TELEMETRY FOR 250,000-G GUN ENVIRONMENT

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Summary Techniques for packaging telemetry components and systems to withstand gun launch accelerations up to 250,000-g are discussed, and the necessary and sufficient conditions for survival are established. The principal requirements are that all voids be eliminated from the package and that encapsulating resins be adequately contained. The ultra-high-g projectiles used in hypervelocity research for which these telemeters were designed are briefly described. In addition, a brief description is given of high-g telemetry systems used in the gun-fired rockets and projectiles of project HARP.

Introduction In recent years aerodynamic research has progressed to the point where wind tunnels cannot provide air flows of sufficiently high velocities and pressures. Therefore, test vehicles must be flown through a free flight range and the desired data, such as temperature measurements, electron density determination, and infrared attenuation must be telemetered. To obtain the required velocities, accelerations as high as 250,000-g may be required. Under sponsorship of the Ballistic Research Laboratories at Aberdeen Proving Ground, the Harry Diamond Laboratories, a segment of Army Materiel Command, has developed several onboard telemetry systems to transmit the required data from such hypersonic projectiles during flight.

Some of the projectiles involved are small. Figure 1 shows a model reentry vehicle, the GE type 3.1 design, which is a high-drag shape. This round is launched from a 105-mm smooth bore gun with discarding sabot at muzzle velocities up to 8000 fps, with peak launch acceleration of 250,000-g. A thin-film platinum resistance thermometer is mounted in the nose to measure heat transfer into the surface of the structure from the stagnation region. It is of incidental interest that these rounds have been fired through a horizontal test range several hundred feet long and recovered from a flat, grassy impact field. Due to high drag with consequent low impact velocity, some of the projectiles have been recovered and fired again, with electronics still operable.

Figure 2 shows an RVX shape, which is also fired horizontally to obtain basic aerodynamic research data. An accelerometer is mounted transversely in the aft section of this model to measure in-flight pitch and yaw. This cone-cylinder-flare configuration has been fired successfully from a 240-176-76-mm light gas gun with propellant powder in the 240-mm section, a plastic piston for driving helium in the 176-mm section, and the projectile with sabot in the 76-mm section. This gun produces muzzle velocities of 12,000 fps with setback acceleration of 250,000-g for a longer period than the ordinary powder gun. In addition, higher time derivatives of distance, such as jerk, are present to a greater degree.

In addition to telemeters for these range-fired projectiles, the Harry Diamond Laboratories has designed telemetry systems for vehicles fired vertically for the High Altitude Research Probe Project (HARP). One of these is a dart fired from a 5-in. gun by chemical propellant. Figure 3 shows this low-drag shape which travels to 250,000-ft altitude. Muzzle velocity is about 5000 fps with setback acceleration in the gun of around 60,000-g.

Figure 4 shows a larger vehicle fired vertically with discarding sabot from a 16-in. smooth bore gun. In addition to these projectiles, telemetry has been installed in several types of gun launched rockets. These were single-stage rockets fired from a 16-in. gun at a muzzle velocity of about 4000 fps. These rockets and projectiles reach altitudes up to 400,000 ft. Figure 5 illustrates an early version of this type vehicle.

The total number of these various rounds fired is small, but operation of the telemeters to date has been quite satisfactory. The small reentry shape described previously has been fired 24 times. Data were received from all of the 20 rounds that successfully traversed the range. The round with the accelerometer has been fired only twice with telemeter on board, and some information was received both times. A total of seven of the 5-in. gun rounds has been fired; data were recovered from six. Of eleven 16-in. gun vehicles successfully launched, data were received from eight. It should be emphasized that little or no flight testing of the telemeter was possible prior to final fabrication.

Techniques Experience with radio-type proximity fuzes has shown that it is possible to fire electronic assemblies from a gun and have them operate afterward. However, the techniques employed previously are not suitable for the more severe environmental conditions encountered in these high-velocity aerodynamic research vehicles.

The problem of electronic system survival under these conditions can be divided into two somewhat related parts. First, the individual component must withstand the forces encountered; and second, the component must be supported so that its inherent ruggedness is not compromised. Previous experience had shown that vacuum tubes would not survive the expected shocks; therefore, transistors, being solid, were the only hope for an oscillator for this environment. Previous tests had indicated, however, that transistors, as a class, are marginal even for conventional gun setback forces, with survival reliability being questionable at 20,000-g. Therefore increasing the inherent ruggedness of transistors is required for a 250,000-g environment. At this point let us digress a bit and consider what we know or can postulate about the fundamental aspects in the ruggedization of electronics.

