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MEASURED IMPACT ACCELERATIONS FOR OVER-LAND AND OVER-WATER SOUNDING ROCKET PAYLOADS[*]

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ABSTRACT

The scientific payload carried by a sounding rocket must survive both the axial and lateral loads upon impact. Limited data are available to describe the impact environment of sounding rocket payloads. This paper presents results of a study to measure both over-water and over-land impact loads using an onboard data acquisition system. Deceleration histories for full-scale over-water and over-land recoveries are presented. In order to ensure reliable recovery of the over-water system, a new parachute system was designed which included a deployable recovery instrumented platform (DRIP). The DRIP is tethered to a buoyant payload and houses the transmitter and strobe light to aid in location and recovery of the payload. Details of this new over-water parachute system are also presented.

INTRODUCTION

Sounding rockets have been extremely useful tools for the exploration of the upper atmosphere for almost half a century. Their relative simplicity and low cost make them attractive for high-altitude research for science communities of many nations. Sounding rocket payloads must be small and lightweight, able to resist the g-levels of rocket acceleration and friction and vibration of a rocket flight. In some cases, the payload must also be able to take the thermal shock of reentry and landing. The recovery system is a key component of a sounding rocket because oftentimes the payload is interrogated after ground or water impact.

Sounding rocket payloads are carefully designed to withstand the high axial shock loads. However, payloads will sometimes still be damaged upon impact which is costly. In some instances, the atmospheric data of interest cannot be obtained again for another season or another year. Of considerable interest, then, is the magnitude and direction of shock loads on sounding rocket payloads upon impact.

In recent years, with the advances in microelectronics, it is possible to obtain very precise deceleration histories with small, lightweight data acquisition systems that ride onboard the payload. Previous deceleration histories were obtained from photometric results or from data recovered through cables which trailed from the base of the vehicle. Recently, Brooks and Anderson completed a study of the dynamics of a space module impacting the water utilizing an onboard data acquisition system[1]. The space module utilizes a parachute, however, the geometry is unlike that of the sounding rocket payload. The space module has a large heat shield which absorbs most of the water impact load. Another example of water impact analysis with onboard data acquisition system is the study performed by Cole, Hailey and Gutierrez[2]. They were interested in obtaining accelerations, base pressure data and scaling relationships for high-speed water entry applications. Their results are limited to non-buoyant water penetrators, entering at speed much higher than that of a sounding rocket payload.

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Similarly, for ground impact, the military community has interest in the deceleration and penetration characteristics of certain geometries for both weapon and cargo systems. Most of that information is not available in the open literature. Impact dynamics research for full-scale aircraft crash testing is another example of a specialized application where accelerometer data and high-speed motion picture results were used to understand damage to aircraft[3].

Computational techniques are available for simulating water- and ground-impact. For example, the authors of Reference 1 are using DYNA3D to simulate water impact. Reference 4 contains a description of a different computational technique, smooth particle hydrodynamics, which can be used to predict both land and water impacts. The computational results are promising, however, they are not sufficiently mature to be considered design tools at this time. Both designers and numerical analysts require deceleration histories from full-scale tests. To the best of our knowledge, no one has obtained such data with application to sounding rocket payloads impacting both ground and water with a parachute. One purpose of this paper is to provide the designer and analyst with deceleration histories obtained from several full-scale flight tests.

A second purpose of this paper is to describe a newly designed over-water recovery system which is fairly inexpensive to manufacture and yet is very reliable. Previous over-water recovery systems, with the careful integration of flotation bag and parachute, are described in Reference 5. The recovery system designed by Johnson[6] has been used with good success for many years by NASA. This system was designed primarily for a nonbuoyant payload and consists of a gas-filled flotation bag attached to the top of a parachute. An antenna and beacon transmitter are mounted on top of the flotation bag. When in the water, the payload is suspended below the water and is attached to the gas-filled flotation bag floating above the surface. The locator electronics ride atop the flotation bag. During high-sea states, there is a possibility of this system tipping over in which case the locator electronics are immersed in water. To ensure reliability of recovery of a buoyant payload for the worst-case-scenario of a recovery occurring several days after water impact because of high-sea states, we describe a new overwater recovery system. The system is designed for buoyant payloads and includes a simple to manufacture, deployable recovery instrumented platform (DRIP) which is tethered to the payload and houses the transmitter and strobe light to aid in location and recovery of the payload.

Finally, data presented in this report were obtained from sounding rocket flight programs whose primary mission was to obtain scientific data. When convenient, impact loads were obtained which limits the amount of data available for analyses. Since water- and land-impact are complicated phenomena which depend on many parameters, we can draw only preliminary conclusions about impact loads. We conclude this article by offering recommendations for additional tests that must be performed before a reliable design tool can be derived.

INSTRUMENTATION AND FLIGHT TESTS

Data Acquisition System

Data were obtained using a commercially available, programmable, totally self-contained environmental data recorder (EDR)[7]. The EDR is designed for a variety of shock and vibration recording applications and monitors accelerations in three axis and temperature, similar to the SDACS described in Reference 8. The piezoresistive accelerometers are rigidly mounted within the recording unit with a range of ± 53 g's with a resolution of 0.1 g. Their frequency response is 1050 Hz. The EDR requires low power, permitting battery operation up to several weeks. The EDR used in this test series was waterproofed and weighed 2.2 pounds (1 kg).

Typically, the EDR was programmed to become active about an hour before launch and was configured to operate in an event-triggered fashion. Data is taken continuously, recorded in memory and overwritten until one or more of the accelerometers exceeds the trigger value (typically set at 1.5 g's). At this point, the EDR stores the acceleration data. When all three accelerometer voltage levels fall below the trigger, value, post-trigger occurs. A prescribed amount of data is taken and then the EDR becomes "dormant," waiting for another trigger acceleration event. Pre- and post-trigger sample lengths are preprogrammed. The EDR contains a microprocessor which interfaces with a 10-bit analog-to-digital converter. Sampling rates for data in this report vary from 1500 to 2500 samples per second.

Before use with full-scale flight tests, the EDR was tested to verify the integrity of the data. The EDR has been used for numerous commercial applications, including documentation of safe shipment of museum exhibits and as crash data recorders for race cars. In 1993, Indy 500 cars were equipped with EDRs because of their rugged design in order to obtain crash data so engineers can more accurately understand crash dynamics[9]. Since recording accelerations associated with a sounding rocket flight was a new application for the EDR, several vibration tests were conducted at NASA Wallops Flight Facility[10]. The power spectral density plots generated with the EDR test data were almost identical to the input test spectrums.

Over-Land Flight Tests

The EDR unit was first used with a flight test conducted at White Sands Missile Range in 1992. NASA flight 31.084 UU consisted of a scientific payload boosted by a two-stage Nike-Orion combination. The payload weighed 465 pounds (211 kg) and descended on a 50.3 ft (15.3 m) nylon cross parachute. The results obtained with the EDR were preliminary and promising. We use the term "preliminary" because the trigger value was arbitrarily set to 15 g's which was too high and in subsequent flights was reduced to 1.5 g's. We use the term "promising" because the measured impact g-loads were very useful in evaluating the performance of the crush ring used to help mitigate the impact shock. Unfortunately, the electronic data was purged and only hard copy plots remain.

Another opportunity to obtain land-impact data occurred in 1994, where data were obtained from two sounding rocket flight tests conducted at White Sands Missile Range. NASA flight 31.107 UU was a two-stage sounding rocket flight consisting of a Nike and an Orion rocket motor. The 31.107 UU payload was recovered, refurbished and flown again on the 31.108 UU vehicle which was also boosted by a Nike-Orion combination. Both payloads descended from approximately 20,000 ft (6 km) suspended from a nylon cross parachute and were successfully recovered. The cross parachute was 50.3 ft (15.3 m) and carried a suspended weight of roughly 460 pounds (209 kg).

Both flight 31.107 UU and 31.108 UU were instrumented with an EDR which was mounted in the bottom of the parabay on the vehicle centerline. The EDR was programmed to record any acceleration registering above 1.5 g's at a frequency of 2498 samples per second. The EDR contained 3.5 megabytes of digital memory capacity. Shown in Figure 1 is the launch configuration of both 31.107 and 31.108. Shown in Figure 2 is the reentry and recovery configuration. The nosecone and rocket motors are ejected before reentry. The crush ring is attached to the touchdown surface of the payload. (31.084, 31.107 and 31.108 all had identical crush ring geometries.) The location of the EDR is also shown Figure 2.

