Galileo

Uncontrolled STS Orbiter Reentry

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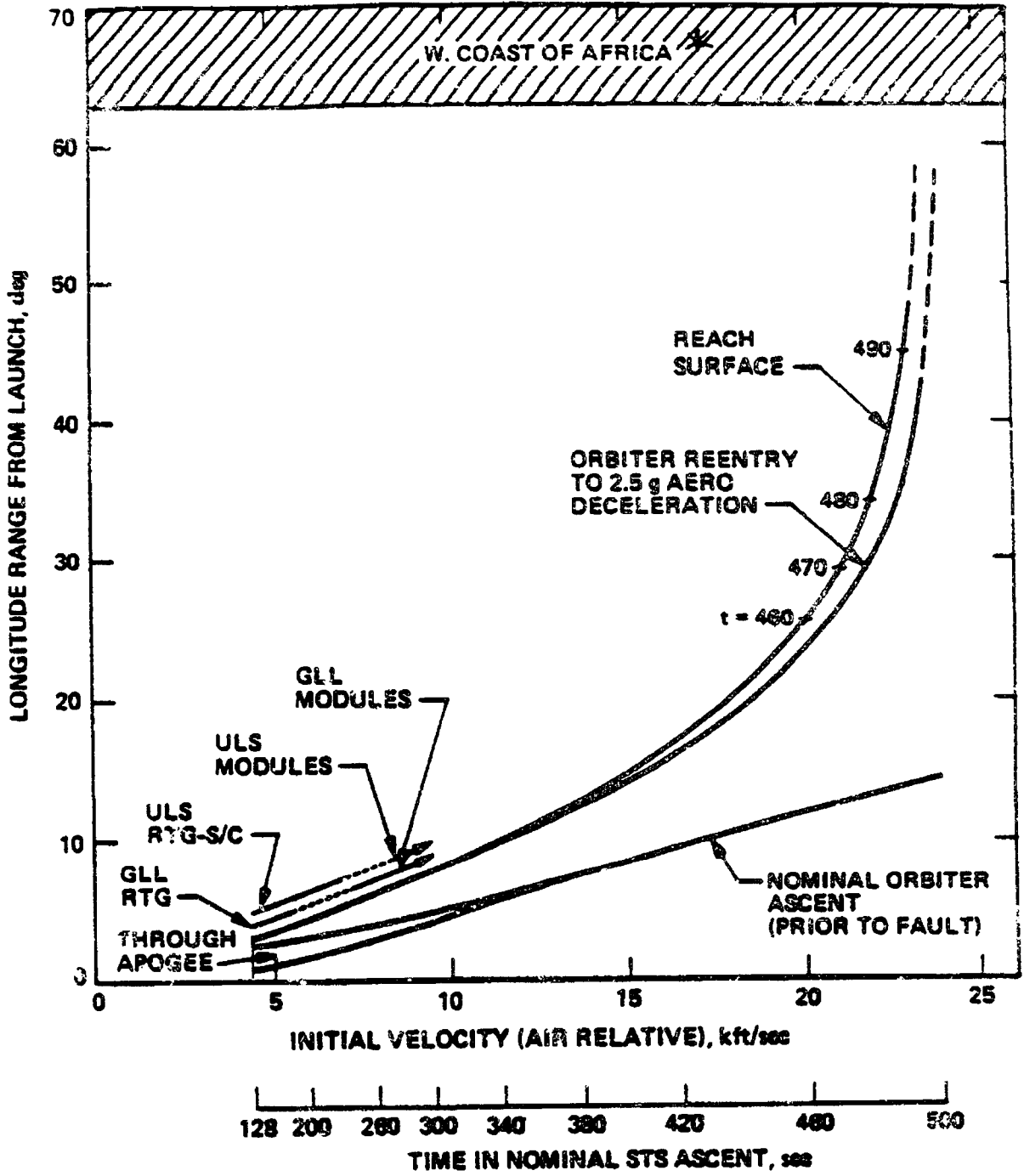JPL D-4895

