Technical Report No. 32-647

High-Impact Survival

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The objective of the impact survival program is the development of the technology required to design and package electronic equipment to be capable of surviving hard impacts such as could occur in unmanned lunar and planetary landings. The experimental work includes component evaluation, component development, packaging investigations and, incidentally, development of special shock test equipment and techniques. A solid state L-band transmitter was developed which is capable of surviving impacts of 5000 g with a velocity change of 200 ft/sec. It is concluded that it is reasonable to attempt to design lunar and planetary landing capsule systems of moderate size and complexity for survival of impacts of the order of 1000 to 10,000 g-peak amplitude at velocities of at least 200 ft/sec.

Author

I. INTRODUCTION

The development of spacecraft electronic equipment capable of withstanding high shock accelerations can benefit the lunar and planetary exploration programs in several ways. The use of such equipment in capsules intended to survive high velocity landings, although not obviating the need for a landing energy dissipation system (or impact mitigation device), will generally ease the design constraints on that system and lead toward increased overall efficiency of the capsule system. Another application of such equipment is in soft landers, where a hard core could survive an abnormal landing and provide valuable diagnostic information. In other applications, increased reliability of performance after exposure to the normal ground handling and flight environments may be realized.

In 1959, the Jet Propulsion Laboratory (JPL) undertook an experimental program to design and package electronic equipment capable of surviving hard impacts such as could result from unmanned lunar and planetary landings. There was some information available concerning the development of proximity fuzes and projectile instrumentation (Refs. 1 and 2) capable of withstanding extreme mechanical shocks; however, it was thought that this information was not sufficiently complete and that much of it was not applicable to the type of equipment under consideration. In addition, an in-house capability for the design of impact resistant equipment was desired. On the basis of the available information, it was not unreasonable to suppose that a number of equipments could be designed to survive shock accelerations much higher than the commonly specified service environments.

Two aspects of the general problem of hard landing an instrumented capsule have been investigated. The evaluation of certain crushable materials (balsa, honeycomb, and foamed plastics) which might be used for impact mitigation has been completed (Ref. 3). In addition, analytic and experimental work has been done at the Laboratory relating to the design of metal honeycomb type materials for energy absorbing purposes (Ref. 4). A continuing effort has been directed toward establishing the technology required to design shockworthy electronic instruments. The latter has included the evaluation of the impact survival capabilities of certain electronic components, development work toward improvement of the shockworthiness of certain critical components, packaging investigations, and assistance in the development of a prototype impact resistant flight beacon. In addition, it has been necessary to develop special shock test equipment and procedures. Much of this has been reported in JPL *Space Program Summaries* and in internal memoranda. This Report will attempt to consolidate that information, as well as to add new design and test information.

One of the most important results of this investigation is the discovery that it is possible, using conventional components and good packaging methods, to design much of the spacecraft electronic equipment of interest for survival of impacts of the order of 1000 to 10,000 g at impact velocities up to at least 200 ft/sec, and that there are not necessarily severe penalties in other areas for so doing. For example, a 2-w, 960-Mc transmitter has been developed which is capable of surviving 5000 g and which is of sufficiently good design that it is now being planned for use in other applications which do not require this impact survival capability. As a further illustration, the Aeronutronic Division of the Philco Corporation has developed (under JPL contract) a lunar landing capsule (Ref. 5) capable of surviving a 200 ft/sec impact against an unyielding surface. The instrument package in this capsule is designed to survive shocks of approximately 3000-g peak amplitude.

II. HIGH-IMPACT SURVIVAL CAPABILITY IN THE HARD LANDING CAPSULE

The potential benefits from impact resistant spacecraft equipment in providing diagnostic information on soft landing capsules and as contributors toward increased reliability of withstanding normal handling and flight conditions are self evident. With regard to the hard landing capsule, though, it appears that there could be some misunderstanding regarding the nature of the benefits resulting from the design of the instrument package to survive high impact accelerations, or "g-loadings."

Consider an instrument package capable of withstanding a maximum shock acceleration, a, impacting a surface with velocity v, and being arrested. Without regard to mechanisms, it is evident from fundamental considerations alone that: the kinetic energy of impact per unit payload mass which must be dissipated is $v^2/2g$ (gravitational units); the minimum distance in which the capsule may be arrested without exceeding the maximum allowable acceleration is $v^2/2a$ (obtained by stopping the payload with constant acceleration a); and the maximum allowable decelerating force per unit payload mass is simply a/g (which is also the maximum allowable acceleration expressed in gravity units).

Consider an impact velocity of 200 ft/sec. The kinetic energy which must be dissipated is 625 ft-lb/lb of payload mass. If the maximum allowable shock acceleration were 2000 g, the minimum stopping distance would be

3.75 in.; if it were only 200 g, the minimum stopping distance would become 37.5 in. Furthermore, the maximum decelerating forces which could be applied in these two examples would be 2000 and 200 lb, respectively, per pound of payload mass.

In general, the kinetic energy of impact will be dissipated (in vibration, deformation, etc. and, ultimately, much of it as heat) in the instrument package, the impacted surface, and the impact limiter (if any). In practice, it would be considered imprudent to subject the instrument package to the extreme accelerations and deformations that would result from an attempt to rapidly dissipate a large amount of landing energy in it. This leaves the impact limiter and the impacted surface as the principle landing energy absorbing media.

