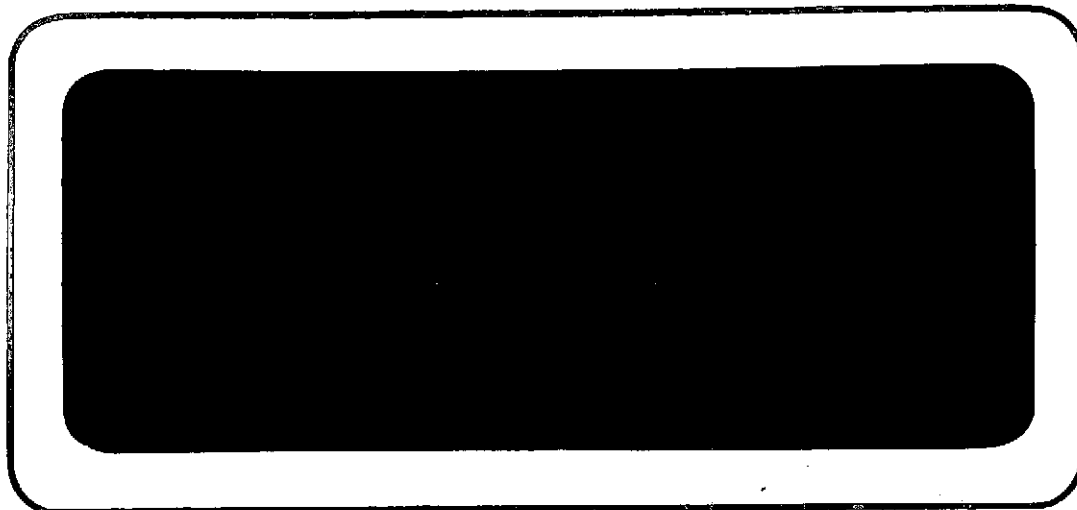


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PIONEER SPACECRAFT OPERATION AT
LOW AND HIGH SPIN RATES

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OPERATION AT LOW AND HIGH SPIN RATES (TRW
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Task 3

October 5, 1973

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1. STUDY OBJECTIVES

During its cruise phase the Pioneer F/G spacecraft operates nominally at a spin rate of 4.8 rpm. Spin rates significantly different from the nominal value are of interest in future missions of spacecraft of the Pioneer series for a variety of objectives. Low spin rates are desirable to permit longer exposure of imaging sensors and radiometers in the observation of faint targets. High spin rates are advantageous in lending greater stability to the spinning spacecraft against orientation changes during high-thrust propulsive maneuvers, e.g., at planetary orbit insertion, and thus reduce thrust pointing errors. In any case the departure from the nominal spin rate is to be of fairly short duration as an added operational mode.

The objectives of this study are to investigate the feasibility of executing major changes upward or downward from the nominal spin rate for which the Pioneer F&G spacecraft was designed, and to determine the extent of system and subsystem modifications required to implement these mode changes in future spacecraft evolving from the baseline Pioneer F&G design.

In the previous study of a Pioneer Jupiter orbiter (Reference 1) the modification of the baseline Pioneer F&G spacecraft required to accommodate a limited range of spin rate variations were investigated. In the present study these results are to be re-examined and updated for an extended range of spin rate variations for missions that include outer planet orbiters, outer planet flyby and outer planet probe delivery. However, in the interest of design simplicity and cost economy, major modifications of the baseline Pioneer system and subsystem concept are to be avoided. Tasks to be performed in this study include the following:

- a) Define and analyze techniques for providing spacecraft spin rates from zero to 45 rpm. Also for changing the spin rate from a nominal five (5) rpm to zero (0) rpm for continuous periods of up to twelve hours, 20 times during a mission.
- b) Define the required spacecraft modifications and the method of accomplishment.

- c) Evaluate effect of proposed modifications on spacecraft performance.
- d) Define required subsystem modifications.

2. FUNCTIONAL REQUIREMENTS AND CONSTRAINTS

This section outlines objectives, constraints and functional requirements that are to be met by operating future Pioneer-class spacecraft at off-nominal, high or low spin rates. Such conditions occur in the outer planet flyby, orbiter and probe delivery missions previously studied by TRW (References 1, 2 and 3). The section also includes a summary of pertinent configuration and mass property data of the Pioneer orbiter spacecraft that will be used in Sections 3 to 5 in the discussion of spin dynamics and control requirements.

2.1 SPIN RATE VARIATIONS IN AN ORBITER MISSION

Figure 2-1 illustrates the sequence of spin rate variations in a Jupiter orbiter mission, as defined in Reference 1. After the initial despin maneuver and appendage deployment which reduces the spin rate to the nominal value of 4.8 rpm, the spacecraft maintains this rate during the cruise to Jupiter, except during high thrust midcourse maneuvers when a higher spin rate is desired (10 rpm in this example) to assure accurate thrust vector pointing. A high spin rate is also used during the Jupiter orbit insertion, and subsequent orbit trims and plane change maneuvers. During the orbital phase the spin rate is periodically reduced to 2 rpm for improved TV camera image resolution whenever the spacecraft is in a favorable viewing position close to the planet. After the periapsis passage the spacecraft resumes the normal operating mode at a spin rate of 4.8 rpm. With highly eccentric orbits typical for this mission, and orbit periods that may exceed 30 days, the spacecraft will actually spend almost all of the orbital mission phase in the normal mode.

Figure 2-2 shows a 14.2-day Jupiter orbit with dimensions of 2.3 by 45.1 Jupiter radii. Time markers along the trajectory indicate that a 12-hour interval, starting at about 10 Jupiter radii, provides favorable viewing angles for observation of the planet's bright side and terminator region. During this time the spacecraft will operate in the low spin rate mode. Opportunities for close-up observation of some of Jupiter's moons (Io and Europa) also may occur during this time. A shift or extension of the low-spin-rate period is required in the case of encounters with Ganymede or Callisto.

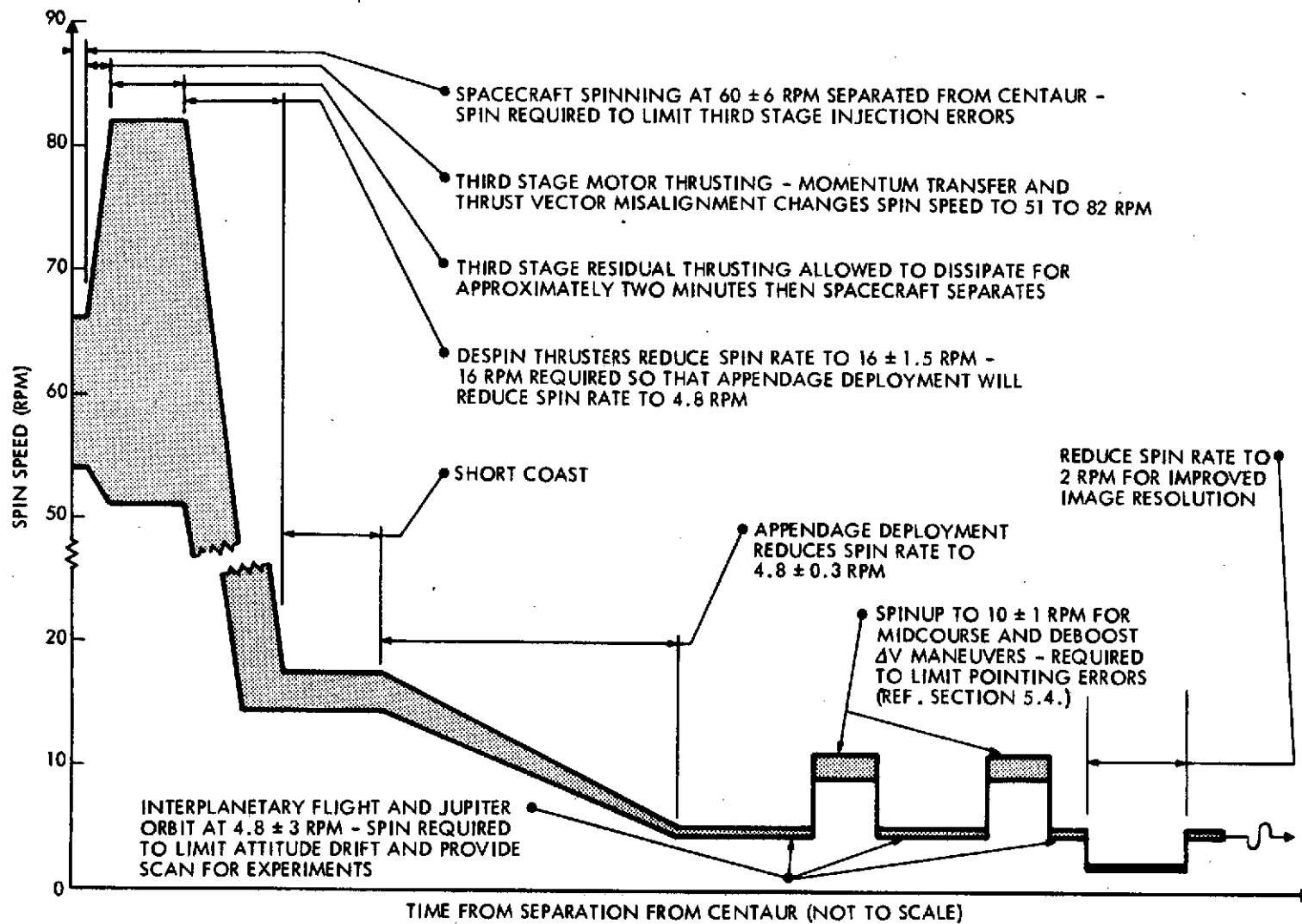


Figure 2-1. Spin Rate Profile in Orbiter Mission

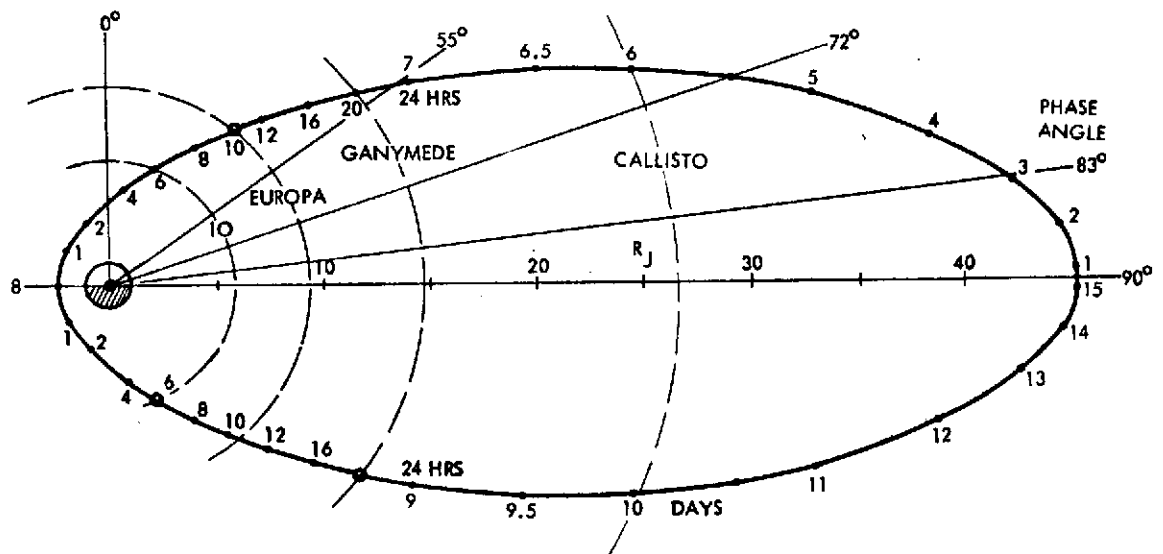


Figure 2-2. Jupiter Orbit with Satellite Encounters
 $2.3 \times 45.1 R_J$ Orbit (Period 14.22 Days)

2.2 LOW SPIN RATE OBJECTIVES

Operation at a low spin rate is desired for the benefit of some of the scientific observations:

- To increase the exposure of the TV image system, and of photometers, radiometers or spectrometers to faintly illuminated or radiating objects
- To reduce image smear in the TV system and thus improve resolution
- To increase mass spectrometer or impact detector dwell time in a given spatial sector.

Some unfavorable aspects associated with scan rate reduction must be weighed against these advantages (see below).

Actually, the preferred spin rate for each sensor depends on a tradeoff of several parameters. This is best illustrated by considering two types of image systems, a vidicon camera and a line scan camera.

To provide a required minimum exposure time, t_{\min} , for each resolution element ϵ_{res} the spin rate must be reduced to a value not exceeding a limit ω_L , where

$$\omega_L = \frac{\epsilon_{\text{res}}}{t_{\min}}$$

Figure 2-3 shows this spin rate limit as function of ϵ_{res} with minimum exposure time as parameter. Shaded regions delineate the resolution range of typical image systems, radiometers and spectrometers. As an extreme example the Mariner 1971 high resolution vidicon camera with $\epsilon_{\text{res}} = 0.02$ mrad and a shutter speed range of 3 msec to 6 sec, is indicated on the left. To use such a camera on a spin-stabilized rather than three-axis-stabilized spacecraft, the spin rate would have to be reduced to the range of 7×10^{-2} to 3×10^{-5} rpm depending on the required exposure.

A phototransistor line scan camera of the type proposed for application on Pioneer (Reference 4) with $\epsilon_{\text{res}} = 0.1$ mrad and exposure times ranging from 0.2 to 10 msec, is indicated to the right of the Mariner vidicon camera. The corresponding spin rates range from 0.1 to 5 rpm. For observation of the outer planets and their satellites the required exposure time is of the order of several milliseconds for the line scan image system, even for a reasonably fast optical system (e.g., 500 mm focal length and f/3 aperture ratio).

The exposure time relation given above also provides a rough approximation of the effect of image smear, by defining the spin rate at which the image smear equals one resolution element for a given exposure time. Thus the data in Figure 2-3 can be used to determine the maximum spin rate permissible from the standpoint of image smear limitation.

