown in the top of the figure. The only significant difference is the use of an ablative heat shield in lieu of the reradiative heat shield. Both configurations are statically unstable



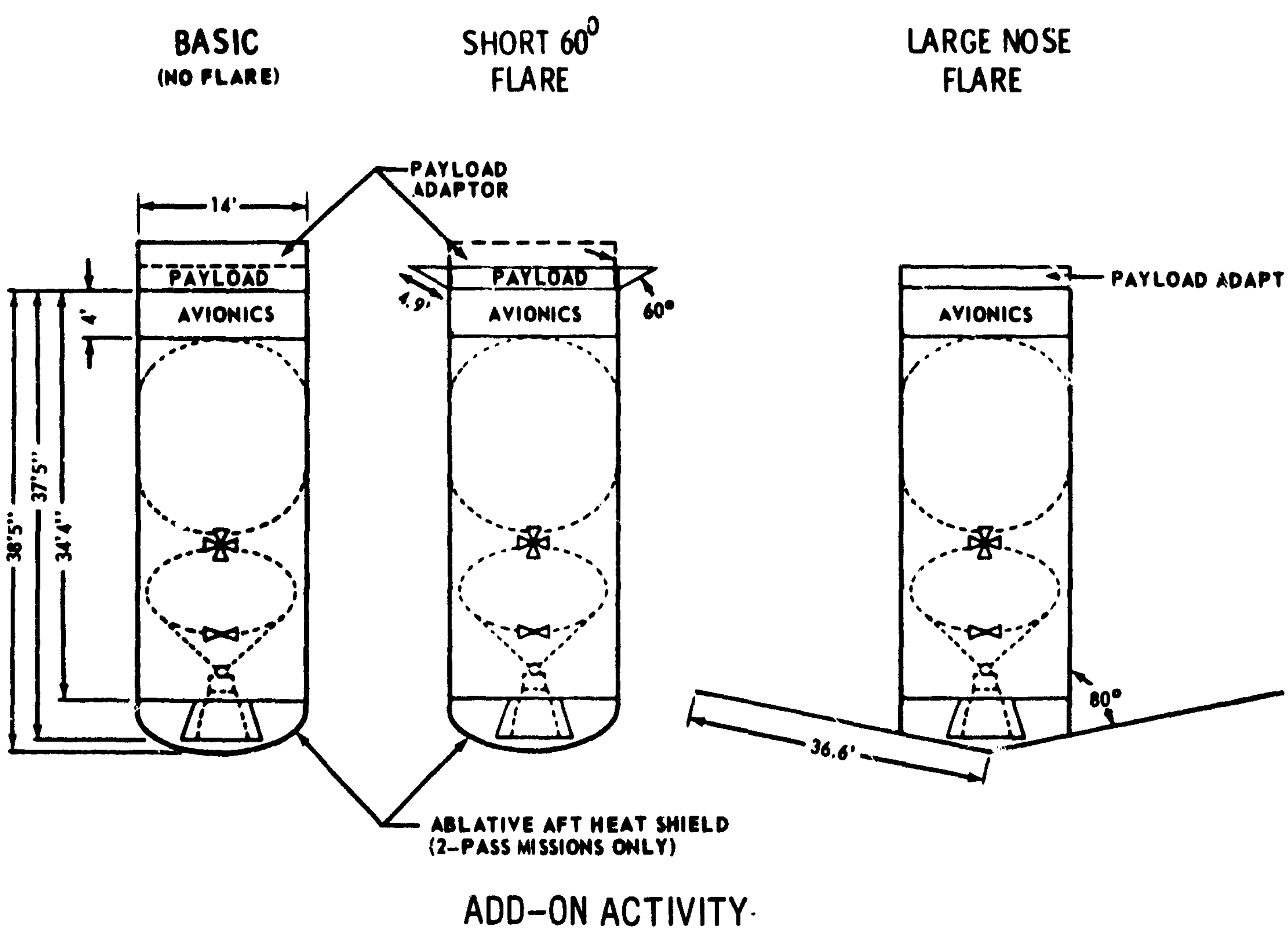


Figure 2.2.0.0-1: SELECTED SPACE TUG AEROBRAKING CONFIGURATIONS

2.2 (Continued)

and require use of the reaction control system to provide stability. The large nose flare configuration uses a forward mounted, combined heat shield and flare. The large flare shields the Tug and no additional thermal protection is required. This configuration is statically stable.

The aerobraking elements of each of these configurations can be applied in a kit form to the Tug for those missions where aerobraking is desirable. The scar weight associated with modifying the conventional Tug for aerobraking is slight. Therefore, the non-aerobraked Tug performance loss due to the scar weight penalty will be insignicant. The Space Tug with this kit assembled to it can be carried within the Shuttle bay.

2.3 SUMMARY OF RESULTS

The study approach was to define the required elements for aerobraking adaptation of the Tug and to define the weight deltas of each of these elements as a function of mission duration. The weight of some of these elements must increase with mission duration while the weight of others will decrease. The minimum aerobraking kit weight will, in general, result in the maximum payload weight. For any of the adaptations to the baseline configuration, a return mission duration of approximately five days will maximize the payload capability. However, technology or operational constraints may dictate either longer or shorter return mission durations for the respective configurations.

The round trip payload capability of the basic (no flare) configuration, as shown in Figure 2.3.0.0-1, varies from approximately 1700 pounds to approximately 3975 pounds as a function of return mission time and optimizes at approximately a 30 pass, 5 day mission.

Round trip payload capabilities of the four configurations employing 30°, 45°, short 60° and 60° aerodynamic flares are also shown as a function of number of return passes. As stated above, it appears that the optimum payload capability is approximately 30 passes for all cases.

The payload capability appears to be relatively insensitive (under three percent) from approximately 20-50 passes (3.5 to 9 days). The maximum payload capability will be provided by a neutrally stable flare configuration. Longer flares provide greater stability but have increased flare weight and result in lesser payload capability than the neutrally stable flare. Shorter flares provide lower flare weight but require additional reaction control system fuel and payload insulation which offset the flare weight savings and result in lower payload capability than the neutrally stable flare.

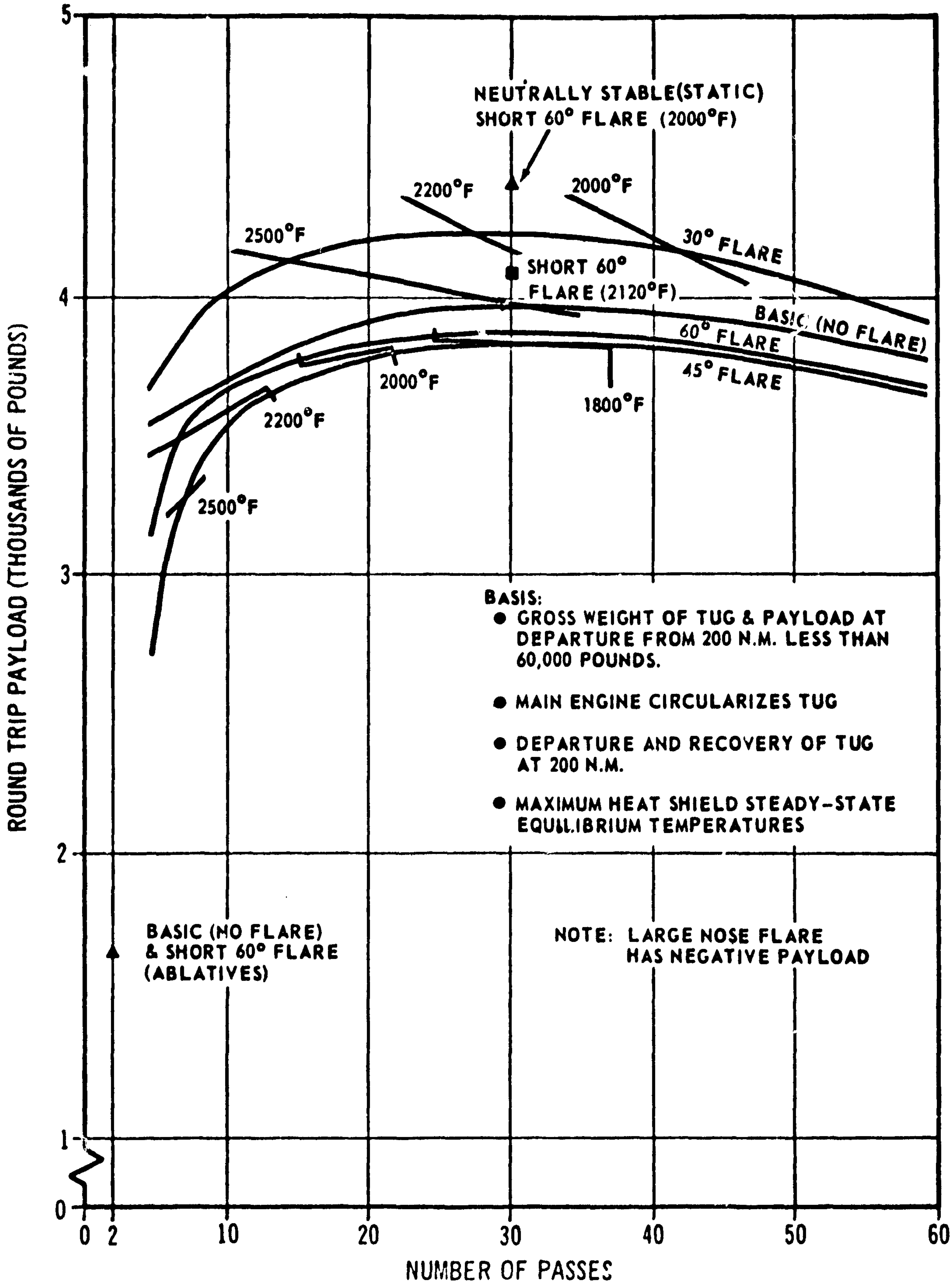


FIGURE 2.3.0.0-1. SYNCHRONOUS ROUND TRIP PAYLOAD VS. NUMBER OF PASSES (200 N.M. RECOVERY)

2.3 (Continued)

For example, the 60° flare configuration was evaluated over a range of flare lengths which varied the aerodynamic properties (drag, stability, air loads, thermal environments, etc.). The flare lengths were varied (4.90, 8.68 and 14 feet slant heights) to achieve unstable, neutrally stable and highly stable configurations.

As shown in Figure 2.3.0.0-1 for the 30 pass mission, the unstable configuration (short 60° flare) resulted in 4100 pounds of payload, the neutrally stable configuration resulted in 4400 pounds of payload and the highly stable configuration 60° flare resulted in 3800 pounds of payload.

The figure also illustrates the temperature as a function of the number of passes for several of the configurations. With the current state-of-the-art materials, an upper temperature limit of approximately 2000°F was used for radiative thermal protection systems (approximately equal to the capability of TD-Nickel-Chrome). With this limit, the minimum number of passes that an aerobraked Tug can return in decreases with increase in flare planform area. For example, the neutrally stable flare (8.68') can return in 30 passes while the highly stable flare (14') can return in 15 passes and stay under the 2000°F temperature limit. If shorter mission durations are desired, either advanced state-of-the-art radiative materials or ablatives are required.