Fig. 5. Longitude range from launch to the fault point, to the reentry, to the Orbiter breakup, and to the surface impact of GPHS modules or RTG.
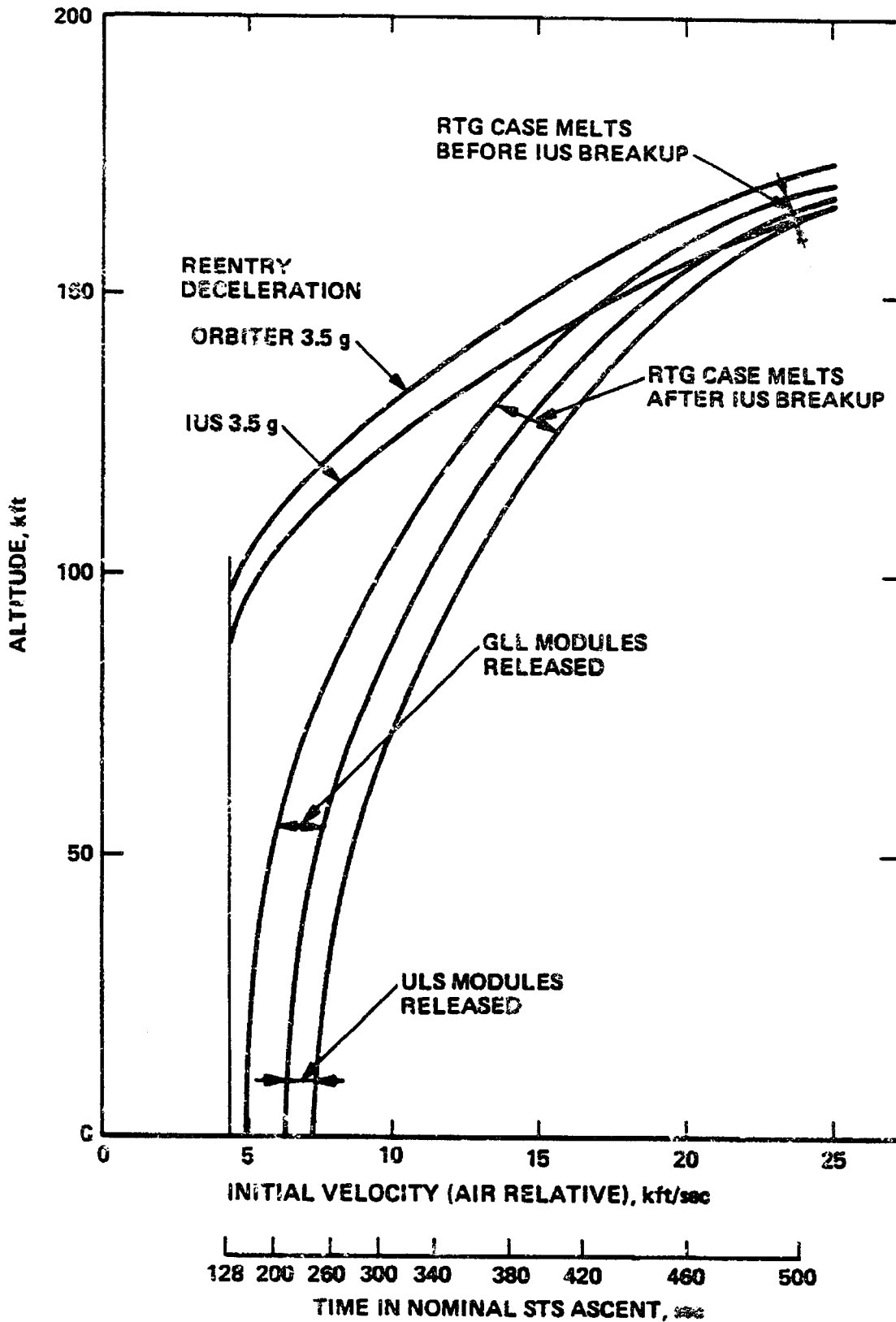
*For 90 deg launch azimuth

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Fig. 4. Reentry breakup altitude vs. time of initial ascent fault: regimes for surface impact of GPHS modules, GLL RTG, and ULS RTG plus spacecraft.