A possible disadvantage associated with large spin rate reductions is the resulting increase in the time interval between samplings of ambient phenomena where measurements depend on spacecraft orientation. For example, with a relative velocity of 30 km/sec at the time of Jupiter periapsis passage and a spin rate of 0.1 rpm, i.e., a sampling interval of 600 sec, the distance traveled between samplings is 18,000 km (about one-quarter of Jupiter's radius). Since at least two samples are required to measure

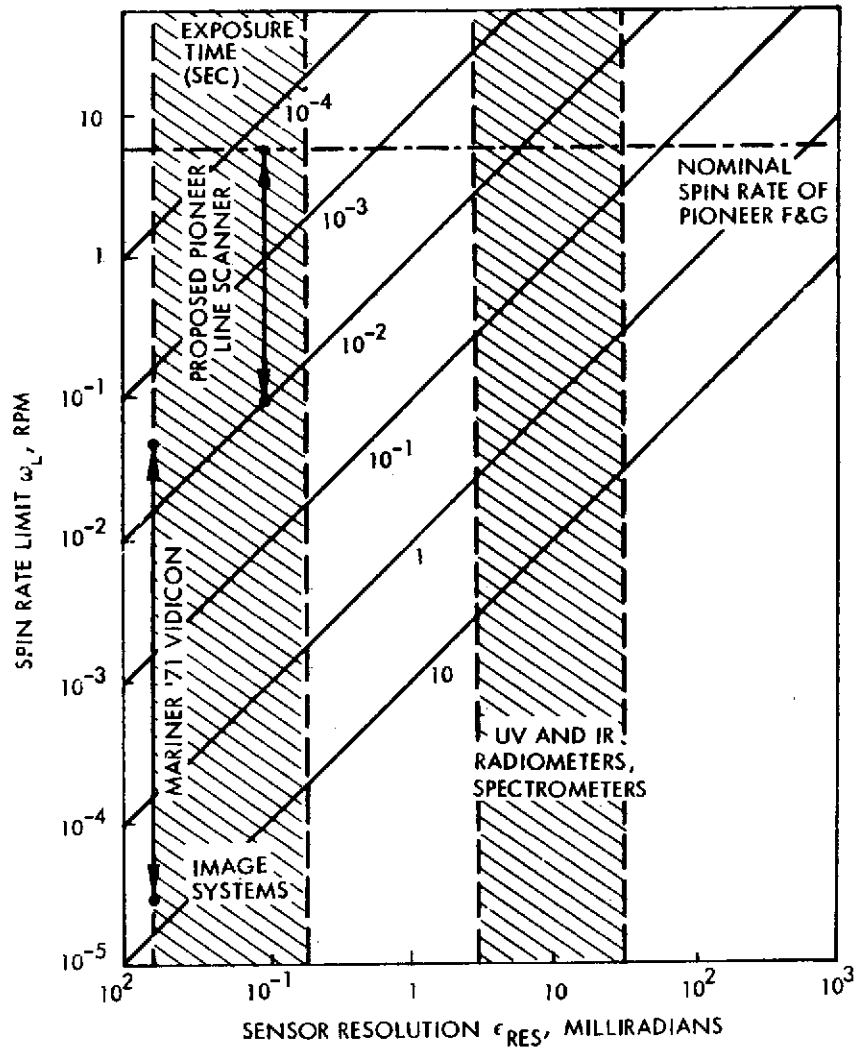
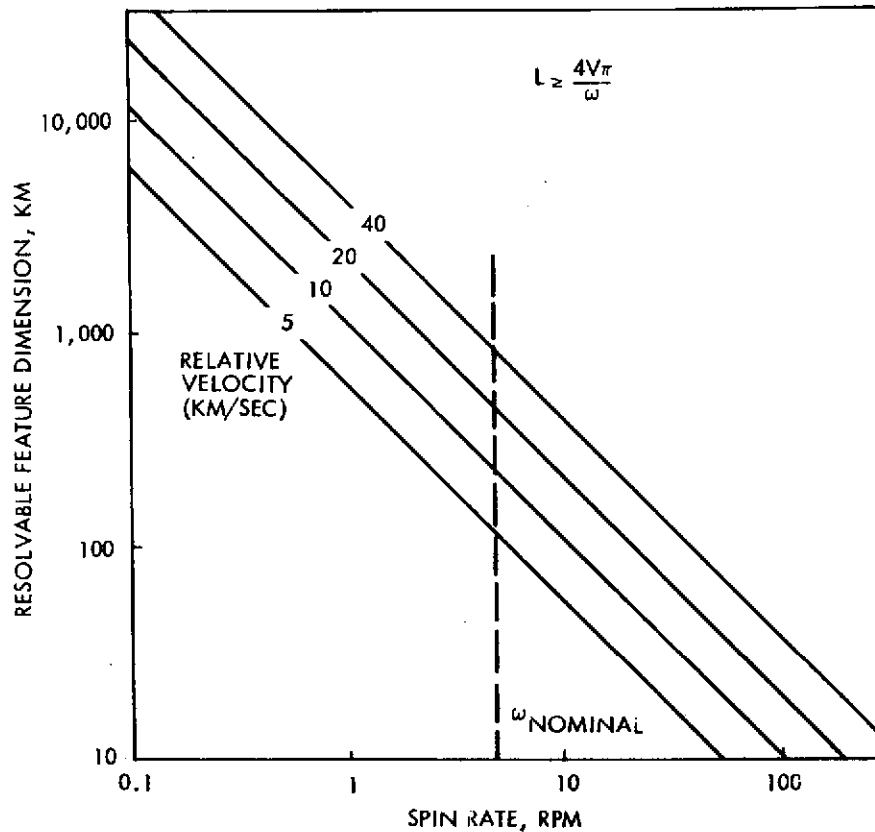


Figure 2-3. Spin Rate Limit Versus Sensor Resolution and Exposure Time

periodic phenomena, the spatial resolution of such phenomena would be extremely poor in this case, i.e., 0.5 Jupiter radii. Figure 2.4 shows the "dimension" of resolvable features as function of spin rate (or sampling interval) and relative velocity. At the nominal spin rate, with the resolvable feature size reduced to 750 km, no problem in the measurement of ambient phenomena near Jupiter should be anticipated.

Further study is required to weigh the possible degradation at low spin rates of in-situ measurements that depend on spacecraft orientation against the desired gain in performance of the image system and other

remote sensors. In an extended orbiter mission the high and low spin rate modes could possibly be used alternatively in successive close approaches to the planet to meet both objectives.



2.3 HIGH SPIN RATE OBJECTIVES

Operation at a higher than nominal spin rate may be required

- To increase spin-axis orientation stability during high-thrust maneuvers for greater thrust pointing accuracy and reduced residual pointing errors
- To impart a higher spin rate to a planetary entry probe prior to separation from the spacecraft bus (a) for reduction of tip-off errors, (b) for greater probe stability until entry into the atmosphere
- To increase the scan rate of scientific payload instruments under special conditions.

Dynamic characteristics of increased spin-stability under the perturbing influence of thrust vector misalignment will be discussed in Section 4. The stiffening effect of increased spin rates on flexible appendages will also be discussed in that section.

Spin rates greater than 5 rpm may be desirable for stability of planetary entry probes. This would be achieved by spin up of the Pioneer spacecraft bus to a higher than nominal spin rate, prior to probe separation. Actually in the recent TRW/McDonnell-Douglas study of the Pioneer Saturn/Uranus entry probe mission (Reference 3) increased probe spin rate was found to cause an undesirable prolongation of gyroscopically-induced nutation during entry pitchover. However, a spin rate increase could have reduced the probe separation tip-off angle error below the attained value of 2.0 degrees, if necessary.

The third objective, increasing the scan rate of science sensors under special conditions, relates to the measurement of ambient phenomena at sufficiently short sampling intervals (see above).

The primary objective, namely improvement of thrust pointing stability and accuracy requires spin rate increases to 10 or 20 rpm. This would occur typically six times during the mission. A representative sequence of high thrust maneuvers for a Jupiter orbiter mission is listed in Table 2-1.

Table 2-1. ΔV Maneuver Sequence in a Jupiter Orbiter Mission

Burn No.	Event	Days from Launch	ΔV Required (m/sec)	Burn Time (sec)
1	Midcourse correction	5	82	190
2	Orbit entry at first periapsis	820	900	1684
3	Plane change	834	350	522
4	Orbit time trim at second periapsis	870	77	112
5	Apoapsis reduction at third periapsis	909	400	513
6	Orbit time trim at fourth periapsis	925	30	34
Total Required			1850	3055

None of the maneuvers exceed a burn time of 30 minutes. Nevertheless, an extension of the high-spin-rate operation may be desirable, to permit ground verification of successful spin-up before commanding the engine to fire, the communications delay being 1.7 and 3 hours at Jupiter and Saturn, respectively.

2.4 REFERENCE PIONEER SPACECRAFT CONFIGURATION AND MASS PROPERTIES

The configuration and mass properties of the Pioneer Jupiter orbiter* (see Reference 1) will be used in the following sections as a basis for the analysis of spin dynamics, acceleration loads, propellant requirements, etc. This configuration is shown in Figure 2-5. Mass properties are listed in Table 2-2. For comparison the corresponding characteristics of Pioneer F&G are also listed:

Table 2-2. Jupiter Orbiter - Mass Properties Estimate (Reference 1)

	Weight (lb)	\bar{X} (in.)	\bar{Z}^1 (in.)	Moment of Inertia (slug-feet ²)			$\frac{I_z}{I_x}$	$\frac{I_z}{I_y}$	$K = (K_x K_y)^{1/2}$
				I_x	I_y	I_z			
At TE 364-4 ignition (spacecraft stowed plus TE 364-4 and adapter)	4403 (2873) ²	0 (0)	-6.0 (-24.5)	1282 (484)	1254 (476)	385 (185)	0.30 (0.38)	0.31 (0.39)	
At TE 364-4 burnout (spacecraft stowed plus burnout motor and adapter)	2286 (756)	0 (0)	21.1 (-5.9)	427 (181)	399 (173)	310 (109)	0.73 (0.74)	0.78 (0.78)	
At separation - stowed (spacecraft stowed less motor and adapter)	2069 (564)	0 (0)	26.8 (19.2)	251 (71)	224 (63)	298 (101)	1.19 (1.4)	1.33 (1.6)	
At start of life - deployed	2069 (564)	0 (-6.3)	26.8 (19.2)	840 (287)	308 (188)	971 (443)	1.16 (1.5)	3.15 (2.3)	0.58 (0.86)
At end of life - deployed	887 (504)	0 (-7.1)	37.0 (19.4)	746 (287)	214 (187)	859 (442)	1.15 (1.5)	4.01 (2.3)	0.68 (0.86)

¹ Longitudinal center of gravity from separation plane

² Pioneer F mass properties in parentheses

* The designation Pioneer Jupiter orbiter used here always refers to the larger configuration (Configuration 2) defined in the reference study, being more representative of advanced Pioneer spacecraft designs than the small Configuration 1.

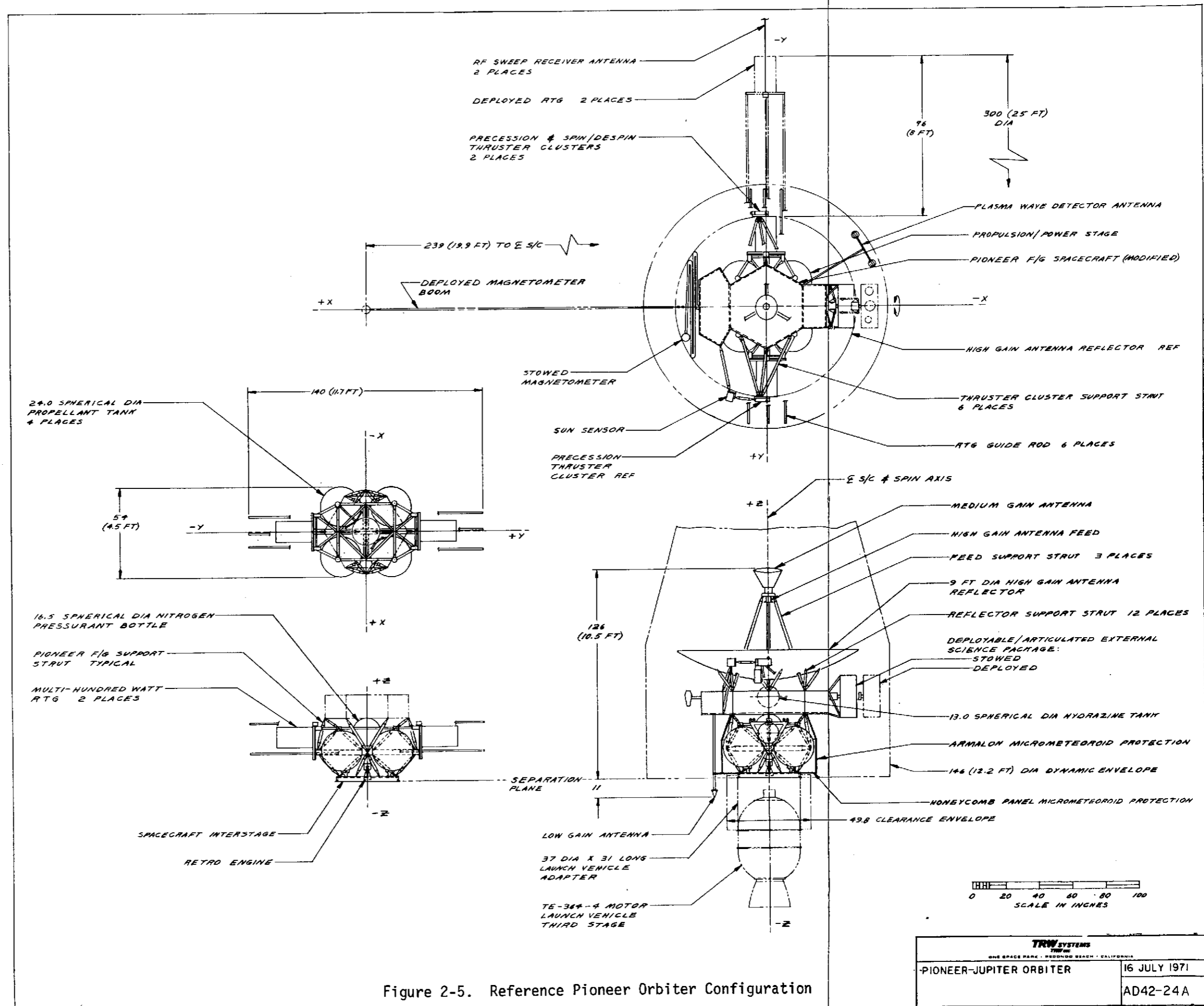


Figure 2-5. Reference Pioneer Orbiter Configuration

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PIONEER-JUPITER ORBITER	16 JULY 1971
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The large spin moment of inertia (I_z) that characterizes the orbiter configuration is similar to that of the outer planets Pioneer and Saturn/Uranus spacecraft bus. Thus the spin-up and despin dynamics requirements of this class of Pioneer spacecraft are comparable. In all cases the addition of heavier RTG's contributes a major part of the increased spin moment of inertia.

