PRIMARY PROPULSION/LARGE SPACE SYSTEM INTERACTIONS

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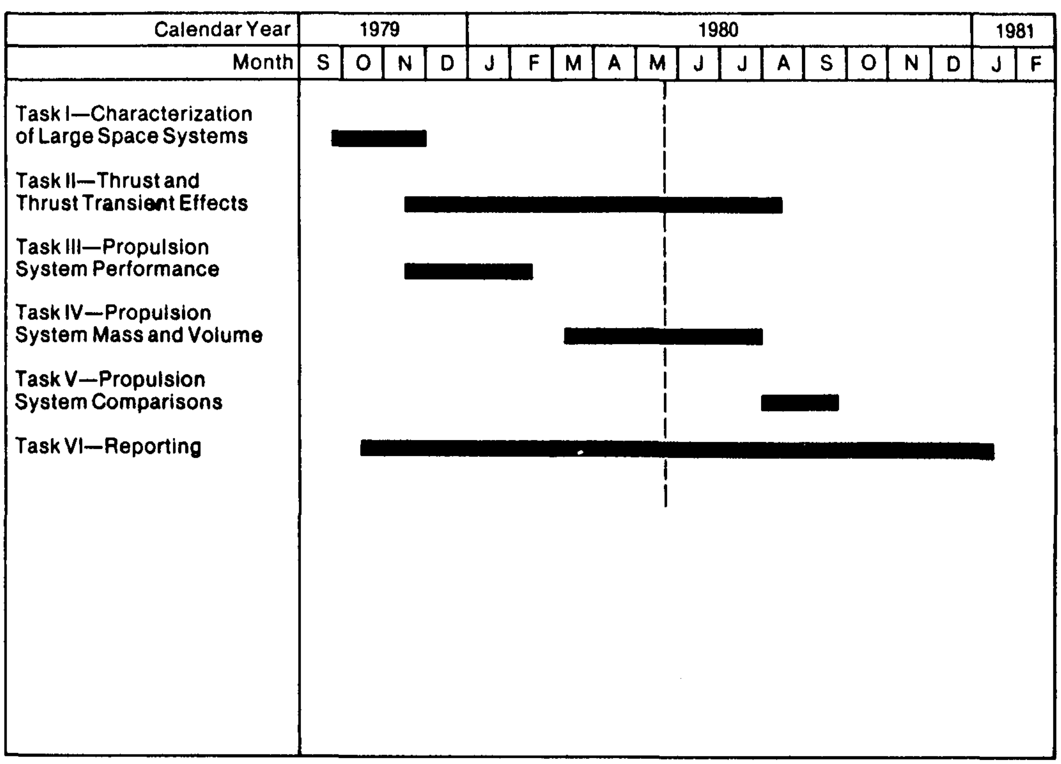
Contract Information

- Customer: NASA-Lewis Research Center
  Mr. Dean D. Scheer

- Contract Number: NAS3-21955

- Period of Performance: 20 September 1979 to 20 September 1980

Program Schedule



PP/LSSI Program Summary

The primary objective of the Primary Propulsion/Large Space System Interaction Study program is to determine the effects of low-thrust primary propulsion system thrust-to-mass ratio, thrust transients, and performance on the mass, area, and orbit transfer characteristics of large space systems.

PP/LSSI Task Objectives

Task I—Characterization of Large Space Systems—Determine the design characteristics of various classes of large space systems that are impacted by the primary propulsion thrust required to effect orbit transfer.

Task II—Thrust and Thrust Transient Effects—Determine the influence of primary propulsion steady-state and transient thrust on the mass and area of designated LSS concepts.

Task III—Propulsion System Performance—Determine the effect of selected primary propulsion system characteristics on deliverable payload mass from low earth orbit to high earth orbit.

Task IV—Propulsion System Mass and Volume—Determine the characteristics of selected pressure-fed and pump-fed stages for orbit transfer of LSSs and the effect of these stages and Space Shuttle constraints on mass and volume available for packaged large space systems.

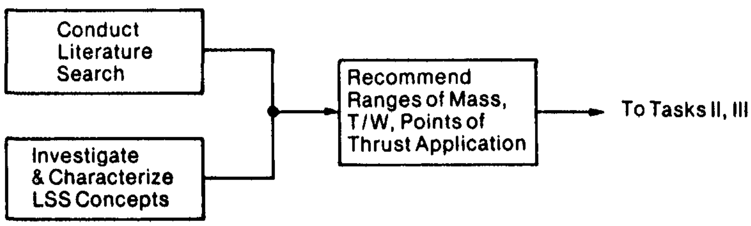
Task V—Propulsion System Comparisons—Determine relative merits of selected primary propulsion systems in terms of deliverable LSS mass, area, and/or length available for payload in the Orbiter cargo bay.

Task VI—Reporting—Monthly technical and financial reports, work plan, and program final report.

Task I - Characterization of Large Space Systems

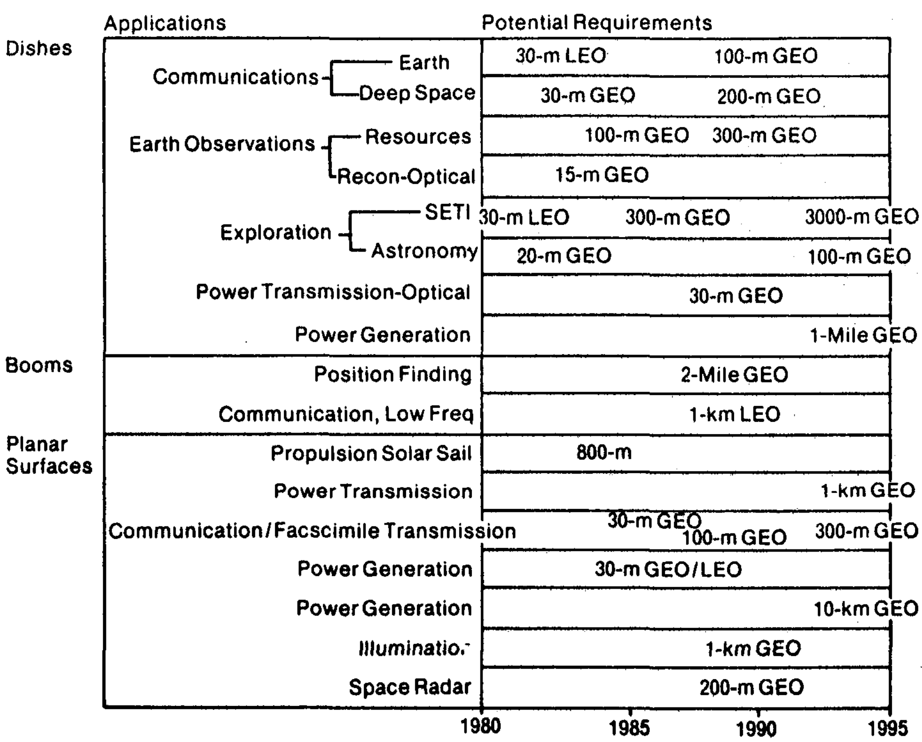
The goal of this task was to select 3 generic types of structural concepts and nonstructural surface densities that, when combined, would be representative of potential LSS applications.