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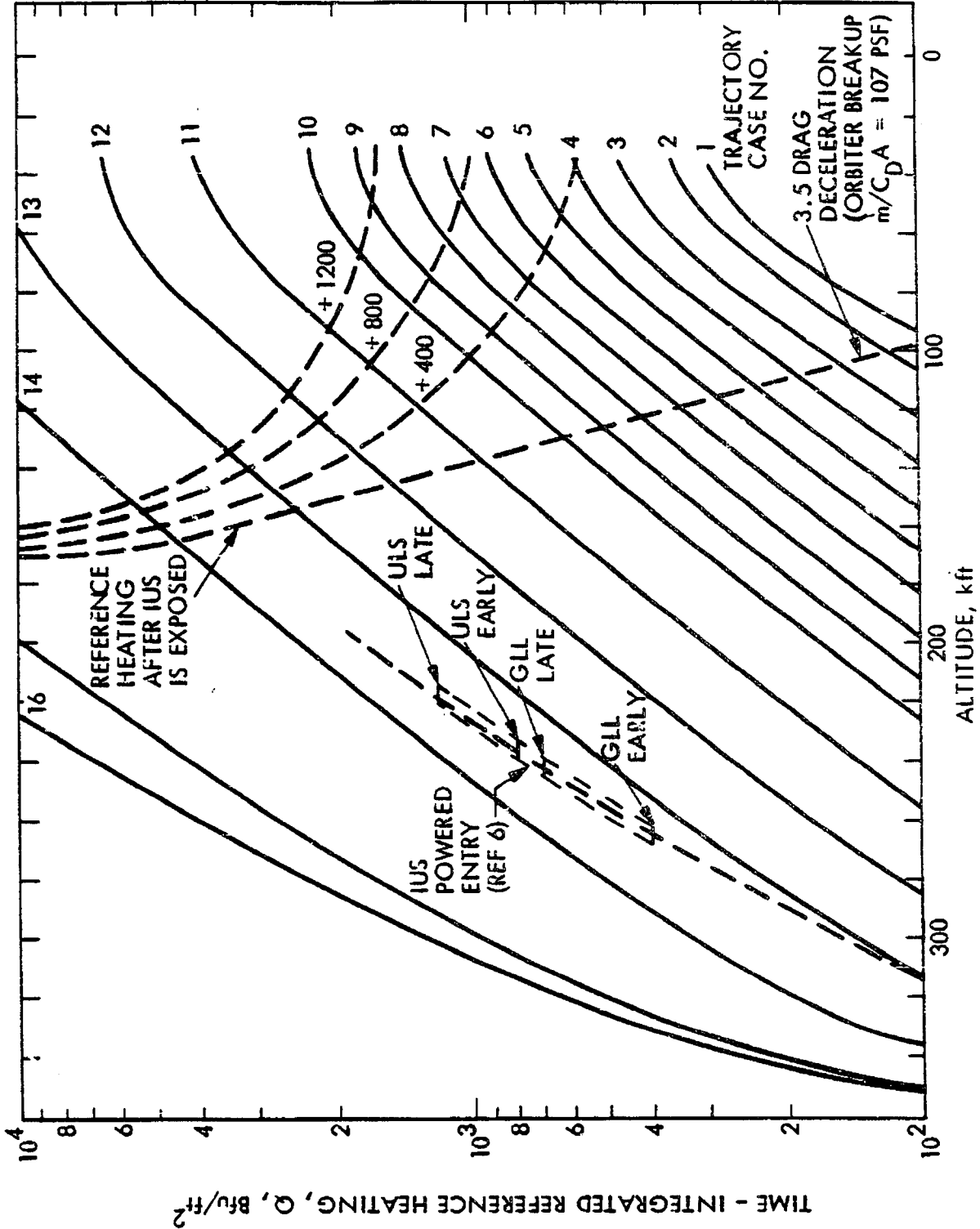
Fig. 3. Time-integrated reference heating Q of the Orbiter vs.
altitude for initial points 1 to 16; and Q for the IUS
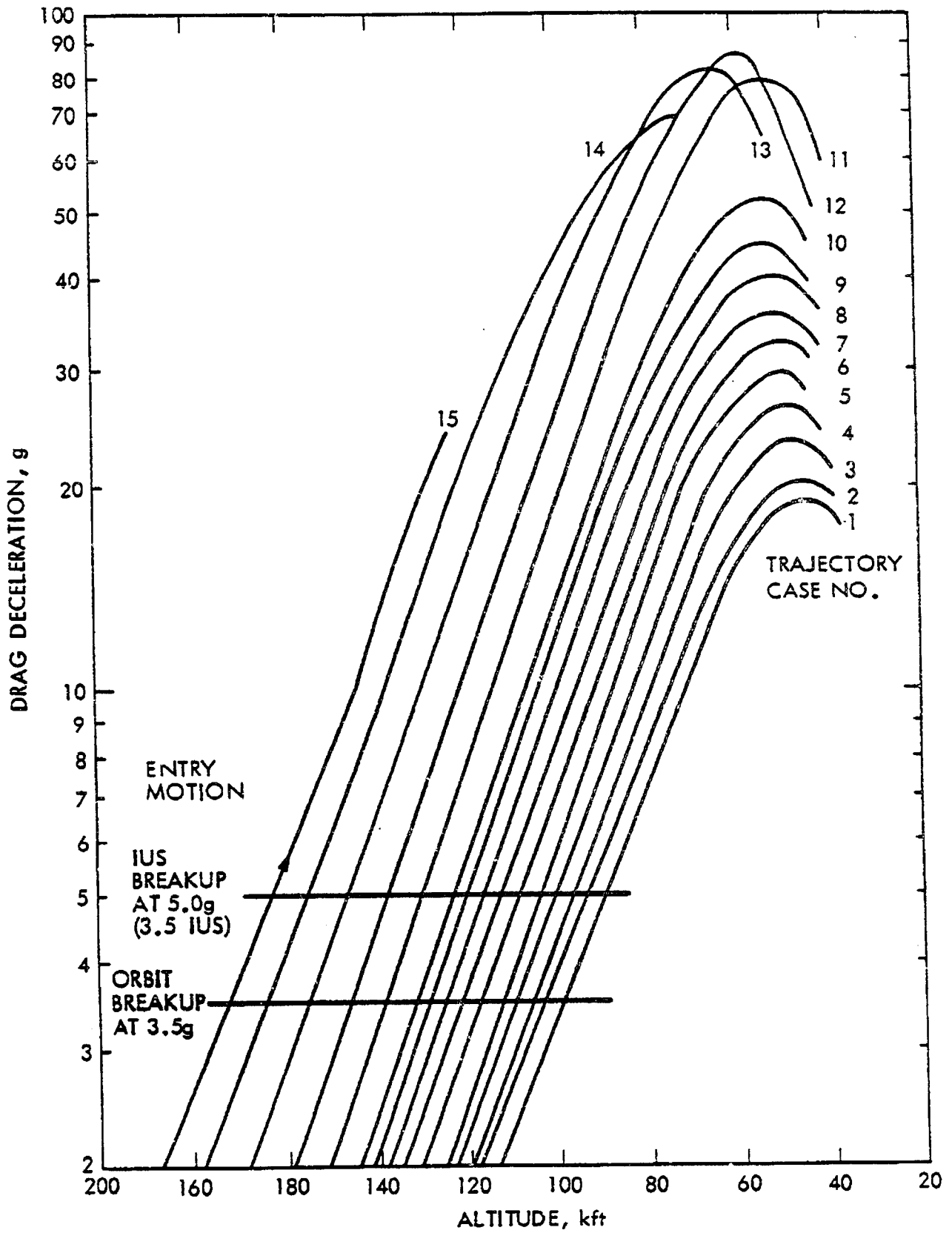after Orbiter breakup.