First, let us think of all solids as being springs. Second, since breakage of things requires separation of molecules, we recognize that things cannot break in compression. Compressive forces can cause things to break in tension or shear, but pure isostatic compression cannot rupture a solid object. Although an object cannot be broken by isostatic compression it can be affected. For example, the phase of a material could change, such as, ice to water; a spring can compress and become smaller, which affects its performance; the resistance of an ordinary carbon composition resistor decreases when subjected to an isostatic compressive force; the capacitance of ceramic and glass dielectric capacitors increase when made smaller by a compressive force uniformly surrounding the component envelope.

Now let us consider what the structure of a ruggedized electronic package should be like. From our discussion above, we can conclude that tensile strength of the various components such as capacitors and resistors is much less than their ultimate compressive strength. Therefore, our structure should support the components to minimize tensile forces, both direct and indirect. Examples of indirect tensile forces are those developed radially when a right circular cylinder has a force applied to each end. The tensile strength required may be minimized by providing adequate hoop strength to contain it radially. Similarly, an electronic assembly may be potted with a material that contains each component in all directions. Then if we form this potting material in a solid cylinder and provide sufficient hoop strength to prevent radial stress in the cylinder from exceeding its elastic limit, then the electronic assembly should be satisfactorily contained. Most practical projectiles are more than two calibers in length; therefore, the shape we expect to have for the electronics is a long cylindrical cavity. Furthermore, structural requirements on the shell itself to prevent collapse in the gun tube are likely to provide adequate hoop strength and rigidity to prevent fracture of the potting material. One exception to this configuration is the one first mentioned, the GE 3.1 high-drag reentry shape. The length of this projectile is about the same as its diameter, and there is no steel shell surrounding it. In this case the shell is composed entirely of the potting material with a steel windscreen to prevent burning in flight. The mechanical hoop strength of this projectile is provided by the gun barrel itself, with forces being transmitted and distributed by a plastic launching sabot.

It is believed that there are three first-order effects due to high-g acceleration of a potted electronic assembly. One of these is the hydrostatic pressure generated during acceleration by elastic flow of the potting material. This pressure probably cannot be avoided. It can be reduced somewhat by using low-density casting resin, such as those incorporating glass microballoon fillers but the density can not be reduced very far without unacceptable loss of shear strength due to the hollow filler balls. Another possibility for reducing this load is shortening column length by introducing steel bulkheads across the axis to support several short columns instead of one long one. This method has the obvious disadvantages of taking a lot of space.

A second effect is compression waves generated by the fast rise time of the pressure pulse driving the projectile. This effect is particularly large for guns that rupture a diaphragm and permit a heavy shock wave to impact the projectile. These compression waves are transient; and should not affect data transmission unless in-barrel telemetry is required. Moreover, they should cause no permanent damage. However, tension waves develop at discontinuities, which reflect a portion of the compression wave energy, and these can cause permanent damage. To minimize damage from these tension waves, the shock waves must be attenuated or discontinuities eliminated.

A third adverse effect develops when acceleration is acting, due to density difference between component and potting material. If the component is heavier, the force tending to make it sink through the potting material is proportional to acceleration times density difference. This force can be reduced by using a potting material of greater density, since electronic parts are usually more dense than casting resins. The need for heavy potting material here is contradictory to our previous desire for low-density medium but it is felt, without direct corroborating data, that heavy potting material is usually better than a low-density material, if adequate container hoop strength is provided.