Over-Water Flight Test

NASA flight 12.046 WT presented another opportunity to measure and record acceleration data from a sounding rocket flight. The primary purpose of this flight test was to test a new sounding rocket vehicle configuration utilizing a Mark XII MOD 1 Terrier and an Improved Orion rocket motors. This new sounding rocket configuration will allow a different family of scientific payloads to be flown at a reduced cost. In an effort to gain as much benefit from the launch as possible, several secondary objectives were attempted including water-impact measurements.

In 1994, the 12.046 WT scientific payload was boosted to apogee of 410 kft (125 km) from Wallops Island by a Terrier-Orion 5A combination. The scientific payload was separated from the nose cone and rocket boosters before reentry. The reentry payload weighed 321.5 lb. (146 kg) and was a different geometry than the over-land payloads. Water impact was measured with an onboard EDR which was triggered to record any acceleration greater than 1.5 g's. The EDR was programmed to record for 1.37 seconds unless interrupted by another event. The EDR was mounted within the sealed, water-tight section of the payload. The reentry configuration and location of the EDR is shown in Figure 3.

12.046 WT RECOVERY SYSTEM

12.046 WT required the design of a new recovery system, with the constraint that the system be inexpensive and utilized as much off-the-shelf technology as possible. The Terrier-Orion 5A combination was new and was flown with a bulbous payload. The standard Ogive Recovery System Assembly (ORSA) was utilized for this mission which has been successfully flow more than 100 times. When the nose cone is deployed during the ascending portion of the trajectory, the heat shield is exposed to air flow. The heat shield is deployed while descending through 20,000 feet (6096 m) and begins the parachute recovery sequence. The ORSA was readily available from sounding rocket stock which fixed the geometry of the recovery system.

Requirements for the recovery system include a maximum recoverable weight of 500 pounds (227 kg). The parachute system must fit inside the ORSA, which has a 17.25-inch (0.44 m) outside diameter, and recover a buoyant payload. The over-water recovery system consists of a 8.56 foot (2.6 m) ribbon drogue parachute; a 25.5 foot (7.8 m) cross parachute; and a Deployable Recovery Instrument Platform (DRIP) which is designed to float alongside a buoyant payload while tethered to the payload. Onboard the DRIP is a transmitter and strobe light to aid in the location and recovery of the payload. Because the DRIP is free-floating and not an integral part of the parachute, the main parachute could be a cross configuration which is very stable and relatively inexpensive to manufacture

All parts of the parachute recovery system are standard Black Brant components except for the following: the main parachute, a shortened 750 pound (341 kg) main parachute bag, and the DRIP. The packed system with dimensions is shown in Figure 4. The nylon cross parachute with dimensions is shown in Figure 5. The drag area is 244.5 square feet (22.7 square meters) and the predicted impact velocity is 41.5 fps (12.6 m/s) for a 500 pound (227.3 kg) payload. (In the case of flight 12.046 WT, the payload suspended weight is less, 321.5 lb. or 146 kg, so the impact velocity will be less.) The drogue parachute deploys the main parachute 14 seconds after drogue deployment.

When the 12.046 WT parachute impacted the water, a Sea Water Activated Switch (SEAWARS)[11] release system was employed to disconnect two of the four confluence points of the parachute so that it did not become a sea anchor, thereby reducing the possibility of sinking the floating payload. The SEAWARS is man-rated and utilized by the Air Force and Navy to provide separation of parachute risers from personnel harness automatically upon water entry. It is salt water activated, approximately 1 second after immersion. Approximately 2 to 3 seconds after salt water immersion, the DRIP deployment bag opened, the DRIP inflated, and was deployed on a 40 foot (12.2 m) length of polypropylene floating rope. The DRIP was tethered to the 12.046 WT floating payload. A 242.0 MHz recovery locator beacon and a flashing strobe light, mounted on top of the DRIP began operation during the inflation process. Photographs of the recovery, taken from the recovery boat, were used to prepare the schematic of the deployed recovery system, shown in Figure 6.

The purpose of the DRIP is to provide a continuous beacon signal for several days in case recovery of the scientific payload is delayed. The DRIP is simply constructed of four flat, polyurethane-coated panels that are heat sealed and form bladders as shown schematically in Figure 7. The panels are inner connected with small openings so CO_2 gas can freely fill all four bladders. The panels are wrapped around and the ends secured to each other to form a cylindrical shape. A one inch (2.54 cm) attachment flap surrounds the bladders so various items can be attached to the DRIP. Beneath the cylinder, the battery pack and ballast weights are mounted, similar to the centerboard on a sailboat, to ensure the DRIP floats stably in the water. The salt-water activated inflation system[11] is mounted in the center of the DRIP package. The beacon, strobe light and tether are mounted on the top of the DRIP.

In order to test the reliability of the DRIP, it was inflated to a gage pressure of 40 inches of water (101.6 cm) and placed in a container of water. The internal pressure was carefully monitored and after 92 hours had decreased to 3 inches of water (7.6 cm). However there was no appreciable change of free board for the DRIP. Approximately 25 per cent of the 16 inch height (0.41 m height) remained submerged with the recovery locator transmitter and strobe light riding 12 inches (0.3 m) above the water line.

The newly designed recovery system performed well on flight 12.046 WT. The use of the cross parachute and the simple construction of the DRIP resulted in a low cost recovery. Future over-water recoveries of buoyant payloads will utilize this system.

RESULTS

Data obtained from the EDR is presented in this section. In all cases, the z-component of acceleration is along the body axis, the x- and y-components are lateral accelerations. Note that times displayed on the axis are not "real" times of flight. Finally, the resultant acceleration is the vectorial summation of the x-, y-, and z-component accelerations.

Overland Deceleration Histories

The payload from flight 31.084 UU impacted onto a hard surface (possibly gypsum). The three components of acceleration obtained from flight 31.084 UU are shown in Figure 8. (Recall that the electronic form of this data was lost and so only several summary hard copies exist.) The resultant acceleration for land impact are shown in Figure 9. The data suggest the payload impacted the hard earth in a fairly vertical orientation, and then deformation of the crush ring occurred, giving rise to the 20 to 40-g fluctuation. After crushup, the unit fell to its side. The axial deceleration was in excess of 40 g's axially and the lateral deceleration was approximately 20 g's. Roughly 5 g's of lateral load were measured as the payload fell to its side. The crush ring sustained damage, as shown in Figure 10. Finally, we would like to note that this payload impacted on a fairly windy day because photographs of the recovery indicate it was pulled across the desert by the parachute for some distance.

Data from flight 31.107 UU were obtained when the payload touched down in the White Sands desert onto dry, medium packed sandy soil. The component deceleration histories and the resultant history are shown in Figure 11. The payload terminal velocity at 4000 ft (1219 m) was 20.3 fps (6.1 m/s). The peak axial deceleration was 39.22 g's and occurred shortly after impact. The payload penetrated the soft soil several inches (centimeters) and the crush ring was intact. At 0.56 seconds after impact, the payload fell onto its side as seen by the large lateral g's in both the x and y axes. We fondly refer to the axial load as the "bop" and the large lateral load as the "plop". Finally, it is important to note that 31.107 UU impacted on a relatively calm day with negligible winds.

Sounding rocket flight 31.108 UU impacted on a relatively calm day into a damp sandy clay. The payload terminal velocity at 4000 ft (1219 m) was 20.3 fps (6.1 m/s). The crush ring remained intact and the payload penetrated several inches (centimeters) of sandy clay. The component deceleration histories and the resultant history are shown in Figure 12 and show the "bop" and "plop" behavior 31.107 UU. The peak axial deceleration was 30.66 g's. Similar to flight 31.107 UU, this payload also received high lateral g's as it fell onto its side: 30.63 g's in the x-direction and 10.28 g's in the y direction. The high lateral g's occurred 0.41 seconds after impact.

A summary of the maximum axial and lateral g's is shown in the table below.