Fig. 2. Aero drag deceleration of the tumbling Orbiter (ballistic coefficient 107 psf) vs. altitude, for reentry initial points 1 to 15.
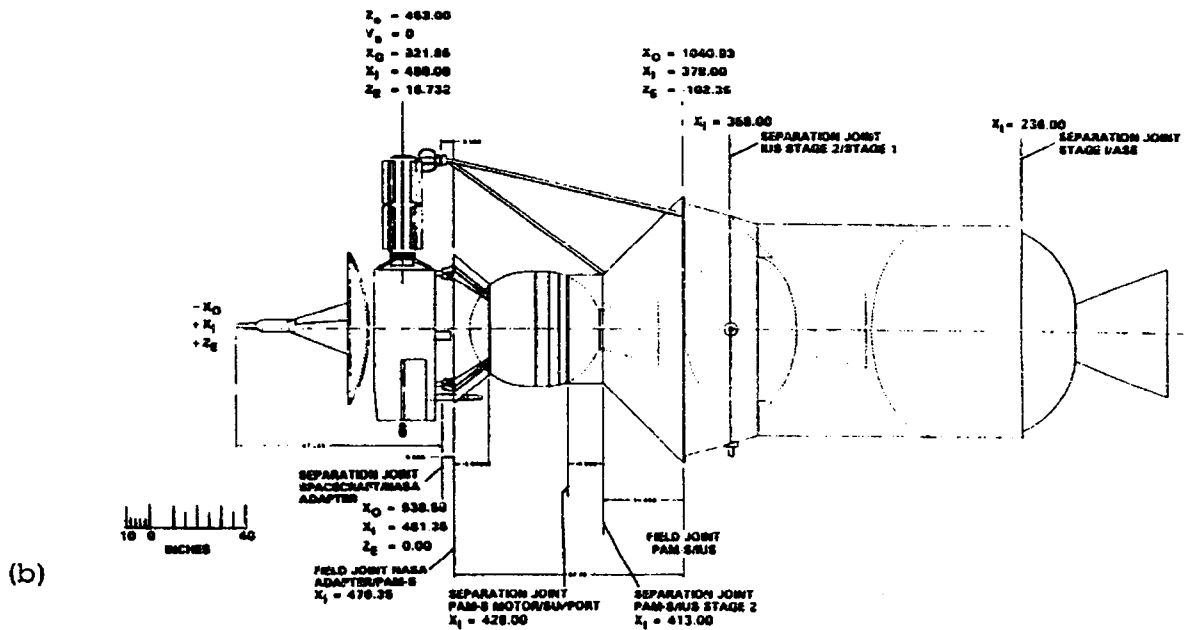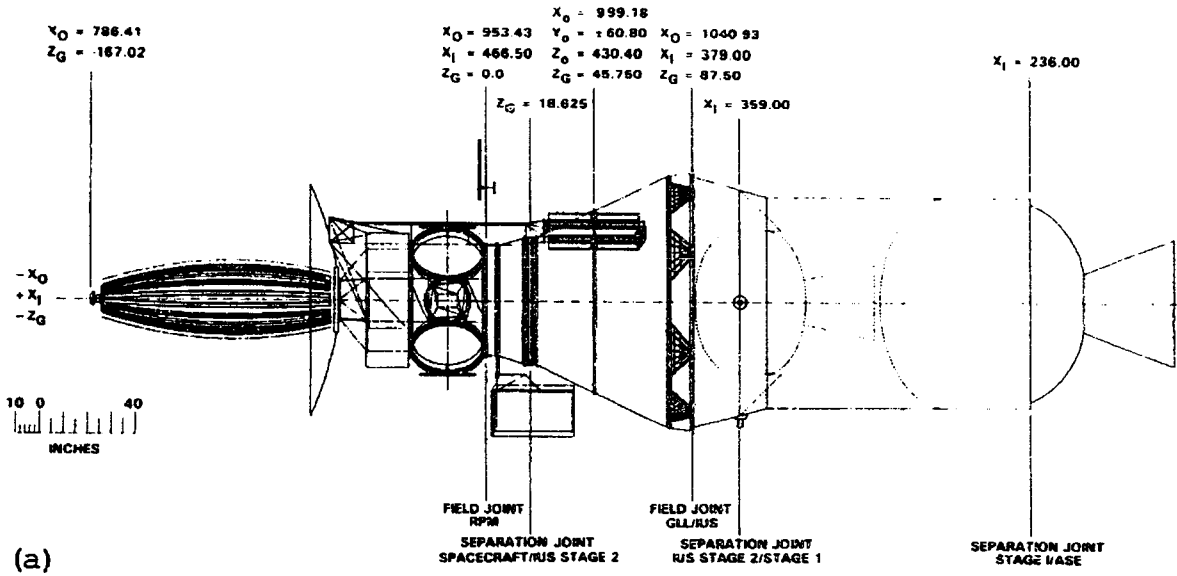
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Fig. 1. Diagram of the IUS Vehicle: (a) with GLL spacecraft;
(b) with Ulysses spacecraft.