Task I—Characterization of Large Space Systems



- Identified and Evaluated More Than 120 References
- Investigated More Than 20 Potential LSS Missions & Concepts
- Categorized 14 LSS Concepts by Potential Usages
- Identified 4 Nonstructural Surface Densities Consistent with Missions

LSS Mission Parameters (Operational Altitude & Diameter)



Reference: "Toward Large Space Systems," *Astronautics and Aeronautics*, May 1977.

Structural Configurations

The following chart presents the 14 specific concepts that were investigated in Task I. The generic concepts to be evaluated in Task I - Thrust and Thrust Transient Effects - were selected from this population. Shown are design concept, the company responsible for the concept, and approximate diameter range compatible with a single STS mission.

Structural Configurations

- Umbrella Radial Rib Double-Mesh Antenna
  —Harris
  —3 to 25 m
- Wrap Radial Rib Antenna
  —Lockheed
  —30 to 300 m
- Erectable Radial Rib Antenna
  —General Dynamics
  —30 to 200 m
- Radial Column Rib Antenna
  —Harris
  —20 to 100 m
- Articulated Radial Rib Antenna
  —Harris
  —20 to 40 m
- Maypole Antenna
  —Lockheed
  —30 to 300 m
- Hoop & Column Antenna
  —Harris
  —30 to 300 m
- Hoop & Column Radar
  —Grumman
  —30 to 200 m
- Expandable Tetrahedral Truss Antenna
  —General Dynamics
  —10 to 175 m
- Expandable Box Truss Antenna
  —Martin Marietta
  —10 to 250 m
- Sunflower Solid Panel Antenna
  —TRW
  —5 to 20 m
- Expandable Astrocell Module
  —Astro Research/Langley
  —5 to 100 m
- Electrostatic Membrane
  —GRC
  —5 to 200 m
- Expandable Box Truss Platform
  —Martin Marietta
  —5 to 100 m

Note: Diameter limitations refer to single Orbiter packaging.

LSS Mission Parameters (Surface Mass Density)

The values shown are selected to provide surface mass densities representative of potential LSS payloads. The mesh surface (0.05 Kg/m^2) is typical for deployable mesh-type low frequency antennae. The high frequency surface (3.42 Kg/m^2) is representative of aluminized honeycomb panels or lump loading of a platform of ≈ 275 Kg/node. The radar antenna and power generation values were selected to include these types of payload in the population.

Bt utilizing these nonstructural surface densities in conjunction with the applicable structural concepts shown later, the full spectrum of potential payloads will be evaluated (mass and area) as a function of applied acceleration level.

LSS Mission Parameters (Surface Mass Density)

- Low-Frequency Antenna (< 20 gHz)
  - —Mesh Surface (i.e., Gold Plated, Moly Wire, Tricot Knit)
  - —Density = 0.05 kg/m^2 (0.01 lb/ft^2)

- High-Frequency Antenna (> 20 gHz)
  - —Rigid Panels (i.e., Aluminized Honeycomb Panels)
  - —Density = 3.42 kg/m^2 (0.70 lb/ft^2)

- Radar Antenna (1-2 gHz)
  - —Phased Array (3-Layer Lens)
  - —Density = 0.15 kg/m^2 (0.03 lb/ft^2)

- Power Generation
  - —Solar Cell Collector
  - —Density = 0.40 kg/m^2 (0.08 lb/ft^2)

Recommended Mission Parameters

The data presented below are in values selected for further evaluation in Task II. The diameter range (20-300 M) is compatible with the candidate concepts and nonstructural surface densities when constrained to launch a single payload in the cargo bay (allowances made for delivery stage volume). The surface mass densities were discussed on the preceding page.

The structural configurations selected are representative of tubular systems (Wrap Radial Rib), trusses and platforms (Expandable Box Truss), and a hoop and column (Grumman/Harris concepts).

Recommended Mission Parameters

- Diameter Range*:
  - —20 to 300 m
- Surface Mass Density
  - —0.05 to 3.42 kg/m^2
- Structural Configurations
  - —Wrap Radial Rib
  - —Hoop & Column
  - —Expandable Box Truss

*Actual diameter limitation based on packaging in Orbiter and payload limitations.

Recommended Configuration - Expandable Box Truss

The next 2 charts present the characteristics for the Expandable Box Truss. The diameter range is, again, approximate relative to cargo bay capability combined with the surface density range, which is representative of all potential payloads. The full range of surface densities is applied due to the truss' inherent load carrying capability. Representative missions are noted.

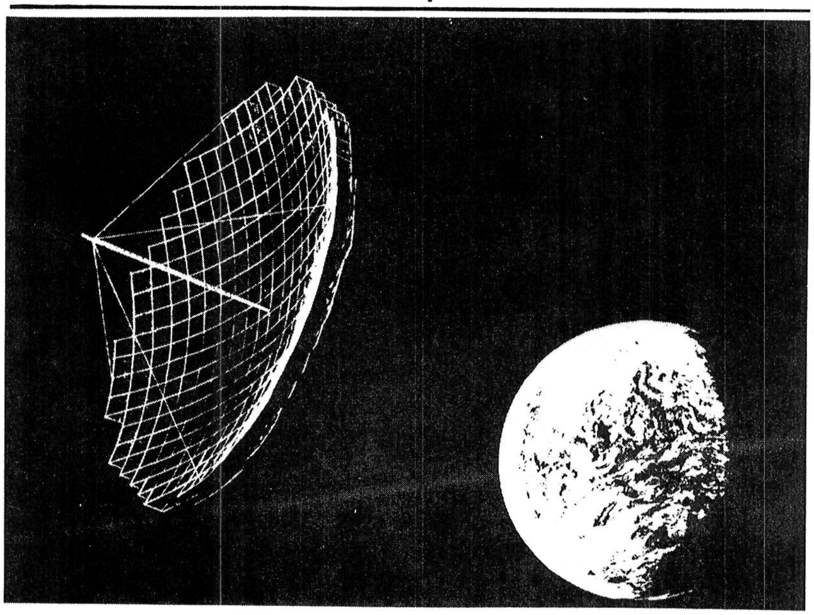
The point of thrust application to be used in the interaction analyses is at the center of the structure normal to its plane. These analyses will be first conducted with a single point of thrust application. Additional work will include multiple points that are yet to be determined.

The range of Thrust-to-Mass ratio to be evaluated is 0.02 to 1.0 g.