The addition of a 20- to 25-pound deployment counterweight at the tip of the magnetometer boom, also a major contributor to the increased I_z value, is a general requirement in Pioneer configurations, with RTG booms mounted 120 degrees apart, that carry large added structures such as a propulsion stage or entry probe. These added structures shift the spacecraft c.g. to a z-axis position significantly below the deployment plane of the three appendages and thus necessitate the deployment counterweight addition for control of the principal axes of inertia.

In considering required modifications of the system and subsystems to implement the high and low spin rate modes of operations, this study will generally refer to Pioneer F&G as a baseline. However, it will also make use of design changes already adopted for the Pioneer orbiter, outer planet and probe mission configurations. These include the RTG and power system changes, the use of X-band, the use of an auxiliary radial thruster pair, and the addition of an add-on equipment bay in some of the configurations.

3. EFFECTS OF SPIN RATE REDUCTION

The reduction of spin rate from the nominal speed of 4.8 rpm has two major effects upon the attitude control subsystem (ACS). First, the reduction decreases the angular momentum so that speed insensitive disturbance torques acting normal to the spin axis have a proportionally greater effect of precessing the spin axis direction. Second, the Pioneer F&G ACS was designed to operate within a range about the nominal spin rate. Spin speed outside this operating range will necessitate modifications to units and assemblies with the number of required changes increasing as spin speed operating range is broadened.

3.1 DISTURBANCE TORQUE EFFECTS

The predominant attitude disturbances in a planetary orbit are caused by gravity gradient and magnetic torques. These disturbances have their greatest effect near periapsis.

The gravity gradient torques on a spacecraft expressed about the x, y, and z body axes are:

$$T_{ggx} = \frac{3\mu_j}{R^3} (I_z - I_y) r_{by} r_{bz}$$

$$T_{ggy} = \frac{3\mu_j}{R^3} (I_x - I_z) r_{bz} r_{bx}$$

$$T_{ggz} = \frac{3\mu_j}{R^3} (I_y - I_x) r_{bx} r_{by}$$

where

μ_j = gravitational constant of the planet

R = distance from planet's center to the spacecraft center of mass

I_x, I_y, I_z = principal moments of inertia of the spacecraft

r_{bx}, r_{by}, r_{bz} = direction cosines of the radius vector \bar{R} (in spacecraft coordinates)

Notice that these torques vary as the inverse cube of the radial distance from the planet center and depend upon the differences in moments of inertia. With each orbital pass the angle between the spin axis and the radial vector will vary. Also, spin about the z axis will introduce periodicity in the projection of the radial direction on the body axes.

A magnetic moment on the spacecraft is caused by the interaction of the planet's magnetic field and the spacecraft magnetic field. The resultant torque is

$$\bar{T}_m = \bar{M} \times \bar{B}$$

where

\bar{M} = spacecraft magnetic dipole moment

\bar{B} = planet's magnetic field vector

The strength of the field varies also inversely as the cube of the radial distance between the spacecraft and the planet's center.

The combined effect of these two disturbances was evaluated for the case of a Jupiter orbiter (Reference 1) assuming moments of inertia and magnetic properties of Pioneer F/G. As a worst case example a skimmer orbit was selected; a magnetic field strength of 10 gauss at Jupiter's surface was assumed. The maximum precession per orbital pass induced by each perturbing effect was combined in an RSS-sense with an initial pointing uncertainty of 0.2 degree (conscan dead zone). The resulting change in pointing angle is shown in Figure 3-1.

Precession buildup is slight at the higher spin speeds, e.g., >3 rpm, and becomes more pronounced as the speed drops, with approximately 0.6 degree pointing error at 1 rpm. Below this speed the precession rapidly increases with further speed reduction.

Permissible error limits for S-band and X-band operation are indicated in the graph. Below approximately 1.25 rpm, the spin axis precession will exceed the error limit for X-band. Without momentum augmentation, this rate would be the minimum suitable spin speed. To permit operation at lower spin rates an ungimballed momentum wheel will be required.

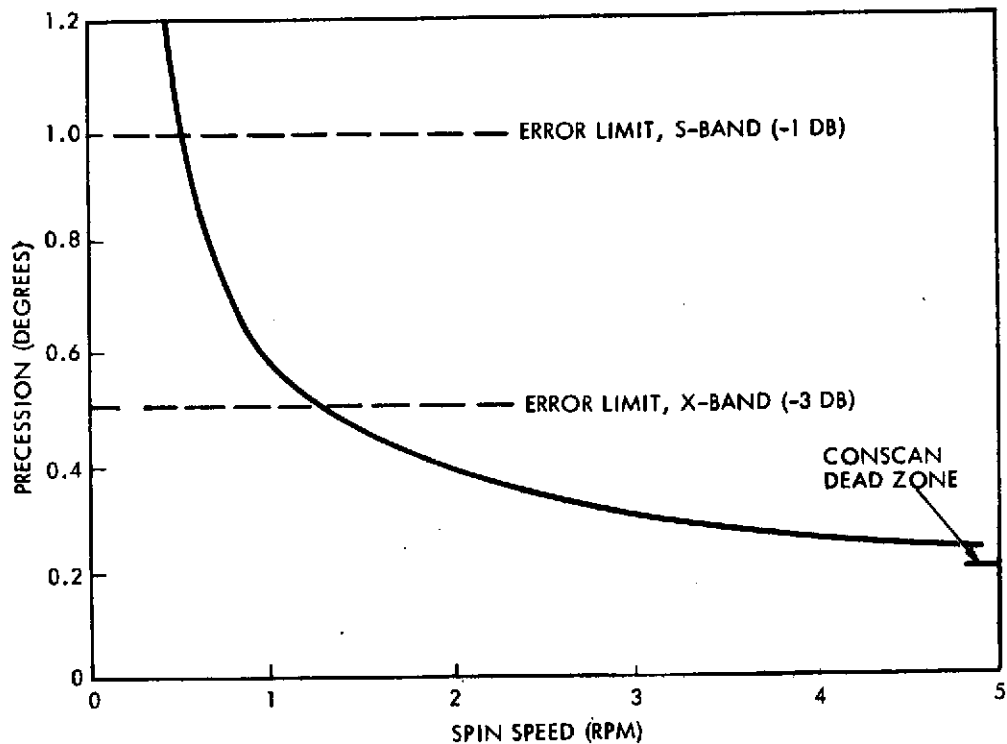


Figure 3-1. Spin Axis Precession from Magnetic and Gravity Gradient Disturbances at Low Spin Rates

3.2 NUTATION DAMPING

Another impact of operation at low spin rate involves the performance of the nutation (wobble) damper. The Pioneer F&G design provides a time constant of 10 minutes or less at 4.8 rpm. The time constant would rise to 100 minutes at 2 rpm. This is illustrated in Figure 3-2. A second curve in this diagram shows the increased effectiveness of the wobble damper due to addition of a large increase in tip mass (deployment counterweight) on the magnetometer boom in the case of the outer planets Pioneer. (Similar performance is anticipated for planetary orbiters that require the same mass balance for principal axis of inertia control as the outer planets Pioneer design.) The time constant of the modified design is approximately 14 minutes at 2 rpm.

Use of a momentum wheel for stability augmentation at spin rates below 2 rpm would essentially hold the wobble damper time constant at the same value as for the unaugmented spinning spacecraft at 2 rpm. If the

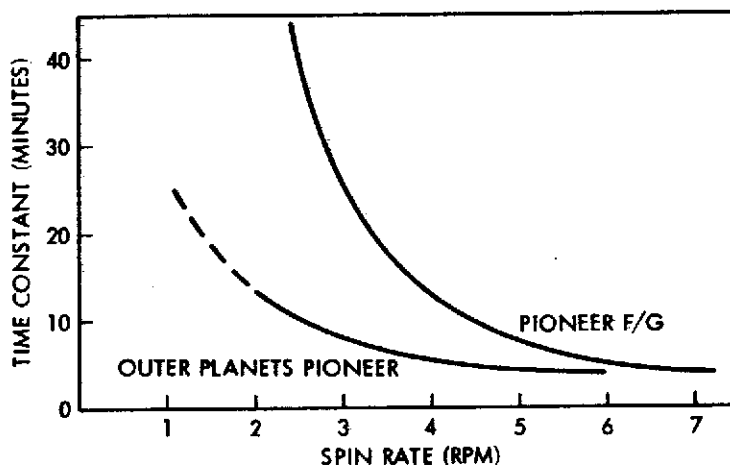


Figure 3-2. Wobble Damper Time Constant Variation with Spin Rate

spacecraft spin rate is to be reduced to 1.5 rpm before turning on the momentum wheel, the damper time constant would increase to about 20 minutes.

However, should it become necessary to reduce the low-spin-speed time constant under these conditions, there exist several alternatives for modification of the existing damper so as to tune its response characteristics to provide optimum performance at low spin rate. This will be discussed in Section 5.

3.3 EFFECT ON ATTITUDE CONTROL SUBSYSTEM OPERATION

The attitude control subsystem designed to operate near the nominal spin rate at 4.8 rpm cannot accommodate the very low spin rates considered here without requiring some modifications. The primary effect of low spin rate operation is to cause a longer bit stream to continue per revolution in several subassemblies of the control electronics assembly and the conscan signal processor, as well as in the roll attitude timer and spin period sector generator of the digital telemetry unit. This would cause an overflow of bit registers and counters in these units unless their capacity is increased. In addition, the exposure time of the sun sensor assembly and star reference assembly would be increased with a resulting loss of accuracy of reference pulse definition. Table 3-1 lists the minimum tolerable spin rate at which the various subassemblies can operate and indicates the required type of modifications to assure functioning if spin rates are further reduced.

Table 3-1. Unit/Assembly Modifications with Spin Rate Reduction

Unit/Assembly	Minimum Tolerable Spin Rate (rpm)	Modification	
		Increase Register Lengths	Perform Equipment Test
Digital telemetry unit	1.875		
Roll attitude timer		x	
Spin period sector generator		x	
Control electronics assembly	3.75		
Star delay		x	
Star time delay		x	
Conscan signal processor	4.0	x	
Sun sensor assembly	2.0		x

Actually, most of these modifications can be avoided if during the short duration of low spin rate phases (a maximum of 12 hours per orbit) these attitude control functions are not exercised and if roll reference signals are received from a separate, free-running precision time clock. This will be discussed in Section 5. However, omission of conscan operations and attitude correction maneuvers during this time interval requires that pointing errors be measured and corrected prior to initiation of each low spin rate phase and that no new pointing errors be introduced through uncompensated precession torques as a side effect of the despin maneuvers. Methods for elimination of precession coupling will also be discussed in Section 5. The inhibition of attitude control related spacecraft functions during periods of close approach to the planet or its satellites when the spin rate is reduced permits maximum utilization of data handling and telemetry channels in support of science data acquisition, particularly image system data which generally constitute the major part of the scientific data volume during each encounter.

4. EFFECTS OF SPIN RATE INCREASE

4.1 REDUCTION IN POINTING ERROR DUE TO THRUST MISALIGNMENT

Temporary increases in spin rate from the nominal rate of 4.8 rpm are required in orbiter missions to improve the accuracy of the orbit insertion maneuver and in subsequent orbit trim and plane change maneuvers, all of which are performed by using the main axial thruster.

The maximum pointing error accruing during the engine firing period as well as the maximum residual error remaining after engine shutdown and nutation decay vary in inverse proportion with the square of the spin rate. Thus, an increase in spin rate to 10 or 15 rpm reduces the upper bounds on these pointing errors by 75 to 90 percent. This is illustrated in Figure 4-1 which shows the reduction in maximum pointing errors achievable in the case of the Pioneer Jupiter Orbiter (see Reference 1). These data were obtained for a thrust level of 100 lb_f and an RMS misalignment torque of 16.5 inch-pounds.

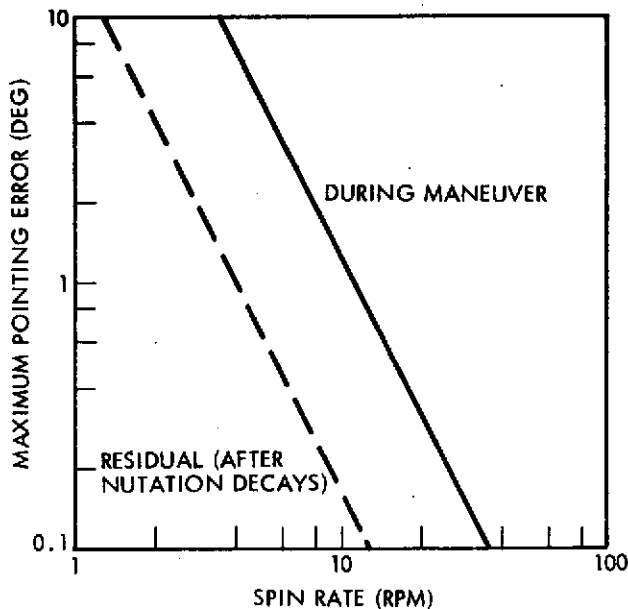


Figure 4-1. Upper Limits of Pointing Errors due to ΔV Maneuvers at High Thrust Level (Misalignment Torque = 16.5 in.-lb)

4.2 ORBIT INSERTION THRUST LEVEL

The selection of the thrust level for the high-thrust engine involves the following considerations:

A high thrust level

- Increases the efficiency of the orbit insertion maneuver by reducing the ΔV penalty ("gravity loss") associated with non-impulsive orbital transfer
- Reduces the maneuver duration and engine burn time

However, it also

- Increases the wobble build-up due to thrust misalignment
- Increases the structural load on deployed appendages, and
- Increases weight and power requirements of the propulsion system.

