MSC-03466

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

APOLLO 11 MISSION

ANOMALY REPORT NO. 3

SERVICE MODULE ENTRY

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MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
NOVEMBER 1970

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SERVICE MODULE ENTRY

STATEMENT OF PROBLEM

The service module jettisoning sequence was such that the service module, upon being jettisoned on a lunar return flight, should have entered the earth's atmosphere, then skipped out into a highly elliptical earth orbit. Thus, the risk of recontact with the command module during entry would have been eliminated. However, on Apollo 8, 10 and 11, the service module did not skip out as expected.

DISCUSSION

Tracking data obtained by C-band radar on Apollo 7 and Apollo 10 indicated that the separation velocity was much less than expected. During Apollo 11, the service module was seen by the crew about 5 minutes after it had been jettisoned, and this could not have occurred if the service module had followed its expected trajectory. (The crew noted at that time that the reaction control thrusters were still firing.) Photographs obtained by aircraft showed the service module entering the earth's atmosphere and disintegrating in the vicinity of the command module entry corridor.

The service module jettison controller in this case was configured so that the four -X translation reaction control system engines commenced thrusting at separation and continued to propellant depletion. Beginning at 2 seconds after separation, four reaction control system roll engines fired for 5 1/2 seconds to spin stabilize the service module about its X-axis. A minimum separation velocity of about 345 ft/sec should have been obtained for a stable service module, more than sufficient for the service module to skip out. The separation velocity for Apollo 10 was about 60 ft/sec (30 ft/sec less than the velocity required for skip out.) Table I compares derived separation velocities with those that were expected for Apollo 7 through Apollo 11.

Conditions which might result in the unexpected trajectory of the service module after jettison are (1) large initial separation moments, (2) failure of the reaction control system hardware, or (3) the dynamics of the propellants in the service module tanks during the thrusting period. The moments resulting from plume impingement, unsettled propellants, offset center of gravity, and asynchronous tension tie release are, by themselves, considered insufficient to cause instability. Hardware failure resulting in one reaction control system engine failure or early termination of thrusting is highly unlikely because of the redundancy in the control circuits and the consistancy of the occurrance in successive missions. Analysis of propellant sloshing shows, however, that the vehicle can become unstable with a resulting low net separation velocity. A pictorial representation of the slosh is shown in figure 1.

The propellants are forced away from the spin vector ($\vec{\omega}$) which, because of tip-off moments at jettison, is not coincident with the service module X-axis. If the spin vector and X-axis are misaligned by some angle (θ), the propellant in one tank will move toward an equilibrium position at one end of that tank, and the propellant in the other tank will move to the opposite end of that tank (as illustrated by the dark areas of figure 1). Misalignment of the spin vector and the X-axis results in precession of the spin vector with a period of about 10 seconds. Thus, after 5 seconds, the spin vector will be on the opposite side of the X-axis, reversing the equilibrium positions of the propellants (as illustrated by the cross-hatched areas of fig. 1). The precession of the service module thus excites logitudinal slosh. The sloshing then dissipates rotational kinetic energy and shifts the spin vector away from the service module X-axis.

A six-degree-of-freedom model was developed to analyze the motions resulting from propellant slosh using residual propellant quantities and separation moments as initial conditions. Figures 2, 3, and 4 show the service module orientation (cosine θ) and the propellant slosh displacements as functions of time. The angle θ is measured from the direction of the spin axis (the service module X-axis at separation) to the direction of the X-axis at subsequent times. Thus, the initial value of cosine θ is 1.0, and, if it remains near 1.0, the service module is stable and its -X translation thrusters continue to fire in the proper direction. Negative values of cosine θ indicate that the service module is rotated more than 90° from the original attitude, so that the -X translation thrusters are decreasing the separation velocity.

Figure 2 shows the effect of a light slosh mass of 1100 pounds on service module orientation. Cosine θ has begun to diverge from 1.0 at about 40 seconds. At about 60 seconds, the vehicle has changed about 50° from its initial attitude and the slosh amplitude is increasing.

Figure 3 shows the effect of a slosh mass of 3300 pounds. At about 35 seconds, the propellant slosh has changed the attitude of the vehicle 90°. Again, when cosine θ goes negative, the -X translation thrusters are decreasing the separation velocity. Toward the end of the simulation represented by figure 3, the fuel and oxidizer masses have stabilized in the upper ends of the tanks, and cosine θ is oscillating near zero. This indicates that the service module is in a stable spin about an axis perpendicular to the X-axis.

Figure 4 shows the effect of a slosh mass of 8600 pounds, which is equivalent to the propellant mass for Apollo 8. Effects similar to those resulting from the 3300-pound propellant mass are present.