	31.084 UU	**31.107 UU**	**31.108 UU**
Terminal Velocity	22.3 fps (6.8 m/s)	20.3 fps (6.2 m/s)	20.3 fps (6.2 m/s)
Soil	hard	soft	soft
Wind	strong	calm	calm
Impact g's			
X-axis	0	8.9	30.6
Y-axis	< 20	27.3	10.3
Z-axis	> 40	39.2	30.7

Ground impact is a very complicated phenomena. Impact data obtained from flights 31.107 UU, 31.108 UU and 31.084 UU involved the same geometry, same payload weight and parachutes which resulted in very similar impact velocities and orientations. The type of soil the payload touched down into was uncontrollable. Similarly, the types of winds during payload descent were uncontrollable. It is interesting to note that 31.084 UU impacted the hard soil which destroyed the crush ring, and then saw very low lateral loads as the vehicle fell to its side. The two payloads which impacted relatively soft soil (31.107 UU and 31.108 UU), penetrated the soil and then saw high lateral loads as the payloads fell over. One of the influences on g-loads is type of soil into which the payload impacts. Another influence on g-loads is the effect of winds. It is interesting to note that the payload which impacted during relatively high winds (31.084 UU) saw limited lateral loading. Possibly, the crushup experienced by 31.084 UU absorbed sufficient energy to eliminate the high lateral loading. Or possibly, the parachute suspension lines remained taunt upon ground impact due to the high winds so the payload had more damping due to the presence of the inflated canopy when compared with 31.107 UU and 31.108 UU where the canopy collapsed around the payload upon impact and offered no lateral shock mitigation. Prior experience with an airdropped container has shown strong winds mitigate the high lateral loads on impact ("plop" loads)[12].

Overwater Deceleration Histories

Similar to the previous section, water impact and entry are complicated phenomena. We obtained data from one flight test which are important results because they show magnitude and duration of g-loads. However, in general, water impact loads depend on geometry, payload weight and buoyancy, impact angle, and impact velocity. So limited conclusions can be drawn from this single flight test.

Water impact loads were measured using the EDR. Prior to water impact, parachute deployment was recorded. The x-, y-, and z-components of deceleration agreed favorably with those obtained from telemetry. Hence, we can assume the EDR was making accurate measurements at water entry. The payload impacted the water at approximately 32 fps (9.75 m/s). The component deceleration histories and resultant deceleration are shown in Figure 13. The maximum axial deceleration measured was 21.9 g's measured shortly after water impact. The maximum lateral load measured at water impact was 6.1 g's. Roughly 1.3

seconds after water impact, the EDR measured a small load in the x- and y-axes. We feel this is the results of a wave impacting the buoyant, floating payload and not part of the water entry event.

Water entry loads measured for the 12.046 WT payload are different than those obtained in Reference 2 for a high-speed water penetrator. In particular, the 12.046 WT data show little of the water entry cavity formation and subsequent cavity closure and collapse that was seen in Reference 2. This is not surprising since 12.046 was entered the water at relatively slow speed with a buoyant payload.

SUMMARY AND RECOMMENDATIONS

Overland and overwater deceleration histories of full-scale, sounding rocket flight tests have been obtained. Such data has been unavailable in the open literature before now and should be of value to both the analyst and the designer. The data is limited because it was obtained from sounding rocket programs whose primary missions were to carry scientific payloads. The data presented is for all three axis which would be very difficult to obtain from photometric techniques. The data also show maximum loads <u>and</u> duration of loads which is of considerable value to the designer.

The influence of both winds and soil can be seen in the overland data. There is insufficient data to draw any conclusions, however, there is some indication that touchdown onto soft soil and no winds results in the "bop" and "plop" behavior (high axial and lateral loading) when compared with touchdown onto hard soil with winds. A crush ring is very effective at mitigating shock loads. The magnitude of both the initial impact load and the crushup load is not much greater than impact loads obtained from a soft soil touchdown where the crush ring survived intact.

Water entry impact load data has also been obtained. Since water entry is a very complicated phenomena, no generalized conclusions can be drawn.

The overwater recovery system designed for flight 12.046 WT performed well. The DRIP represents a very simple, inexpensive recovery technique for buoyant payloads utilizing off-the-shelf technology. We anticipate one significant improvement to the DRIP which will make it an even more cost effective system. The salt water activated switch (SEAWARS), used to disconnect two of the four confluence points of the parachute, can be replaced with a less expensive component. A three-ring release system with a salt-water activated cutter can be used. Three-ring releases have been used reliably by tandem jumpers for inflight separation[13].

Finally, we present some recommendations for follow on studies. Clearly, more full-scale data must be obtained. At a minimum, we hope NASA will utilize an EDR to measure impact loads on future flight tests. It is a very lightweight, unobtrusive device that does not interfere with the scientific payload mission. The data obtained is of great importance to the design and analyst community, even if the impact conditions cannot be controlled.

If possible, several full-scale flight tests with better control over impact conditions would be desirable. Both overland and overwater impact depend on vehicle geometry, parachute, weight, impact velocity, and impact angle. Overland impact depends on wind and soil conditions as well. Overwater impact depends on vehicle buoyancy and possibly on sea state. A test program which would utilize a "typical" sounding rocket payload and parachute and would allow impact velocity and angle to vary would be of considerable value. Especially, if for overland impacts, the soil type could be held constant.

ACKNOWLEDGMENTS

Many individuals contributed to the success of flight tests 12.046 WT, 31.107 UU and 31.108 UU. We would like to acknowledge the dedication and interest of two individuals at NASA GSFC/Wallops Flight Facility in obtaining the EDR data: Chris Shreeves for 31.107 UU and 31.108 UU and Charles Brodell for 12.046 WT. We also acknowledge the efforts of the Captain and Crew of USCGC Point Highland for recovery of the 12.406 WT payload in the Atlantic.

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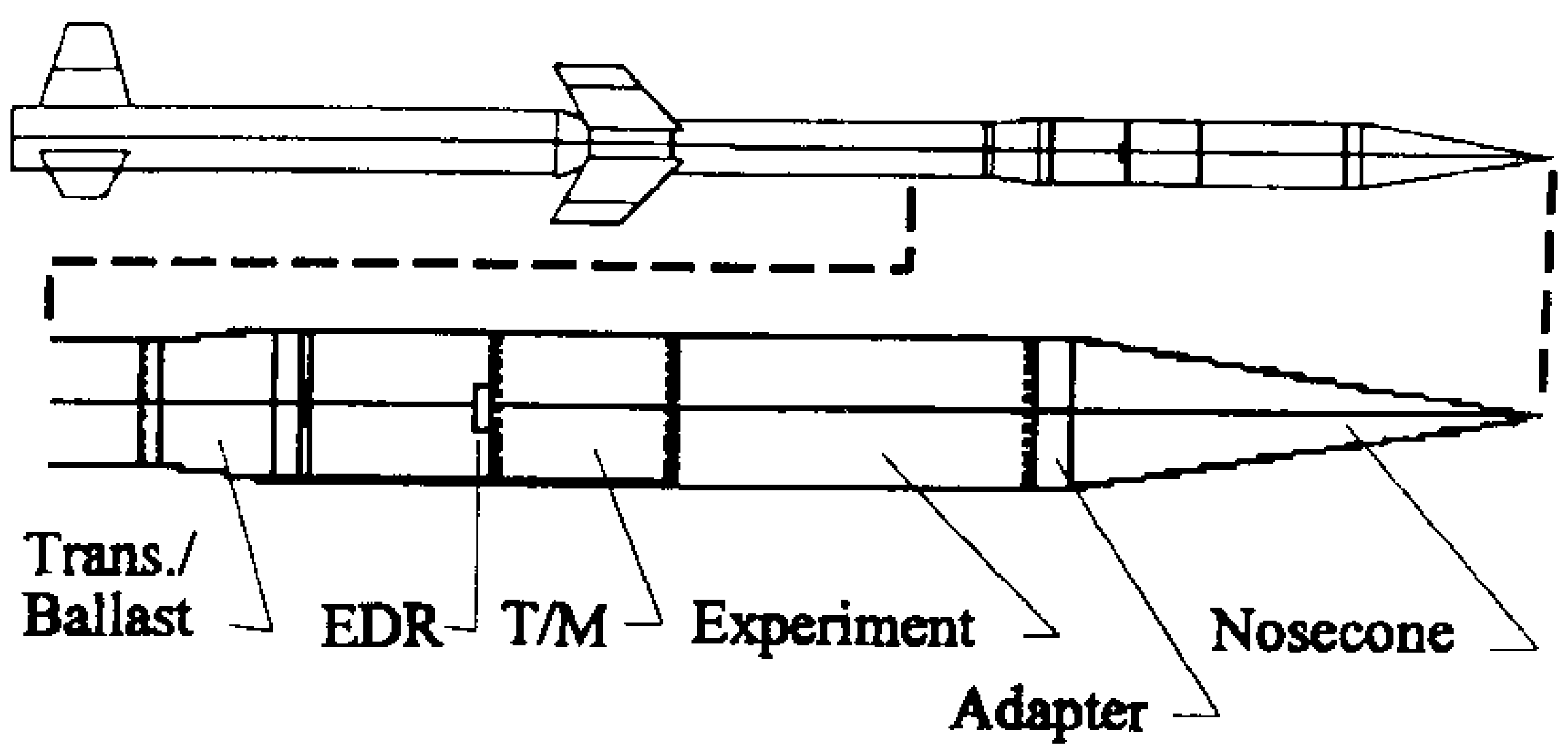