The tradeoff between the ΔV penalty due to finite thrust level and structural penalty to accommodate high accelerations is illustrated in Figure 4-2 for the case of the Pioneer Jupiter Orbiter. The center of the figure shows acceleration levels sustained during firing of the high-thrust

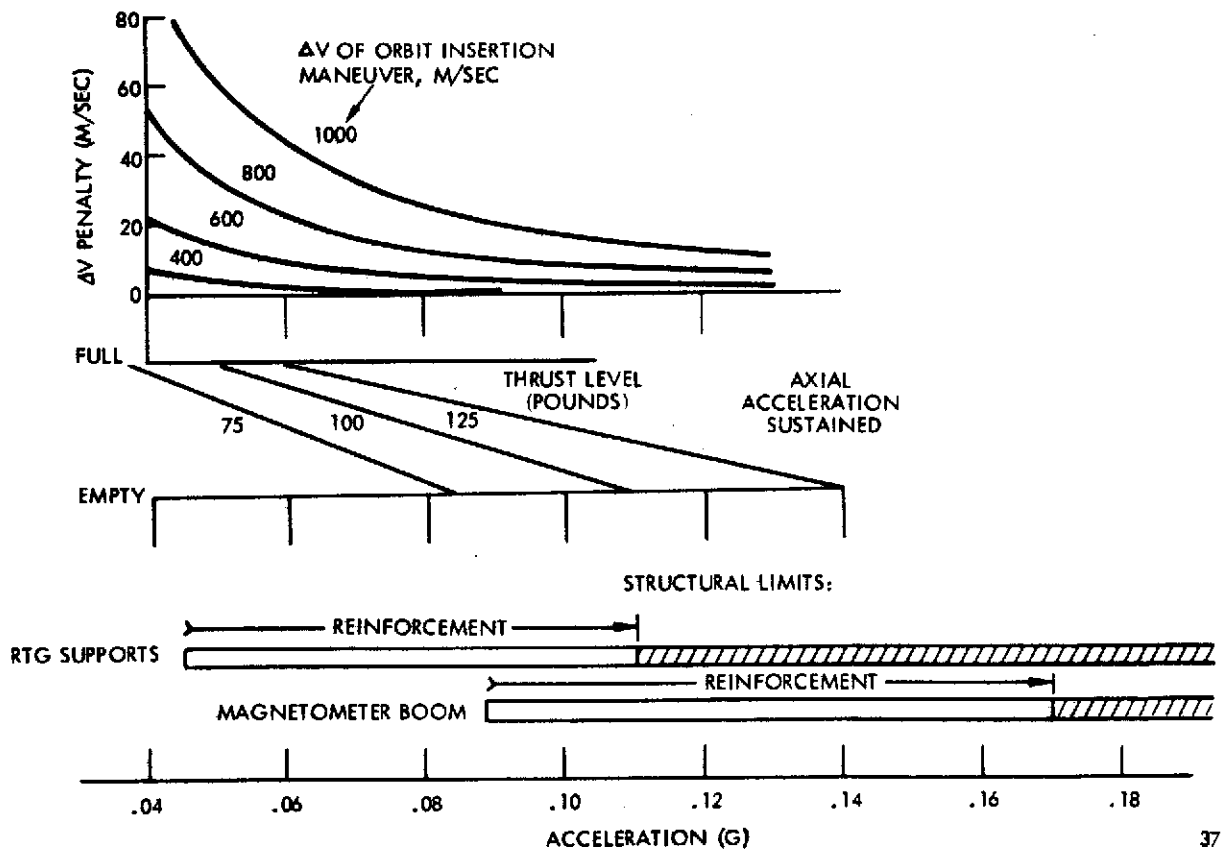


Figure 4-2. Thrust Level Considerations

engine, with the Tower limit occurring when the tanks are full and the upper limit when they are empty. Thrust levels of 75, 100 and 150 lb_f are illustrated. At the top of the figure is seen the ΔV penalty for an orbit entry maneuver of given magnitude at a close periapsis. At the bottom are seen accelerations tolerable by Pioneer F&G deployed structure as it is now designed, and if straightforward reinforcement is applied. The thrust levels shown will incur ΔV penalties of probably no more than 20 to 30 meters/second (for orbit entry maneuvers up to 800 m/sec), and structural penalties are modest.

In the Jupiter Orbiter study (Reference 1) a 100-pound orbit insertion thrust was selected as a result of these tradeoffs and because several applicable engines with that thrust level are available from previous flight programs, i.e., engines built by TRW and Bell Aerosystems for use in USAF spacecraft, and the Marquardt R4-D engine used in the Apollo program.

4.3 STRUCTURAL LOAD EFFECTS OF INCREASED SPIN RATE

4.3.1 Interaction with Axial Loads

The axial loads on spacecraft appendages induced by high thrust application interact with the radial loads caused by the centrifugal effect due to spinning. This interaction becomes more pronounced as the spin rate is increased and leads to an effective stiffening of the deployed appendages against bending due to axial spacecraft accelerations. Figure 4-3 schematically illustrates the stiffening effect at low and high spin rates as a result of the vector combination of the axial (F_a) and radial (F_r) reaction forces that are applied at the appendage end masses. This is discussed in greater detail in Appendix A. Typically, the deflection of the magnetometer boom due to a 0.1 g axial acceleration is reduced by about 50 percent if the spin rate is increased from 4.8 to 10 rpm.

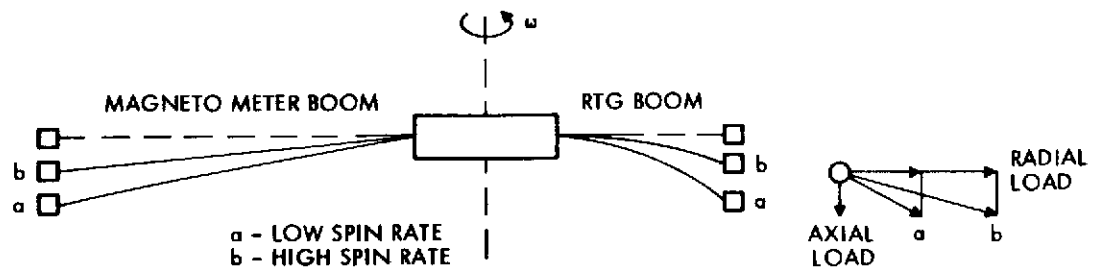


Figure 4-3. Effective Stiffening of Appendages due to Increase in Spin Rate (Schematic)

The interaction also tends to keep the tip deflection of the magnetometer boom and the RTG booms approximately equal, so that asymmetry of mass distribution due to boom deflection, and hence tilting of the principal axis of inertia is minimized. Preliminary analysis shows that the worst-case tilt angle occurring for a 100 lb_f thrust and empty propellant tanks is about 0.5 degrees at 10 rpm and only about 0.25 degree at 15 rpm.

Increasing the spin rate also has the advantage, from a structural load standpoint, of increasing the tensile stress in the guide rods of the RTG deployment arms. Since the tensile load increases with the square of the spin rate, the net compressive load acting on the lower guide rods as a result of bending of the deployed structure due to axial thrust can be greatly reduced, as illustrated in Figure 4-4. Thus, the safety margin of these long, slender rods against buckling is effectively increased. A

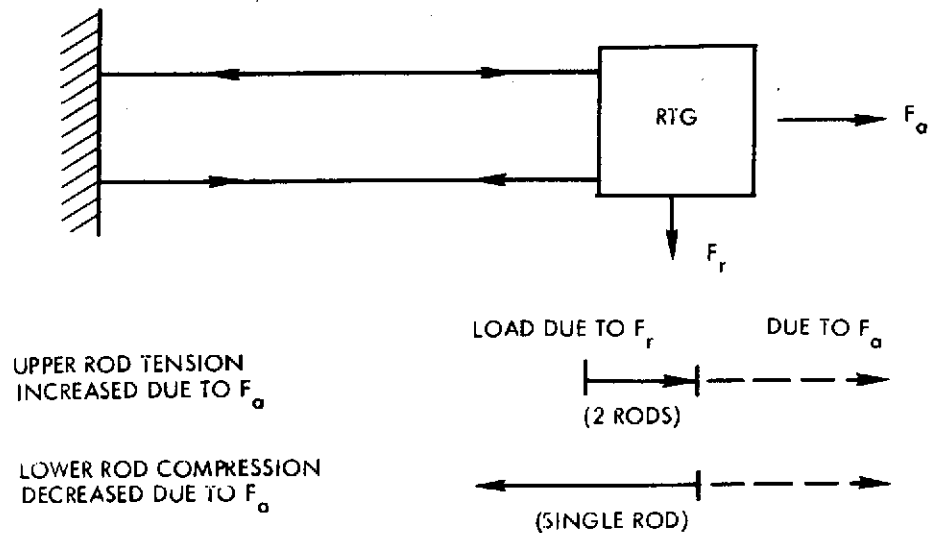


Figure 4-4. Tensile and Compressive Loads on RTG Guide Rods

preliminary analysis of this effect is included in Appendix B. Figure 4-5 shows the reduction of buckling loads with spin rate increase for three levels of axial thrust. Under an axial load of 0.125 g corresponding to 100 lb_f thrust and empty propellant tanks, and at the nominal spin rate, the lower guide rods of the Pioneer F/G design without added reinforcement

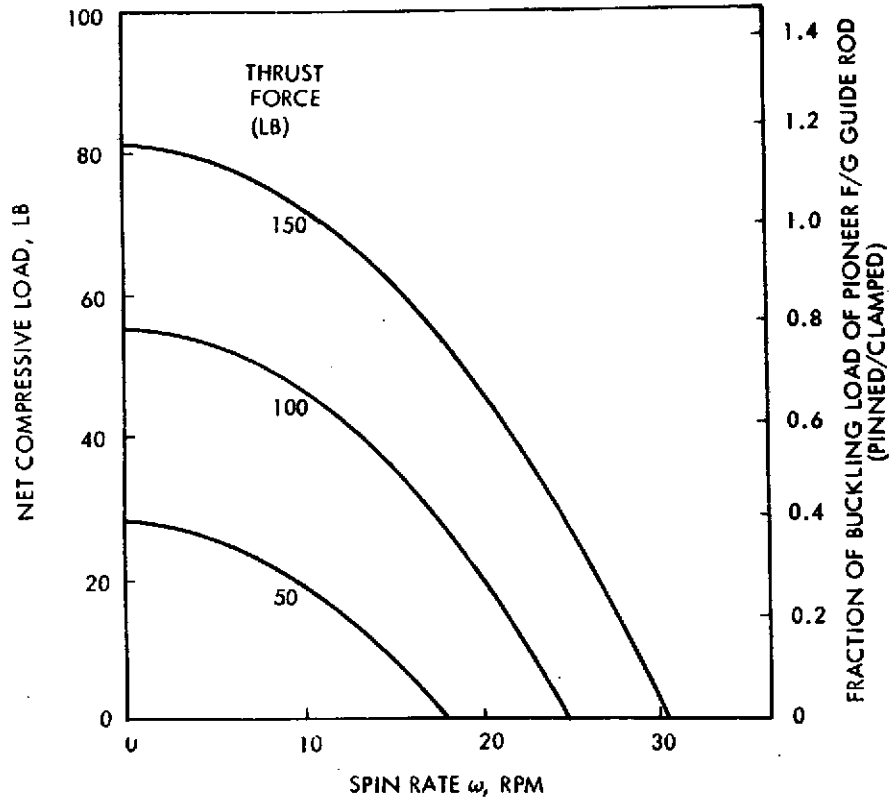


Figure 4-5. Worst Case Net Compressive Load on Lower Pioneer F/G Guide Rod Due to Axial and Radial Acceleration

would be subject to about 80 percent of the critical buckling load. This is clearly unacceptable since the rod is under a combination of compressive and bending stresses. The data in Figure 4-5 show that at 15 rpm the buckling load is reduced to 50 percent of the critical value and to zero at about 25 rpm, where the tensile load equals the compressive load on the rod.

A conservative estimate of bending stresses acting on all three guide rods of the RTG deployment arm (see Appendix A) indicates that for the dimensions of the Pioneer F/G design a maximum stress of about 40,000 psi could be reached under worst-case conditions at the critical attachment points to the RTG assembly. A structural stiffening of the tubular rods by increasing the wall thickness from 0.7 to 1.5 mm is proposed to reduce the combined maximum stress to a safe value (for Aluminum 6061) of about 20,000 psi. This reflects in an acceptably small total weight increase of less than three pounds.

4.3.2 Structural Load on Magnetometer Boom

Structural loads on the long magnetometer boom due to higher spin rates are negligible compared to the loads imposed by the initial deployment sequence. The increase in magnetometer boom tip mass by a 25-pound deployment counterweight in probe-carrying and orbiter configurations of Pioneer (not needed in Pioneer F/G) and the higher loads occurring during simultaneous magnetometer boom and RTG boom deployment (see Reference 3) necessitate a structural redesign of the boom, e.g., using a scissors-type configuration as shown in Figure 4-6. This configuration can readily accept the increase in tensile load imposed by a 15-rpm spin rate, and can withstand the small bending load imposed by the angular acceleration due to spinup (0.01 g at the tip mass). The reinforced structure can also readily accept the axial acceleration load imposed during thrust phases, particularly with the effective stiffening occurring at increased spin rate.

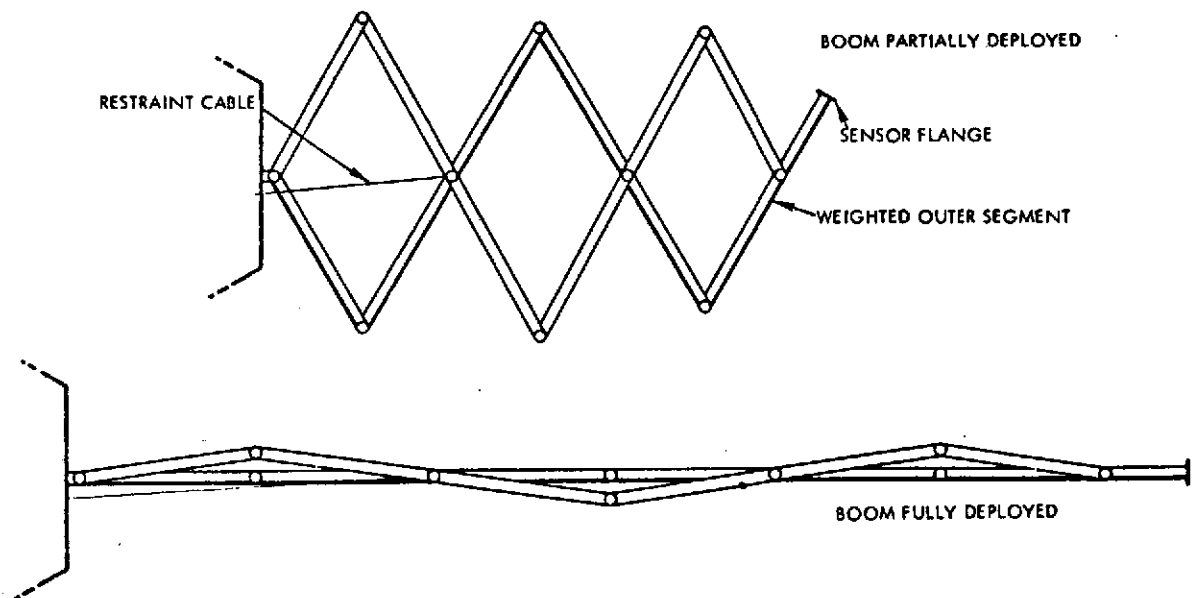


Figure 4-6. Scissors Type Magnetometer Boom

4.3.3 Structural Loads on Spacecraft Center and Propulsion Stage

The increase in spin rate to 10 or 15 rpm at various stages in the mission profile is of no consequence regarding structural loads on the

spacecraft center structure, the support structure of the propulsion stage and the propellant tanks, since these structures must be designed to withstand the much larger centrifugal loads occurring at 60 rpm during the launch phase, prior to spacecraft deployment.