Recommended Configuration—Expandable Box Truss

- High-Frequency (< 20 gHz) Large-Diameter Reflector, Radar or Power Generator
  - —30 to 200-m Diameter
  - —0.05 - 0.15 - 0.40 - 3.42 kg/m²
- Missions
  - —Communications
  - —Earth Observations
  - —Space Exploration
  - —Radar
  - —Power Generation
- Point of Thrust Application at Center of Structure Normal to Plane
- Thrust/Mass = 0.02 - 1.0 g

Expandable Box Truss Concept



Recommended Configuration - Hoop & Column

Data similar to those presented for the Expandable Box Truss are shown for the Hoop & Column Concept. The surface densities do not include the value associated with rigid panels since the Hoop & Column LSS concept is not compatible with deployment of these types of surfaces.

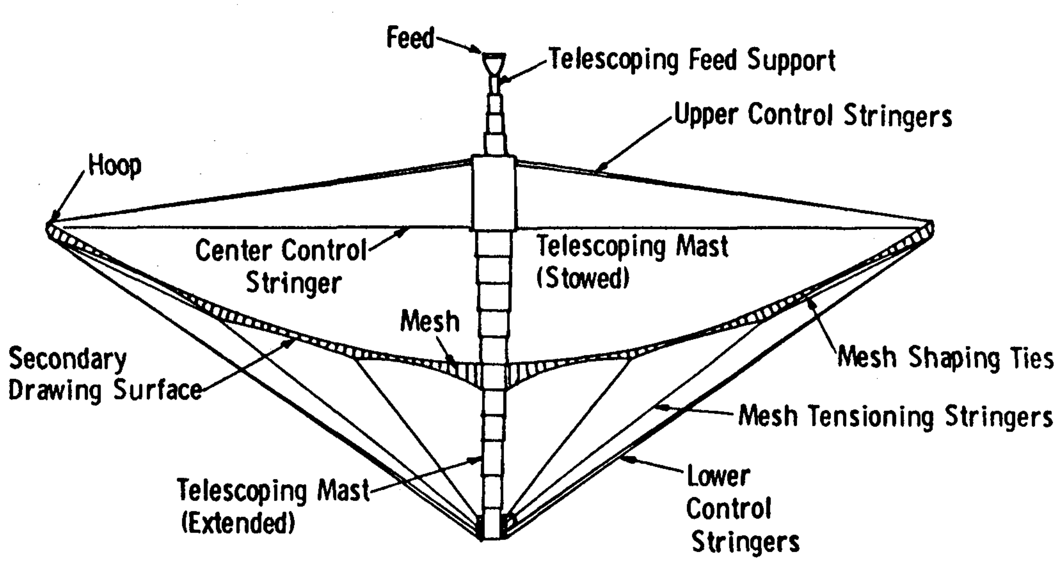
Again, representative missions are shown; the point of thrust application is at the end of the aft telescoping mast; and the Thrust-to-Mass ratio range is 0.01 to 1.0g.

Recommended Configuration - Hoop & Column

- Low-Frequency (< 20 gHz) Large-Diameter Reflector, Radar or Power Generation
  - —30 to 300-m Diameter
  - —0.05 - 0.15 - 0.40 kg/m²
- Missions
  - —Earth Observations
  - —Communications
  - —Space Exploration
  - —Radar
  - —Power Generation
- Point of Thrust Application at End of Aft Telescoping Mast
- Thrust/Mass = 0.01 - 1.0 g*

*Structure probably limited to less than 1.0 g.

Hoop/Column Concept



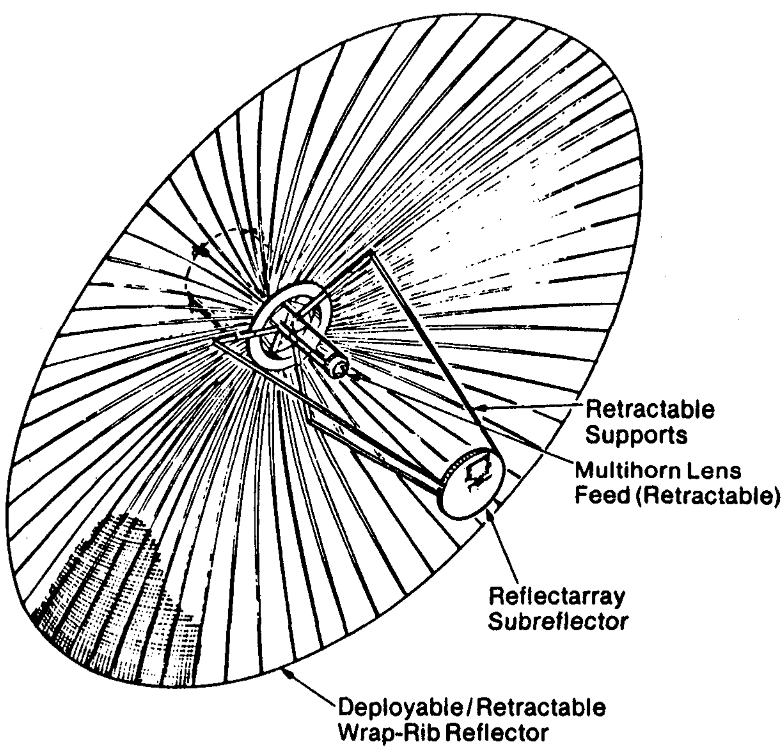
Recommended Configuration - Wrap Radial Rib

Similar data are presented for the Wrap Radial Rib concept. For this configuration, only mesh-type surfaces are considered (0.05 Kg/m^2) since the Wrap Radial Rib can only deploy this type of low frequency antenna.

Recommended Configuration—Wrap Radial Rib

- Low-Frequency (< 20 gHz) Large-Diameter Reflector
  - —30 to 300-m Diameter
  - —0.05 kg/m^2 Surface Density
- Missions
  - —Earth & Obervations
  - —Communications
  - —Space Exploration
- Point of Thrust Application at Hub
- Thrust/Mass = 0.02 - 1.0 g

Typical Lockheed Wrap-Rib Antenna: Deployed Configuration



Preliminary Diameter Limitations

To provide a realistic diameter range over which parametric mass and area relationships as a function of acceleration for Task III will be derived, the maxima presented on the facing page were determined.

The LSS payload value of 5440 Kg was derived by subtracting inert spacecraft mass (1360 Kg) from total mass in GEO (6800 Kg). These data were based on results of trajectory analyses previously performed and are representative of typical values for a cryogenic stage (Isp ≈ 450 sec) with a mass fraction of ≈ 0.85 and T/W ≈ 0.05 g.

By combining the surface density with a structure with a total payload structure to nonstructure mass ratio of 1.5 and the maximum mass of 5440 Kg, the diameters shown result.

These values are only approximations but do bracket the range for the interaction analyses.

Preliminary Diameter Limitations

Surface Mass, kg/m²	Surface and Structure, kg/m²	Maximum Diameter, m
0.05	0.125	235
0.15	0.375	136
0.40	1.00	83
3.42	8.55	28

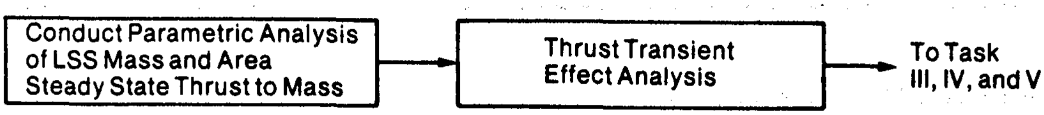
Note:
1. Typical payload ≈ 6800 kg (15,000 lb).
2. Typical Assumed Spacecraft ≈ 1360 kg (3000 lb).
3. Therefore, LSS payload ≈ 5440 kg (12,000 lb).
4. Typical low thrust-to-weight, structure/nonstructure ≈ 1.5.
5. Single Orbiter flight.