A possible method considered for correcting the problem was to employ very high spin rates to achieve additional gyroscopic stability of the service module. However, the higher rates associated with the structural limit of the service module (150 deg/sec) did not noticeably improve its stability. The observation that large spin accelerations are required to overcome the effect of acceleration due to -X translation in order to force fluids to the outer walls of the tanks suggested that a possible method of averting propellant slosh and improving service module stability was to reduce the service module spin rate and spin accelerations. The simplest possibility was to eliminate the roll thruster firings entirely, but in simulating this procedure, the service module tumbled in about 10 seconds because of the torque produced by a misalignment of the thrust vector with the vehicle center of mass. Further simulations showed that the optimum spin rate corresponded to a roll thruster "on" time of 2.0 seconds, and that the service module remained stable in this case for about 25 seconds.

A parametric study of this sequence was made to determine the response of the service module for various propellant loadings from empty to completely full. Figure 5 shows the history of the service module attitude for three different sump tank loadings. For the lighter two loadings, the service module remains stable, and for the heavier one, it diverges to 90° in about 35 seconds. These data show that limiting X-axis thrusting to the period before the cosine θ becomes negative will give a maximum net velocity change. Figures 6 and 7 show the relative position and relative velocity of the service module at thrust termination, 25 seconds after service module jettison, plotted as functions of the total service module propellant loading at jettison. The service module is stable during the thrust period for all cases. The variation in relative position and velocity is due primarily to the reduced acceleration associated with heavier service module loadings. For the heaviest propellant loading, corresponding to a full service module, the total separation velocity is reduced to 6.0 ft/sec. This separation velocity will not prevent service module entry but should prevent service module recontact with the command module.

CONCLUSION

Tip-off moments applied to the service module at jettison cause the spin vector to be misaligned with the service module X-axis. The rigid body spin motion of the service module excites longitudinal slosh of the propellants in tanks. The sloshing then becomes the dominant force and causes the spin vector to approach a position normal to the service module X-axis. The sloshing can orient the service module spin axis such that the net -X thrusting over a period of 300 seconds can not only reduce the separation velocity of the service module but also reverse its direction. This condition introduces a remote possibility of recontact between the service module and the command module. An optimum separation velocity can be obtained for a range of propellant loads by restricting the spin thrusting to 2 seconds and the X-axis thrusting to 25 seconds of firing time.

CORRECTIVE ACTION

The service module jettison controller for the Apollo 13 vehicle and subsequent vehicles has been modified to give the following jettison sequence.

Figure 8 shows the changes made in the service module jettison controller.

Time after separation (seconds)	Event
0	Four -X jets on
2	Four roll jets on
4	Four roll jets off
25	Four -X jets off

TABLE I.- COMPARISON OF DERIVED AND EXPECTED SEPARATION VELOCITIES

Mission	Propellant, lb x 100	Expected separation ΔV, ft/sec	Derived separation ΔV, ft/sec
[a,b]7	71	275	[c]30
8	95	78	(d)
[b]9	24	132	[c]134
10	33	345	[c]60
[a]11	45	360	(d)

[a] Service module sighted by crew after jettison.

[b] Earth-orbital missions.

[c] Velocities are based on trajectory reconstruction using a service module state vector at 400 000 ft obtained from C-band radar.

[d] No service module tracking available.