Preliminary analysis shows that attachment fittings of the RTG deployment rods and the magnetometer boom do not require reinforcement as a result of spin rate increase only. The magnetometer boom fittings, however, require reinforcement due to the greater launch and dynamic deployment loads occurring in the proposed orbiter and probe-carrying Pioneer configurations (References 1 and 3). RTG fittings may have to be strengthened because of increased RTG mass.

4.4 EFFECTS OF INCREASED SPIN RATE OPERATION ON ELECTRICAL SUBSYSTEMS AND PRECESSION MANEUVER REQUIREMENTS

An increase in spin rate above 4.8 rpm has its greatest effect upon the precession maneuvering spacecraft operations. All attitude control related subsystems will have essentially identical performance at the higher spin rates. Register and counter lengths require no modifications, although quantization errors will increase, assuming that the counter drive pulse rates are maintained at their original values.

The conical scan signal processing accuracy is spin rate dependent. The number of signal-averaging cycles is based upon the inertia properties of the configuration and a signal-to-noise consideration. The latter will require assessment at the higher spin rate, since the signal filtering bandwidth would have to be expanded accordingly, with some degradation in resultant signal-to-noise ratio expected. Moreover, the phase error in processing is established prior to launch and a selectable (but permanently fixed) program plug compensates for most of the phase error at the nominal spin rate. An increase in spin rate to 15 rpm will introduce phase error estimated at 20 to 30 degrees, which will result in a timing retardation or advance in the precession thrust firing pulse while in the conscan mode.

Open-loop precession maneuvers at the higher spin rate will require proportionately more propellant since the angular momentum increases linearly with spin rate.

Actually, since operation at increased spin rate is restricted to high-thrust propulsion events which are generally of short duration (as discussed in Section 2.4), it is possible to avoid conscan operation and precession maneuvers during these intervals. Hence, no requirement for electrical subsystem modification related to high spin rate is anticipated.

5. IMPLEMENTATION OF LOW AND HIGH SPIN RATE CAPABILITY

This section identifies system and subsystem modifications and operating mode changes from the baseline Pioneer F&G design that are necessary to provide low and high spin rate capabilities. As discussed in the preceding sections, the operating range is to be extended from the nominal 4.8 rpm spin rate to zero on the low side and to about 15 rpm on the high side. Larger spin rates with an upper limit of 45 rpm are considered as unrealistic because of the greatly increased centrifugal loads on deployed appendages and the appreciable extra spin/despin propellant requirements for operating in this range and are omitted in the implementation study.*

5.1 MOMENTUM WHEEL ADDITION FOR OPERATION NEAR ZERO SPIN RATE

Augmentation of the spacecraft angular momentum by addition of an auxiliary momentum wheel becomes necessary when the body spin rate is to be reduced below 1.5 rpm as was discussed in Section 3.1. This permits maintaining the body spin axis within 0.5 degree of the earth line in spite of external perturbations that occur on close approach to the planet, as required for effective X-band communication. At zero body spin rate the momentum wheel provides a substitute for spacecraft spin stabilization so that a changeover to three-axis attitude control requiring extensive changes in attitude control electronics and the addition of new attitude control sensors (or modification of the existing ones) can be avoided. The addition of a momentum wheel is regarded as a much simpler modification of the existing Pioneer spacecraft design.

The use of an auxiliary momentum wheel for frequent changes of the spacecraft spin rate to low values is analogous to the control concept adopted for the earth-orbiting Atmospheric Explorer Spacecraft C, D and E. This spacecraft will also operate periodically in a spinning or despun mode to cater to a variety of scientific objectives, with spin rates ranging from 8 to 1 rpm. The Explorer spacecraft has sufficient mounting

* This change from the initial task definition was agreed on in a discussion on September 14, 1973, with Mr. Ben Padrick of NASA/Ames Research Center.

space to accommodate a large (4-foot diameter) lightweight (8-pound) momentum wheel with an angular momentum capacity of about 60 ft-lb-sec. This capacity is about one-half of that required to augment Pioneer. However, in the Pioneer application size and mounting constraints are more restrictive than in the Explorer spacecraft as dictated by the different configuration and structure.

5.1.1 Spin Rate Control by Combined Use of Thrusters and Momentum Wheel

Figure 5-1 is a graph of angular momentum versus body spin rate that illustrates various modes of combining the use of the existing spin/despin thrusters and the momentum wheel to exercise spin rate control.

- 1) Mode A, characterized by line 1-2-3-5, uses only the momentum wheel, not the thrusters, in the speed range below the limit $\omega_L = 1.5$ rpm (point 3) where unaugmented operation of the spacecraft would become unsatisfactory. Body spin rate reduction in the range below ω_L is achieved gradually by spinning up the momentum wheel to the appropriate spin speed.
- 2) Mode B (line 1-2-3-4-5) spins up the momentum wheel to its maximum rate while firing the despin thrusters to compensate for the momentum change, thus holding the body spin rate temporarily at the fixed value ω_L (line 3-4). Subsequent spin rate changes are performed by thruster firing, while the momentum wheel maintains runs at constant spin rate (line 4-5).
- 3) Mode C (line 1-2-4-5) is similar to Mode B except for spinning up the momentum wheel gradually over a range of body speeds (line 2-4)
- 4) Mode D (line 1-2-3-5 followed by 5-3-6, etc.) relies on the momentum wheel exclusively to perform all despin and spinup operations starting at point 3. This point is reached initially by applying despin thrust.

Of the above methods Mode A appears preferable since the total momentum wheel running time is held at a minimum and the required momentum storage capacity can be made smaller than for Mode D. However, a prerequisite is the ability of the wheel drive motor to provide controlled intermediate spin rates. This mode as well as Mode D minimizes the total number of thruster firings.

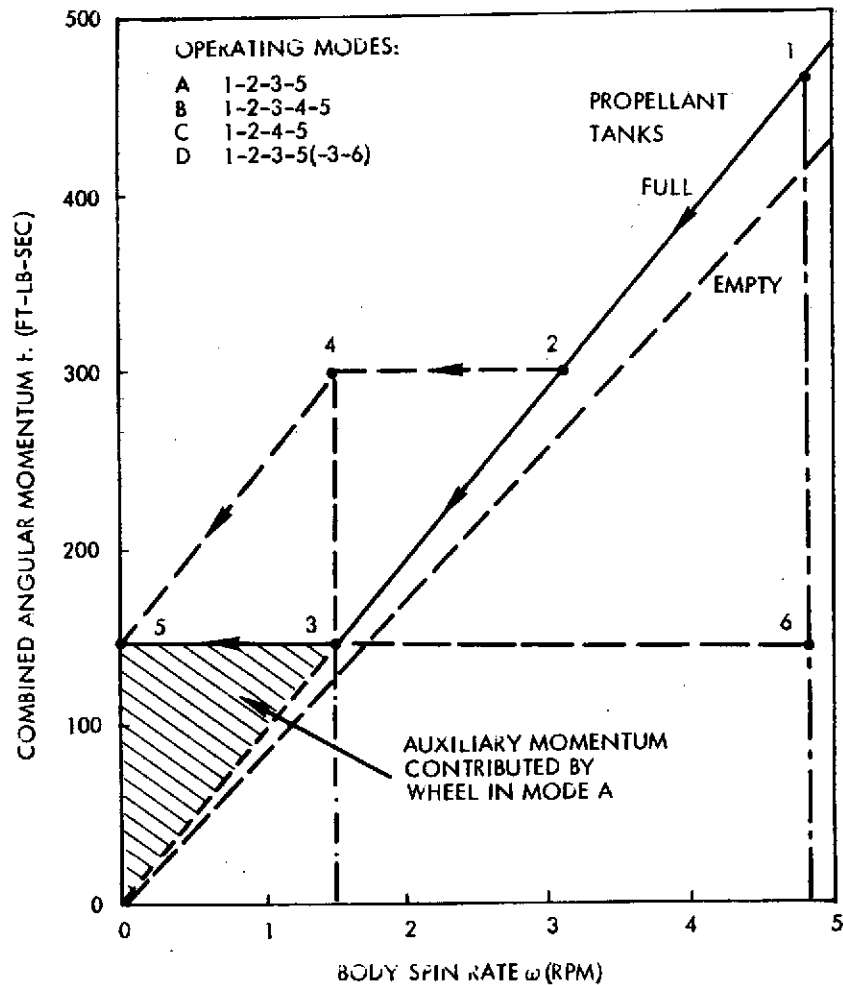


Figure 5-1. Alternate Modes of Using Thrusters and Momentum Wheel in Combination

The smallest momentum storage capacity in Mode D is obtained if the spinup and despin portions of the momentum line (5-3-6) are equalized. In this case the required momentum storage capacity is still 60 percent greater than for Modes A, B and C. It must also be kept in mind that Mode D is the only one considered here that requires a reversal of momentum wheel spin direction at point 3 where line 5-6 crosses the line of combined spacecraft-wheel angular momentum. In general, the momentum wheels currently available are designed only for unidirectional spin operation.

It would not be practical to employ a momentum wheel for rpm variations from low to high spin rates (15 rpm) since this would require a wheel with about five times the storage capacity envisioned only for the low rpm operations as in Mode A.

5.1.2 Momentum Wheel Sizing and Placement on the Pioneer Spacecraft

Figure 5-1 shows that a momentum wheel storage capacity of about 150 ft-lb-sec is required to augment the momentum of the spacecraft proper in the range from 1.5 rpm to zero body spin rate.

In view of the very restricted choice of possible mounting areas, and tight weight, size and power constraints the selection and placement of the wheel assembly must be carefully considered.

For a required momentum storage capacity H_w the weight of the wheel (m_w) increases in inverse proportion with the square of the diameter (D_w) and the maximum running speed (ω_{Max}):

$$m_w \cong \frac{4 H_w}{D_w^2 \omega_{max}}$$

Momentum wheel characteristics are presented graphically in Figure 5-2 as a function of wheel momentum and incremental compensated spacecraft spin speed. The required compensated spin speed is the difference between the minimum spin speed without a wheel and the preferred operating speed, and will be no more than 1.5 rpm. Data to construct the weight and power curves was obtained from existing reaction wheel assemblies, with spin speeds ranging from 1000 to 3000 rpm.

For the small dimensions of possible mounting areas on Pioneer the wheel would tend to be heavy unless high spin rates of 5000 to 10,000 rpm are used. Newer momentum wheel designs applying improved bearing technology provide spin rates in this range.

Characteristics of a representative design (Model 45) by Sperry Phoenix Division are listed in Table 5-1.

Typical for momentum wheels of this type is the long spin-up period that is required if the spin-up power level is to be held low. With a bearing friction of about 1.5 inch-oz and a motor torque of 2.5 inch-oz at 15 watts the net accelerating torque is only 1.0 inch-oz. Doubling the power level would increase the net accelerating torque by a factor of 3.5

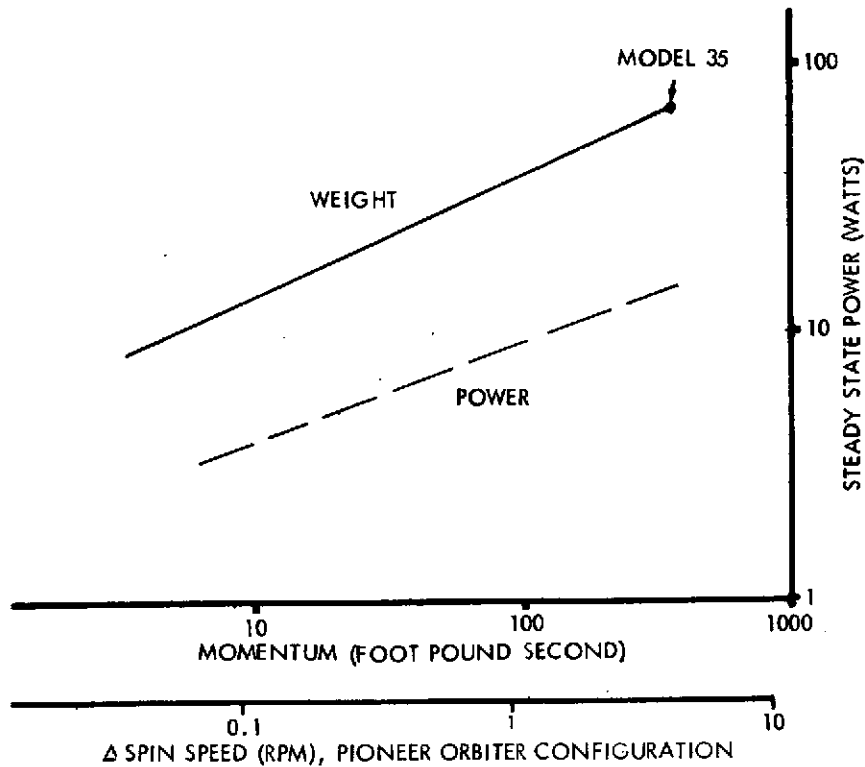


Figure 5-2. Momentum Wheel Weight and Power

Table 5-1. Characteristics of Sperry Model 45 Momentum Wheel

Storage capacity at 5500 rpm at 8000 rpm	100 ft-lb-sec 150 ft-lb-sec
Assembly dimensions: Diameter Height	15 inches 10 inches
Assembly weight (excluding electrical components)	30 pounds
Power required for full spin up in 6 hours	15 watts
Steady state sustaining power	~9 watts
Minimum operating temperature	70°F

Notes:	
<ul style="list-style-type: none"> • Housing must be vented to space to accommodate outgassing • This model has been qualified in accordance with specifications of a current USAF program (5-year operating life), but not flown as yet • Dormancy for 4 to 5 years in prolonged space missions must be avoided, i.e., intermittent turn-on is required. 	

and reduce the spin-up time correspondingly to 1.7 hours. This would be preferable so as to reduce loss of observation time on approaching the planet, if enough power for wheel spin-up can be provided (possibly by temporary turn-off of unused science sensors). After power cutoff the bearing friction drives the spin rate to zero in about 4 hours.