Task II - Thrust and Thrust Transient Effects

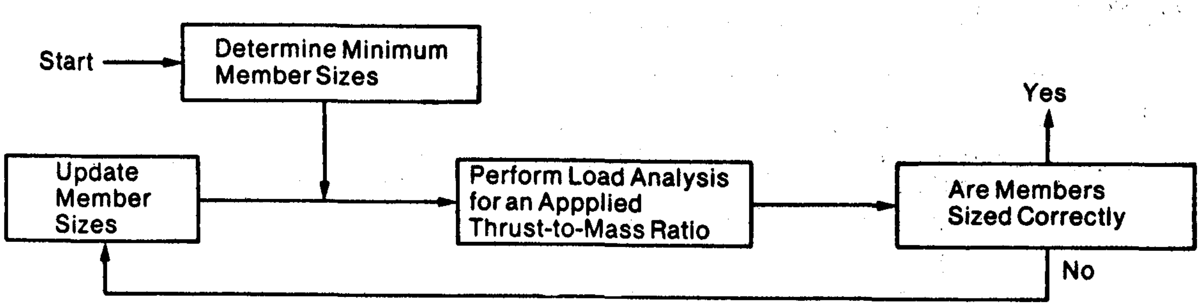
The principal output of this task will be LSS concept mass and area as a function of acceleration level during transfer from LEO to GEO. The analysis is divided in two parts - steady state and transient.

The key to the steady state analysis is starting with a representative minimum gage structural system. The criteria for minimum gage for the 3 structural concepts are shown. The iterative, rigorous finite element analysis is predicated upon failure of the structure when compared to failure modes such as Euler column buckling, local crippling, exceeding material allowables, etc. If any of these criteria are not met, the members are resized and the analysis is repeated.

Task II—Thrust and Thrust Transient Effects



- **Steady-State Analysis**



Minimum mass systems derived based on the following criteria:

- Expandable Box Truss—No member smaller than 3.8 cm (1.5 in.) diameter by 0.044 cm (0.0175 in.) thickness;
- Wrap Radial Rib—A baseline tapered rib for a 100-m-diameter design is scaled to maintain a tip deflection proportional to the antenna diameter under constant mesh loads;
- Hoop and Column—A maximum diameter hoop member at minimum gage is assumed, stay tapes are 2.5 cm (1.0 in.) by 0.044 cm (0.0175 in.), column based on Grumman-type design mass.

Task II - Thrust and Thrust Transient Effects (Concluded)

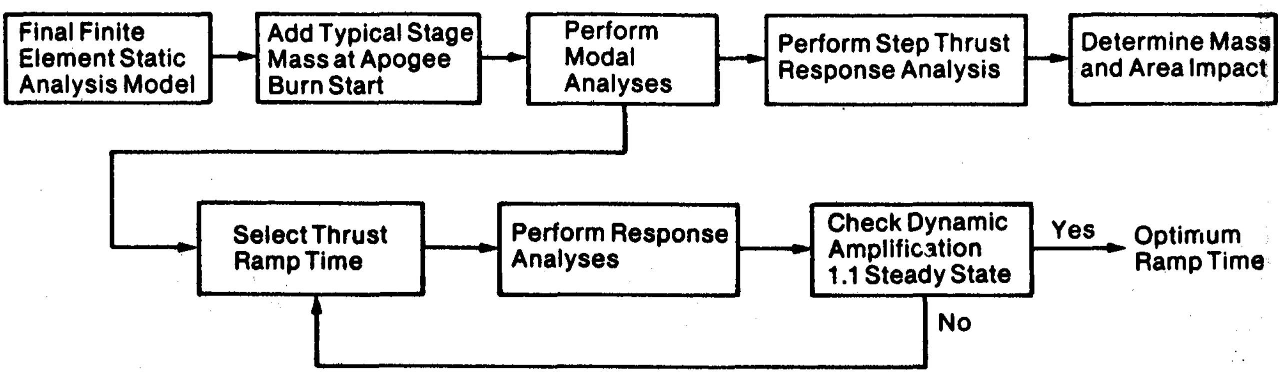
The transient analyses will evaluate the effects on mass and area of the structural concepts for two modes:

- o A step input.
- o A linear ramp input, varied to the point where dynamic amplification is $\leq$ 1.1 of the steady state value.

The 1.1 factor was selected to account for the effects of a multimode system when performing single mode system analyses. The value appears to be acceptable from a structural standpoint and achievable from an amplification standpoint.

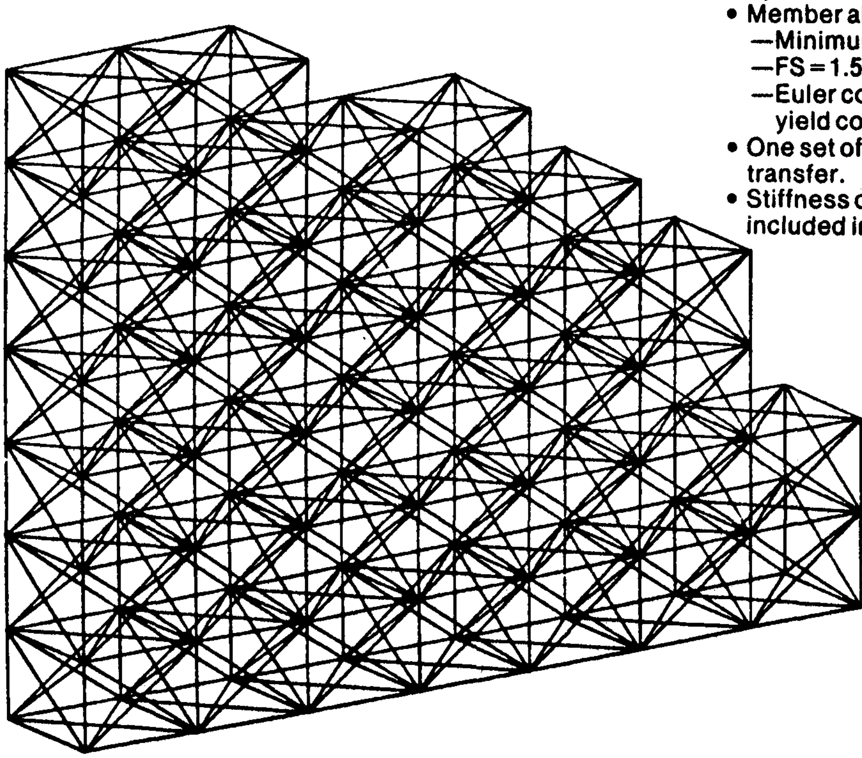
Task II—Thrust and Thrust Transient Effects (concl)

- **Thrust Transient Effects Analysis**



- **This analysis will be performed on representative configurations for 3 LSS concepts.**
- **Results will be extrapolated for remainder of configurations based on fundamental natural frequencies ($T_{ramp} = 1/f_n$).**

Steady-State Structural Analysis Approach



Assumptions for Array Size Determination

- Structural and nonstructural masses lumped at nodes.
- Member weight determined using 20% margin.
- Inertial loads (maximum g) applied to nodes.
- Symmetric load condition.
- Member allowables determined using:
  —Minimum Properties
  —FS = 1.5
  —Euler column, local bucking, and material yield considered as failure modes.
- One set of diagonals goes slack during orbit transfer.
- Stiffness characteristics of slack diagonals not included in finite element model.