Further, prior to selection of the desirable flare angle and slant height length, wind tunnel testing will be required to determine (1) the degree of flow separation at the flare periphery, and (2) other flare interactions with the slip stream.

This study showed that the three sigma onboard navigation and update uncertainty at first perigee can be limited to ± 0.6 n.m. for a five day (30 pass) mission. Any errors in the trajectory of the vehicle can be corrected to approximately this navigation uncertainty by using the reaction control system (RCS).

The impact of these navigation uncertainties when coupled with the unpredictable atmospheric dispersions will not severely impact the Space Tug aerobraking configuration. Several methods of compensating for these uncertainties and dispersions were identified. One method would be to set the target perigee density altitude such that the Tug temperatures at the worst case density altitude would not exceed the design temperatures. This would result in increased return trip times. Another option would be to provide a target drag profile in the navigation system which would be compared with actual drag data from accelerometers upon entry into the sensible atmosphere. If the measured drag exceeds the target drag, lift could be applied and held up to (but not through) perigee by using aerodynamic control and/or the RCS system. This option would result in increased weight. The desirable method is one which corrects for the atmospheric disper-

2.3 (Continued)

sions and navigation error with the same burn. A combined corrective burn near or at entry would take advantage of the best trajectory knowledge obtainable from the Astrionics system.

To maximize the payload capability of the aerobraking Tug, it appears that the optimum mode of operation is one in which the Tug is deployed in and later returns to an orbit above the nominal 100 n.m., e.g., 200 n.m. The waiting Space Shuttle would then rendezvous and dock with the Tug and transport the Tug and the returned payload to earth.

2.4 STUDY LIMITATIONS AND FOLLOW-ON REQUIREMENTS

While the results of this study are indicative of the aerobraking potential, the study was not in sufficient depth to (1) fully investigate all of the parameters which could potentially increase or reduce the weight and complexity of the aerobraking kits, or to (2) examine sufficient aerobraking configuration options and operational modes to define the optimum performance/cost system. The economic advantages of aerobraking due to fewer required Shuttle launches, however, are obvious and represent a potential for a major reduction in space program costs. These cost savings were not studied and should be assessed in future studies.

More detailed studies must be completed to develop the design and operational detail of the aerobraked Space Tug concept to a level comparable with that of the Space Tug configurations previously investigated or presently under investigation. Such follow-on studies should refine and update the Tug configurations considering the evolving Shuttle era technology, the total mission model, optimal operational modes, Shuttle/Tug/payload interfaces and economic considerations.

Supporting technology programs should include (1) in-depth analysis and wind tunnel testing of aerobraking configuration options, (2) investigation of alternative aerobraking kit concepts, (3) investigation of thermal protection system concepts and materials, (4) integrated structure design, (5) identification of characteristics and designs of advanced sensor systems, (6) further investigation of guidance laws and targeting, (7) study of reaction control systems concepts and operational modes, and (8) further identification of potential atmospheric anomalies. Also, the application of advanced technologies to further enhance the potential of the aerobraked Tug should be considered.

This spectrum of recommended future study programs are further identified and discussed in Volume II of this report (Appendix E - Recommended Aerobraking Follow-On Activities).

3.0 STUDY ACTIVITIES AND RESULTS

The study objective was to investigate the feasibility and practicality of the aerobraking return trajectory mode for the Space Tug from equatorial geosynchronous orbit. To accomplish this objective, the study was directed to provide the following results:

1. Aerobraking aerodynamic and trajectory data with thermal, guidance and control, and operational implications.
2. Inert weight penalties associated with aerobraking, such as thermal protection systems, aerodynamic drag and stability devices, payload adapters and astrionics systems.
3. Sensitivity of the trajectory parameters to the entry environments.
4. Sensitivity of the Space Tug weights to the entry environments.
5. Comparison of operational modes and payload capabilities of conventional versus aerobraking trajectories.
6. New technology requirements and future studies required to enhance the potential of aerobraking for Space Tug usage.

The study Technical Approach, as shown in Figure 3.0.0.0-1, was initiated with the development of preliminary trajectory data and configuration characteristics for specified aerobraking adaptations to the baseline Tug configuration. These data were then applied to the aerodynamic analysis which supplied (1) airloads data used to determine pressure loads and associated structural weight penalties, (2) drag data used to develop more refined trajectory performance, and (3) stability data used with the trajectory data to define the control requirements and the associated reaction control systems weight penalties. The trajectory analysis also provided input to the thermal analyses which defined the thermal environments, the thermal protection system material requirements and associated weights. The trajectory data was also used in the guidance avionics analysis which defined navigation system capabilities and requirements, reliability requirements, power requirements, radiation impact and associated weight penalties.

The resulting data were then used to define payload capability as a function of number of return passes through perigee for each of the aerobraking configurations. Sensitivity of these data were then analyzed with respect to (1) trajectory uncertainties due to atmospheric density variations, (2) earth oblateness, (3) lunar and solar gravitational effects, (4) navigation uncertainties. All of the study data were then reviewed and assessed to provide the final study results, conclusions and recommendations for new technologies and/or follow-on Space Tug aerobraking studies.