Figure 1: Launch Configuration of 31.107 UU and 31.108 UU

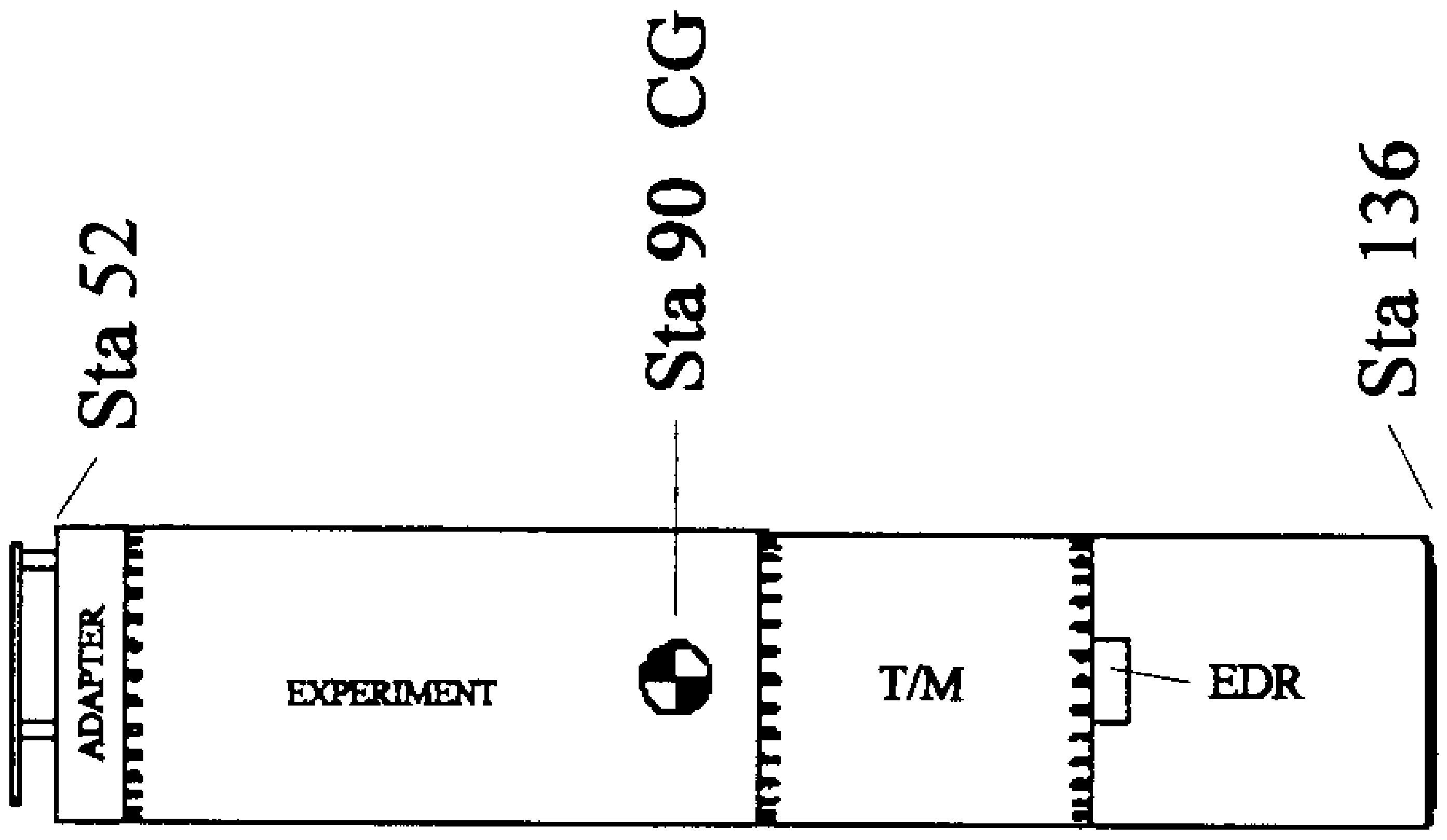


Figure 2: 31.107 UU and 31.108 UU Recovery Configuration. $I_{roll} = 3.92$ sl-ft^2 (5.3 kg-m^2) $I_{pitch} = 65.7$ sl-ft^2 (89.1 kg-m^2)

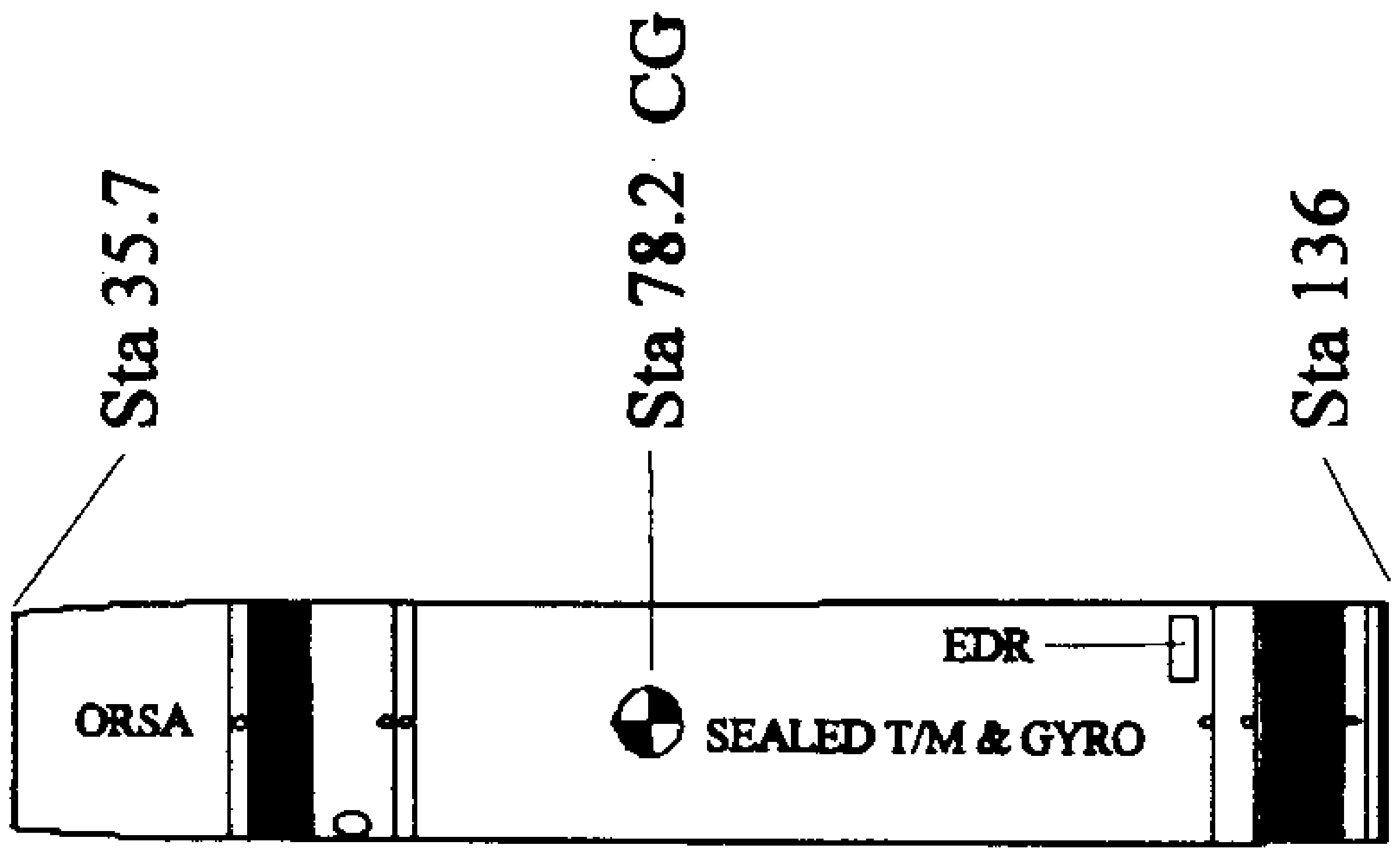
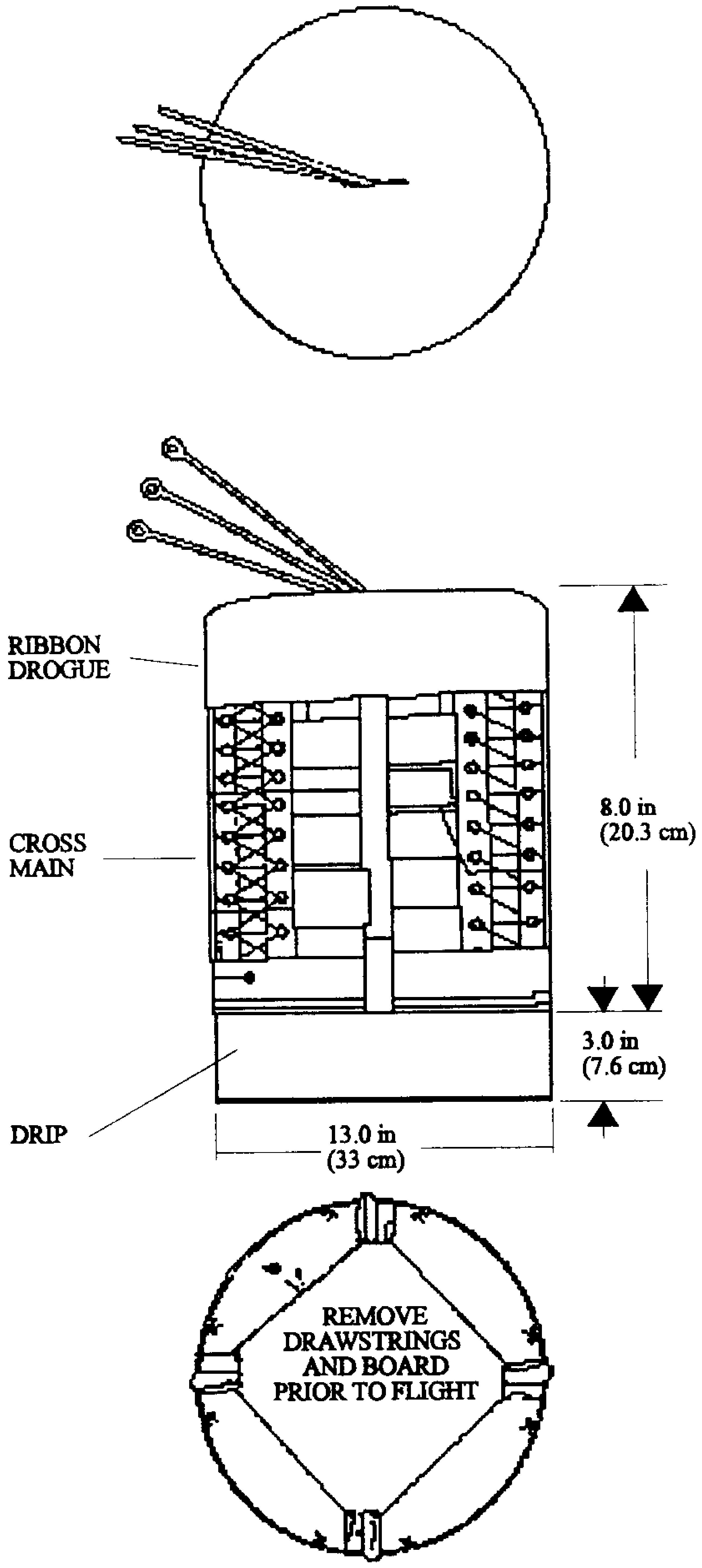