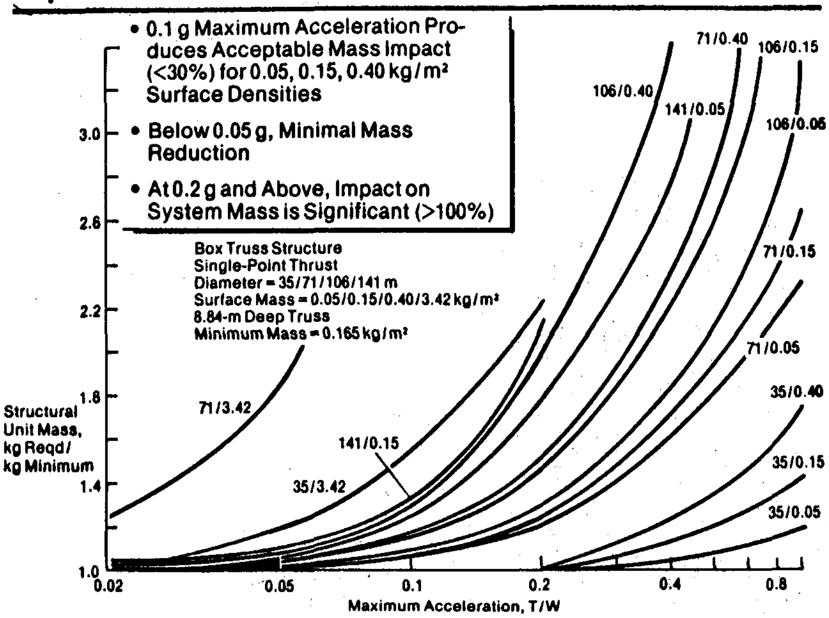
Expandable Box Truss - Unit Mass vs Thrust to Weight

This chart presents the results of the steady state analyses for the Expandable Box Truss. The structural unit mass is a factor of required mass to withstand the load applied divided by the minimum mass as represented by the previously presented minimum gage system.

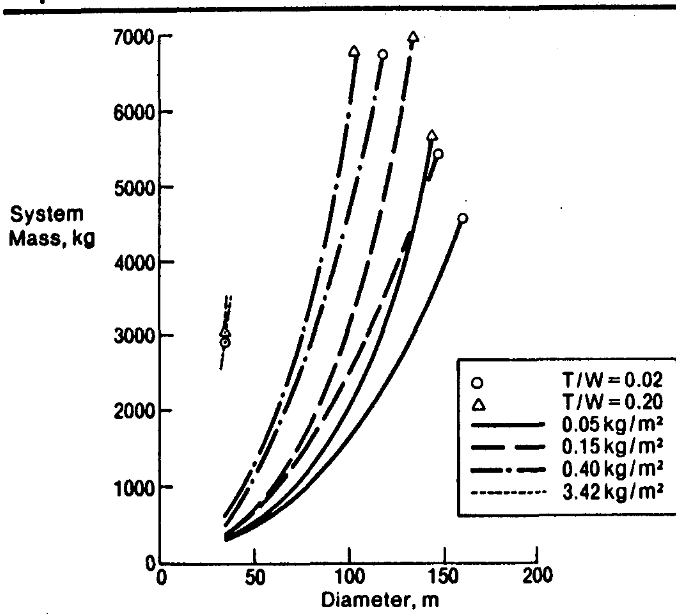
All assumptions and conclusions are shown on the figure. It is interesting to note that 0.05 g is equivalent to 500 to 1000 lb_f of thrust, depending upon orbit transfer strategy, specific impulse and resultant payload weight. This thrust range appears to be best-suited for all diameters and surface densities except large (71 m) diameters with 3.42 Kg/m^2 nonstructural surface loading.

The structural weights include an allowance for joints, hinges, fittings, and diagonals. The baseline for these elements is again minimum gage and they increase in mass proportionally with the truss members.

Expandable Box Truss—Unit Mass vs Thrust to Weight



Expandable Box Truss—System Mass vs Diameter



Structural Mass/Truss Depth Relationships

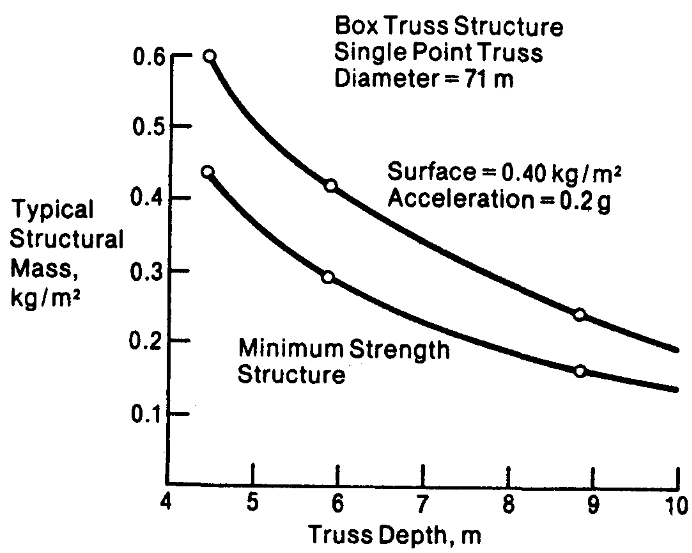
The graph presents data relating structural mass in Kg/m^2 to truss depth. The minimum strength curve shows the effect on mass as the truss depth decreases for an unloaded structure. The increase is caused by the necessity to add more fittings and mechanisms as the depth decreases for a fixed diameter array. For example, a 10 M truss cube is replaced by eight 5 M cubes with an attendant increase in corner fittings from 8 to 26.

The upper curve shows the effect of the surface (0.40 Kg/m^2) on the structural mass. The divergence near the origin is attributed to the reduction of load - carrying capability of the truss as its depth decreases, resulting in an increase in individual member gage.

Since deeper trusses are inherently lighter and stronger, the conclusions that shorter transfer trusses are inherently lighter and stronger, with the single Orbiter flight constraint imposed in this study.