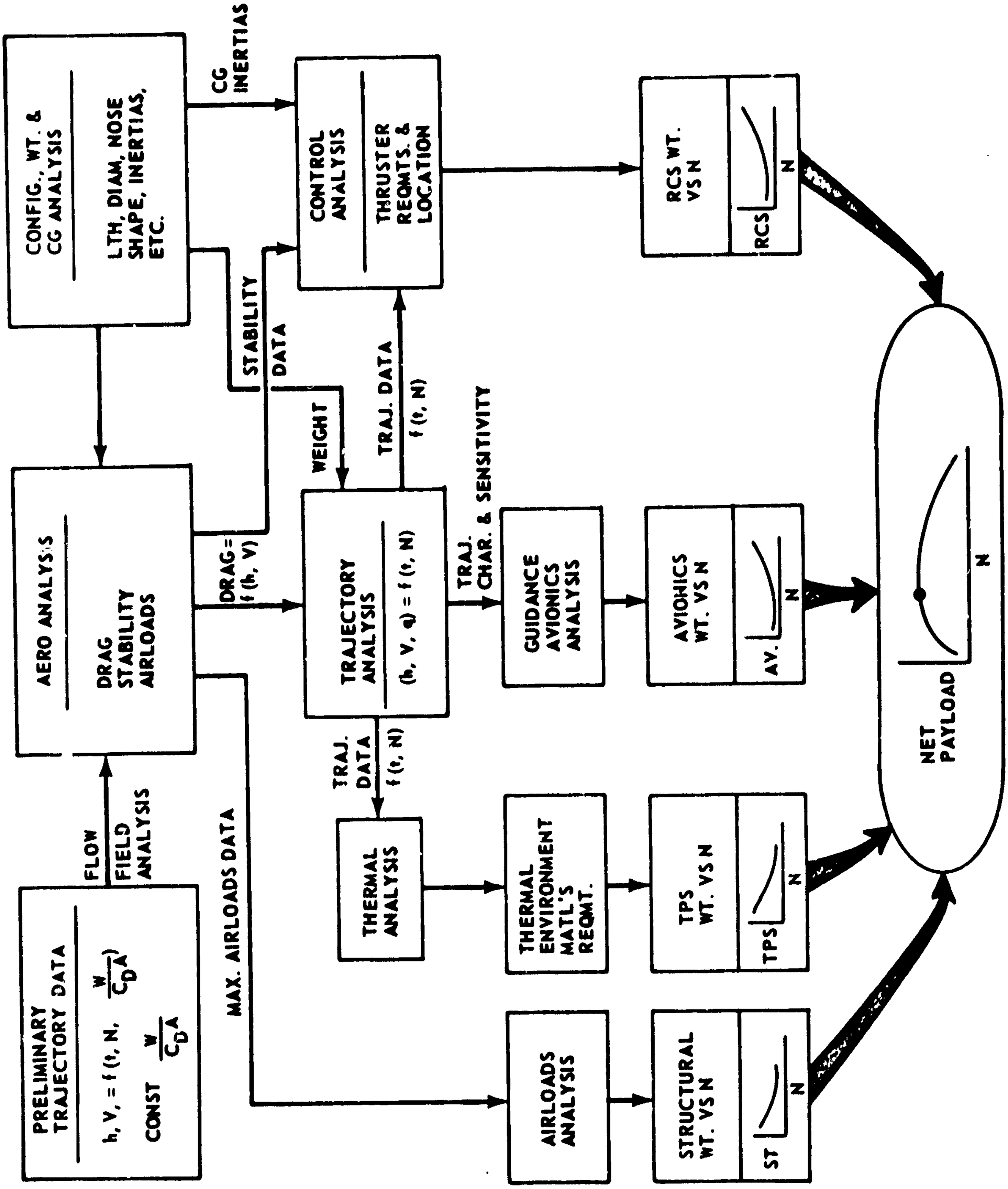


FIGURE 3.0.0.0-1: SPACE TUG AEROBRAKING STUDY TECHNICAL APPROACH

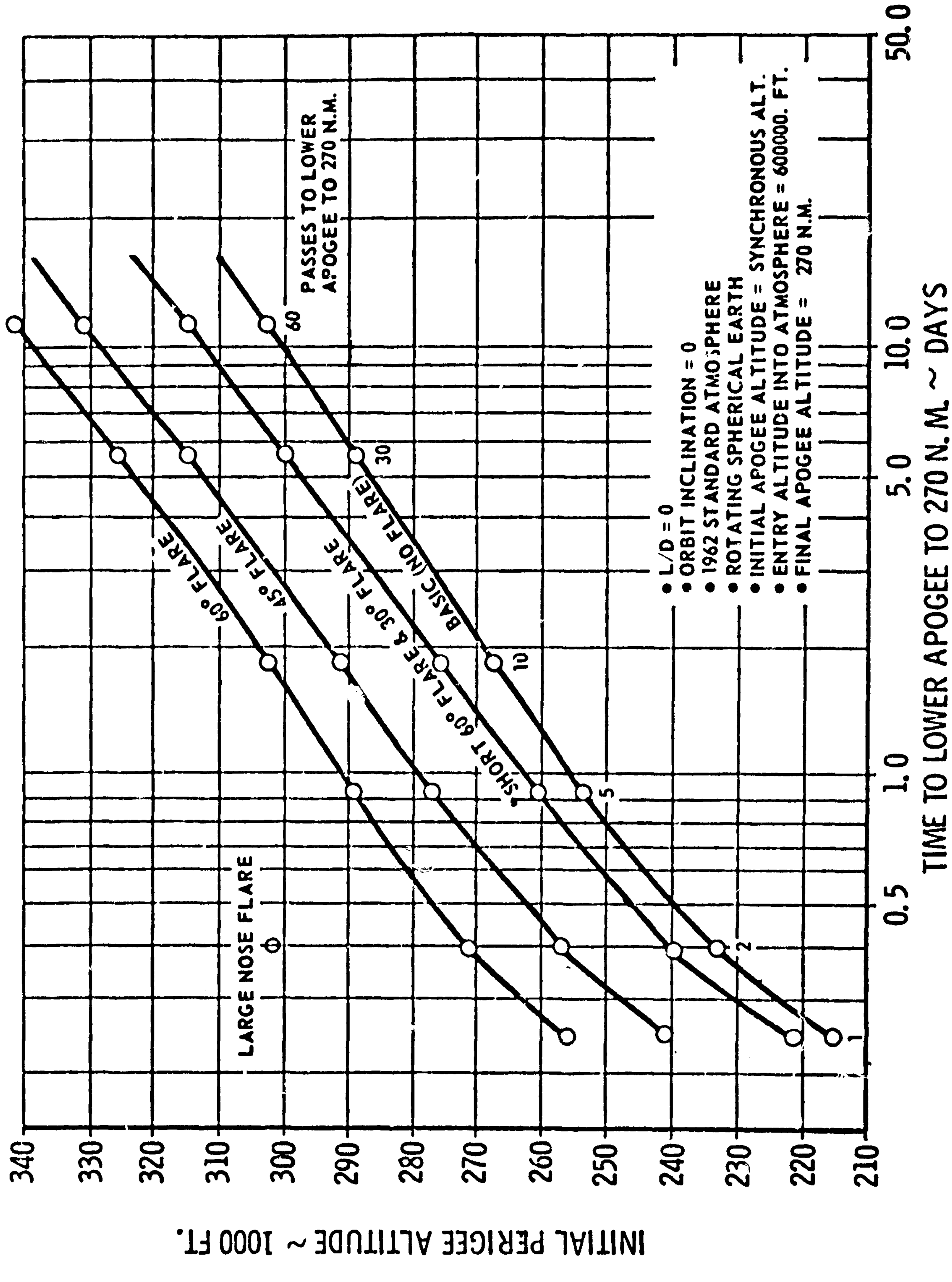


FIGURE 3.1.0.0-1 SPACE TUG AEROBRAKING RETURN TIME FROM SYNCHRONOUS ORBIT

3.1 TRAJECTORY ANALYSES

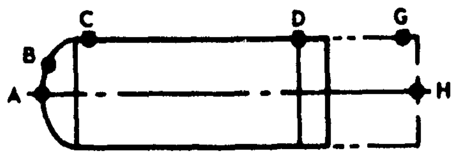
For each of the configurations, trajectory analyses were conducted using the drag coefficient data developed in the aerodynamics analysis. The trajectory scheme used a target initial perigee altitude with subsequent lower perigee altitudes as dictated by the orbital mechanics of the decreasing energy orbits. Return trip time was therefore a direct function of initial perigee altitude for any fixed ballistic coefficient (configuration weight divided by the product of configuration frontal area and drag coefficient: W/C_DA). Figure 3.1.0.0-1 shows the relationship of trip time to initial perigee altitudes for the configurations of interest. As shown in Figure 3.1.0.0-1, the initial perigee altitude is higher for the flared configurations for accomplishing the mission in the same return time than that of the non-flared configuration because of the higher drag (lower W/C_DA) values obtained with the flared configurations. These higher initial perigee altitudes will result in lower temperature on the vehicle as discussed below and will result in lower pressure loads than will be encountered with the basic (no flare) configuration.

3.2 THERMAL ANALYSIS

Figure 3.2.0.0-1 shows the maximum equilibrium temperatures, at various points on each of the configurations, as a function of the number of passes required for return. As shown, the maximum temperature decreases with increasing number of passes for the return mission. The maximum temperature for each configuration exists at the stagnation point of the aft heat shield. These temperatures vary for the 2 pass mission from 3680°F for the basic (no flare) configuration to 1410°F for the two pass large nose flare configuration. Increasing the number of passes to 30 (the optimum payload performance condition) decreases the aft heat shield temperature to approximately 2000°F for each of the flare configurations. Further increases in the number of passes continues to lower the thermal environment encountered but at a lesser rate of change. Beyond 60 passes the temperature is relatively insensitive to the number of passes.

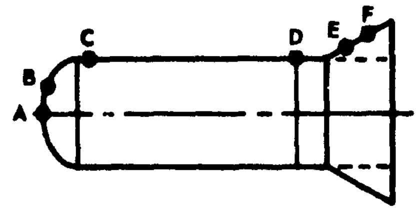
On the cylindrical sections of the Tug, the maximum temperatures for the two pass mission range from 1790°F (no flare configuration) to 1048°F (60° flare configuration). The temperatures on the flares (1527°F to 927°F for a two pass mission) are significantly less than those for the aft heat shield and approximate those to be encountered on the Tug cylindrical sections.

Note: The temperatures shown for the radiative heat shields, sidewall and flares are the surface temperatures of thin films. The effect of heat sink was investigated for only a single case, that of the basic (no flare) configuration. The heat sink effects could reduce the stagnation temperature approximately 300°F for a 30 pass mission if a hot structure is used for the aft heat shield. Because of the anticipated thicknesses of the micrometeoroid shielding and flare material, the temperature of the Tug sidewall and flare will approach the thin film temperatures shown.



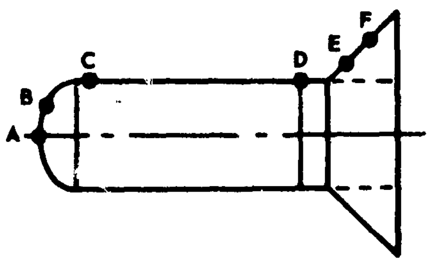
SPACE TUG BASIC CONFIGURATION

TRAJECTORY	MAXIMUM EQUILIBRIUM TEMPERATURES (°F)					
	A	B	C	D	G	H
2 PASS	3680	3520	1789	1275	1170	779
5 PASS	3320	3175	1585	1120	975	682
10 PASS	2990	2860	1410	987	875	591
30 PASS	2540	2420	1166	797	720	451
60 PASS	2240	2140	1005	676	615	364



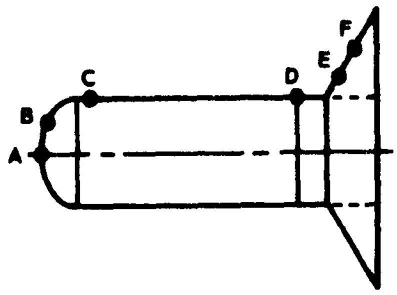
SPACE TUG 30° FLARE CONFIGURATION

TRAJECTORY	MAXIMUM EQUILIBRIUM TEMPERATURES (°F)					
	A	B	C	D	E	F
5 PASS	2940	2800	1382	1082	1272	1293
10 PASS	2630	2520	1215	943	1104	1124
30 PASS	2160	2060	957	733	850	869
60 PASS	1880	1790	809	605	706	729



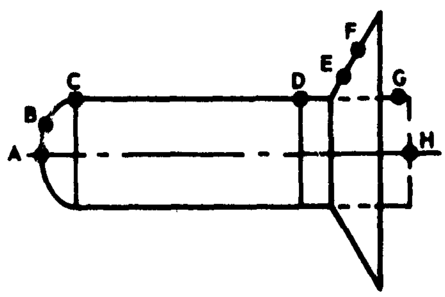
SPACE TUG 45° FLARE CONFIGURATION

TRAJECTORY	MAXIMUM EQUILIBRIUM TEMPERATURE (°F)					
	A	B	C	D	E	F
5 PASS	2590	2480	1195	927	1037	1085
10 PASS	2300	2205	1040	800	874	919
30 PASS	1866	1798	812	608	635	680
60 PASS	1660	1580	691	507	513	558



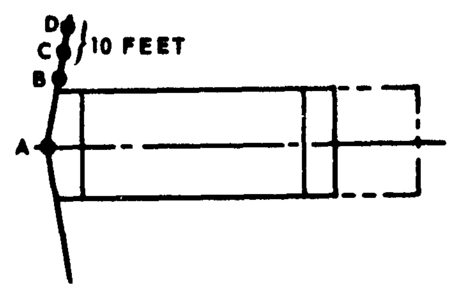
SPACE TUG 60° FLARE CONFIGURATION

TRAJECTORY	MAXIMUM EQUILIBRIUM TEMPERATURE (°F)					
	A	B	C	D	E	F
5 PASS	2325	2220	1048	806	943	970
10 PASS	2080	1990	917	697	804	829
30 PASS	1740	1660	733	540	621	648
60 PASS	1512	1467	609	439	503	538



SHORT 60° FLARE

TRAJECTORY	MAXIMUM EQUILIBRIUM TEMPERATURE (°F)							
	A	B	C	D	E	F	G	H
2 PASS	3290	3140	1590	1240	1490	1527	1138	758
30 PASS	2120	2070	980	748	852	889	687	458



LARGE NOSE FLARE

TRAJECTORY	MAXIMUM EQUILIBRIUM TEMPERATURE (°F)			
	A	B	C	D
2 PASS	1410	1403	1380	1337

Figure 3.2.0.0-1: MAXIMUM EQUILIBRIUM TEMPERATURE PROFILES

3.2 (Continued)

Figure 3.2.0.0-2 lists the materials used for the aerobraking kit components. The radiative materials were selected for their strength-to-density capability at the temperatures encountered. The ablative and insulation materials were selected based on low weight. The Fansteel 60 and 85 materials were considered advanced state-of-the-art. All other materials represent current technology.

3.3 CONTROL ANALYSIS

The control analyses used the center of pressure data and the coefficient of normal force data developed in the aerodynamic studies plus the trajectory data to determine the Tug control requirements. These analyses were directed specifically to define the requirements during aerobraking considering (1) limit cycle requirements, (2) the aeromoment requirements, and (3) directional control requirements.

The limit cycle requirements were established assuming an allowable 5° pitch and yaw dead band when the vehicle is out of the sensible atmosphere (above 600,000 feet). Within the sensible atmosphere, the analysis assumed a 1° pitch and yaw dead band. The dead band for roll was considered to be 2.5° throughout the aerobraking mode.

Requirements for stabilizing the vehicle against the destabilizing aeromoments were defined assuming maintenance of the dead band as the allowable angle of attack through the sensible atmosphere. Static stability only (no dynamic stability) was investigated.

For directional control, it was assumed that the vehicle would require 360° rotation per pass in the pitch or yaw plane.

As shown in Figure 3.3.0.0-1, the attitude control propellant requirements increase with increasing return times. The RCS propellant requirements for the unstable (basic and short 60° flare) Tugs differ significantly from the stable (large nose flare, 30°, 45° and 60° flare) Tugs. Approximately 500 pounds more RCS fuel is required for the basic Tug-30 pass mission and approximately 200 pounds for the short 60° flare Tug-30 pass mission. The short 60° flare has some stability influence but it is not sufficient to provide complete stability without some RCS support.