Three possible locations for placing the momentum wheel on the Pioneer spacecraft have been considered and are illustrated schematically in Figure 5-3. Location 1 is above the equipment platform and permits a larger diameter (about 36 inches) than the other options, but would require a cutout in the center of the high-gain antenna dish. Location 2 is inside

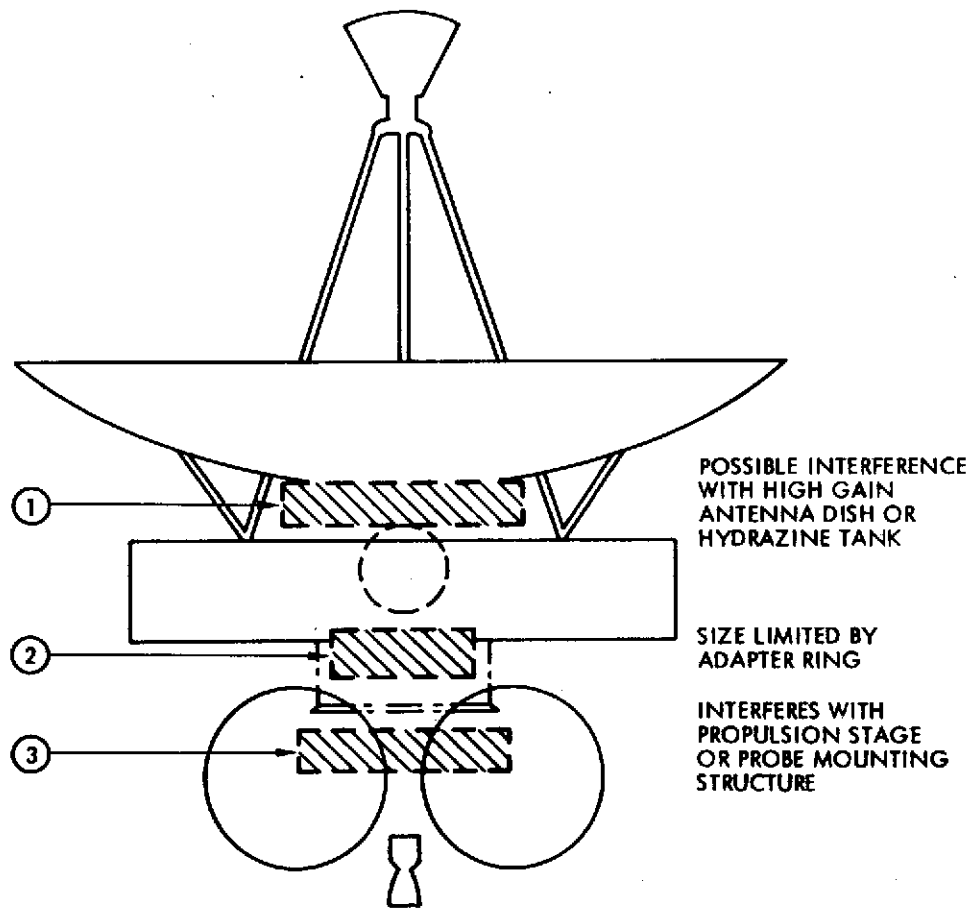


Figure 5-3. Mounting Options of Momentum Wheel

the present (Pioneer F/G) adapter ring which restricts the wheel assembly outer diameter to about 22 inches. This adapter ring was retained in the Pioneer outer planets and probe-carrying configuration concepts studied in References 2 and 3 but omitted in the orbiter configuration (Reference 1). Location 3, below the adapter ring, would potentially be less restricted in outer wheel assembly diameter, but this location may interfere with the propulsion stage structure in the Pioneer orbiter or with the probe mounting structure used in the Saturn/Uranus probe mission configuration. At present the second location appears preferable. It can accommodate the Sperry Model 45 wheel assembly with 20-inch outer diameter, regardless of whether the adapter ring will or will not be retained in its present configuration.

Asymmetrical (off-axis) placement of the wheel would be possible, in principle, but is unattractive because it requires a considerable redistribution of other equipment to restore mass balance.

5.2 SPIN/DESPIN PROPELLANT REQUIREMENTS

The requirements for repeated spin rate variations during the mission reflect in an appreciable propellant increment. With an average spin moment of inertia of 900 slug-ft^2 for the Jupiter orbiter, and a maximum of 20 despin/spin up cycles (40 maneuvers) to low spin rates and 6 spin up/despin cycles to high spin rate (15 rpm), a total increment of 27.4 pounds of hydrazine will be required (14.8 pounds for low speed and 12.6 pounds for high speed operations). This is nearly one-half of the propellant supply of Pioneer F/G. A total of 6.4 pounds of propellant is saved by avoiding despin thrust to zero speed, using the momentum wheel augmentation (in the preferred Mode A) instead. Intermittent momentum wheel activations required during the cruise phase (see Section 5.1) may consume an additional small amount of despin/spin-up propellant.

The required hydrazine propellant allocation (30 pounds) defined in the Jupiter Orbiter Study includes propellant for several spin-up maneuvers to 10 rpm. Thus only about 20 pounds of the total increment stated above reflect new spin/despin propulsion requirements. This amount can be accommodated if the 16.5-inch hydrazine tank of the present Pioneer F/G configuration is retained for orbiter missions.

The requirement for making ΔV corrections with a thrust component normal to the earth line while maintaining the spacecraft in the earth-pointing mode (as defined in the outer planets Pioneer and Saturn/Uranus probe mission studies) rather than by axial thrust in the off-earth-pointing mode requires additional hydrazine propellant which is not reflected in the propellant weights stated above.

5.3 ADDITION OF SPIN/DESPIN THRUSTERS

The required despin/spin-up thrust operations would involve appreciable precession coupling if only one pair of thrusters were to be used as in Pioneer F/G. This is due to the z-axis location of the present spin/despin thruster pair, about 1 foot above the c.g. of the F/G configuration, or 34 inches above the c.g. location of the Jupiter orbiter configuration at the beginning of life (full tanks), 24 inches above the c.g. at the end of life (empty tanks).

This coupling effect was already studied in detail for the Jupiter orbiter configuration, and addition of a second pair of spin/despin thrusters was necessary in that configuration to provide precession torque compensation by balancing the unwanted individual torque effects.

Addition of the second spin/despin thruster pair also increases reliability by adding redundancy in missions where as many as 40 additional spin/despin maneuvers for low spin rate operation and 12 maneuvers for high spin rate operation may be required. The total number greatly exceeds the number of such maneuvers in the Pioneer 10 and 11 mission. The extra weight for this addition is about 3 pounds.

In the Jupiter orbiter study it was found that the residual unbalance of the spin/despin thruster pairs ($\pm 0.04 \text{ lb}_f$) can cause residual precession coupling with maximum pointing errors of 0.4 and 0.2 degree during spin-up to 10 rpm and despin to 4.8 rpm, respectively, after nutation decays.

In the proposed Pioneer orbiter configuration a pair of radial hydrazine thrusters may also have to be added (for purposes of providing major off-earth pointing ΔV maneuver components while the spacecraft is in the earth-pointing mode (e.g., for planetary orbit inclination changes). These radial thrusters also can provide precession trim torque pulses to compensate for any residual precession coupling due to spin thruster unbalance.

This function cannot be exercised by the present ΔV /precession thrusters because they generate precession torques around the body x-axis which is perpendicular to the axis around which a compensation torque is required.

5.4 NUTATION DAMPING

As previously discussed in Section 3, the existing Pioneer F&G nutation damper provides improved performance, i.e., a shorter time constant, than was attained on Pioneer F&G (see Figure 3-2), in the modified spacecraft configuration because of the increased tip mass (deployment counterweight) on the magnetometer boom. A time constant of approximately five minutes will be achieved for spin rates of 4.8 rpm or greater. At spin speeds below 4.8 rpm the time constant increases to approximately 14 minutes at 2 rpm.

Should it become necessary to reduce the low-spin-speed time constant, there are several modifications which can be made to the existing damper, or a second damper tuned to provided optimum performance at low spin can be added. One simple, but very effective, modification is to reduce the viscosity of the damping fluid and replace the flexural pivot with a negative spring having the proper rate to tune the magnetometer boom to the spacecraft's relative precession rate (see Figure 5-4). Replacement of the flexure with a negative spring would involve some development work.

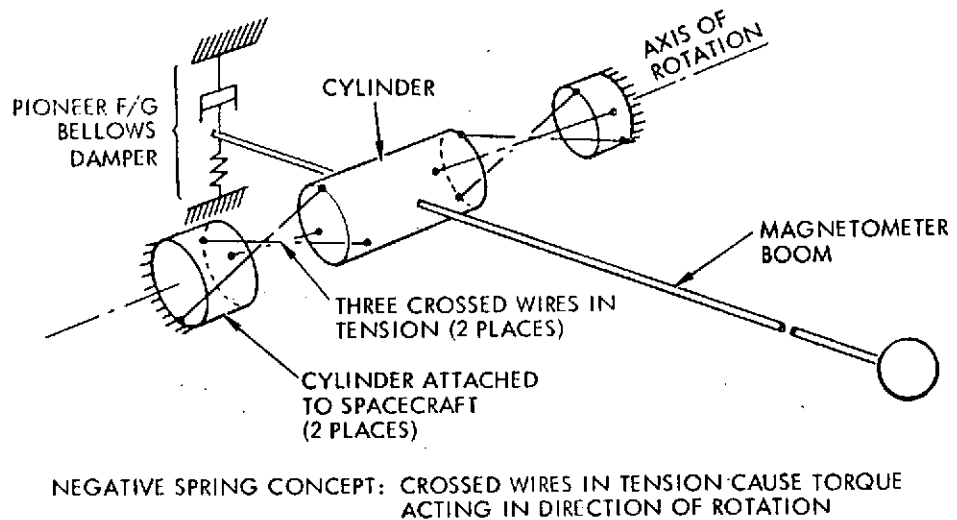


Figure 5-4. Modified Nutation Damper

The effect of tuning the damper-and-boom combination optimally to the relative precession rate of the spacecraft was analyzed in the Pioneer orbiter study and is illustrated in Figure 5-5 for that configuration. The damper modifications assumed in this case are listed in the legend of the figure.

5.5 ATTITUDE CONTROL SUBSYSTEM

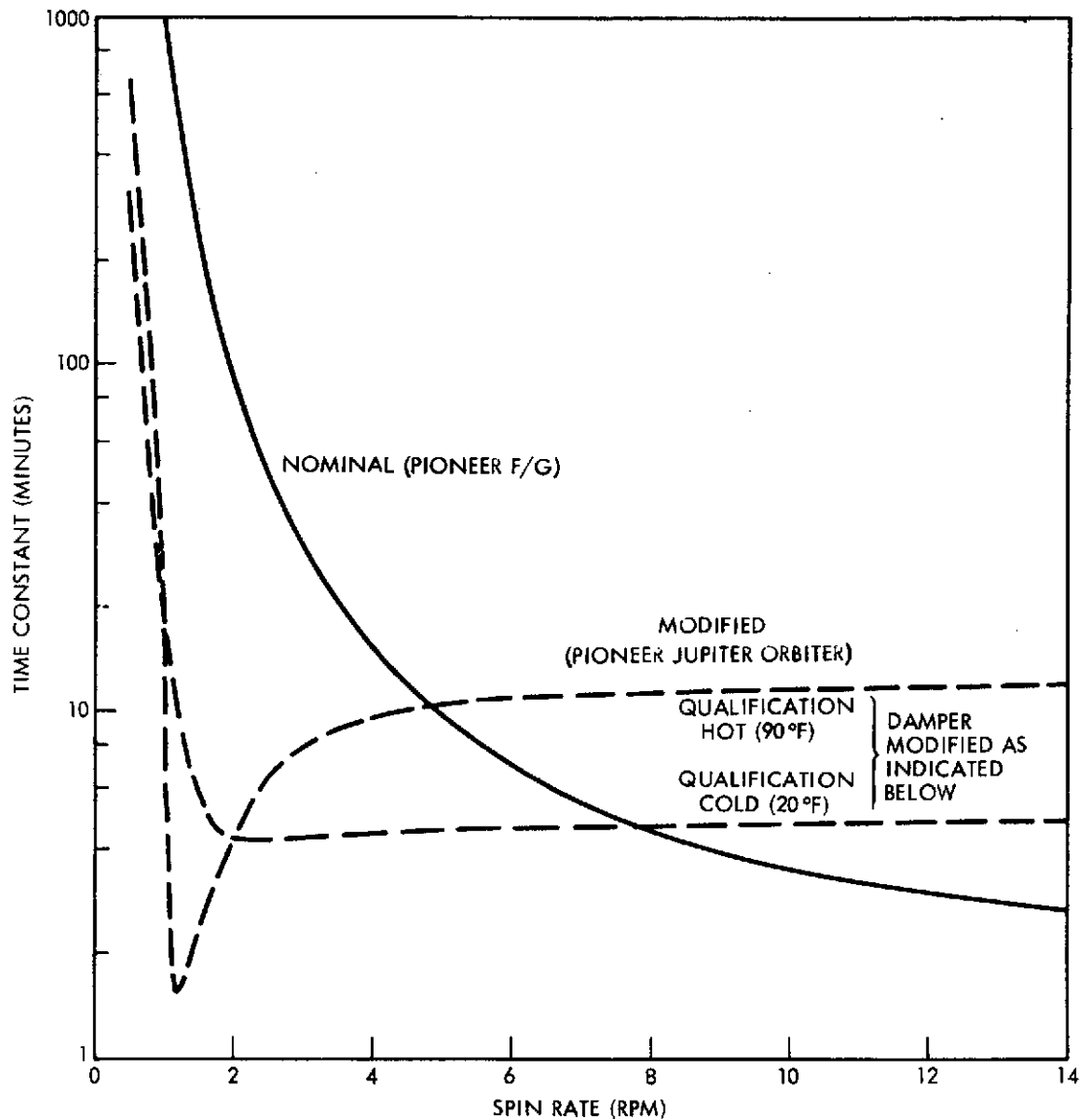
5.5.1 Modifications for Low Spin Rate Operation

Modifications in the attitude control subsystem are limited to those functions which the present Pioneer F/G ACS cannot perform properly at low spin rate but which are essential for achieving the desired scientific objectives. They are limited essentially to the control electronics assembly and involve roll reference pulse generation and processing.