At this point let us summarize the requirements of the potting materials. In the first place, the potting material prior to curing must be a low-viscosity liquid in order to flow into cracks and crevices. Furthermore, this liquid must have high wetting ability, and must creep into fissures, pushing air out as it goes in. Molten waxes meet these criteria, but are unsuitable because of high shrinkage. When the circuit is potted in the containing cylinder, this high shrinkage often causes the hardening material to pull away from the walls of the container instead of reducing the level of the potting material. Such voids would permit development of high radial tensile forces and are thus unacceptable. We therefore can add high adhesive force to the list of requirements for our potting resin, the idea being that good adhesion helps prevent shrinkage voids. These requirements bring the epoxy and polyester polymers to mind, both of which are usable without high temperature curing. The polyesters exhibit less shrinkage than epoxy, and, in addition, are lower in cost and release less heat while curing. Their adhesive and wetting properties are poor compared with those of epoxy, however, and the epoxies are therefore considered superior. One other feature that is required is ease of use. A projectile telemeter of the kind used here may be fabricated in steps that require potting to be done in several stages from individual component through subassembly to final assembly. A potting material such as NBS casting resin, which requires a number of chemical steps for completion, is highly undesirable since electronic engineers and technicians must be able to handle the necessary chemical steps without difficulty.

Another significant factor for some applications is dielectric constant and loss factor for high-frequency current. NBS casting resin is superior in these respects but even so) the difficulties involved in its use makes one willing to accept the higher loss factor of more conveniently used material.

Considering these factors, it appears that epoxy resins are most nearly suited for these applications. Even so, they exhibit several undesirable characteristics such as considerable heat release during curing, large loss tangent, and brittle fracture at relatively low stresses. By addition of appropriate modifiers and additives, however, this class of resin works quite well for ruggedizing electronic assemblies for a quarter million g. A modifier to increase impact strength was necessary to obtain intact launch of the small high-drag shape mentioned previously. A 60:40 mixture of epoxy and polysulfide rubber resins was found to be satisfactory. This mixture has an impact strength a factor of ten larger than that of the epoxy. The polysulfide rubber modifier copolomerizes with the epoxy to produce a tough, slightly flexible resin, which has other significant advantages. The exothermic reaction is reduced so that larger sections can be potted. More important, the residual internal stresses, as disclosed by polariscopic examination are essentially eliminated, whereas epoxy resins generate severe internal stresses while curing.

Use of another additive has significantly alleviated other shortcomings inherent in the straight epoxy resins. For casting large sections, a silica filler is added, but not in the usual manner; 20-30 mesh Ottawa silica is used, in a quantity of four parts by weight of silica to one part of resin. The desired mixture is a resin completely saturated with the silica or expressed differently, a potting material composed of sand with the interstices between grains filled with resin. Mixing is accomplished in two ways, one, by pouring resin into the cavity, then sprinkling with sand which sinks to the bottom. With the full amount of sand added, the level is raised by a factor of about three. The second way is to pour the cavity full of sand, then pour resin over the sand. If the bottom is vented so that air can escape, by a small hole or by a tube extending to the atmosphere, air pressure of 15 psig will force the resin down through about 20 in. of sand before it thickens too much for further wetting. The net result is a concrete with density about 2.1 gm/cc, which has a coefficient of thermal expansion more nearly matching that of the embedded parts, lower loss tangent for high frequencies, and greatly reduced exothermic reaction so that large castings can be cured rapidly at room temperature without reaching excessive temperatures. In addition, the residual stresses due to curing are substantially reduced. This capability for casting large volumes is quite desirable in cases like the rocket shown in Figure 5, which contains over a gallon of potting material.

A third additive has been used for yet another property. The RVX shape shown in Figure 2 is also composed mostly of potting material. This being the case, the epoxy modified with polysulfide rubber was not strong enough to withstand launch. Therefore, the resin body was reinforced with an outer shell made of fiberglass-reinforced resin. These were launched successfully demonstrating the very high strength of this composite material. Shells reinforced with roving, tape, and mat were all satisfactory.

Electronic Components Several years ago, provision of sufficiently rugged transistors was the most pressing problem. High-frequency devices were available only in germanium, and since none of these were potted by the manufacturers, it was necessary to develop techniques to internally pot available transistors. One basic technique of value is to adjust the coefficient of thermal expansion of the potting material to more nearly match that of the wafer material. A mixture of fine-mesh silica and epoxy may be used for this purpose. Another technique that worked very well on the 2N502 was to precoat the inside surfaces with a thin film of silicone oil. This helped prevent contamination of the germanium by the amine catalyst. This coating does not cause the wafer to break at 250,000-g, and, in fact, it is felt that it improves the ruggedization of potted components. The situation today is much better, since all silicon devices seem to be largely undamaged by the direct application of epoxy resins. Such potted transistors may not survive extensive temperature cycling, but have proved adequate for these applications. In addition, there are at least two commercially available transistors that are potted as supplied. Further, there is a high-frequency high-power transistor that has survived 50,000-g impact tests as supplied. It is not potted but is reported to have aluminum lead wires inside instead of the usual gold, which has a much lower strength-to-weight ratio. Carbon composition resistors of various ratings have been successfully used, ranging from 1/10 to I watt. Limited data have shown a 2-percent shift in value for a 250,000-g launch acceleration. To date only solid resistors have been used'. but recent laboratory tests show that the resistor formed on a glass tube with molded case has about 1/3 as much shift in resistance due to hydrostatic load. Film resistors and potentiometers have not been evaluated. Laboratory tests show about 21 percent change in resistance for the solid composition resistor for 10,000 psi isostatic load, and about 7 percent change for the glass-tube composition resistor.