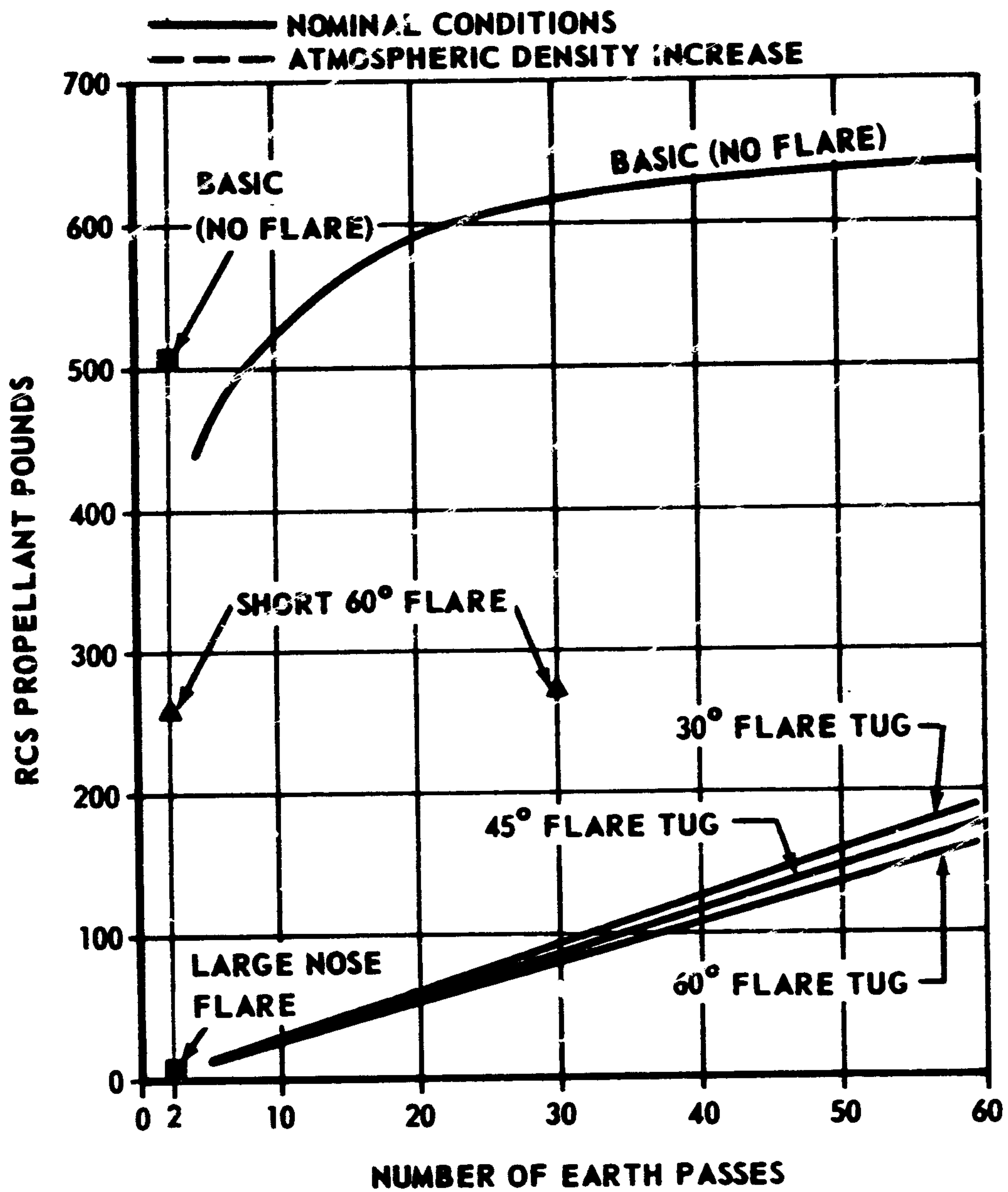
The impact of atmospheric dispersions on RCS consumption was also investigated and is shown on the right of Figure 3.3.0.0-1. Approximately 10 percent more fuel is required to compensate for dispersions.

3.4 CONFIGURATIONS

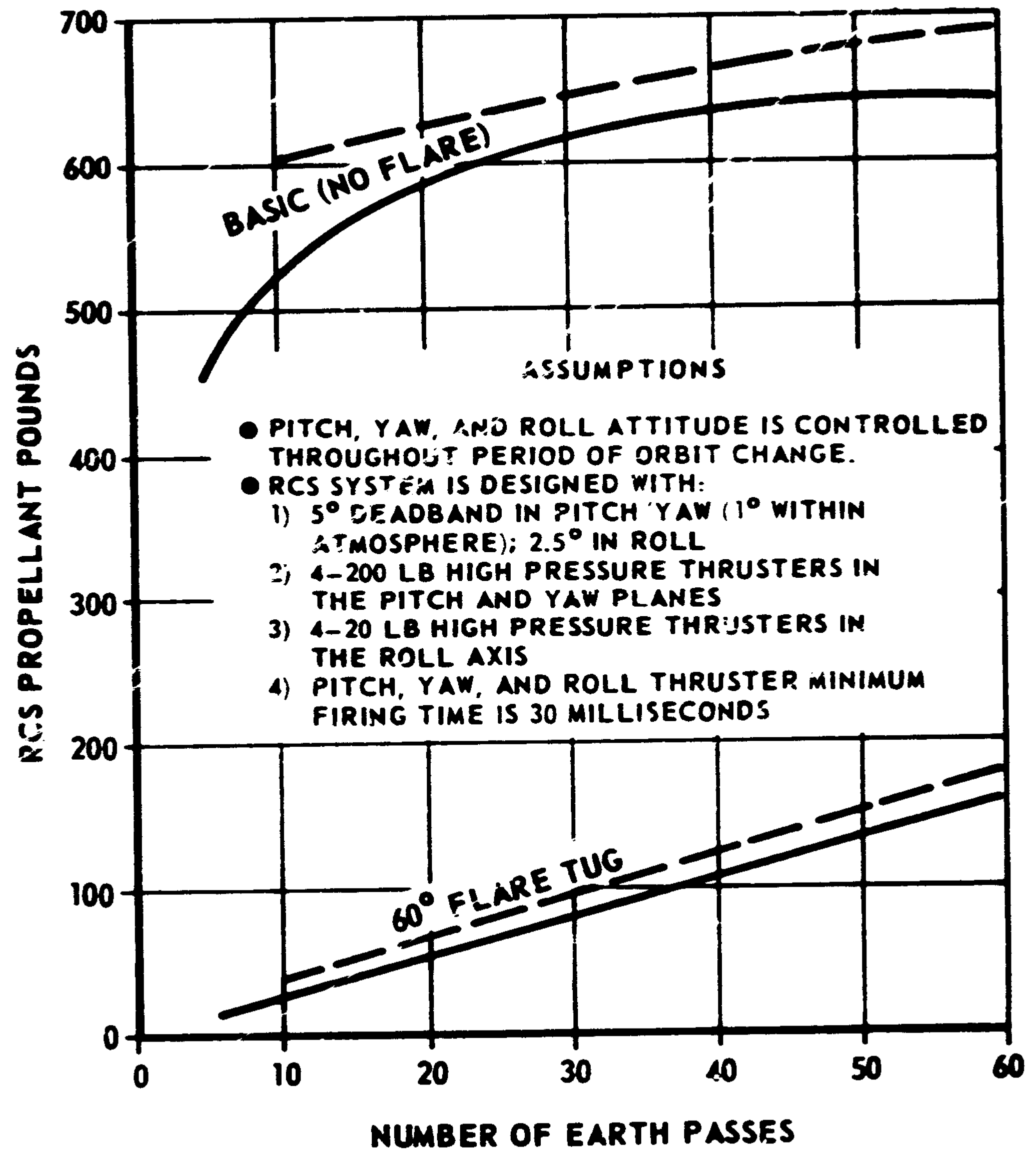
The conventional Tug configuration must be modified for adaptation to the aerobraking mode. The aerobraking adaptation kit components include aft heat shields, aerodynamic flares, sidewall insulation, astrionics modifications and payload adapters.

LOCATION	TEMPERATURE (°F)	MATERIALS
● <u>HEAT SHIELD</u>		
ABLATIVE	OVER 3000°	ESA-3560 IIA OVER TITANIUM SUPPORT STRUCTURE
RADIATIVE	2500° - 3000°	FANSTEEL 60
	2000° - 2500°F	FANSTEEL 85
	1500° - 2000°	TD - NI - CHROME
	UNDER 2000°	RENE' 41
● <u>SIDE WALL</u>		
INSULATION	ALL TEMPERATURES	MICROQUARTZ
OUTER FOIL	OVER 800°	L-605 COBALT ALLOY
OUTER FOIL	UNDER 800°	TITANIUM
● <u>FLARES</u>		
	OVER 1300°F	RENE' 41
	UNDER 1300°F	INCONEL 718
		(TITANIUM USED AS SUPPORTING STRUCTURE FOR FLARES)

FIGURE 3.2.0.0-2 THERMAL MATERIALS USED FOR AEROBRAKING TUG COMPONENTS



RCS PROPELLANT CONSUMED DURING CHANGE OF ORBIT PERIOD



EFFECT OF ATMOSPHERIC DISPERSIONS ON RCS PROPELLANT CONSUMPTION

FIGURE 3.3.0.0-1: RCS PROPELLANT CONSUMPTION

3.4 (Continued)