Structural Mass/Truss Depth Relationships

- Truss Structural Mass Decreases with Truss Depth because of Reduced Number of Fittings and Mechanisms
- Deeper Truss Also Reduces Impact of Orbit Transfer Load on Structural Mass
- Minimum Propulsion Stage Length Is Desirable to Maximize Truss Depth



Wrap Radial Rib Unit Mass vs Thrust to Weight

These data are similar to those presented on the Expandable Box Truss on page 120 herein.

The ground rules for sizing this concept are stated on the figure:

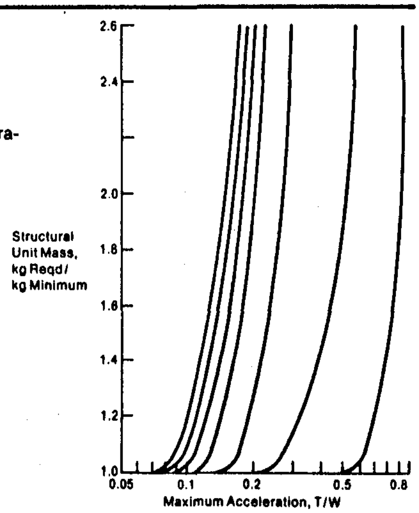
- o Surface 0.05 Kg/m^2 (mesh antenna).
- o Number of ribs proportional to $\sqrt{\text{diameter}}$.
- o Rib deflection proportional to diameter - this is based on the premise that antenna performance is reduced as diameter increases and, therefore, deflection can increase with diameter.
- o The baseline from which scaling was performed is a published 100 m, 96 rib Lockheed design.

In addition, a constant taper ratio (root to tip) of 3/1 was assumed. The baseline material of construction is graphite epoxy and the rib crossection was assumed to be elliptical with major to minor axis ratio of 5/1.

The results of this analysis indicate that accelerations between 0.05 and 0.10 g are preferred for the diameters considered. The diameters not shown are, from left to right, 194, 176, 158, 141, 106, 71, and 35 meters for the individual curves.

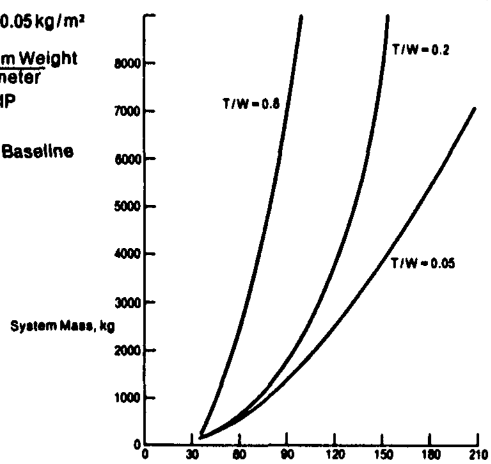
Wrap Radial Rib Unit Mass vs Thrust to Weight

- Baseline Parameters
  - —Surface = 0.05 kg/m^2
  - —Number Ribs α $\sqrt{\text{Diameter}}$
  - —Rib Deflection α Diameter
  - —100-m Diameter
- Rib Highly Sensitive to Acceleration Level



Wrap Radial Rib—System Mass vs Diameter

- Surface Unit Weight = 0.05 kg/m^2
- Radial Rib Antenna
- Hub = 10% Total System Weight
- Number of Ribs α $\sqrt{\text{Diameter}}$
- Rib Size Defined by δ_{TIP} α Diameter
- Graphite Epoxy Ribs
- 100-m Design Used as Baseline (96 Ribs)



Maximum Acceleration for <10% Structure Mass Impact

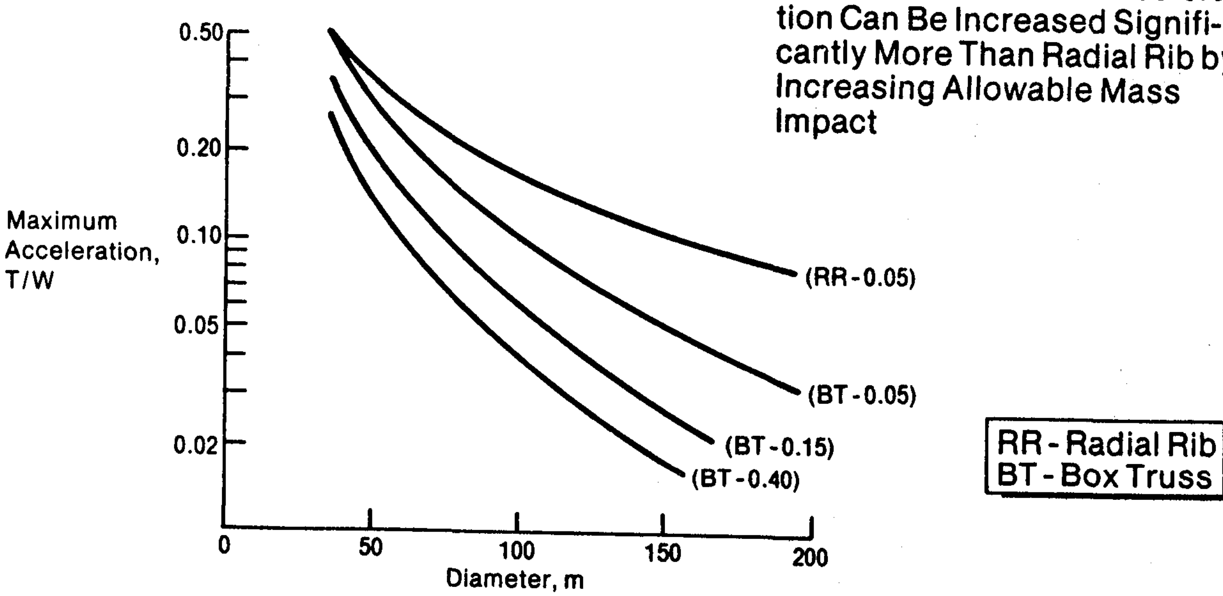
These curves present LSS diameter vs Acceleration level for the Wrap Radial Rib and Expandable Box Truss. Comparing the two concepts at a surface density of 0.05 Kg/m^2, it can be seen that the wrap rib has greater allowable acceleration capability than the box truss. This is primarily due to the stiffness of the ribs that results from the tip deflection constraint previously discussed.

The 10% mass impact was selected as a minimum. If this value is increased, the values for the truss and rib concepts will tend to converge due to the inherent load-carrying capability of the truss.

Acceleration levels between 0.05 and 0.10 g are again preferred for both concepts for diameters (150-200 m) compatible with a single Orbiter Flight.