Figure 3: 12.046 WT Recovery Configuration. $I_{roll} = 2.88$ sl-ft^2 (3.9 kg-m^2) $I_{pitch} = 60.8$ sl-ft^2 (82.4 kg-m^2)



REMOVE DRAWSTRINGS AND BOARD PRIOR TO FLIGHT

Figure 4: Packed Overwater Recovery System for a Buoyant Payload

PLANFORM

INFLATED PROFILE

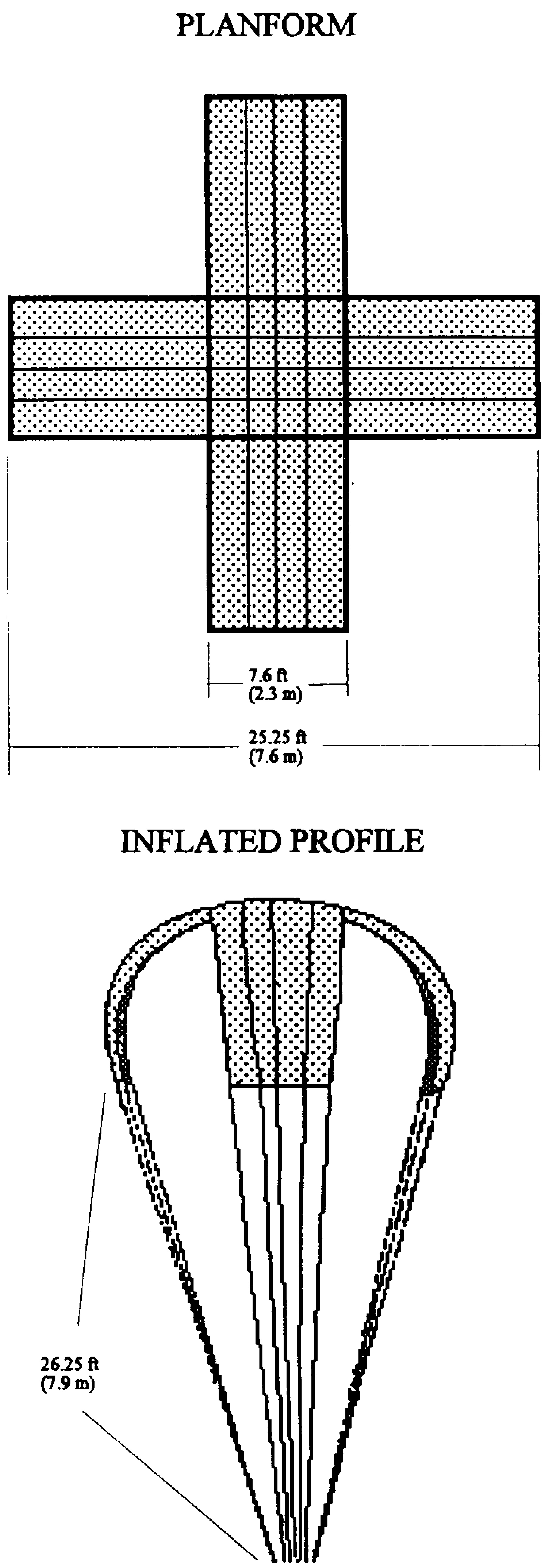