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CONCLUSIONS

The following conclusions may be drawn from this analysis.

A fault occurring at time 128 to 510 sec in the nominal Orbiter ascent, involving loss of control, and presumed to lead to separation of the External Tank, loss of thrust, and tumbling, will result in the following events:

(1) the Orbiter and the IUS will always break up in flight, will never reach the surface intact;

(2) for time of initial fault about 128 to 155 sec (initial speed 4.4 to 4.9 kft/sec), the two GLL RTG's reach the surface without melting;

(3) for time of initial fault about 155 to 210 sec (initial speed 4.9 to 6.3 kft/sec) the GLL RTG's reach the surface either intact, or the fuel modules have been released prior to impact;

(4) for time of initial fault above 210 sec (initial speed above 6.3 kft/sec) the GLL fuel modules are released prior to surface impact;

(5) for time of initial fault 128 to 210 sec (initial speed 4.4 to 6.3 kft/sec) the ULS RTG does not melt, reaches the surface attached to the spacecraft bus;

(6) for time of initial fault 210 to 238 sec (initial speed 6.3 to 7.2 kft/sec) the ULS RTG reaches the surface unmelted, attached to the spacecraft bus, OR the case melts and the fuel modules separate prior to impact;

(7) for time of initial fault above 238 sec (initial speed above 7.2 kft/sec) the ULS fuel modules are released prior to surface impact.

(8) Surface impact for all fault times evaluated will occur in the ocean except for those near the end of SSME burn.

Figure 5 shows the longitude range from launch for these events. The horizontal scales are again the air relative speed at which the fault occurs, and the corresponding time. The vertical scale is the longitude range from launch. The bottom curve is the nominal ascent. The next curve up on the left is the range to apogee; because the ascent flight path is horizontal for speeds of about 13 kft/sec and upward, the second curve merges with the bottom curve for high speeds. The next curve going up is the longitude range to the 2.5 g entry deceleration, breakup value of the Orbiter, and the top curve, a separate curve only on the right of the figure, is the range to surface impact. At the left on the top curve the arrows indicate small regions where various configurations impact the surface. We first note that there is never impact of the Orbiter nor the IUS; at the speeds in question these vehicles always break up during the reentry due to mechanical force when tumbling. Starting at the left there is first a region, up to speed 4.9 kft/sec, where the GLL RTG's are predicted to impact intact, without melting of the case. Between speed 4.9 and 6.3 kft/sec for GLL there may be impact of the case or of the fuel modules; beyond speed 6.3 kft/sec there is impact of modules only. For ULS at low speed, up to 6.3 kft/sec, there is impact of the RTG attached to the spacecraft bus; for speed 6.3 to 7.2 kft/sec we have impact of fuel modules, or of the RTG case attached to the spacecraft bus; beyond speed 7.2 kft/sec there is impact only of fuel modules, for ULS also.

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RESULTS

The results are shown graphically in Figs. 4 and 5. Figure 4 shows the locus of several events on a plot for which the horizontal axis is the initial air relative speed; a second horizontal scale is given, showing the time during the nominal Orbiter ascent at which the fault occurs. The vertical axis is altitude. The top curve is the 3.5 g deceleration level adopted as a breakup criterion for the Orbiter. Below this curve is a parallel curve showing the 3.5 g deceleration adopted as breakup of the IUS. Figure 1 also has a separate group of three curves, beginning on the right between the Orbiter and IUS breakup curves, crossing the IUS curve near the right hand side, and coming down to intersect the horizontal axis. These three curves represent melting of the RTG case; because of the tumbling motion the fuel modules are assumed to be released as soon as the case melts.

We can illustrate the use of Fig. 1 by examples. For instance, for a fault that occurs late in the nominal ascent, say at a speed of 20 kft/sec (time 460 sec), we proceed down the vertical line at speed 20 kft/sec; we find a level of Orbiter deceleration of 3.5 g at altitude 165 kft, altitudes for RTG case melting at about 160, 155, and 151 kft; and an IUS deceleration level of 3.5 g at altitude 155 kft. Thus, for this fault we predict that the Orbiter will break up at 165 kft, the GLL RTG cases will melt, releasing the fuel modules, in the range 160 to 155 kft, the ULS RTG case will melt in the range 155 to 151 kft, releasing the fuel modules, and the IUS will also break up at about 155 kft.

As another example we take a fault occurring at an initial speed of 8kft/sec (time 250 sec); proceeding down a vertical line at 8 kft/sec as before, we meet the Orbiter breakup at 123 kft, the IUS breakup at 116 kft, and the three RTG case melt lines at 84, 62 and 40 kft, respectively. This means that the Orbiter breaks up at altitude 123 kft, the IUS breaks up at 116 kft, and the RTG's fly on alone. For GLL the RTG case melts in the altitude range 84 to 62 kft; for ULS the RTG case melts in the altitude range 62 to 40 kft.