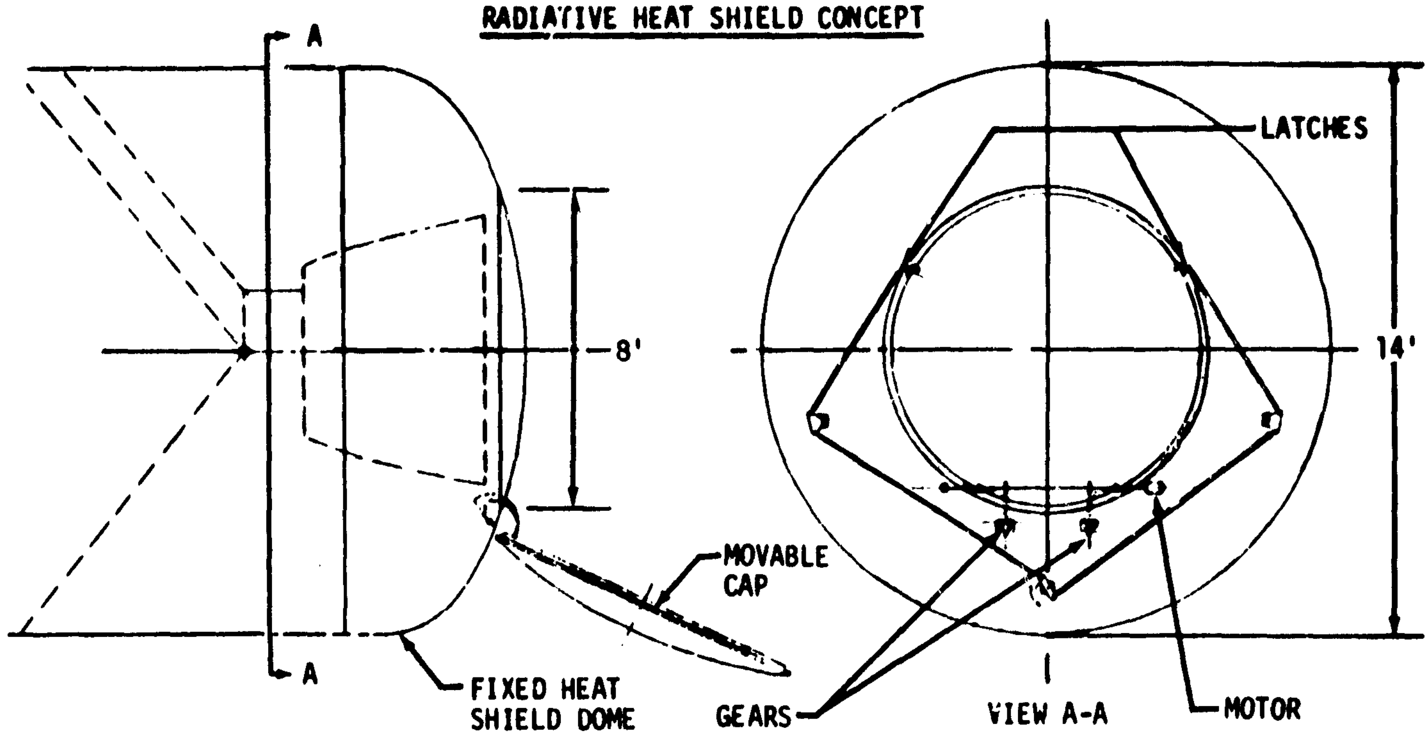
Several heat shield concepts were investigated with regard to feasibility and compliance with the Shuttle dimensional constraints and functional performance. The trades on the heat shield design were, however, principally limited to those involving heat shield weight. The upper portion of Figure 3.4.0.0-1 illustrates a low weight concept selected as the baseline radiative heat shield for further analyses.

During the delivery of the Tug to orbit by the Shuttle, the heat shield will be mounted over the nozzle. After the Tug has been removed from the Shuttle, the Tug heat shield latch will be released and an electric motor will rotate the gear mechanism to open the module cap portion of the heat shield. The cap will remain open throughout operation of the Space Tug main engine. The cap will be rotated sufficiently outward toward the sidewall to assure that the main engine exhaust plume does not impinge upon the heat shield cap. Prior to initiation of aerobraking (after performance of the plane change and deorbit burn) the cap will be rotated back to the closed position by the electric motor/gear mechanism and locked in place. As the radiative heat shields will operate with high stagnation temperatures (1400°F to 3000°F), the components behind this structure require insulation. A lightweight thermal reflector or barrier may have to be added to protect the lower temperature capability main engine components. Heat blocks will be provided to reduce the heat transfer back to the main structure.

The lower portion of Figure 3.4.0.0-1 illustrates the ablative heat shield concept required for the high thermal environment, short duration missions. This heat shield, unlike the radiative heat shield, is a one piece shield with the seal joints located at the Tug sidewall. This method is required to reduce the temperature at the seal joint location so that a proper seal can be obtained when required and the seal can be broken when required. The heat shield is rotated outward by an electric motor (lever mechanism). At full rotation outward, the heat shield is mounted alongside the Tug sidewall and pinned in place. Prior to aerobraking, the pin is released and the heat shield is mounted over the engine again. The ESA-3560 IIA ablative is mounted atop a titanium support structure. The ablative will maintain a 400°F temperature at the ablative/titanium interface.

The sidewall insulation kit will cover the cylindrical section of the propulsion module, the astrionics module and the payload adapter for the basic (no flare) and short 60° flared Tugs. As the temperature (except for short duration missions) encountered by the payload adapters used with the 30°, 45° and 60° flares will not exceed 300°F, no payload sidewall insulation are required for these configurations. For short duration missions, the same thermal protection system as used on the propulsion and astrionics sidewalls will be used for the payload adapter. The large nose flare Tug does not require sidewall insulation because of the protection offered by the large flare.

RADIATIVE HEAT SHIELD CONCEPT



ABLATIVE HEAT SHIELD CONCEPT

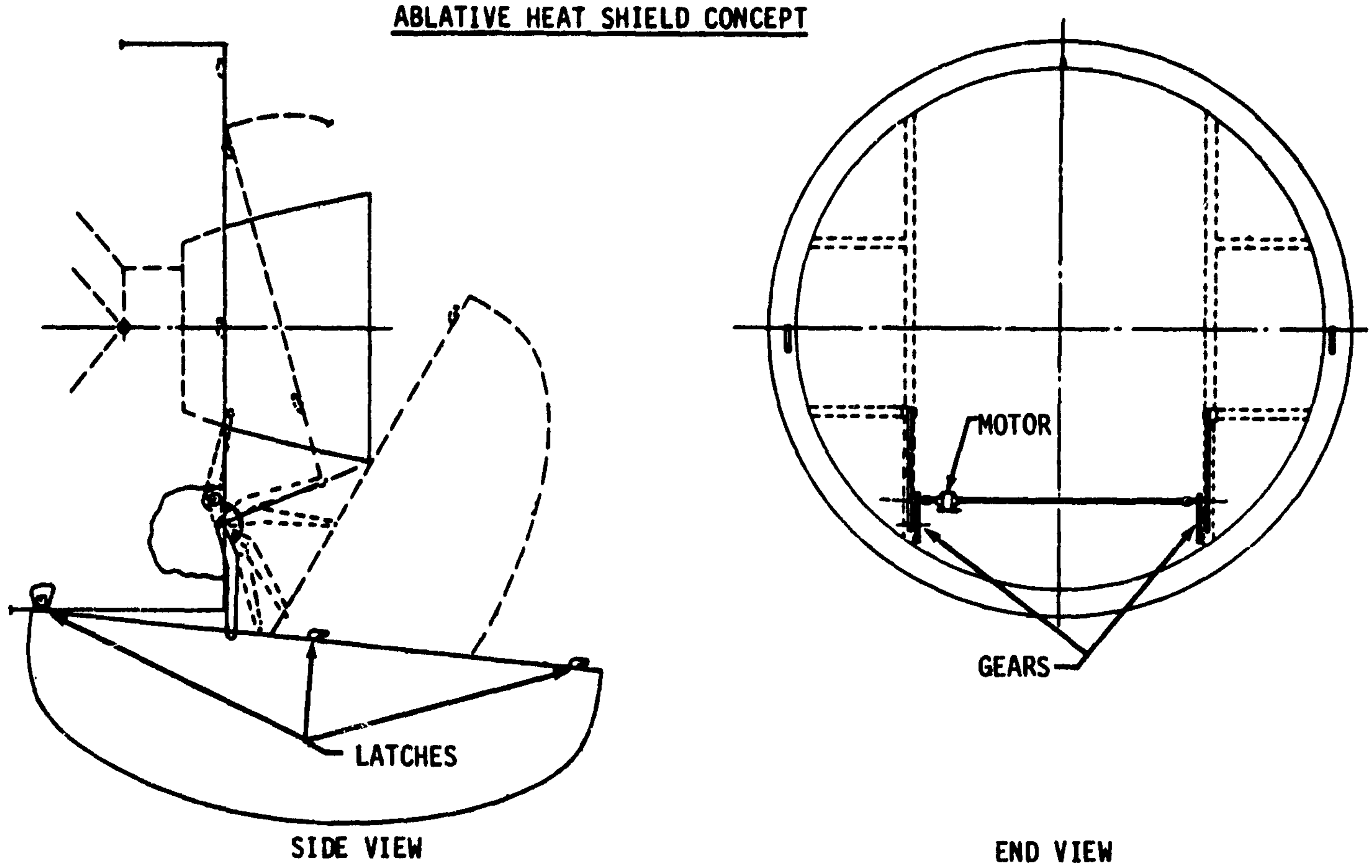


FIGURE 3.4.0.0-1 AFT HEAT SHIELD

3.4 (Continued)

The aerobraking sidewall insulation kit was designed to maintain a maximum temperature of less than 400°F on the sidewall of the baseline Tug. A low density microquartz material (3 pounds per cubic foot) can provide the insulation properties. As the temperature on the sidewall decreases from the heat shield interface to the payload adapter interface, a tapered sidewall insulation was designed. An external thin sheet of titanium (low temperature) or L-605 (high temperature) foil (0.002 inches) will be used as a radiative heat shield and to protect the microquartz from damage during handling and transportation.

The options available for design of the aerodynamic flares were somewhat restrictive. The baseline Tug was designed with a 14-foot outside diameter to fit within the 15 foot diameter Shuttle bay. The flare must, in its retracted position, fit between the 14 foot diameter Tug wall and 15 foot diameter Shuttle bay wall. Several flare configurations were investigated to define a feasible, relatively lightweight system. One configuration utilizes metallic panels which may be extended during the aerobraking operations and retracted along the Tug sidewalls during the normal (non-aerobraking) Tug operations. Figure 3.4.0.0-2 illustrates this concept which was used as the baseline for the 30°, 45° and 60° flare concepts. The flare consists of 18 rigid inner panels, 18 outer panels and 36 intermediate panels (which are spaced alternately with the inner and outer panels). The intermediate panels do not extend all the way down to the Tug sidewall. The panels are jointed by piano hinges. Structural rigidity is provided by a peripheral rib on each panel, by axial ribs along the panel edges at the hinge points and by 36 folding support struts located at 10° intervals. The folding support struts are mounted to the Tug sidewall and to the flare at a point approximately two-thirds of the way down the flare. When retracted, the flare increases the Tug diameter by 7 inches to 14.6 feet (still within the 15 foot diameter constant). Retraction is accomplished by using an electrically driven drum to retract a cable connected to the strut mid-point hinge. The strut will fold, and in so doing, will collapse the flare and will pull it down along the sidewall. Flare deployment is achieved by releasing the cable. Spring hinges at the flare/sidewall joint and the strut/sidewall joint spring the flare into the open position.

The short 60° flare employs the same inner/outer/intermediate panel concept as described above, except the number of panels were reduced and the support struts are actuated differently. The twelve support struts are elevated by threaded rods and followers. A reversible drive motor, a drive chain and twelve drive sprockets provide the actuation for the support struts.