By restricting the operating modes of the spacecraft at low spin rate other modifications can be omitted. These include conscan orientation determination and correction, open-loop precession and ΔV trim maneuvers, normally also performed by the ACS.

Roll Reference Signal Generation. In the present Pioneer F&G either the star reference assembly (SRA) or the sun sensor assembly (SSA) can be used to provide roll reference pulses. For operation in planetary orbit where the low spin rate mode is used at close planetary approach the SSA only gives marginal roll angle determination accuracy since the angle between the sun line and the spacecraft spin axis is generally quite small. In close vicinity of the planet both the SSA and SRA may be subject to malfunctions caused by the strong trapped radiation environment.

As described in the Pioneer orbiter study a search coil magnetometer will be added as an auxiliary roll reference sensor. In the case of a Jupiter orbit mission it is anticipated that the magnetometer will generate a strong signal as far out as 10 planet radii. (This is based on an estimated field strength of 10 gauss at the surface of Jupiter.) Time intervals of 12 hours, as required by the study guidelines, are generally encompassed by an orbital segment that falls within this distance. Except in the rare cases where the magnetic field lines are locally parallel to the spacecraft spin axis, the relative geometry of the orbital passage



DAMPER MODIFICATIONS: (TIME CONSTANT SHOWN IN DOTTED LINES):

FLEXURE REPLACED WITH NEGATIVE SPRING TO TUNE BOOM TO 0.04 CPS (RELATIVE PRECESSION RATE AT 1.5 RPM).

NUTATION DAMPER SILICONE FLUID VISCOSITY CHANGED FROM 200 CENTISTOKES AT 12 CENTISTOKES PROVIDING A DAMPER FACTOR OF 20% TO 50% OVER THE QUALIFICATION TEMPERATURE RANGE

Figure 5-5. Modification of Nutation Damping Time Constant by Optimum Damper Tuning

near the planet generally provides adequate conditions for a magnetic roll reference pulse pickup. However, the relative orientation of the field lines changes during the passage and must be accounted for in the interpretation on the ground of roll attitude indexing information of the science sensors derived from these pulses.

The signals generated alternatively by the SRA, the SSA, or the magnetometer are used in the spin period sector generator (SPSG) to generate roll attitude indexing pulses. At low spin rates any of the sensors (if still operative) can provide the reference signal. However, the bit stream from the reference clock runs for much longer periods between sensor-generated roll reference pulses which is not compatible with the present SPSG counting and index pulse generation logic. In the modified SPSG a reference register, a storage register, a comparator and counter will be added for use during extended clock operation. Several modes of operation are provided so as to permit SPSG operation for extended spin periods or for an extended number of spin periods, e.g., averaging accumulated external roll reference pulses once every 64 periods. A further modification is required from that defined for 2 rpm operation mode in the Jupiter orbiter to accommodate spin periods of 10 minutes and more.

At very small roll rates the roll reference sensors will provide reference pulses with poor timing accuracy because of the extended dwell time of the reference source within the detector field of view. However, the reference pulse angular definition is less strongly degraded since the product of roll rate and timing error remains essentially invariant.

Control Electronics Assembly. The star time gate circuit of the Pioneer F&G control electronics assembly (CEA) has a 6-bit time gate register and a 6-bit ripple counter. Used in conjunction with the 4 Hz clock rate, the maximum time gate is 16 seconds, which corresponds to a spin rate of 3.75 rpm. To accommodate a spin rate reduction to 0.1 rpm, both the time gate register and ripple counter require a 6-bit length increase to 12 bits. In addition, the transfer gates (between the time gate register and ripple counter) must be modified accordingly.

The star delay circuit of Pioneer F&G contains a 12-bit delay register and 12-bit ripple counter. Counting up in the ripple counter (which

contains the complement of the delay register) is done at 256 Hz, providing a maximum delay of 16 seconds, corresponding to the spin rate of 3.75 rpm. Operation at 0.1 rpm requires an increase in the length of the ripple counter and delay register to 18 bits with a corresponding change in the number of transfer gates.

The CEA must also be modified to accommodate and control all added thrusters.

Spin Rate Control Circuit. Spin rate signal processing and control circuits must be added to the control electronics assembly to permit accurate control of the maneuver at very low spin rates. The despin sensor assembly presently used on Pioneer F/G is designed only to signal when the initial high spin rate has been reduced sufficiently to permit safe RTG deployment, and is not suitable for adaptation to the new control requirement.

Conceptually, in this application, the control circuit could operate by comparing sun or star sensor pulses with pulses from the reference clock and stop the despin or spin-up process at a commanded clock setting of clock pulses per revolution. This circuit can be designed to function both in the low and high rpm range. When the spacecraft is operating in the momentum wheel augmented mode the magnetic piper signals available from the momentum wheel can also be used as an alternative to give indirect indication of body spin rates, in the range of very low spin rates where star or sun sensor reference signals deteriorate.

Conscan Signal Processor. This circuit can remain unchanged if conscan operations are omitted from the low spin rate operating mode.

Precession Control Logic. With precession maneuvers either in conscan or open-loop mode excluded from the low spin rate phase, a modification of the precession control logic becomes unnecessary. A prerequisite is the elimination of precession coupling during despin maneuvers by the use of paired thrusters so that sufficient accuracy of pointing during the low rpm operating phase is assured (see Section 5.3).

5.5.2 High Spin Rate Operation

Operation in the high spin rate mode for high thrust engine firing is limited to even shorter periods than operation at low spin rates. Thus with the same restrictions on attitude control modes applied as in the low spin rate condition, no modifications of the attitude control subsystem appear necessary.

The roll reference sensors are qualified to operate to spin rates of at least 45 rpm, and no problems in SPSG, star time gate and star delay operation are anticipated at roll rates of 15 rpm, except some loss in accuracy due to greater quantization error. Thus, in principle the 15 rpm mode of operation can also be used for scientific observations if desired.

5.6 OTHER ELECTRICAL SUBSYSTEMS

Data Handling and Storage Subsystems. In principle, the data handling and storage subsystems are not affected by the addition of a spin rate variation capability to Pioneer except by their interface with roll attitude timing and spin period sector indication pulses.

These interfaces are simplified by the elimination of conscan and precession control operations during the high and low spin rate modes. Roll attitude indexing for science data remains intact, with outputs of the modified RAT and SPSG circuits connected to the digital telemetry unit (DTU) as during the nominal operating mode. The DTU will possibly require a modification in data formats to support the increased emphasis on science data (imaging system data) during the low spin rate mode.

The data storage unit (modified for the Pioneer orbiter and other outer planets missions for other reasons) is not affected by the variable rpm modes per se.

Modified and Added Command Signals. The addition of high and low rpm modes and speed control functions, particularly the addition of a momentum wheel and its control circuits, requires additions and modifications of the present Pioneer F&G command list and command distribution logic. Added commands are required for:

- Turning the momentum wheel on or off (2)
- Enabling or disconnecting the speed control channels for high and low rpm operations (4)
- Connecting or disconnecting the use of the momentum wheel speed indicator signal to the speed control channels (2)
- Selecting additional DTU formats (if any) (2-4)
- Miscellaneous mode switching commands, including science sensor operating mode changes (6).
- Operation of the added thrusters (4).

The total number of added commands is estimated to be about 20. These can be readily accommodated by the existing command distribution unit, since less than 190 discrete commands are being implemented on Pioneer F&G in a system capable of processing up to 255 commands.

6. SUMMARY OF REQUIRED SYSTEM AND SUBSYSTEM MODIFICATIONS

The overall modification requirements of the Pioneer system and subsystems for purposes of implementing the high and low spin rate modes are summarized below, and estimated weight and power requirements are listed.

6.1 MODIFICATIONS

- | | |
|------------------------------|---|
| Attitude Control | <ul style="list-style-type: none">● Addition of momentum wheel assembly (approximately 20-inch diameter) |
| Attitude Control Electronics | <ul style="list-style-type: none">● Addition of control circuits for momentum wheel● Addition of spin rate sensing and control circuits● Enlargement of register and counter bit capacity in RAT and SPSG● Change in SPSG logic● Change in reference clock signal utilization logic |
| Attitude Sensors | <ul style="list-style-type: none">● Sun and star sensor may require adaptation to permit operation at extremely low spin rates |
| Propulsion Subsystem | <ul style="list-style-type: none">● Addition of extra spin/despin thruster pair and control devices opposite existing ones (already required in some other advanced Pioneer design concepts)● Addition of extra spin-up/despin propellant (use Pioneer F/G tank) |
| Command Distribution | <ul style="list-style-type: none">● Addition of about 20 new commands (preliminary estimate) |
| Digital Telemetry Unit | <ul style="list-style-type: none">● Possibly some format changes to accommodate change in science data flow |
| Science Payload Interfaces | <ul style="list-style-type: none">● Additional mode switching and control capabilities required● Science data roll indexing at very low spin rates may be degraded (i.e., image data may be used to augment attitude interpretation on ground) |

Structure and Fittings

- Mounting structure for momentum wheel added (may require cutout in equipment platform center)
- Added fittings for extra spin/despin thruster pair
- Modification of magnetometer mounting flexure joint as required for improved nutation damping

6.2 WEIGHT AND POWER ESTIMATES

	<u>Weight (pounds)</u>	<u>Power (watts)</u>
Momentum wheel assembly including drive motor and control circuits	36	15
Added structure and fittings	5	
Added spin/despin propellant ¹	30	
Added spin/despin thrusters ²	3	(2) ³
Modified/added control circuitry	<u>5</u>	<u>5</u>
Total	79	20 ⁴

Notes:

- 1 Partly accounted for in previous estimate of spin/despin control propellant requirement of Jupiter orbiter
- 2 Already accounted for in Jupiter orbiter
- 3 Radioisotope heater unit
- 4 15 watts for 6 hours momentum wheel spin up (30 watts for 1.7-hour spin up) can be provided by temporary turn-off of other equipment, e.g., some science sensors.

6.3 CONCLUSION

In summary, the proposed extension of Pioneer operational capabilities by addition of high and low spin rate modes is feasible with some modification of existing electronic subsystems, addition of control circuitry and incorporation of a compact 30-pound momentum wheel. Most of the required modifications (including weight and power increases) are required to implement the low spin rate mode (below 1.5 rpm). Structural changes are minimal. Additional study of performance near zero spin rate is required, especially regarding attitude reference sensor characteristics.

The total weight increment of about 80 pounds tends to be excessively large, at least for some missions now being contemplated. A tradeoff is indicated in this case to select only the most essential modifications, curtail the number of maneuvers, or limit the low speed operation to rpm values where the momentum wheel can be omitted. For example, in Saturn orbiter mission opportunities of the late 70's and early 80's the weight margin may be tight for a Titan 3E/Centaur/TE 364-4 launch, even if a relatively eccentric planetary orbit is selected, and a total weight increment of 80 pounds could not be accommodated. The prospect of launch by Shuttle/Centaur rather than a Titan class booster will have a strong influence on the weight and performance margins.

APPENDIX A

STRUCTURAL LOADS ON APPENDAGES DUE TO COMBINED SPIN AND THRUST EFFECTS

1. REDUCED BOOM DEFLECTION DUE TO SPIN STIFFENING

The bending deflection of a cantilevered boom (Figure A-1) is reduced due to the addition of a radial force at the tip mass. Boom mass is neglected in this analysis. The result is given by

$$h_1 = \frac{h_0}{1 + \frac{F_r}{F_a} \frac{h_0}{L}}$$

where

h_0 = deflection of boom in absence of radial force F_r

h_1 = deflection of boom for radial force $F_r \neq 0$

F_r, F_a = radial and axial forces applied to tip mass

L = boom length.

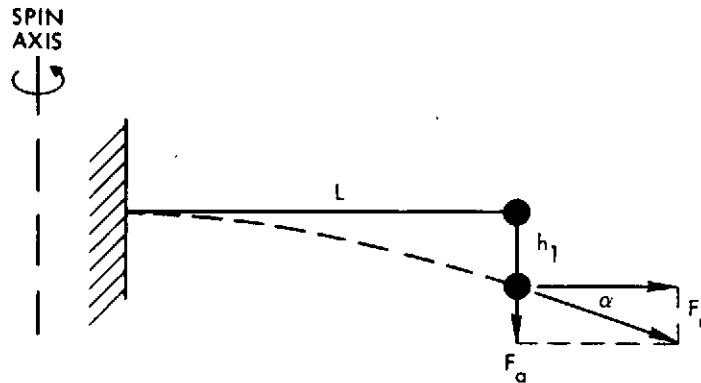


Figure A-1. Cantilevered Boom under Axial (F_a) and Radial (F_r) Load

Figure A-2 shows the deflection ratio h_1/h_0 as function of the force ratio F_r/F_a with the normalized deflection h_0/L as parameter. The tilt angle α of the resulting force at the end mass is given by

$$\alpha = \tan^{-1} (F_a/F_r),$$

also indicated at the abscissa of the graph. For $F_a/F_r = 5$ (or $\alpha = 12$ degrees) the deflection h_1 is only about 65 percent of h_0 if the parameter h_0/L is 0.1. For a very flexible appendage (such as the magnetometer boom) the effect is much more pronounced, with h_1/h_0 reduced to about 30 percent at the same force ratio F_a/F_r if $h_0/L = 0.4$.