Figure 5: Nylon Cross Main Parachute

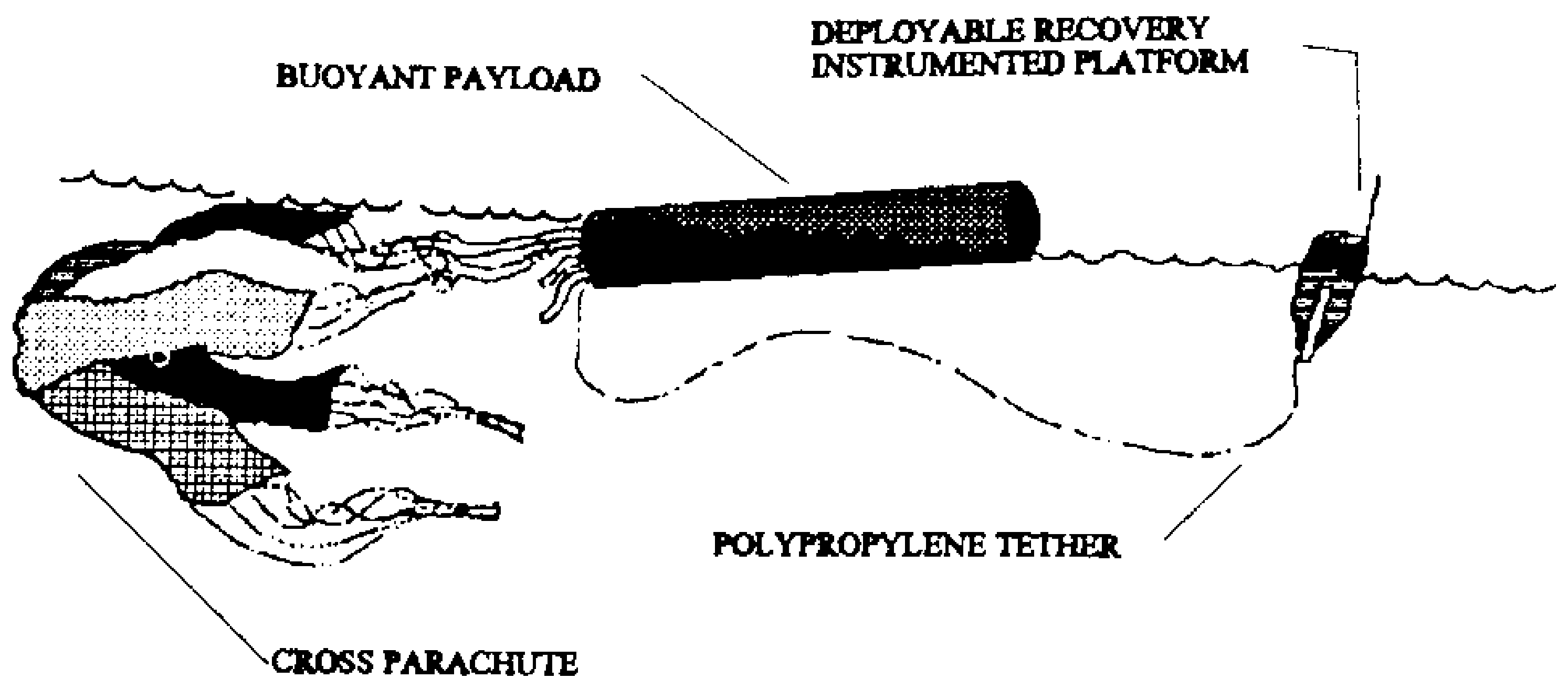


Figure 6: Schematic Showing Deployed Recovery System

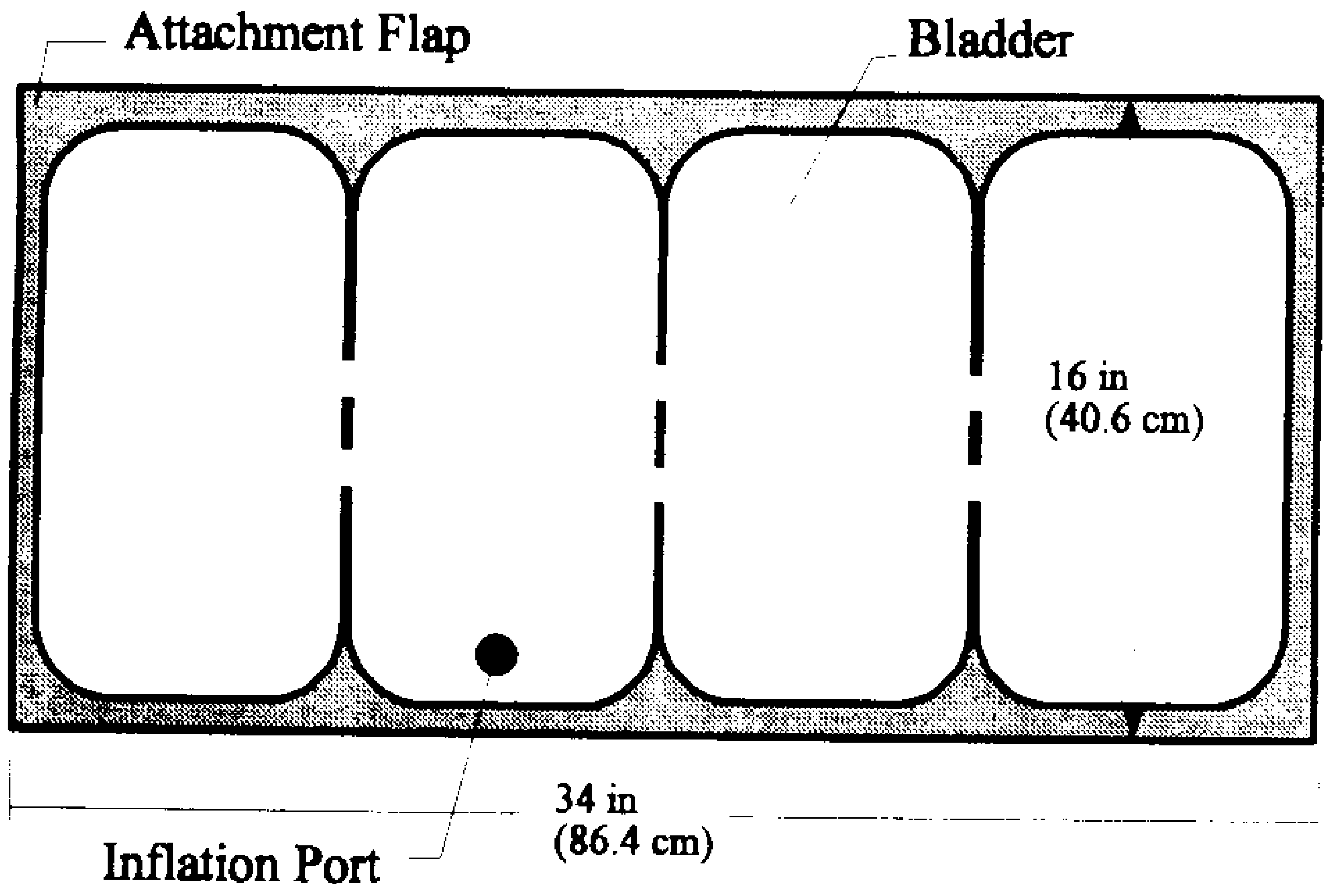


Figure 7: Schematic of DRIP Construction

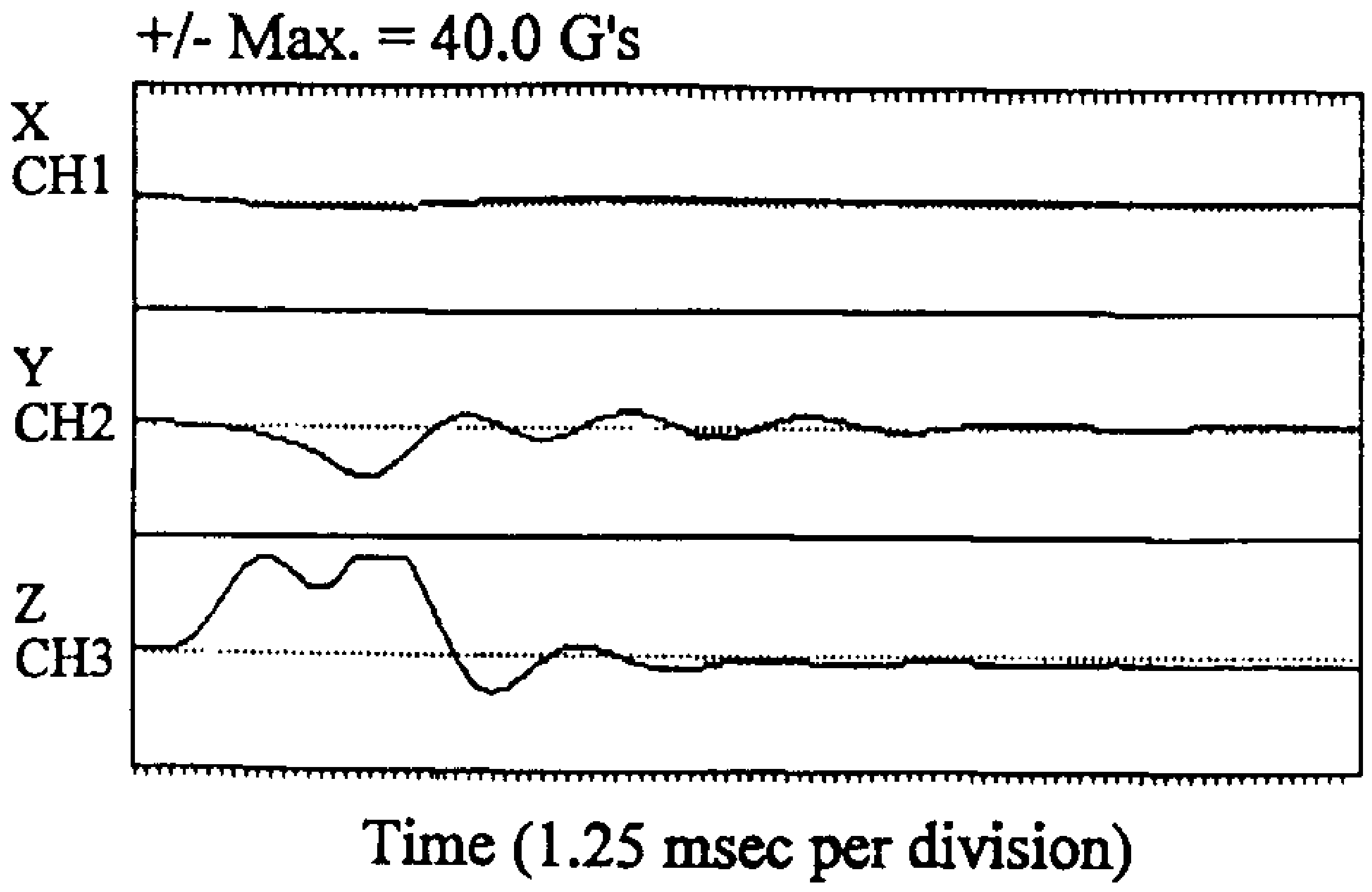