The large nose flare concept employs a radiative flare located forward of the propulsion module. The Rene' 41 panels are hinged to the Tug at the start of the cylindrical section of the propulsion module. The panels are tapered to provide minimum overlap at the

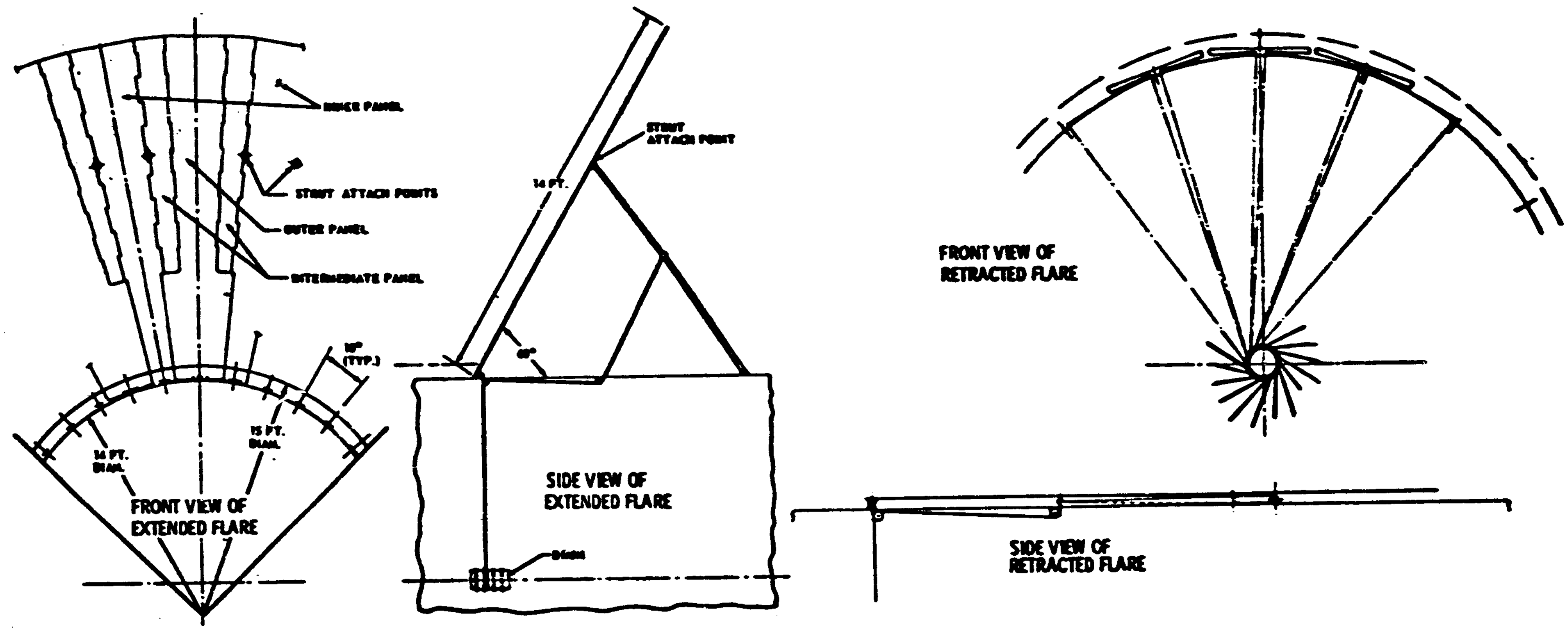


FIGURE 3.4.0.0-2 BASELINE FLARE CONCEPT (60° FLARE)

3.4 (Continued)

forward end and sufficient surface to accommodate the large area at the end of the flare. The 24 flare panels are extended first and then the support system is positioned behind. The support system consists of twelve legs mounted behind alternate panels. The support legs are elevated and retracted by an electric driven cable system.

Other alternate configurations were identified but these were not examined in depth. They included (1) inflatable deployment devices (2) mesh or Kapton skins on umbrella type support structure, (3) flares with open structure near the Tug sidewall (low drag effect region) to minimize weight, and (4) variable contoured flares for applying lift.

The 30°, 45°, 60° and short 60° flares provide maximum static stability when located aft of the astrionics module. The mounting mechanism for the flare, therefore, required a new structure. As the payload requires an adapter, the flare mounting structure and the payload adapter were combined into one structure for the flared configurations.

The payload adapter for both the basic (no flare) and flared aerobraking Tug concepts consists of three ring frames, 36 longitudinal stringers, a guide cone and guide tubes, and payload holddown and latching devices. The lower ring frame is used to bolt the adapter to the astrionics module. The intermediate ring frame provides structural rigidity while the aft ring frame provides support for the payload guide cone. The guide cone and the guide tubes are used to reduce the impact of Tug payload misalignment during docking and to align the payload within the adapter with the holddown fixtures.

The payload centering and holddown devices, solenoid actuated, are located at the adapter base and are 90° apart. An aluminum skin covers the 36 stringers. Figure 3.4.0.0-3 illustrates the integrated payload adapter.

For the larger 30°, 45° and 60° flare configurations, the payload adapter does not require additional thermal protection. However, for the basic (no flare) and the short 60° flare configurations, the sidewall aluminum skin of the payload adapter is covered with microquartz insulation and a 0.002 inch thick titanium or L609 alloy outer skin. A payload adapter base cover is also provided and consists of an aluminum inner skin, microquartz filler and a titanium or L609 alloy outer skin. This payload adapter thermal protection system is required to maintain a 300°F payload temperature.

The payload adapter (for the flared configurations) will serve as a flare mounting structure, flare actuation system housing structure as well as a payload adapter; and therefore, will require internal cross beams to mount the flare cable drum and the electric motor. These actuation fixtures are mounted in the first six inches of the payload adapter.

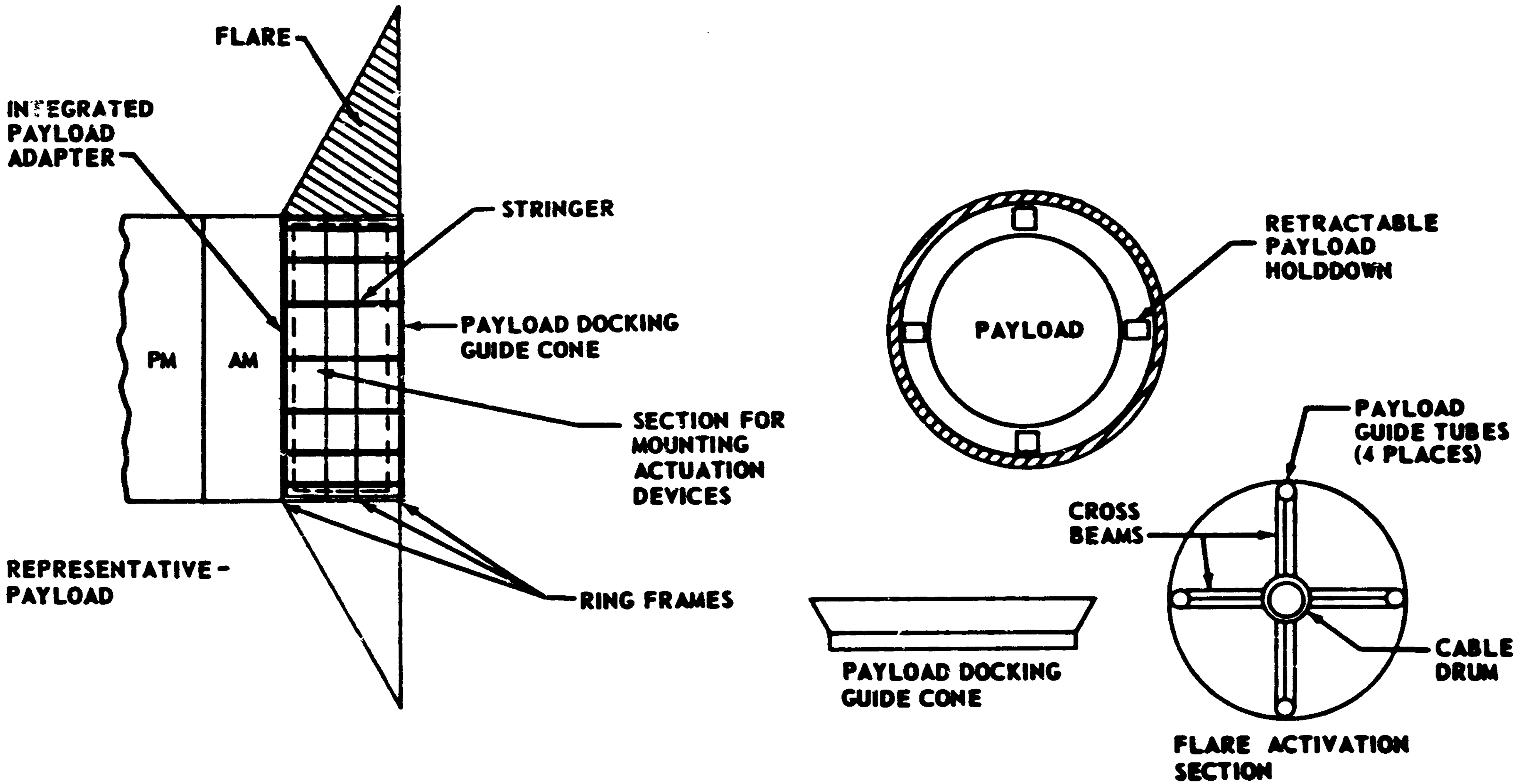


FIGURE 3.4.0.0-3: PAYLOAD ADAPTER CONCEPT FOR FLARED AEROBRAKING TUG CONCEPTS

3.5 ASTRIONICS ANALYSIS

The astrionics analysis consisted of determining the system requirements for navigational updating during successive passes, including navigation sensors required, accuracy attainable, correction burn impacts, electrical power requirements, radiation effects, system redundancy and a weight assessment. The astrionics system proposed for the conventional trajectory Space Tug was found to be readily adaptable to the aerobraking mode. Navigational sensor components available within the Shuttle development era, together with incorporation of Kalman filter computing techniques provide a minimum modification system which attains aerobraking accuracy requirements.

The navigation scheme selected for the aerobraking Space Tug employs the basic navigation sensor components including Inertial Measuring Unit (IMU), star-tracker, horizon sensor, and landmark tracker together with a Kalman filter to process the sensor data recursively to obtain an optimal estimate of the vehicle "state".

Figure 3.5.0.0-1 shows the navigation update history of a typical aerobraking mission. At departure from synchronous orbit, the Kalman filter computing technique is initialized and a horizon sensor is used for navigation (update every 1000 seconds). At 1800 seconds prior to perigee, the landmark tracker is initiated and for 1300 seconds provides updating at 10 second intervals (at high altitudes) and later at 5 second intervals (near perigee altitude). For 500 seconds before perigee and for a 300 to 500 second interval after perigee, no navigation readings are taken. The landmark tracker is then reactivated together with the re-initialized Kalman filter for approximately 1400 seconds. After coasting to the new apogee altitude, the horizon sensor system is reactivated at the new apogee position and the navigation cycle is repeated.

For a typical mission of 30 passes, the initial pass radial position error at perigee, without use of the navigational update and corrective control burn, would be approximately 1.7 miles (1 sigma). Use of navigation correction and control burn, Figure 3.5.0.0-2, can reduce this error as follows:

a. After 500 seconds of landmark tracking, a corrective burn will decrease the error to 0.5 miles (1 sigma), or

b. After 1300 seconds of landmark tracking, the position error can be reduced by a corrective burn to 1/10th of a mile (1 sigma value).