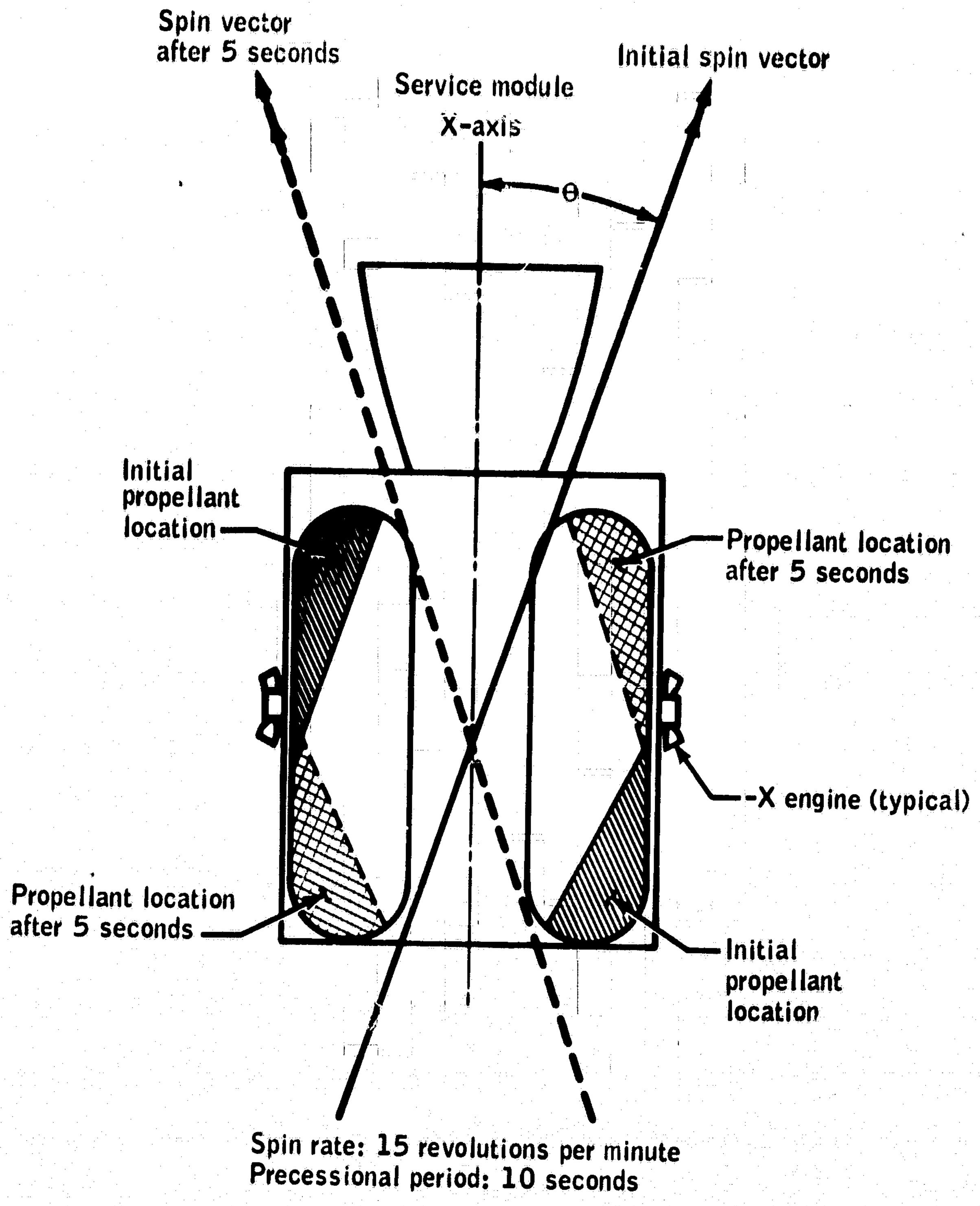

Figure 1.- Precessional excitation of longitudinal slosh.