A variety of ceramic and glass dielectric capacitors have been used successfully. In fact, no failures due to capacitors or resistors have occurred to date. Failures have been reported due to wet-type tantalum capacitors. We have successfully flown the dry slug-type tantalum with vacuum applied conformal case, without gross failure. There seems to be some question remaining about their stability under conditions of heavy g-loading.

One electronic component likely to be ignored is connecting wires. For example, a piece of copper wire 1/2 in. long supported axially by one end would develop breaking stress at 250,000 g without support from the potting resin. For this reason, all spaghetti is avoided and only magnet wire or bare copper is used for this g level. If a long axial run is necessary, the wire is spiraled or bent back and forth ladder fashion so the resin can provide adequate support without relying too heavily on its adhesive Properties. Coaxial cable should not be used for long axial runs since the adhesion between center conductor and insulator is usually poor. Connectors of course are not used, but circuit boards with either printed wiring or terminal construction have been used. It is believed that orientation of components or type of layout is not critical.

Several sizes of mercury cells have been used as power supplies, without known failures, except for usual shelf-life or temperature extreme problems. There is some slight evolution of gas from these, however, which may crack or craze the resin after some months on the shelf. Nicad button cells have been used for 20,000-g applications and have been tested satisfactorily at 50,000-g. We plan to use small cells of this type for 250,600-g applications.

Antennae are a problem that must be solved within the boundary conditions imposed by the individual vehicle configuration, which is predetermined by aerodynamic and mechanical requirements. The antenna for the projectile in Figure 1 is a helix, which occupies the aft end and radiates through the potting resin. This particular resin is quite lossy, but the transmitting range is only a few feet, so the loss can be easily tolerated. The RVX vehicle also required only a short transmission distance and uses a similar antenna. An early version of the 5-in. gun dart used an insulated nose with loading coil to complete a dipole antenna, but was very inefficient due to the large capacitance across the antenna. Later versions use a loaded quarter-wave stub imbedded in a plastic nose. The 250-Mc carrier frequency matches this antenna and good efficiency is achieved, which permits reception over the 50-mile or greater range required. The 16-in. gun projectile also uses a quarter-wave stub antenna, except no loading coil was included, and the length was 14 instead of 8 in. The rocket shown in Figure 5 used a quadraloop antenna, with feed-point near the ground connection.

Conclusion Our experience has shown that it is practicable to ruggedize certain electronic circuits used for telemetering in-flight information from shells launched with setback accelerations up to a quarter million g. The necessary and sufficient conditions are removal of all voids from transistors and other individual components as well as the complete assembly, with replacement by appropriate potting material, and avoidance of components containing liquids. The potted assembly must in turn be supported by a surrounding container of adequate hoop strength.