Figure 8: Three Components of Acceleration Obtained from 31.084 UU

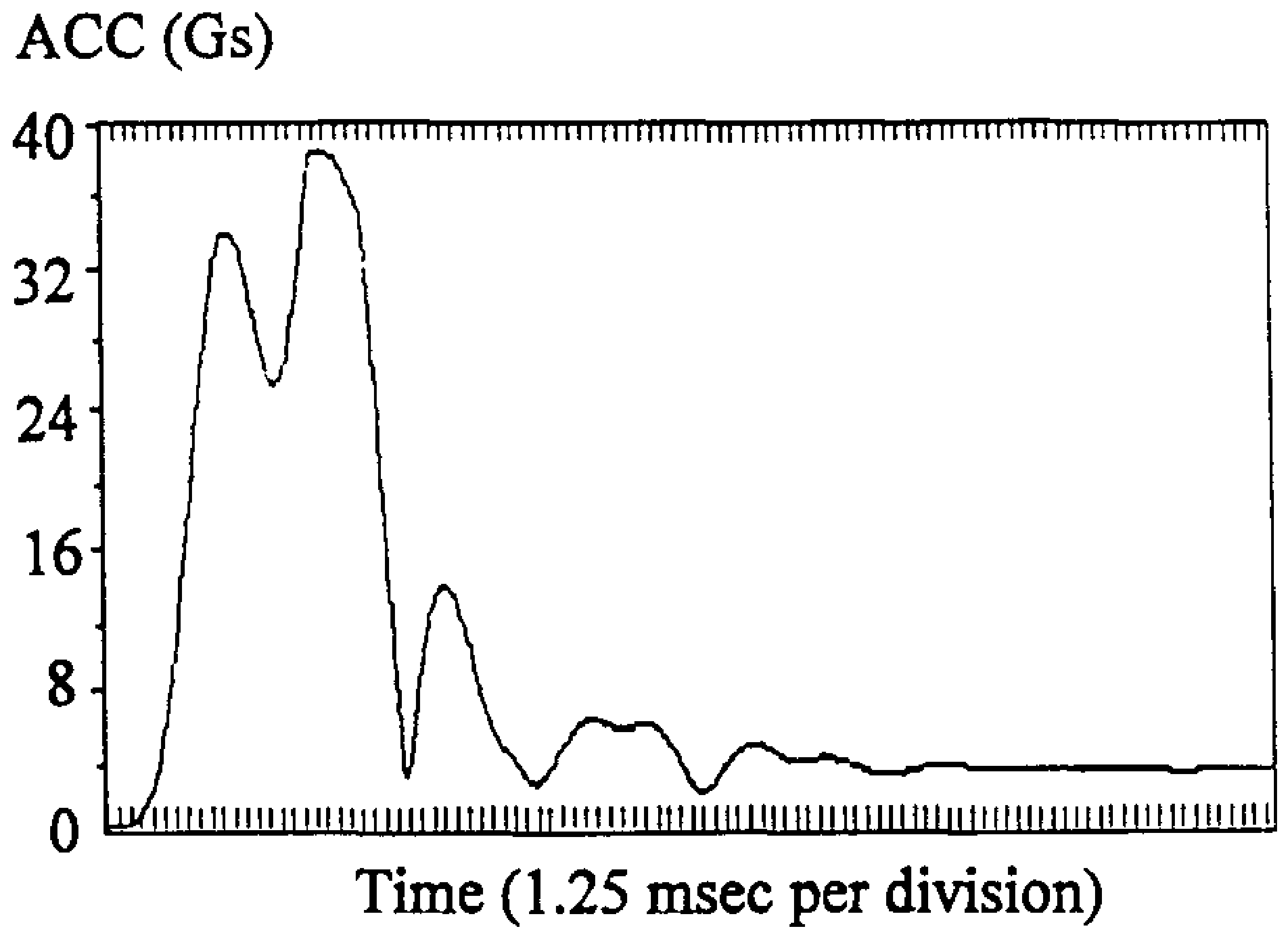


Figure 9: Resultant Acceleration Obtained from 31.084 UU

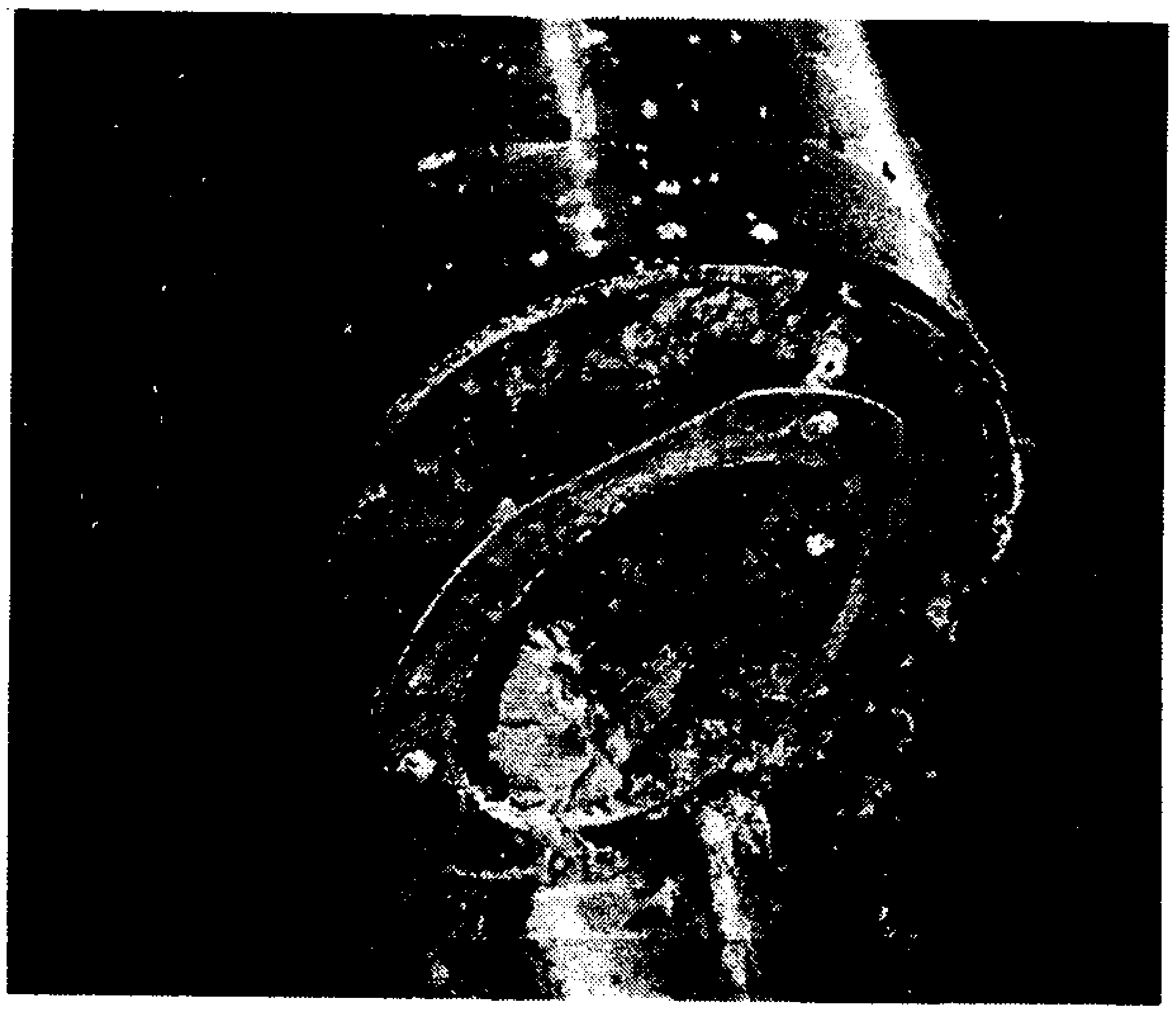


Figure 10: Crush Ring Damage on 31.084 UU

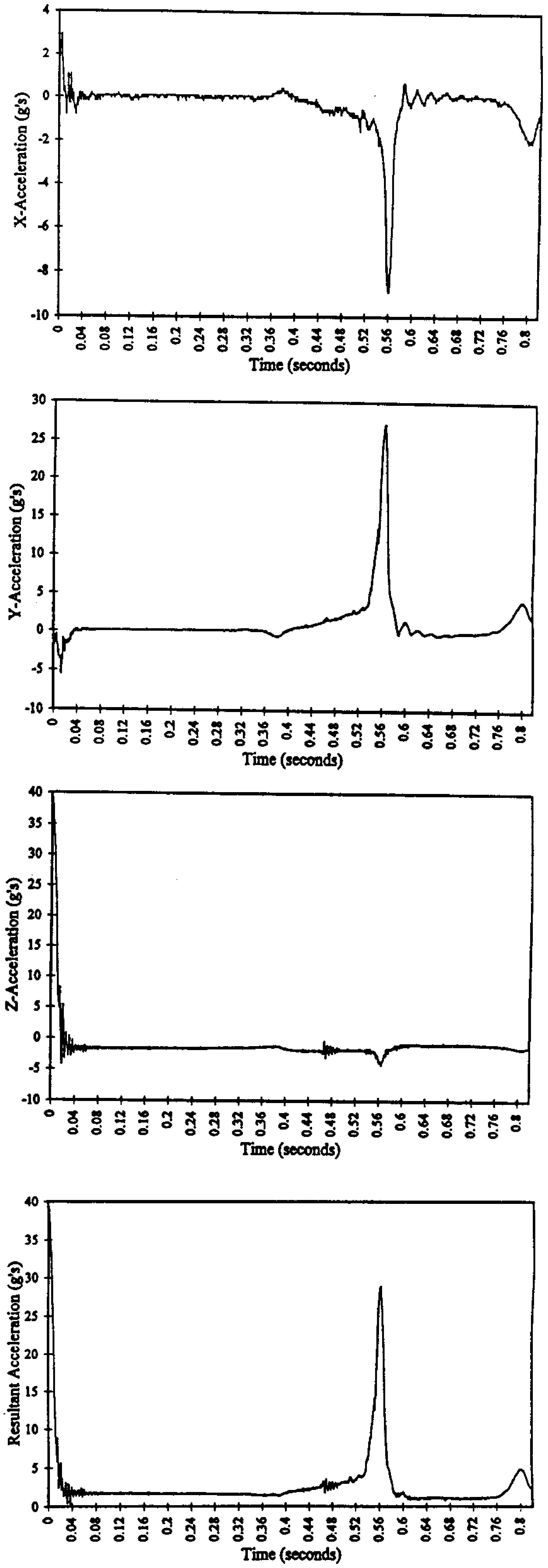