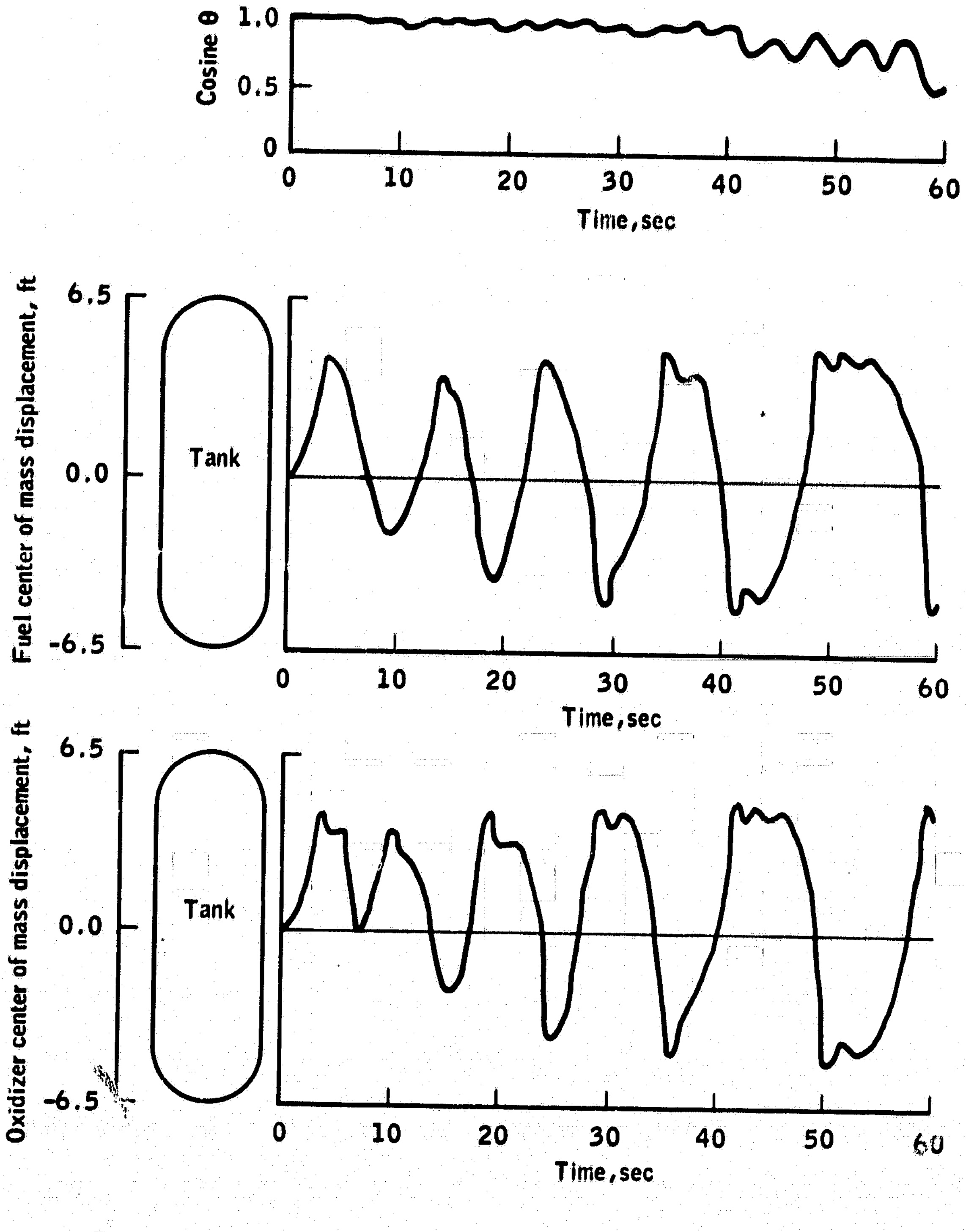

Figure 2.- Service module orientation and propellant displacements for an 1100-pound propellant mass.

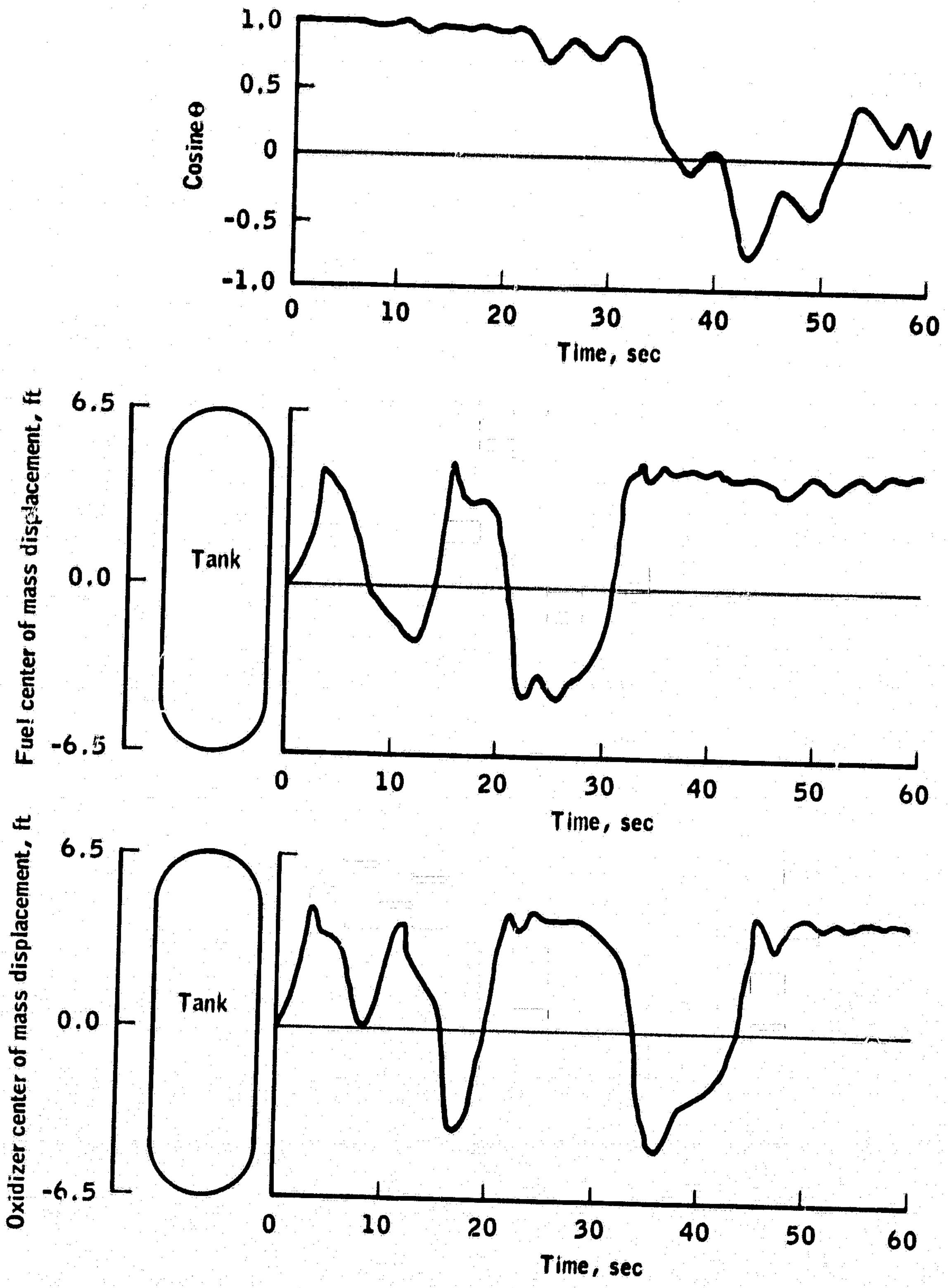

Figure 3.- Service module orientation and propellant displacements for a 3300-pound propellant mass.