As a third example, we see that a fault occurring at 128 sec would lead to breakup of the Orbiter at 101 kft, and breakup of the IUS at 90 kft, but would not provide enough heating to melt the RTG case. For GLL the two RTG's would fly alone from 90 kft, probably reaching terminal speed and impacting the surface without melting; for ULS the RTG would impact the surface without melting the case, and attached to the spacecraft bus.

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Additional data from Ref. 1, giving the range in vacuum for near orbital speeds, are shown in Table 4. For near-orbital speeds the 3.5 g deceleration occurs at altitude about 170 kft. Therefore the range in vacuum to 170 kft was calculated for additional speeds as shown in Table 5. This range is the sum of the range to the fault in the ascent (about 14 deg), plus the range from an apogee of 360 kft to altitude 170 kft, evaluated inertially and then adjusted for Earth rotation. Table 5 also gives the calculated range to the surface, for comparison with the data of Table 4. The actual range of components of the Orbiter, IUS, RTG etc is expected to fall in the area between the 3.5 g value and the vacuum impact.

Table 4. Angular Range at Near-Orbital Speed

Ascent time, sec	Angular range, deg to surface (Ref. 1)	Var kf/s (Ref. 1)
460	25.0	20.10
470	28.6	21.05
480	34.0	21.99
490	44.1	22.94
500	77.3	23.86
502	98.0	24.03
504	147.6	24.20

Table 5. Angular Range to 170 kft

Var kft/sec	Angular range, deg to 170 kft	to surface
23.27	33.9	48.3
23.53	37.3	54.2
23.78	42.9	64.3
23.91	47.8	73.4
24.04	56.2	90.1
24.09	61.6	101.9
24.17	74.7	141.1

From the trajectories for reentry cases 1 to 16 the drag deceleration curves of Fig. 2 were drawn, i.e., deceleration vs altitude, from which the breakup altitudes for 3.5 and 5.0 g drag deceleration can be read off. The trajectory data were also used to draw Fig. 3, which shows the time-integrated referen e heating Q vs altitude for the 16 trajectories. Note that in bo..n Figs. 2 and 3 the entry trajectories begin on the left and ..o e up and to the right.

Figure 3 also shows the curve of Q for the powered reentry case analyzed in Ref. 3, and indicates the range of release altitude for the GLL and ULS GPHS modules. The powered entry case is included here to show that the powered entry parameters '.peed, path angle) are similar to those of the present entry cases, so that it is valid to use time-integrated heating as a criterion of case melting. In the powered entry the melting of the case was calculated in detail on a thermal model; here the time-integrated heating is used as a short-cut to avoid the use of a detailed thermal model.

If we assume that the heating of the IUS begins when it is freed from the Orbiter cargo bay at drag deceleration of 3.5 g, we can calculate the point at which Q reaches 400, 800, etc, to determine the melting of the RTG case. For example, on curve 10 the 3.5 g point (Fig. 2) is an altitude of 132 km; on Fig. 3 the Q value is 600 at height 132; on curve 10 a Q value of 1000 = 600 + 400 is reached at height 101 km. In this way we construct the curves on the right upper part of Fig. 3, showing the altitudes for which the IUS has Q values of 400, 800, etc for curves 5, 6, 7 etc. These curves indicate the altitude for melting of the RTG case for GLL and ULS. The data of Figs. 2 and 3 can be combined to draw Fig. 4, which shows the height at which this analysis predicts breakup of the Orbiter (at 3.5 g tumbling deceleration), breakup of the IUS (at 5.0 g on Fig. 2, equivalent to 3.5 g on the IUS), and melting of the RTG case (Q of 400-800 and 800-1200 for GLL and ULS, respectively).

LONGITUDE RANGE

The longitude range from launch to the initial fault point of the ascent is given in Table 3, which also shows the range to surface impact in vacuum. The latter i: true anomaly range, i.e., great circle angular range, but is approximately longitude range for small values of the range. Two additional longitude ranges were calculated: (1) the range from the fault point on ascent to the corresponding reentry at the same height, and the longitude range from entry to aero deceleration of 3.5 g.   For speed above 10 kft/sec there is no apogee (the ascent flight is nearly horizontal); and for speeds above about 22 kft/sec the entry range increases rapidly and is difficult to calculate accurately.

For the tumbling Orbiter we took an average area as seen in the direction of the 3 axes: average of 690, 2290 and 3950 is 2310 sq.ft., and a Cd value as average of a sphere (0.9) and a cylinder in cross flow (1.25), i.e., 1.07; with a mass of 260 klb, this average m/CdA is then 107 psf. For the tumbling IUS it was estimated that the average m/CdA is 160 psf, i.e., about 50% greater than for the Orbiter. This means that the IUS experiences 3.5 g deceleration at the trajectory point where the original Orbiter would show about 5 g, if it were intact, and this value was taken for the IUS breakup.

ASCENT CASES

A number of cases were computed, each beginning at a point on the nominal Orbiter ascent trajectory, as shown in Table 3, in the time range 128 to 510 sec. Table 3 gives the time, height, speed, and path angle, and also the longitude range from launch and the predicted range to vacuum impact, in true anomaly (central angle). For each case the ascent air-relative speed (Var) and height, and the negative of the path angle were taken as the initial values for the reentry. A two degree of motion trajectory was computed numerically, i.e., motion in a plane, taking an average Earth rotation speed of 1300 ft/sec, zero average lift, and an average drag ballistic coefficient of 107 psf.