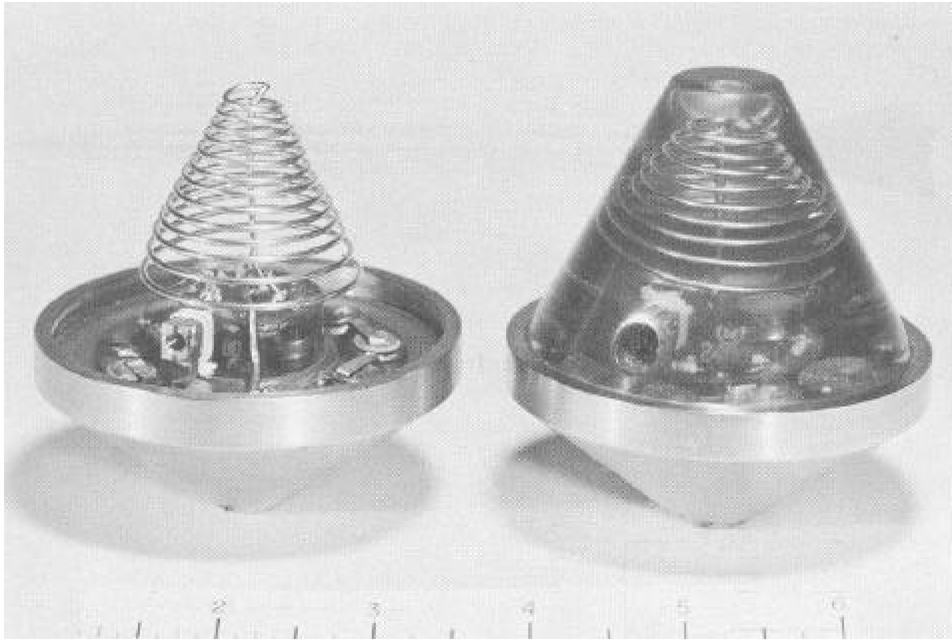

Fig. 1. Model re-entry vehicle before and after potting.

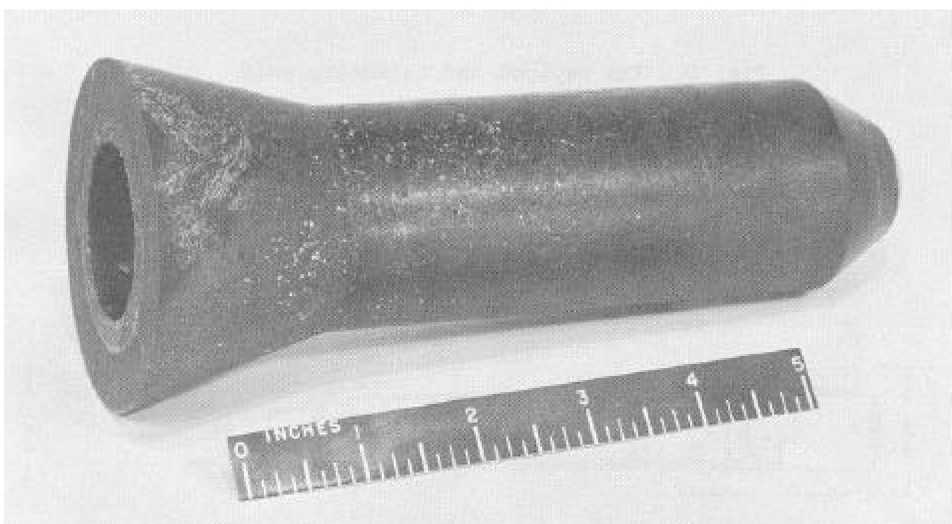

Fig. 2. RVX vehicle

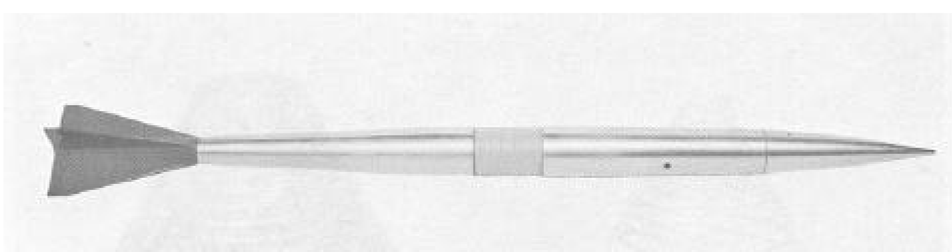

Fig. 3. Five-inch gun dart.