Figure 11: Component and Resultant Deceleration Histories for 31.107 UU

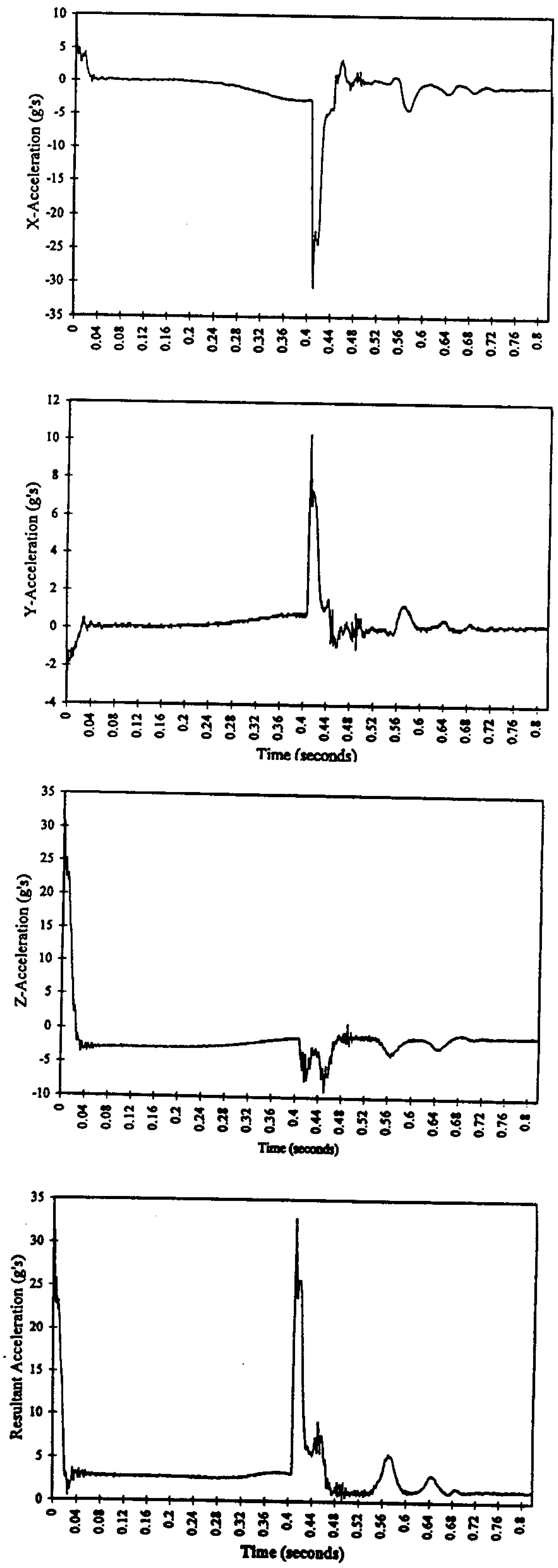


Figure 12: Component and Resultant Deceleration Histories for 31.108 UU

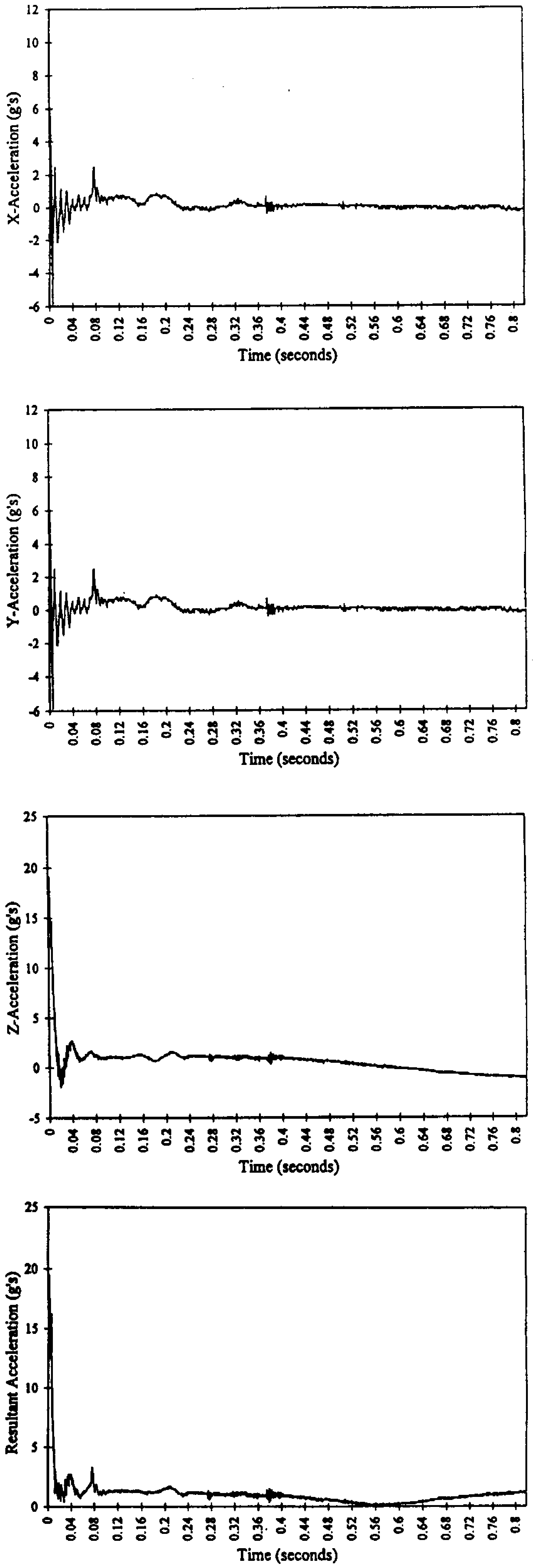


Figure 13: Component and Resultant Deceleration Histories for 12.046 WT