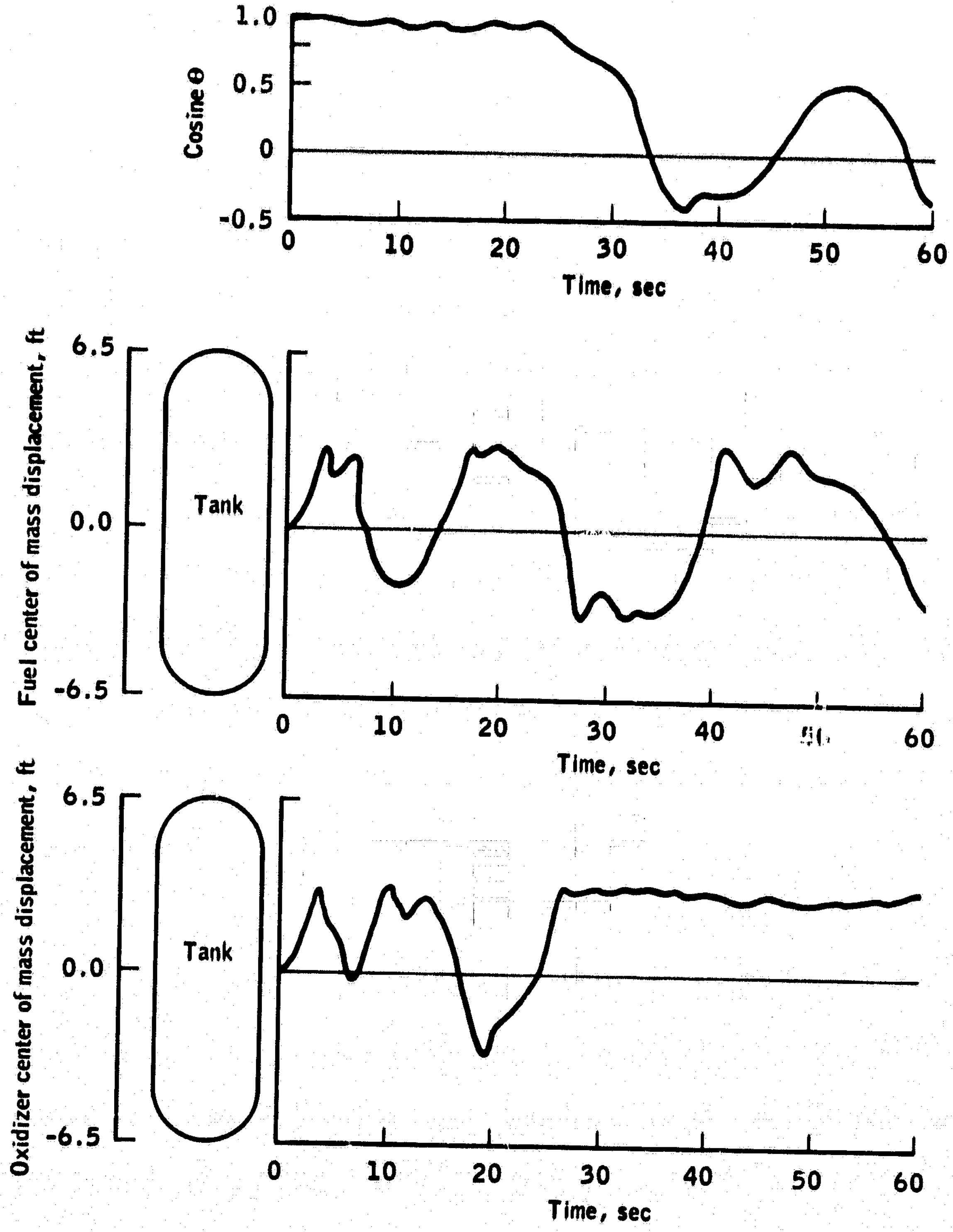

Figure 4.- Service module orientation and propellant displacements for an 8600-pound propellant mass.