Therefore, correction burns made after at least 500 seconds of landmark tracking result in relatively small perigee errors. These navigation correction burns can be combined with the atmospheric correction burns, thereby reducing the total mission delta velocity requirement.

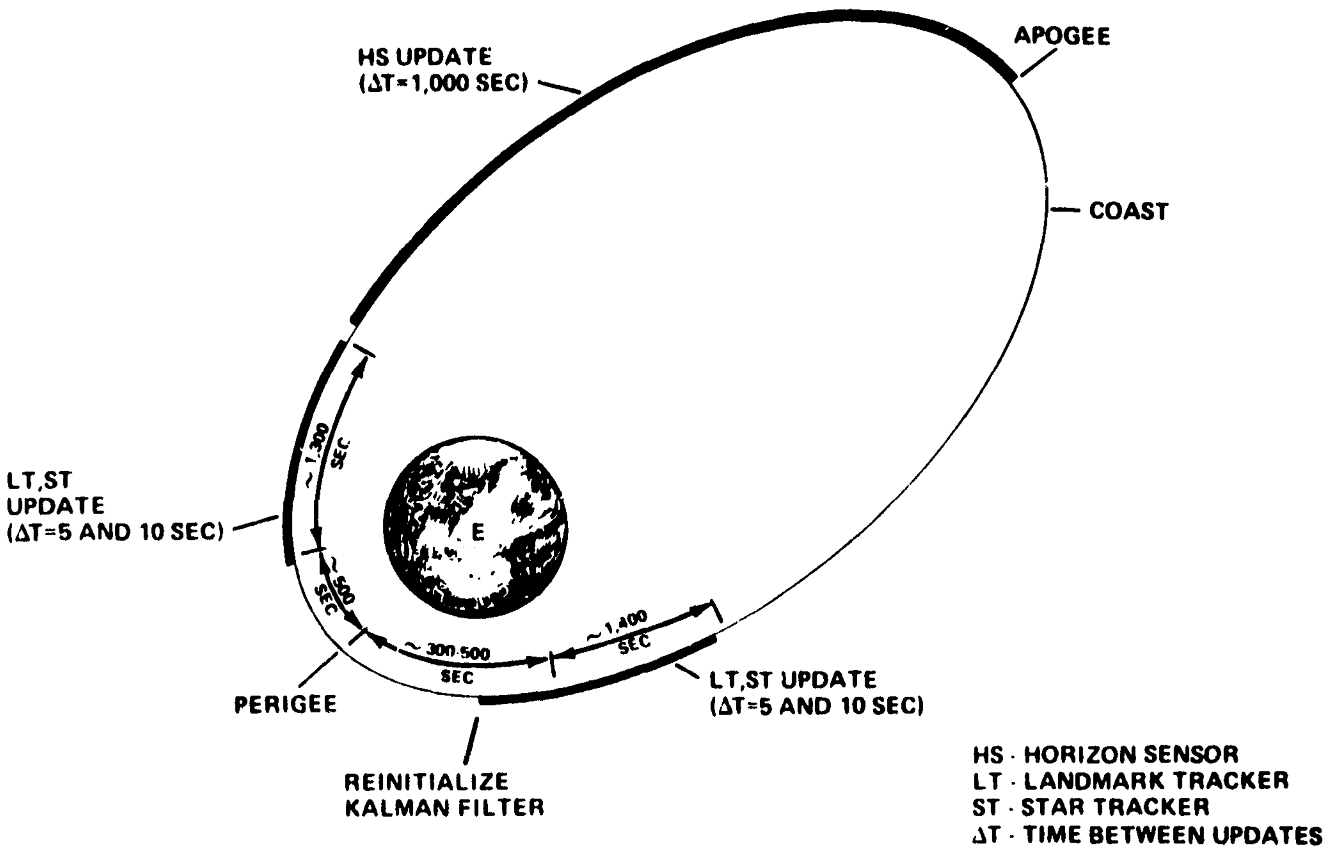


FIGURE 3.5.0.0-1 NAVIGATION UPDATE HISTORY

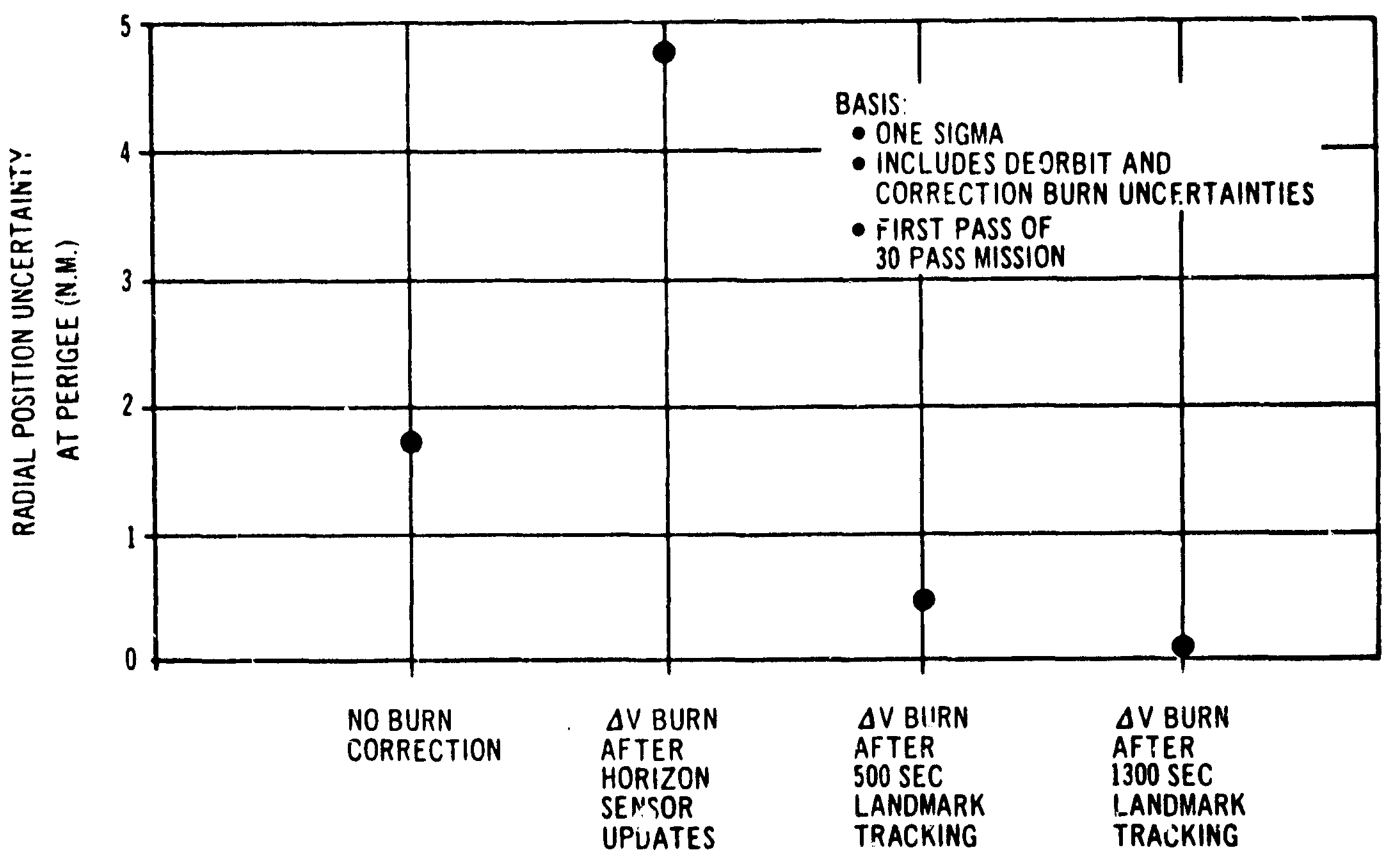


FIGURE 3.5.0.0-2: RADIAL POSITION UNCERTAINTY AT PERIGEE

3.6 WEIGHTS

One of the key study guidelines was to maximize the payload capability by minimizing the weight penalty associated with performing the aerobraking operations. For each of the selected configurations, the weights of the aerobraking components were determined as a function of number of passes. Figure 3.6.0.0-1 (upper left) illustrates the weight of the aft heat shield dome as a function of the number of passes for each of the configurations. The radiative dome materials were changed from tantalum (for temperatures above 2500°F) and columbium type materials (for temperatures above 2000°F) to TD-nickel-chrome as the temperatures encountered decreased to below 2000°F and finally to Rene' 41 for temperatures of 1400°F. The two pass data reflects the use of an ablative heat shield with a titanium support structure.

Similar type data was developed for the flare configurations and are shown in Figure 3.6.0.0-1 (upper right). For each of the 30°, 45° and 60° flare options, the flare weight was determined as a function of the number of passes. At approximately 30 passes, the material thickness will reduce to where it will be necessary to maintain a minimum thickness for handling rather than that required for the pressure loads and thermal environments. For the short 60° flare and for the large nose flare only specific point designs were investigated and these points are plotted on the figure.

The payload adapter weight is insensitive to the number of passes. The payload adapter weighs 350 pounds (exclusive of insulation) for the basic Tug. The payload adapter for the flare configurations will require additional 40 pounds (390 pounds total) for the payload actuation system (cross beams for support of the motor and draum). The basic (no flare) and the short 60° flare configurations require insultation on the sidewall and over the aft opening. The weights of the insulation for the payload adapter are included in the sidewall weights.

The sidewall insulation requirements are shown in Figure 3.6.0.0-1 lower left. The titanium or L-605 foil outer coating is a constant thickness for all configurations. The microquartz insulation thickness was varied depending on the thermal requirements to maintain a 400°F sidewall temperature on the aluminum below the microquartz insulation. The sidewall protection covers the cylindrical section of the propulsion module, the astrionics module and where applicable, the payload adapter.

Figure 3.6.0.0-1 (lower right) illustrates the astrionics module weight change as a function of the number of passes. The mission duration effected only the electrical power requirements and the redundant systems required to maintain the desired reliability.

Figure 3.6.0.0-2 shows the combined weights of all aerobraking components as a function of the number of passes and determines the minimum weight system.