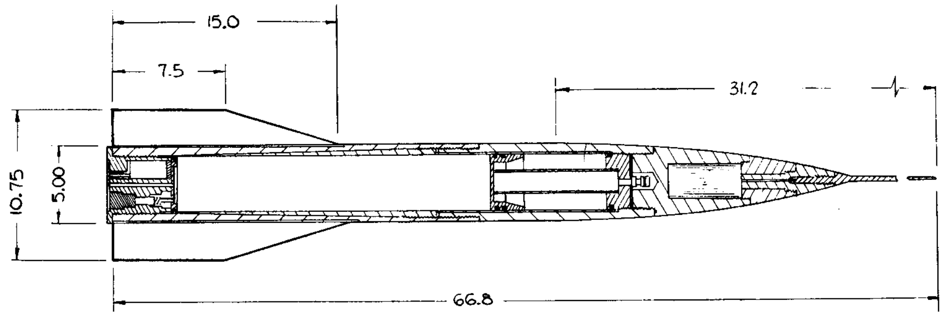

Fig. 4. TMA payload and telemetry unit.

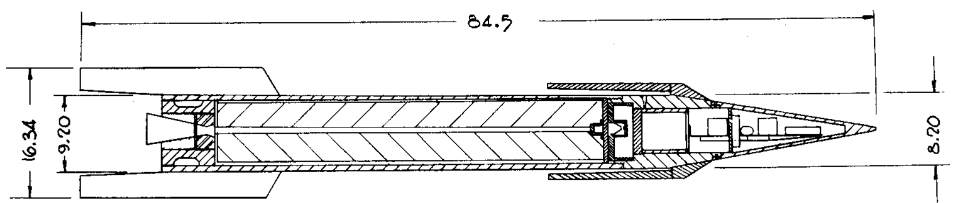

Fig. 5. Rocket vehicle with magnetometer payload and telemetry.

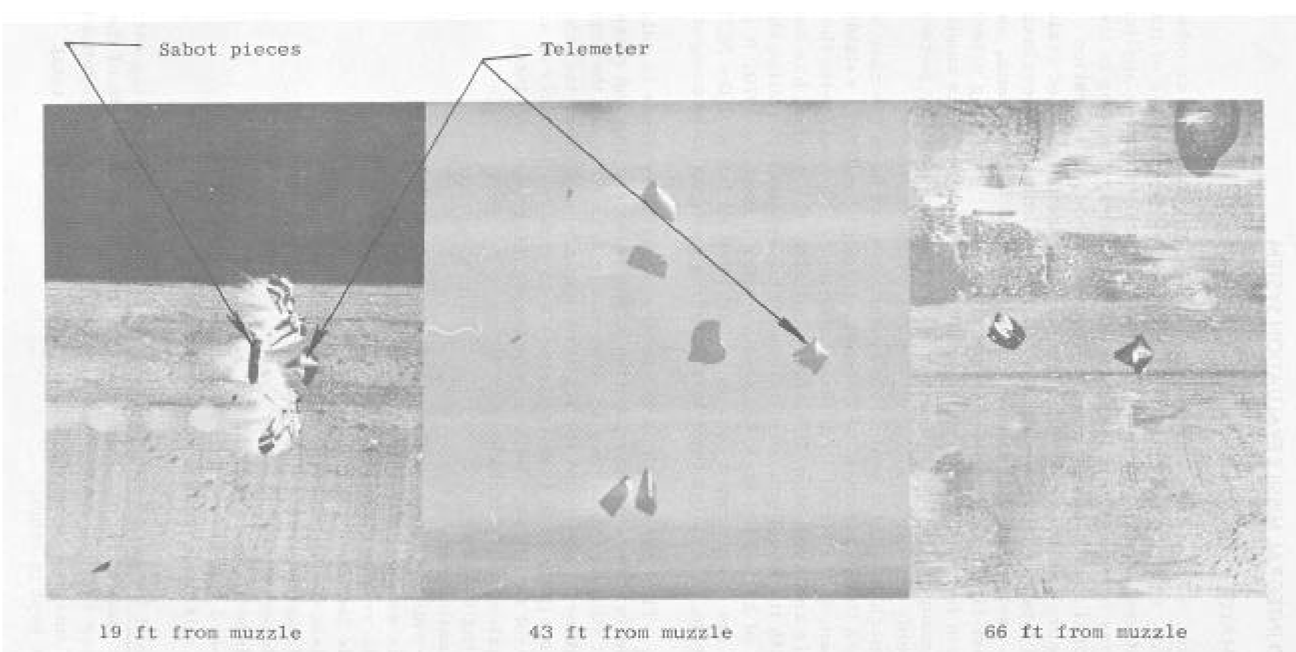

Fig. 6. Missile-sabot separation (smear camera record), launch of temperature telemeter by BRL.