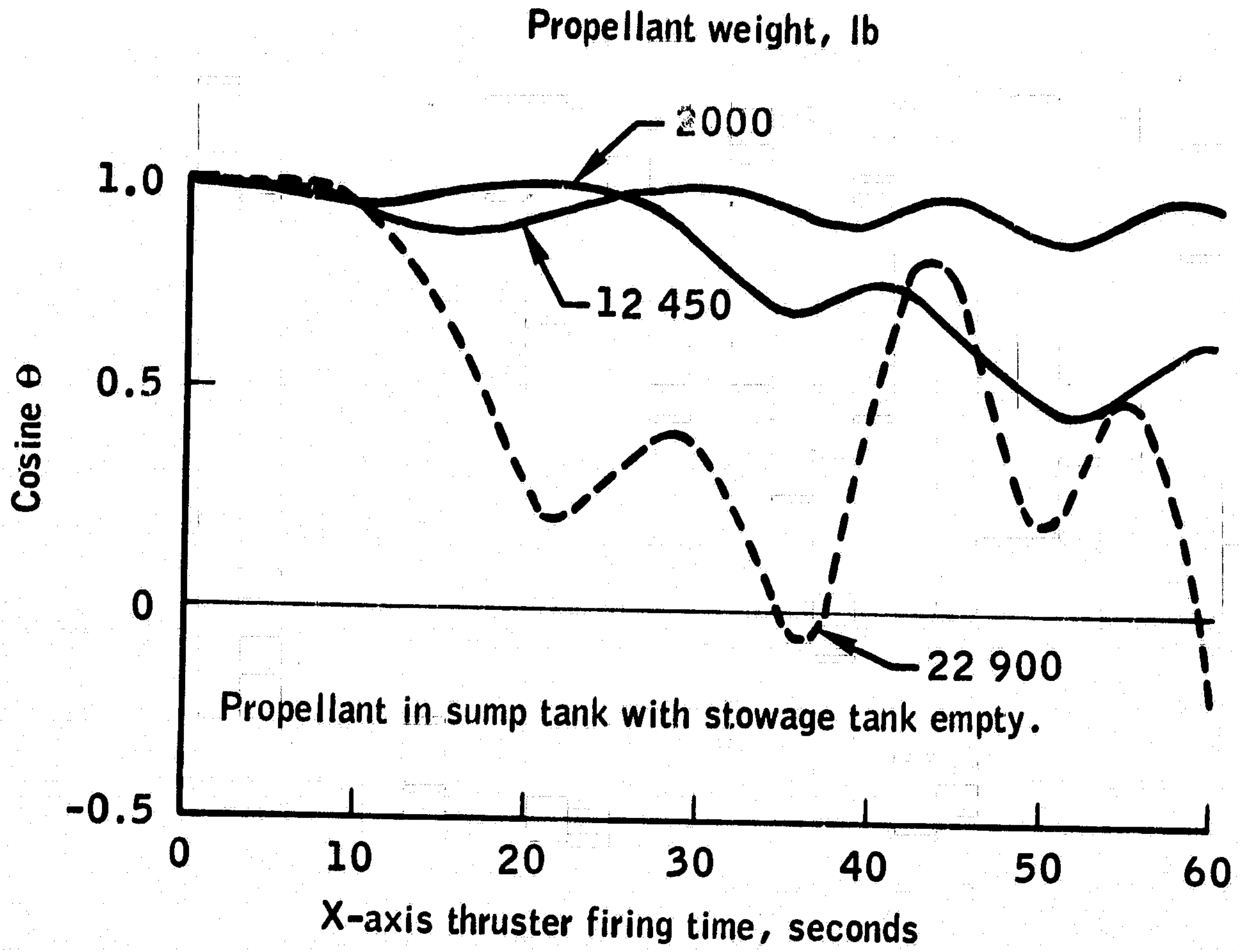

Figure 5.- Service module orientation plotted against time for a two-second roll jet firing.