The program also computed a reference convective heating rate, the heating rate to the stagnation line of a cylinder of radius 1 ft normal to the flow, and its time integral. A modified Fay-Riddell correlation was used (Ref. 7).

Table 3. Cases Chosen for Computation*

Case Number	Time t,sec	Height Z,kft	Speed Var,kft/s	Path Angle, deg	Long deg	Range to Impact, deg
1	128	155.9	4.417	26.9	0.58	2.5
2	140	179,1	4.620	23.7	0.73	2.8
3	160	213.8	5.018	18.8	1.01	3.3
4	180	244.0	5.483	14.8	1.32	3.8
5	200	269.8	6.011	11.4	1.66	4.4
6	220	291.5	6.600	8.6	2.05	5.0
7	240	309.5	7.248	6.4	2.47	5.7
8	260	323.8	7.957	4.6	2.93	6.5
9	280	335.0	8.729	3.2	3.44	7.3
10	300	343.2	9.569	2.1	4.00	8.1
11	340	352.4	11.480	0.6	5.29	10.2
12	380	354.5	13.773	.0	6.87	13.0
13	420	353.2	16.58	−0.1	8.67	17.0
14	460	353.7	20.097	0.2	10.90	25.0
15	500	359.8	23.862	0.6	13.57	77.3
16	510.4	362.6	24.310	0.7	14.33	−

*Data are from STS 51E-C1 Nominal Range Safety Tape Printout (Due East Launch), received by JPL from JSC March 8, 1985.

APPROACH

The approach followed here is to choose a number of initial
times in the time period 128 to 510 sec of the nominal ascent.
For each point a reentry trajectory was calculated numerically,
taking the reentry speed, path angle and height to be the values
at the time of the fault, but with the path angle reversed to
give a reentry in lieu of an ascent. A total of 14 points were
selected along the nominal ascent trajectory (given in detail in
Ref. 1); for each point a trajectory was computed, using a
program written for motion in a plane (the reentry plane is the
same as the ascent plane), zero average lift, and with a drag
ballistic coefficient of 107 psf. The trajectory was run out
for sufficient time to show drag decelerations exceeding 3.5 g.

Because the speed and angle did not change much during the
first part of the reentry, the trajectory was almost independent
of the ballistic coefficient, and only the level of drag decele-
ration would change if one assumed different ballistic coeffic-
ients, not the dynamic pressure and height as a function of time.
In fact, for this reason the same trajectory can be used to
represent subsequent entry of the IUS vehicle, readjusting the
drag deceleration to suit a new ballistic coefficient.

MASS, AREA, DRAG OF VEHICLES

Table 1 gives details of the mass of the Orbiter and IUS vehicles
and their areas as seen in different directions: front, side and
in plan view. The Orbiter data are from Ref. 6. Figure 1 shows
the IUS plus the GLL spacecraft (a), and the ULS spacecraft (b).

Table 1. Mass and Area of the Orbiter and the IUS

		Orbiter	IUS + GLL s/c	IUS + ULS s/c
mass, m, klb		240	38.2	38.5
area, A, ft2:	end	690	68.4	68.4
	side	2290	337	277
	plan	3950		
	wing ref.	2690		
m/A	end	347.8	558	563
	side	104.8	113.4	139.0
	plan	60.8		

Table 2. Drag coefficient Cd of Orbiter at Mach 15

Angle of attack, deg	0	10	20	30	40	45	50
Cd	.08	.081	.19	.44	.82	1.05	1.31

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The Orbiter was presumed to break up due to mechanical force, and to release the IUS, contained in the Payload Bay, without serious damage to the IUS. In its subsequent flight the IUS was modeled as a vehicle with the size and shape of the undamaged IUS, tumbling, with an average ballistic coefficient of about 160 psf. The initial tumbling was assumed to persist throughout the reentry. In the subsequent flight the breakup criteria used were as follows: (1) the IUS was assumed to break up at a level of 3.5 g deceleration, freeing the spacecraft and the RTG's; (2) the Galileo RTG cases were assumed to melt at a reference heating integral of 400-800 btu/ft2; (3) the Ulysses RTG case was assumed to melt at a reference heating integral of 800-1200 btu/ft2. The reference heating rate is the convective stagnation line heating rate for a 1 ft radius cylinder with axis normal to the flow, and the integral is the time-integral of this rate. The values for case melting were derived in the analysis of an IUS powered entry (Ref. 3), and the range represents uncertainty in the orientation of the RTG's relative to the tumbling plane of the IUS, i.e., the degree of exposure of the RTG to the flow. We note that the RTG case melting competes with the IUS breakup; if the IUS breaks up first, the RTG is assumed to release and fly alone until the case melts; if the case melts first, the fuel modules are released while the remnant of RTG case is attached to the IUS. In the Ulysses case the RTG remains attached to the spacecraft bus until the RTG case melts.

The breakup and melting of the RTG case and release of the GPHS modules has been examined in detail also for a number of additional reentry cases, in Refs. 4 and 5, for the GLL and ULS spacecraft, respectively. These studies also support the concept of integrated heating used here to predict melting of the RTG case and release of modules.