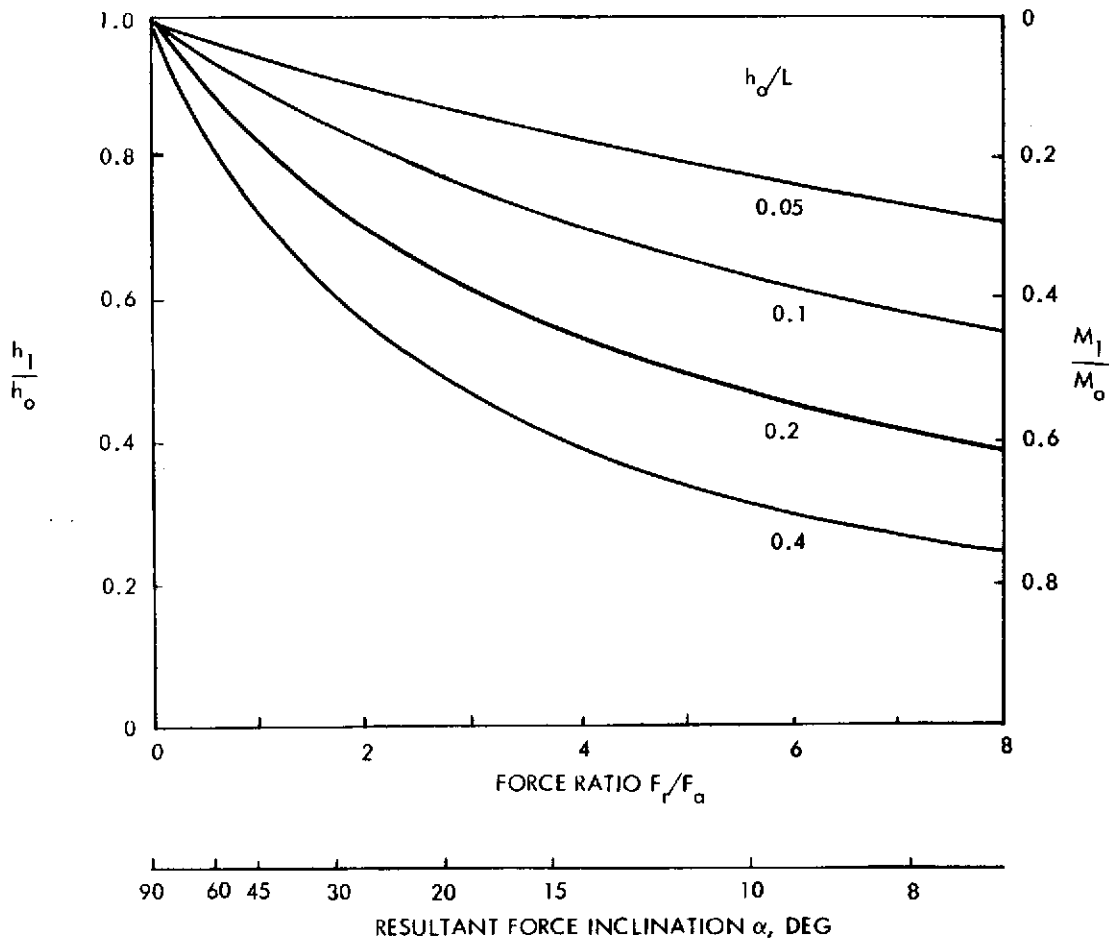


Figure A-2. Effect of Spin Stiffening on Tip Deflection and Maximum Bending Moment of Cantilever Beam

At 20 rpm the force ratio is about 1/10 for the 10-foot RTG booms and 1/20 for the 20-foot magnetometer boom, assuming a worst-case axial acceleration of 0.125 g (100 lb_f of thrust, empty tanks).

The non-dimensional expression h_1/h_0 also appears in the equation which gives the reduction of the maximum bending moment at the root of the boom:

$$M_1 = F_a L - F_r h_1 = M_0 \left(1 - \frac{h_1}{h_0}\right)$$

where M_1 and M_0 designate the moments with and without F_r . A second scale on the ordinate of Figure B-2 indicates this result. Thus in the second example above a deflection of 30 percent of h_0 corresponds to a reduction of M_0 by 30 percent, i.e., an increase in stiffening due to F_r reduces the deflection h , which in turn diminishes the effect on the bending moment.

2. EFFECT ON BUCKLING LOADS ON LOWER RTG GUIDE RODS

In Figure 4-4 (in Section 4) the reduction of the compressive load in the lower RTG guide rods by the added tensile preload due to F_r was shown.

The critical buckling load in these rods, assumed as pinned and clamped at their ends, is expressed by

$$P_{\text{crit}} = 2\pi^2 EJ/L^2$$

The dimensions of the Pioneer F&G RTG rods are

$$L = 2060 \text{ mm}$$

$$D = 15.9 \text{ mm (outer diameter of tube)}$$

$$d = 14.5 \text{ mm (inner diameter of tube).}$$

Thus $J \cong 0.05 (D^4 - d^4) = 950 \text{ mm}^4$. Assuming $E = 7000 \text{ kg/mm}^2 \cong 10^7 \text{ psi}$ for Aluminum 6061 we obtain a critical buckling load of 70 pounds for this rod. Figure A-3 shows the variation of compressive load with spin rate for three values of thrust force. The second scale on the ordinate gives the percentage of critical load. At the nominal spin rate and with 100 lb_f

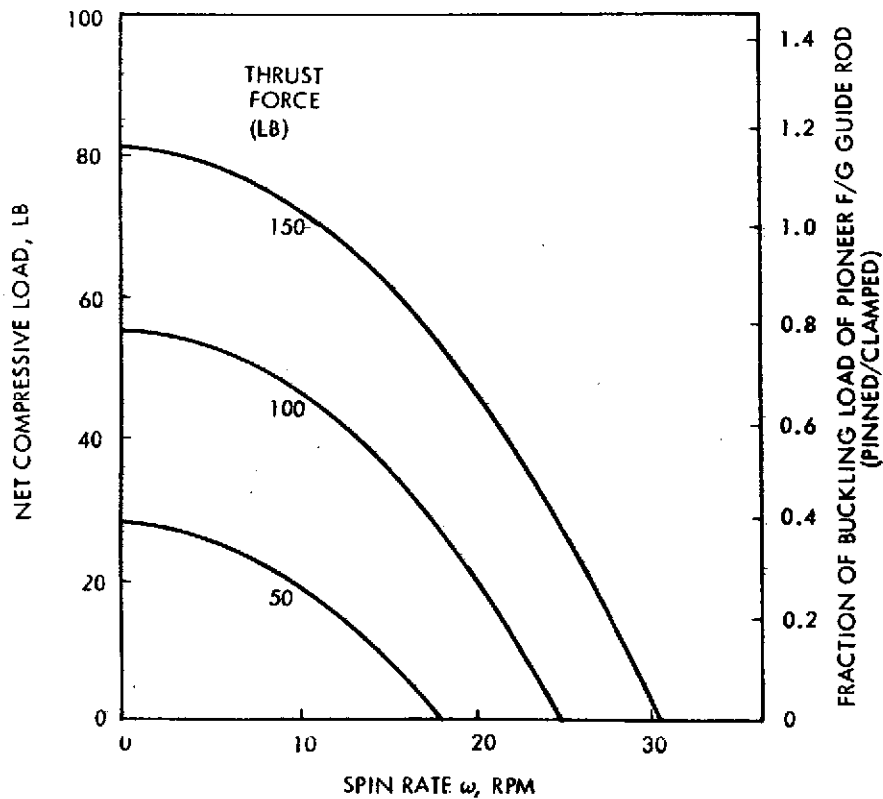


Figure A-3. Worst Case Net Compressive Load on Lower Pioneer F/G Guide Rod Due to Axial and Radial Acceleration

of thrust, the rod is loaded to 75 percent of the critical value, at 15 rpm only to 50 percent. At 25 rpm the compressive load is cancelled by the tensile load. These results indicate the desirability of spinning up to 15 rpm rather than only 10 rpm, if the Pioneer F&G rod dimensions are used.

The increase in tensile load and stress of the upper RTG rods with spin rate is illustrated in Figure A-4. Even at 25 rpm this load (and the resulting stress of 1700 psi) is quite insignificant.

3. BENDING OF RTG BOOM AND GUIDE RODS

The model used to analyze bending effects due to F_a is sketched in Figure A-5. For simplicity we assume the rods to be pinned at the base and clamped at the RTG side. The maximum bending stress in each rod in this case is given by

$$\sigma_{B_{max}} = \frac{1}{3} \frac{F_a L}{Z}$$

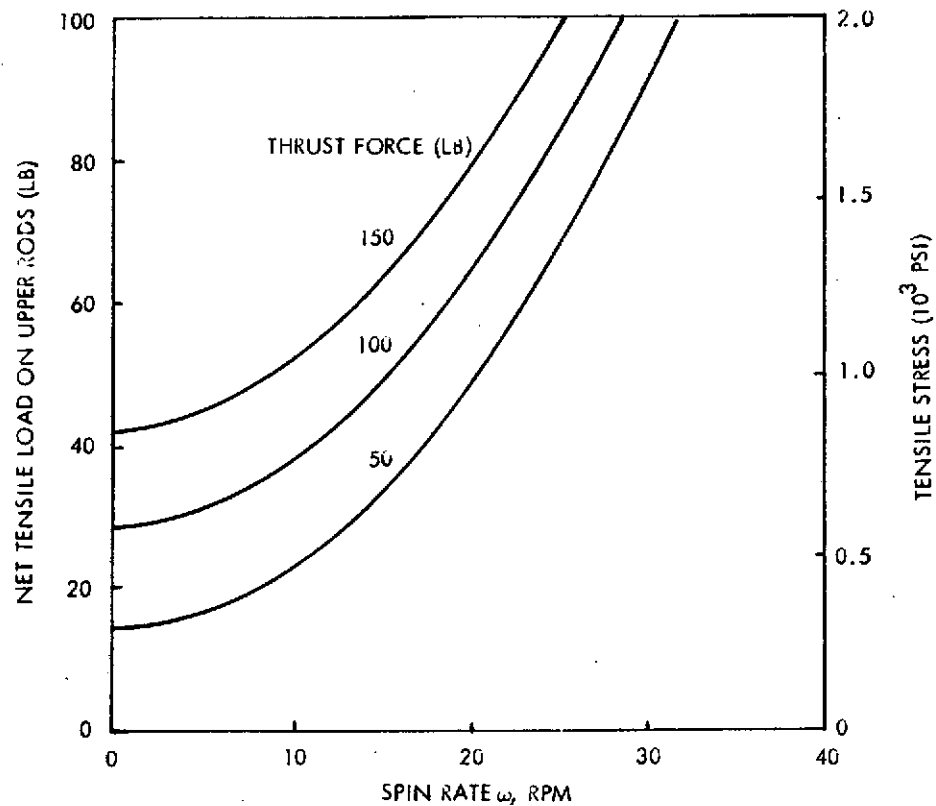


Figure A-4. Worst Case Net Tensile Load on Upper RTG Guide Rods

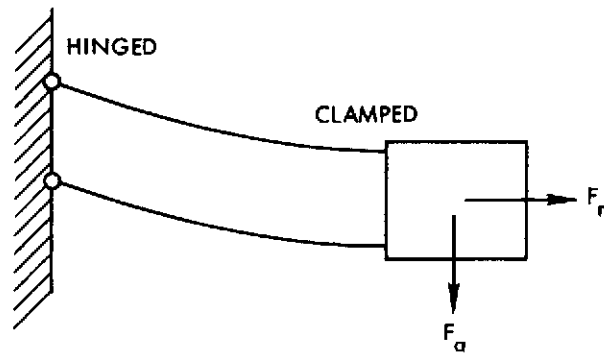


Figure A-5. RTG Boom Bending Model

and would be 37,000 psi if the Pioneer F&G tubular rods with a section modulus $Z = 120 \text{ mm}^3$ are used unchanged. Depending on the details of rod attachment on both ends the maximum stress may actually be considerably less, e.g., only 18,500 psi with both ends of the rod clamped. To these stresses a tensile or compressive stress component of 1000 psi corresponding

to a 15 rpm spin rate must be added. Also, some stress reduction due to the effect discussed previously is to be anticipated. On the other hand, the existence of significant buckling loads in the lower rods requires an adequate safety factor (about 1.5).

Without more detailed analysis it appears that the worst case stresses are too high for aluminum rods, and reinforcement by increasing the wall thickness is to be contemplated. Figure A-6 shows the reduction of stresses by increasing the wall thickness from the present 0.7 mm to 1.5 mm. The figure also shows the corresponding total weight increment of the six rods. A 1.5 mm wall thickness is probably more than adequate, reducing the maximum bending stress to 20,000 or 10,000 psi, respectively, for the conservative and the less conservative assumptions on rod attachment made here. The total weight increment is only 3 pounds in this case.

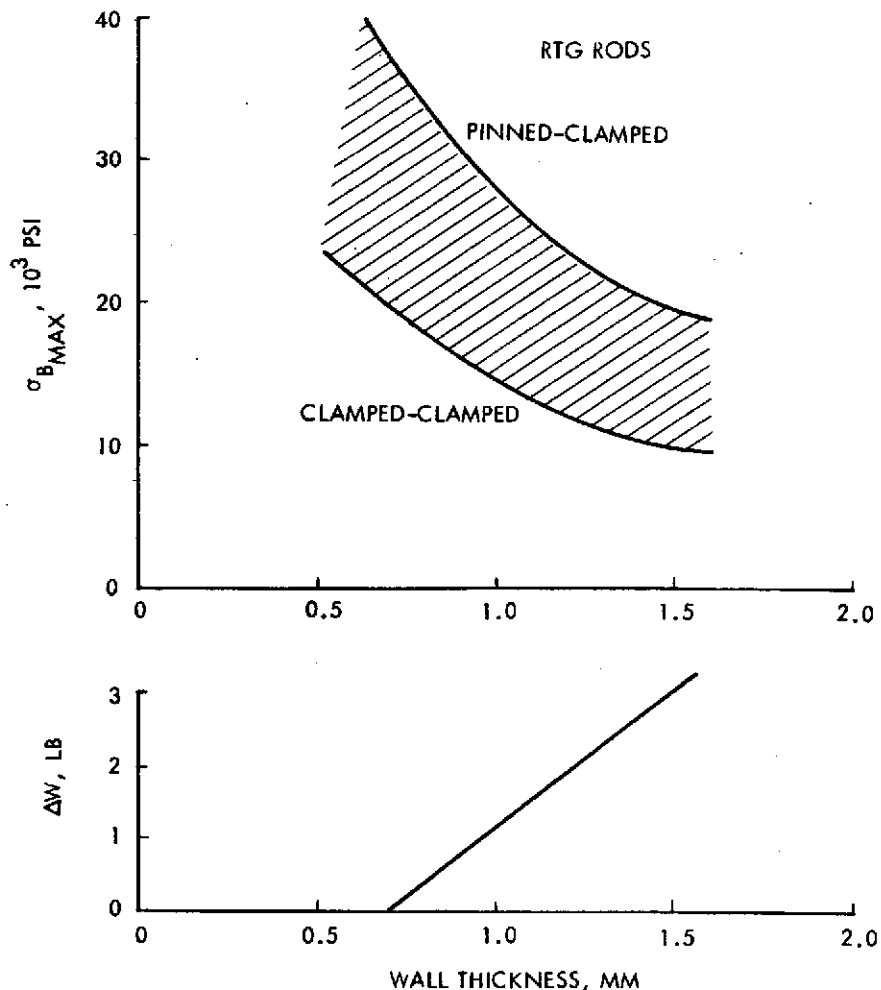


Figure A-6. RTG Rod Reinforcement by Increased Tube Wall Thickness

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