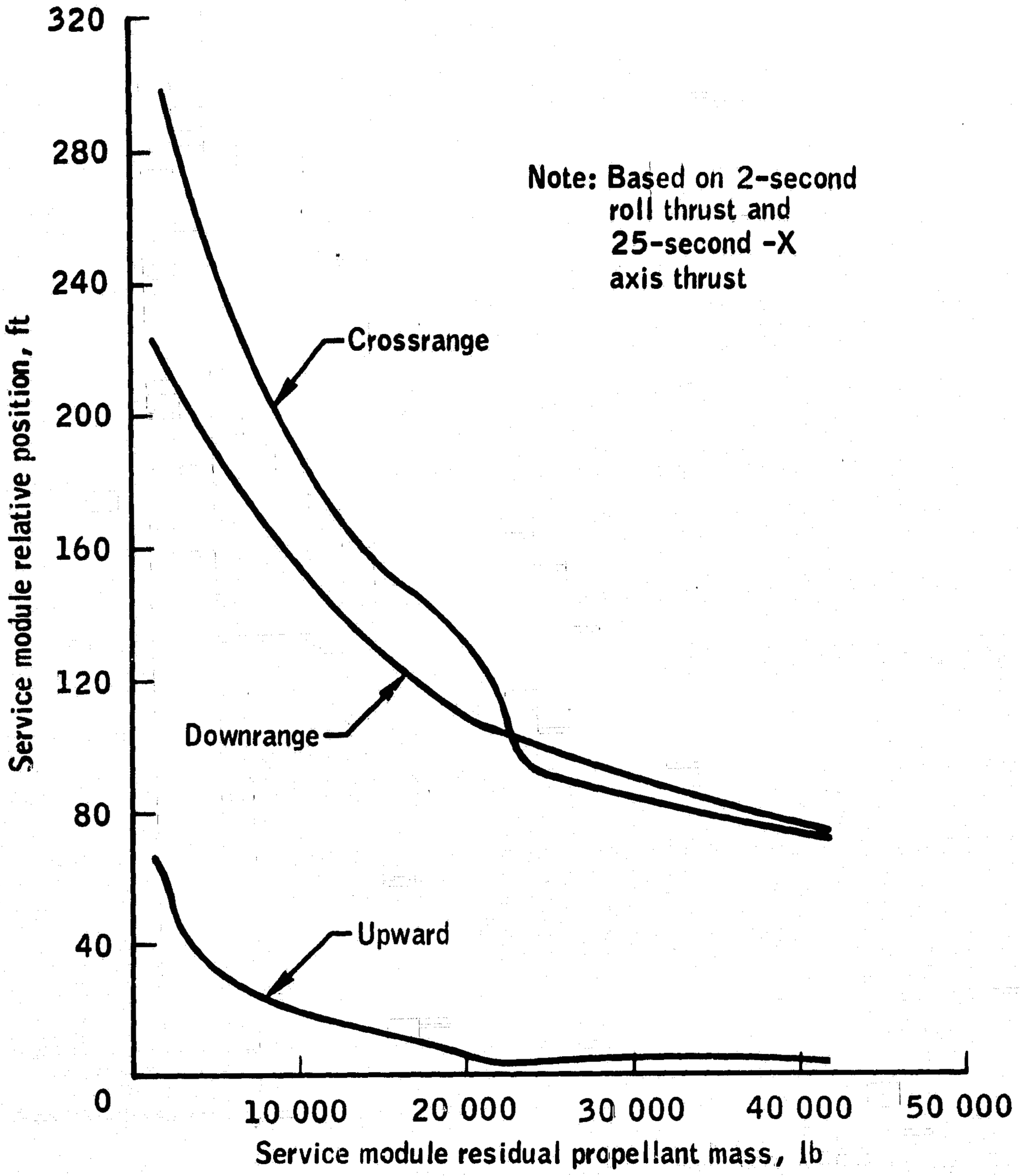

Figure 6.- Service module position relative to the command module at service module thrust termination.