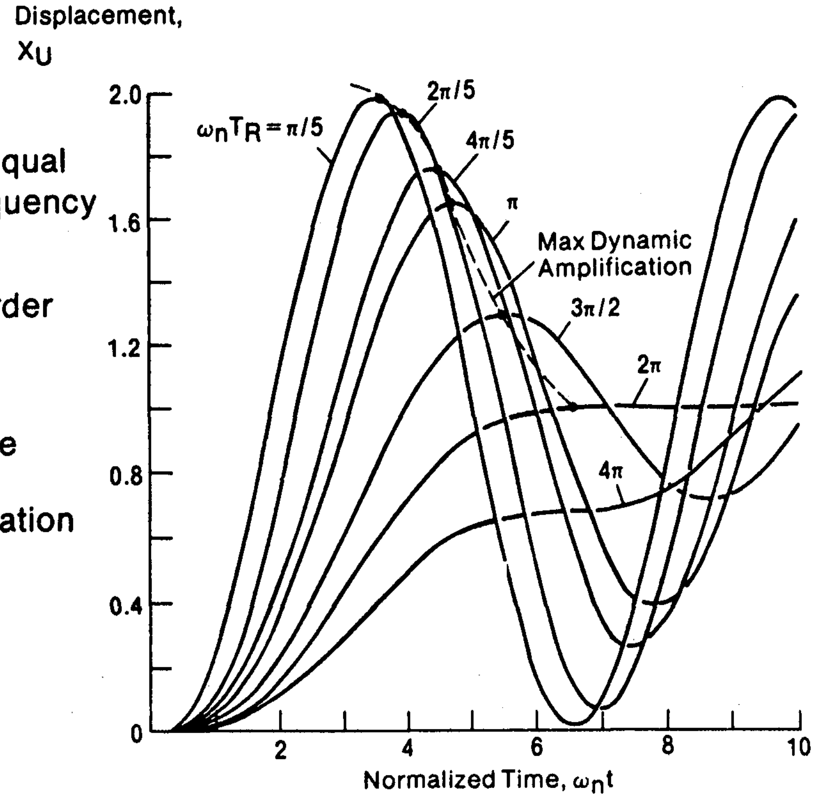
Maximum Acceleration for < 10 % Structural Mass Impact

- Radial Rib Has Greater Allowable Acceleration at Large Diameters due to Stiffness Criteria That Increases Member Sizes with Diameter
- Box Truss Allowable Acceleration Can Be Increased Significantly More Than Radial Rib by Increasing Allowable Mass Impact



Response to Typical Ramp Input

- Optimum Ramp Time (T_R) equal to system fundamental frequency (f_n)
- For Real System, Higher Order Modes Modify This Pure Function
- Preliminary Results Indicate $T_R = 1/f_n$ Is Valid within 10% Amplification



Task III—Propulsion System Performance

Ground Rules

- Orbit transfer from LEO (160 n-mi circular orbit at 28.5° inclination) to GEO (19,368-n-mi circular orbit at 0° inclination)
- Initial Mass - 60,000 lbm
- Specific Impulse Range - 300 to 450 sec
- Number of Perigee Burns - 1 to 8
- Final Thrust-to-Mass Ratio Range - 0.01 to 1.0
- Constant Thrust and Constant Acceleration Analyses

Approach

- Three-Degree-of-Freedom Parameter Targeting and Optimization Program
- Thrust Segments Numerically Integrated
- Coast Segments Propagated using Keplerian Equations
- Gravity Turn during Perigee Burns
- Multiple Burns Split on Equal ΔV per Burn Basis
- Targeting Independent Variables
  —Argument of Vehicle for Startup of Perigee Burns
  —Apogee Altitude of Transfer Orbit
  —Latitude of Startup of Apogee Maneuver
  —Pitch and Yaw Attitude Angles during Final Orbit Insertion

Comparisons Between Constant Thrust and Constant Acceleration

The results of the trajectory analyses are summarized on the facing table and are presented graphically on pages 31 through 34 herein.

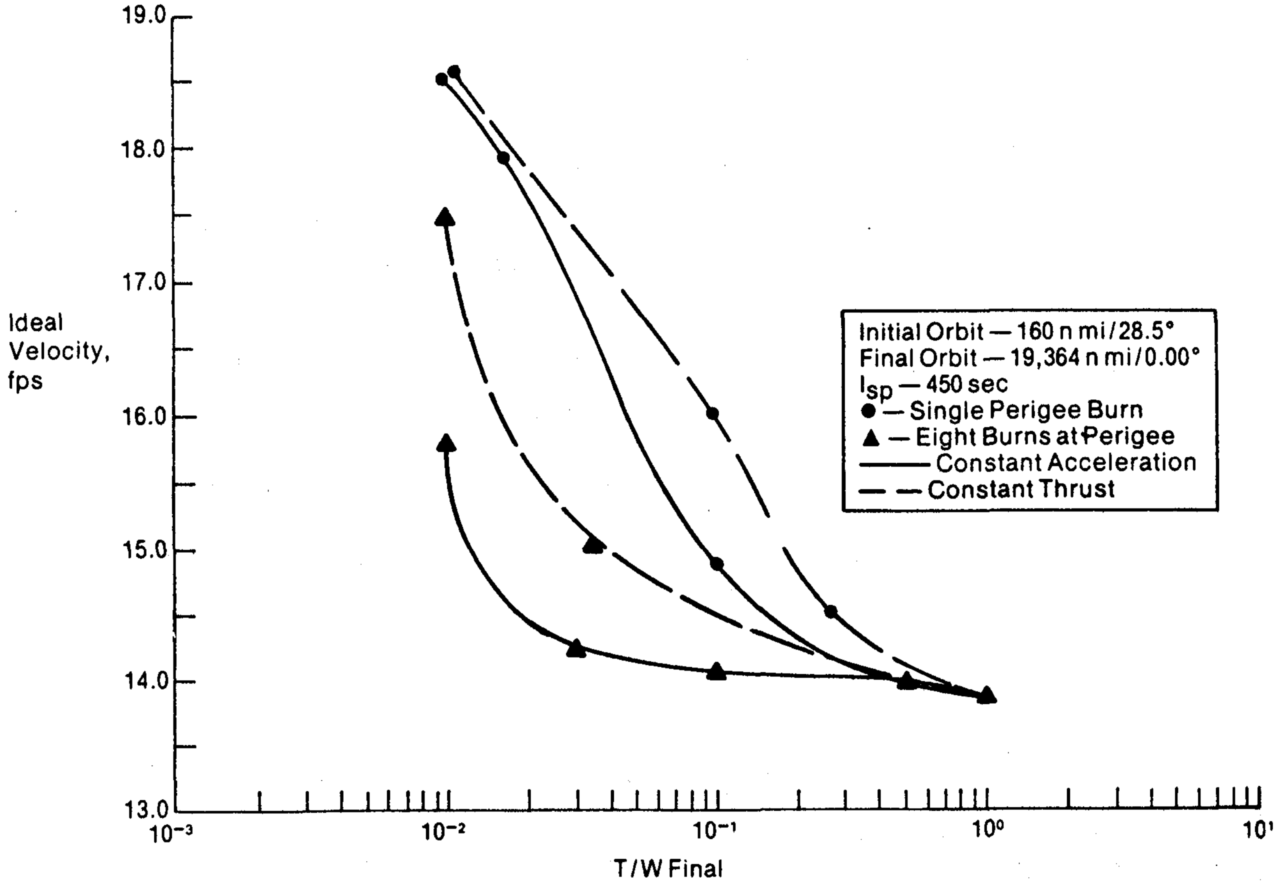
From these data, the following conclusions can be made:

- o Constant acceleration (throttling) requires less ΔV than constant thrust.
- o Constant acceleration requires less engine burntime than constant thrust.
- o Constant acceleration produces shorter trip times than constant thrust.
- o Constant acceleration results in increased payload capability when compared to constant thrust.
- o 8 perigee burns are more efficient than a lesser number for all parameters except trip time where coast time dominates total mission duration.
- o Acceleration between 0.05 and 0.10 g is preferred from a performance point of view and is compatible with the structure data previously discussed.