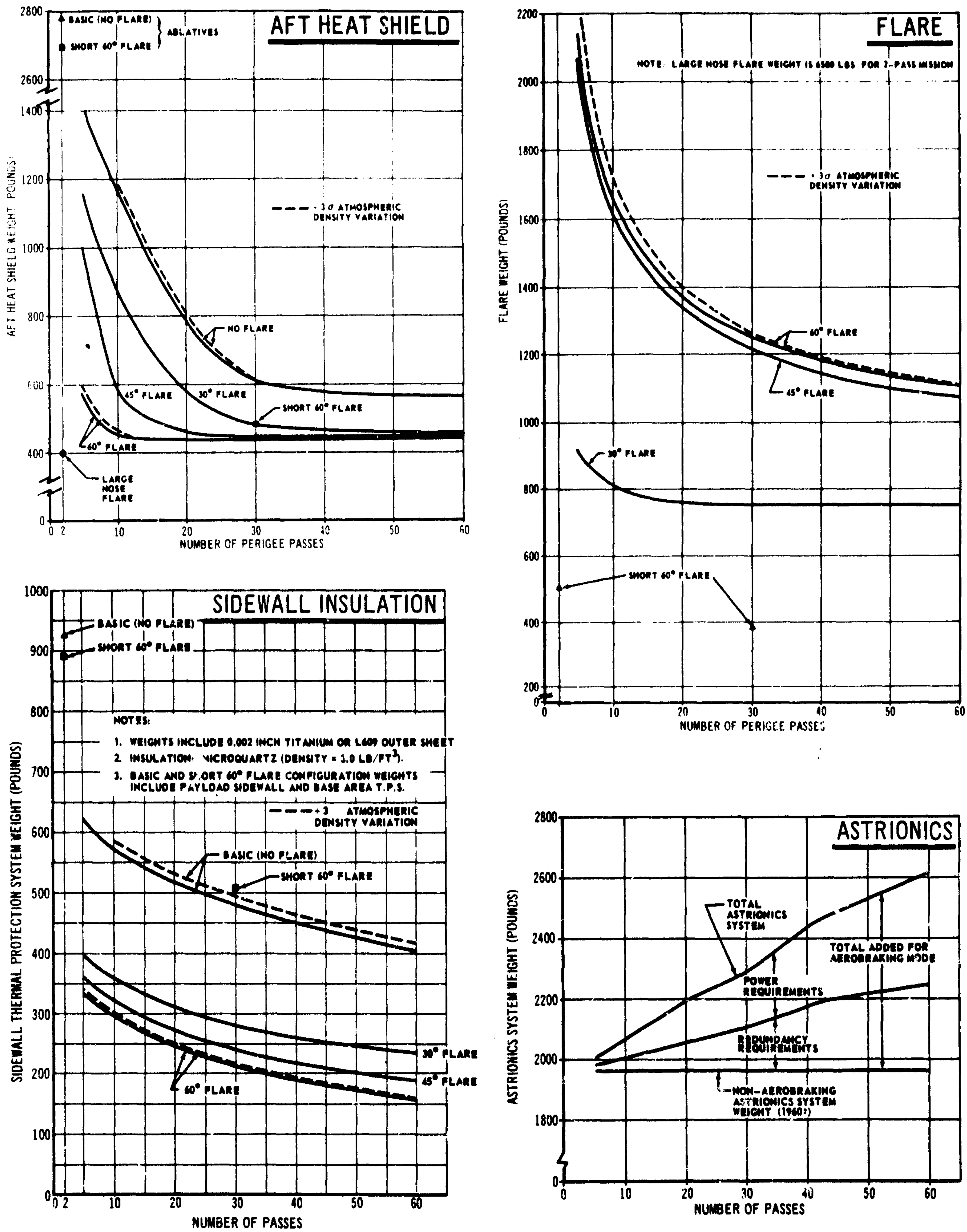


Figure 3.6.0.0-1: AEROBRAKING KIT WEIGHTS VERSUS NUMBER OF PASSES

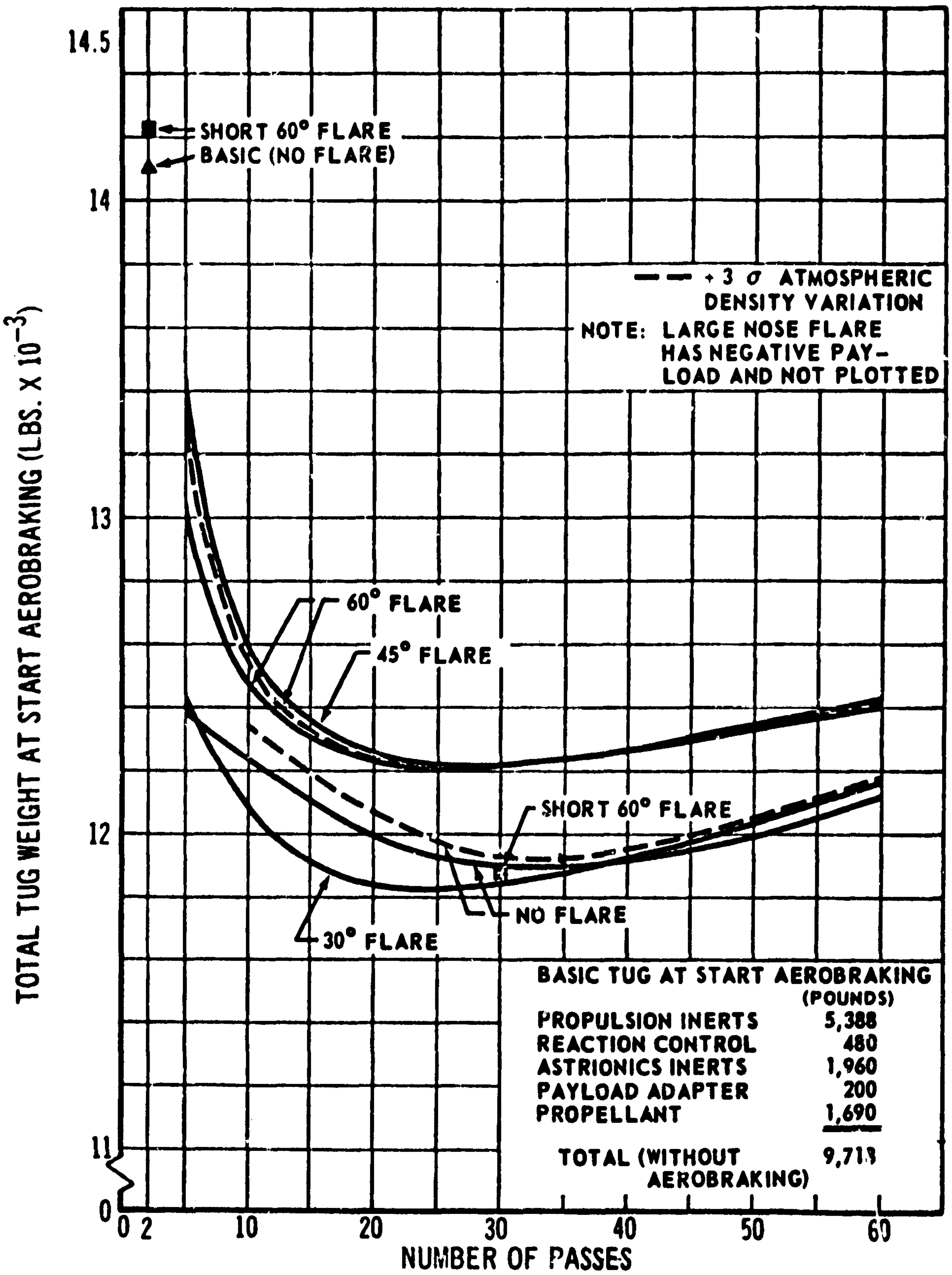


FIGURE 3.6.0.0-2 TOTAL TUG WEIGHT VS. NUMBER OF PASSES

4.0 ASSESSMENT OF THE SPACE TUG AEROBRAKING STUDY

After completion of the study activities, an assessment of the study's approach, limitation, results and recommendations were made by the study manager and his team. The results of this assessment are shown below.

The study's objective was to investigate the feasibility of an aerobraking return mode for the Space Tug from high energy missions. The study activity was directed to use an existing Space Tug configuration as the baseline Tug to be modified for aerobraking. Design effort was limited to the depth required for preliminary weights and stress analyses. The study results indicated that aerobraking is a very promising approach which should be considered in future Space Tug planning. It offers a method of applying existed technology to the Space Tug to accomplish missions. Thus, the high development risks and costs associated with the advanced technology Tug may be avoided. If the advanced Tug concept is developed, aerobraking offers higher payload capability when applied to the advanced Tug or if the advanced Tug technology goals are not met, it offers a way to still meet the mission payload objectives.

Therefore, aerobraking should be further pursued to investigate areas not considered (or restricted) in the study due to monetary and/or time constraints. These activities should include:

1. Configuration Optimization - Only an aerobraked kit modification of a conventional Space Tug point design was studied. Optimal aerodynamic shapes were not investigated.

2. Aerodynamic Properties - There is a lack of experimental and analytical aerodynamic data in the perigee region of the aerobraking Tug's flight path.

3. Aerobraking Kit Weights - Only a limited design effort could be expended on this study. The stress and weights analysis were likewise impacted by the limited effort. As inert weight is a major factor in defining payload capability, more detailed weight saving design and stress analyses of the optimum aerobraking kits are required.

4. Cost Analysis - The costs of the kit development, and production were not determined. The significant cost advantages of aerobraking need to be computed and compared to conventional Space Tug programmatic costs.

5. Tug Design Integration - The aerobraking kit elements were designed as add-ons to a point design and, as such, were heavier than multi-purpose systems. The advantages of an integrated insulation and purge system that could be applied to both the conventional and aerobraked Tug requires examination.

4.0 (Continued)

6. Heat Shield and Flare Reliability Assessment - The heat shield and flares were designed to meet the thermal and pressure loads environments. More detailed study of the reliability of the operational features (e.g., deployment and retraction) and sealing methods are required.

7. Flare Geometry - Only a few concepts could be investigated for low ballistic coefficient analysis. Light weight concepts and their aerodynamics need further study.

8. Flight Dynamics - Only static stability was investigated. Flight dynamics need study to determine if "coning" or "fish-tailing" is a problem.

9. Thermal Analysis - The thermal analysis conducted examined steady state thermal effects. The transient (heat sink) effects need to be defined. Further, the impact of protuberances, heat pockets, hot/cold cycling need investigation.

10. Aerobraking Kit Scar Weight - The aerobraking kit should be designed to be removable from the Tug for non-aerobraking missions. The permanent inert weight the non-aerobraked Tug must carry due to the aerobraking option should be defined and its impact on performance defined.

11. Shuttle Interface - The use of an aerobraking kit on the Tug should be assessed as to its impact on Shuttle interfaces, deployment and retrieval modes and Shuttle environments impact on the aerobraked Tug.

12. Shuttle/Tug Operational Modes - The aerobraked Tug will return to a predetermined orbit. The phasing operations of the Tug orbit with the orbit of the Shuttle requires investigation.

13. GSE and Launch - The impact of the pre-launch and launch operations on the aerobraking Tug were not defined. This area requires further investigation.

14. Guidance and Targeting - The investigation of these parameters was generally conducted as separate items. This total inter-related area, including the latest varying atmosphere model requires an integrated analysis.

Although the aerobraking feasibility was proven, the study was limited. The above areas require investigation to prove aerobraking practicality and to optimize the systems and operations. The potential of aerobraking the Space Tug appears so advantageous, both technically and economically, that the above areas should be studied as soon as possible.

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