With these simplifying assumptions the analysis can proceed. We see that the higher the initial speed at which the fault occurs, the higher the height at which the Orbiter breaks up in its subsequent uncontrolled reentry. At high speed we expect the IUS breakup and melting of the RTG cases to occur also at high altitude. The question arises: is there a low speed in the nominal ascent at time beyond 128 sec when the subsequent reentry has insufficient speed to break up the Orbiter. That is, can the Orbiter reach the surface intact, and similarly can the IUS reach the surface intact, for a certain range of initial speed. The results below show that neither the Orbiter nor the IUS can reach the surface intact, following a fault leading to loss of control at time beyond 128 sec in the nominal ascent.

2

INTRODUCTION

This document gives supporting details of an analysis reported in summary form in Section 6.6 of NSTS 08116,"Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis" (Ref. 1).

This study addresses a subclass of STS Orbiter launch accidents, to evaluate the possibility of high-speed ground impact of the intact Orbiter. While the two SRB's are present (up to 128 sec), a fault involving loss of vehicle control is considered almost certain to lead to breakup of the Orbiter in the transient interplay of large aerodynamic and thrust forces. This breakup precludes the possibility of intact impact. Thus, only failures occurring after 128 sec are considered here, and it is assumed that such a failure results in the Orbiter separating, relatively intact, from the External Tank and flying alone, out of control, with no thrust, and tumbling.

Reference to the nominal ascent trajectory indicates that the air relative speed of the Orbiter in the time 128 to 510 sec is about 4.4 kft/sec up to orbital speed. Since at 128 sec the dynamic pressure is about 1% of the peak (which occurs about 60 sec), the Orbiter in its tumbling and uncontrolled ascent meets a relatively small dynamic pressure, insufficient to cause breakup. A criterion of 3.5 g was adopted, in consultation with Alden Mackey of JSC (Ref. 2), for breakup of the Orbiter, and this level is met when the Orbiter reenters the atmosphere, after passing through an apogee at low atmospheric pressure. Reentering at the same speed, height and flight path angle (opposite sign) as it had when the fault occurred, the Orbiter thereafter meets a rapidly increasing dynamic pressure and heating rate. An average ballistic coefficient of 107 psf was taken to represent the tumbling Orbiter, and the height at which 3.5 g deceleration is reached was determined, for various points in the nominal ascent.

For the IUS the information available was that the static transverse load limit is about 1.5 g (Section 10 of NSTS 08116, Ref. 1). In the interests of being definite and certain a breakup deceleration level of 3.5 g was adopted for the IUS. This is conservative in the sense that the real breakup is likely to be earlier than that predicted using the 3.5 g level. Because the ballistic coefficient for the IUS is approximately 1.5 times that for the Orbiter, this is equivalent to about 5 g deceleration in the Orbiter trajectory.

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ABSTRACT

This document gives supporting details of an analysis reported in summary form in Section 6.6 of NSTS 08116, "Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis" (Ref. 1). This report documents the results. The analysis was performed by JPL in support of the NASA-Johnson Space Center regarding STS accident environments for RTG safety studies for the Galileo and Ulysses Projects.

This document addresses the question of uncontrolled reentry of the STS Orbiter following a fault during the latter part of the ascent, from the time at which the SRB's are dropped (nominal 128 sec) to the end of the ascent burn (510 sec). The fault is assumed to leave the Orbiter relatively intact, separated from the External Tank, therefore with no thrust, and tumbling and uncontrolled. After passing through a high-altitude perigee the Orbiter reenters, and is expected to break up at an aerodynamic deceleration level of 3.5 g, assuming zero average lift and a ballistic coefficient m/CdA of 107 psf. The Orbiter breakup is assumed to free the IUS plus spacecraft relatively undamaged from the cargo bay; the IUS continues a tumbling and uncontrolled reentry, and is expected to break up when its drag deceleration reaches 3.5 g. Competing with IUS breakup is melting of the RTG case due to aerodynamic heating. A range of 400-800 and 800-1200 btu/ft2 of reference convective heating is used for melting of the RTG case, on the basis of prior studies of reentry breakup of the IUS vehicle plus Galileo or Ulysses spacecraft. Altitude boundaries are found for breakup of the Orbiter, and of the IUS, and for melting of the Galileo (GLL) and Ulysses (ULS) RTG case, as a function of the initial speed or time at which the fault occurs.

It is found that both the Orbiter and the IUS always break up before reaching the surface, and that the RTG case melts, freeing the GPHS (General Purpose Heat Source) modules, for faults occurring after 210 sec for the GLL mission and after 240 sec for the ULS mission. For a fault in the time interval 128 to 155 sec for GLL and 128 to 210 sec FOR ULS the RTG reaches the surface without melting, flying alone in the GLL mission and attached to the spacecraft in the ULS mission. For a fault occurring in the intervening time interval, i.e., 155 to 210 sec for GLL and 210 to about 240 sec for ULS, either the RTG case or the modules may reach the surface. The longitude range from launch is about 3.5 deg for a fault at 128 sec. Surface impact for all fault times, except those near the end of the SSME burn, will occur in the ocean.