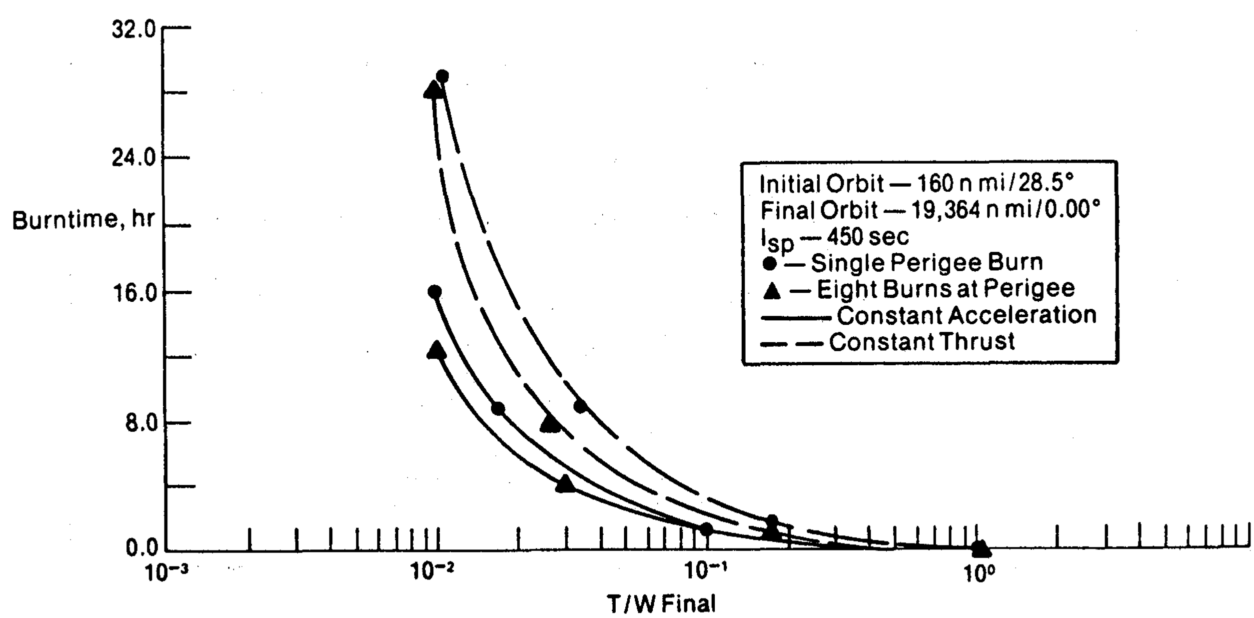
Comparisons between Constant Thrust and Constant Acceleration

Trajectory Variables	Advantages/Disadvantages
Velocity Requirement	• Constant thrust requires an 11% increase in ΔV over constant acceleration at low T/W. • Constant thrust requires a 2% increase at low T/W using one burn. • There is no significant difference in ΔV at T/Ws above 0.4. • ΔV transition occurs for both modes between 0.01 and 0.1 final T/W.
Burntime	• Small differences in total burntime between single and multiple burn transfers. • Constant thrust requires a 115% increase in burntimes relative to constant acceleration at low T/W.
Trip Time	• Constant thrust increases trip time by 65 to 88%, depending on the number of perigee burns. • Using high-thrust multiple burns, coast time dominates burntime; however, using low thrust, burntime dominates. • Multiple burn trip times are nearly invariant to T/W.
Payload	• Constant acceleration increases payload by 3 to 15% depending on the number of perigee burns employed. • There is no appreciable difference in payload performance above a T/W of 0.5.

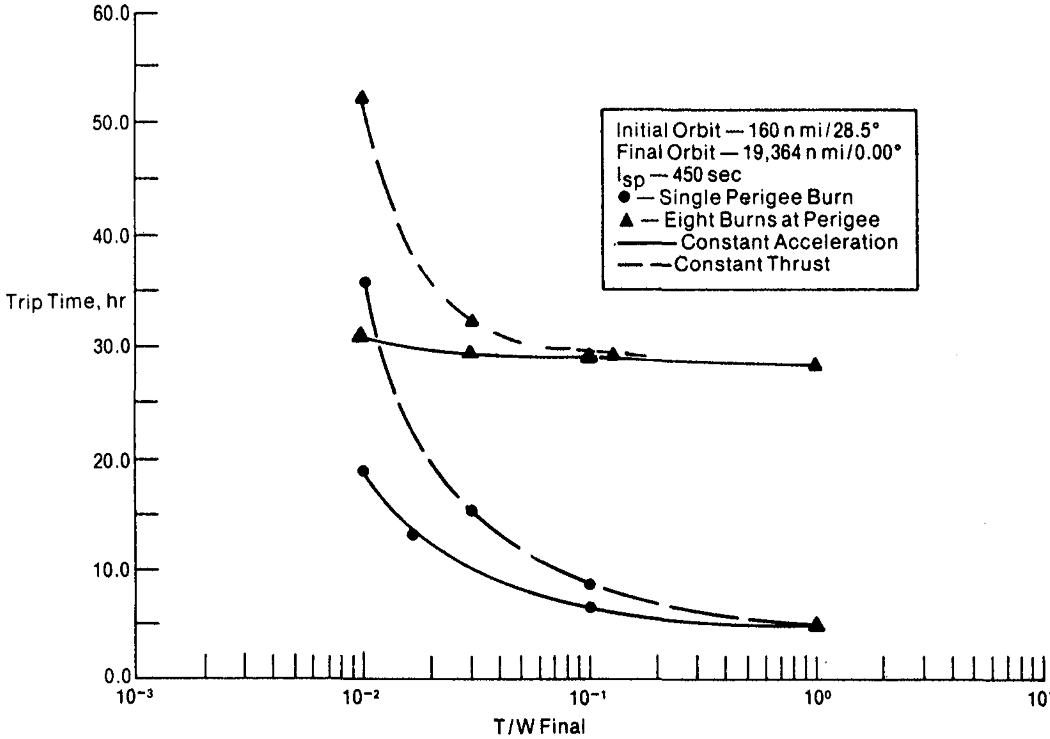
Ideal Velocity Requirements



Burntime Requirements



Trip Time Requirements



Payload Capabilities vs T/W