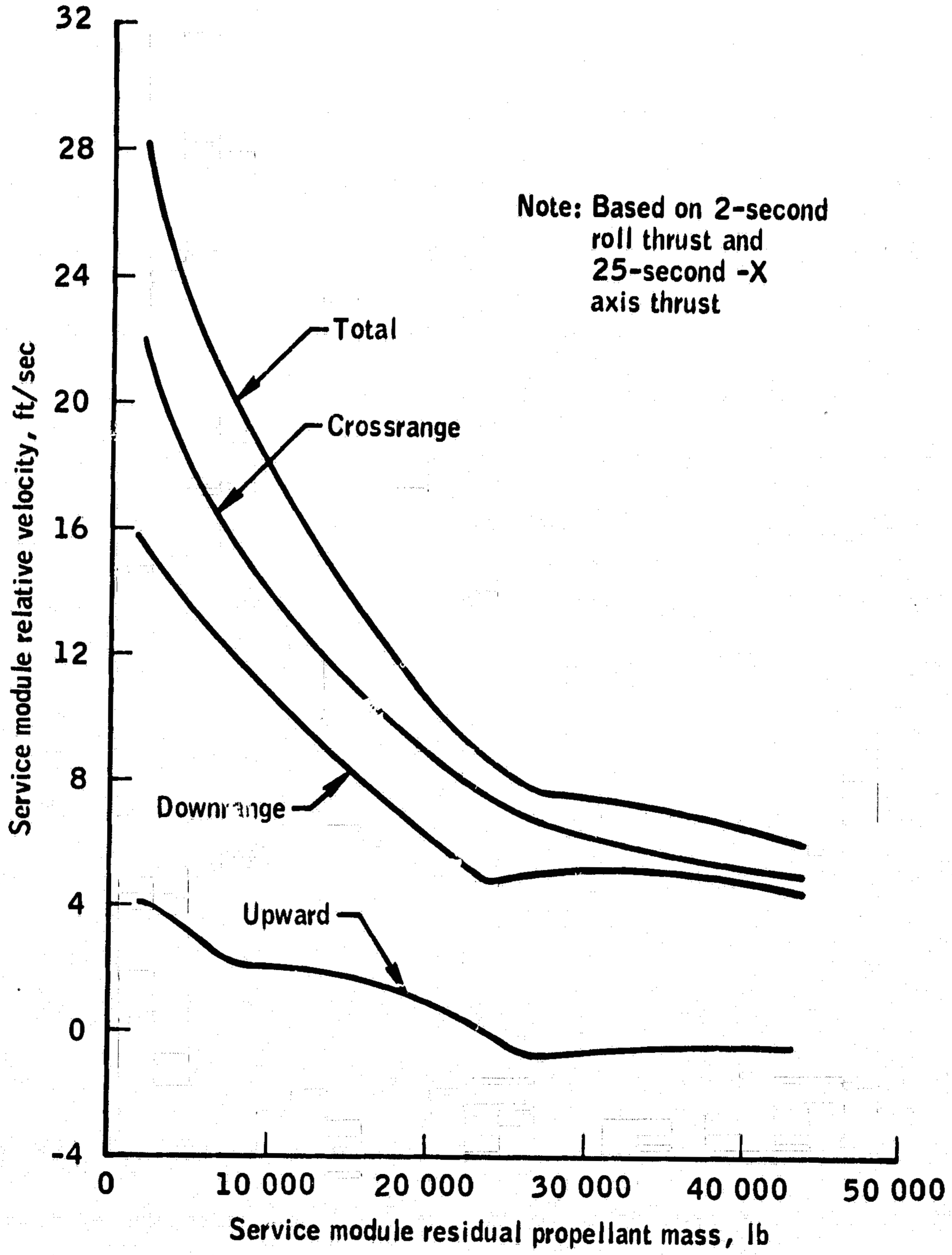

Figure 7.- Service module velocity relative to the command module at service module thrust termination.

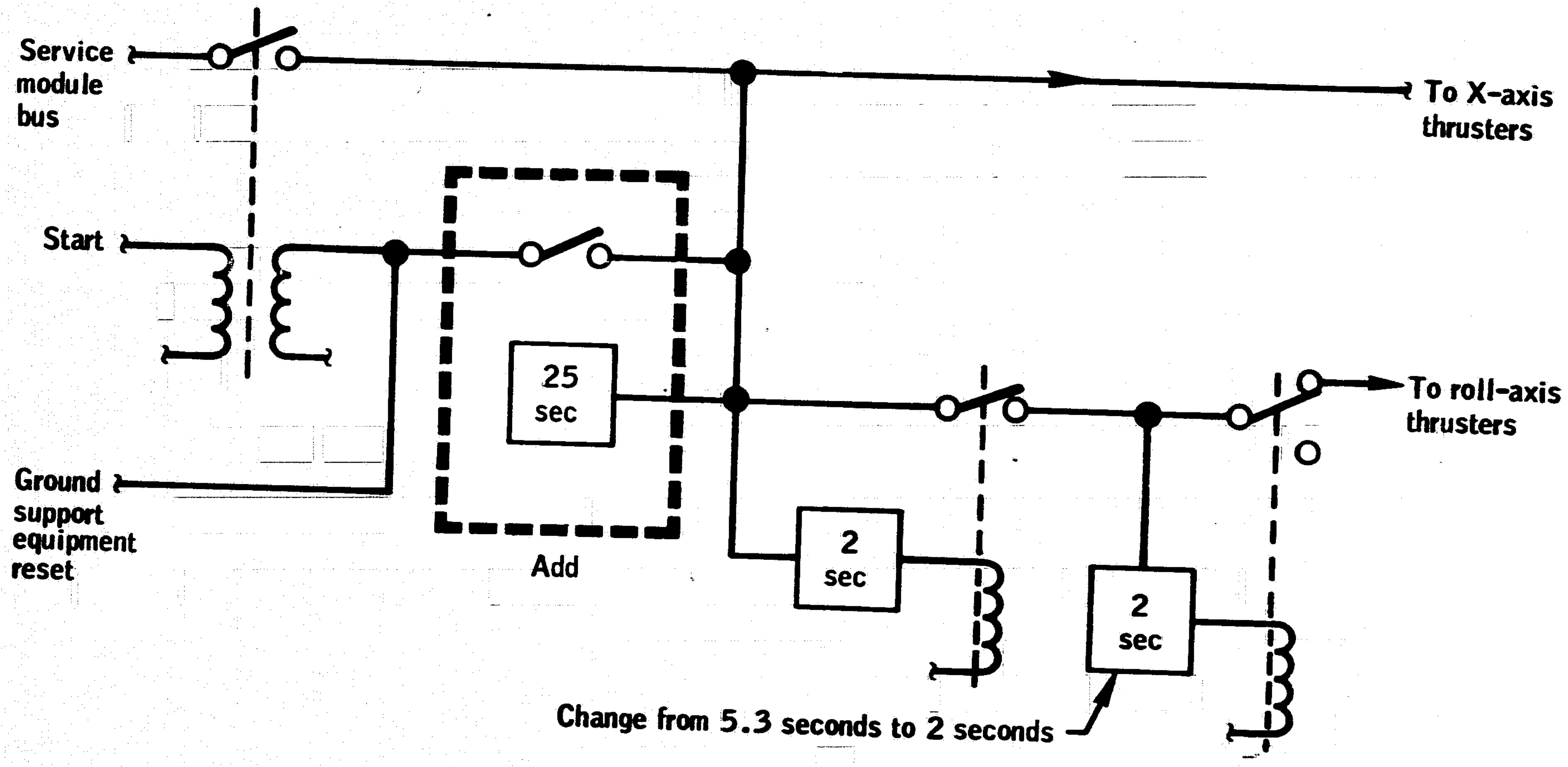

Figure 8.- Service module jettison controller changes.