Suppose that the instrument package impacts without rebound against an unyielding surface. With the additional assumption that it is unsafe to dissipate the impact energy within the instrument package, then *the instrument package, no matter how great its shock survival capability, must be protected by some form of impact mitigating device.* The function of this impact limiter is to absorb the kinetic energy of the impacting payload while limiting to a safe value the acceleration applied to the instrument package.

A number of crushable materials have been found to yield at substantially constant pressure for deflections up to a large fraction of their original uncrushed thickness and to exhibit negligible elastic recovery (desirable properties for a material to be used as a "one-shot" impact limiter). Table 1 lists typical properties for certain of these materials under ideal conditions (i.e., when all of the material is uniformly crushed to the point of rapidly increasing load with stroke). It should be noted that most of these data were obtained with impact velocities of approximately 50 ft/sec, and caution should be exercised in applying them to situations involving significantly higher impact velocities.

Table 1. Dynamic properties of typical crushable materials*

Material	Density, lb/ft^3	Specific energy absorption** ft-lb/lb	Crushing strength, lb/in.^{2}	Maximum stroke** (fraction of original thickness)
Styrofoam T-22	1.5	2500	60	0.6
Styrofoam HD-1	3.0	2000	75	0.55
Styrofoam HD-2	4.5	4000	200	0.5
Aluminum honeycomb	8.0	11000	945	0.8
Balsa, end grain	6–12	24000	1500–3000	0.8

**Specific energy absorption and maximum crushing stroke measured to point of rapidly increasing load with stroke.

*Based on impact testing at approximately 50 ft/sec (except for balsa, which was tested up to approximately 200 ft/sec). For a more complete discussion, see Ref. 3.

If the impact limiter were composed entirely of crushable material, and if all of this material could be crushed with ideal efficiency, then the mass of the impact limiter would be independent of the maximum shock survival capability of the instrument package; it would be a function only of the mass of the instrument package, the impact velocity, and the specific energy absorption capacity of the impact limiter material. *It is in actual application, where the limiter is not composed entirely of crushable material, and this material is not used with ideal efficiency, that the advantage of designing the instrument package for the survival of high shock accelerations becomes apparent.*

In general, the known materials which exhibit high specific energy capacity also possess rather high yield strengths and densities. It is evident that the overall impact limiter mass will be less if the shock survival capability of the instrument package is such that one of these high efficiency materials can be employed in a limiter of comparatively thinner section and larger area (where the crushing efficiency may closely approach the ideal) than if one must, in order to protect a more fragile payload, either: redistribute this same high efficiency material into a section of smaller effective area and greater thickness (where column effects will reduce the efficiency); or employ a material of lesser crushing strength (and specific energy absorption capacity) in a section of comparable area but greater thickness.

Consider the normal impact of a 100-lb payload (including impact limiter) at 200 ft/sec against an unyielding surface, and assume that conditions are such that unidirectional protection may be employed. Assuming ideal crushing efficiency and using the data of Table 1, 2.7 lb of balsa would be capable of absorbing the impact energy of 62,500 ft-lb. If the payload could withstand a 2000-g impact, this idealized limiter might take the form of a block of balsa (6 lb/ft^3 density) with an area of 160 in.^{2} and a thickness of 4.8 in. If the payload could withstand only 200 g, this same amount of balsa would have to be redistributed as a column of effective area 16 in.^{2} and length 48 in. Another alternative would be to use a column of Styrofoam HD-1 of area 265 in.^{2} and length

98 in., weighing 31.5 lb. Whereas the 200-ft/sec, 2000-g impact limiter design can be reasonably approached in practice, the two 200-g examples would present rather formidable engineering challenges and, if achievable at all, would undoubtedly leave much less available weight for the instrument package. In addition, the 2000-g capsule would be much more compact and place fewer constraints on the delivery vehicle.

As a further example, it has been estimated that a Mars landing capsule employing an entry body of low ballistic coefficient (0.2 slug/ft^2) for aerodynamic braking might impact with a velocity as great as 450 ft/sec. This is based on the least dense of the current Mars atmosphere models (surface pressure of 11 mbar). This impact velocity represents a kinetic energy of 3140 ft-lb/lb of capsule. Table 1 shows that Styrofoam could not be used as an impact limiting material in this application, but that balsa could (assuming that its low velocity dynamic properties are valid up to 450 ft/sec). If one assumes that the balsa could be used with 50% efficiency, the limiter would comprise approximately 25% of the total capsule weight. If the instrument package were designed to survive 5000-g shock at the assumed impact velocity of 450 ft/sec, the balsa thickness could be of the order of 1 ft. For a survival capability lower than this, the limiter would have to be designed for a longer stroke, with possible conflicts with the requirement for an aerodynamically stable entry body of low ballistic coefficient.

Yet another potential advantage of the instrument package designed for high-shock survival capability is in the possibility that the impacted surface (no longer assumed unyielding) might be used for an impact energy absorber. With adequate knowledge of the mechanical properties of the impacted surface, and with suitable landing constraints, it might be possible to penetrate the impacted surface either with the instrument package or with a landing spike attached thereto and thus use it as an impact limiter. A high-shock survival capability would permit landing on harder surfaces or using a shorter more rugged spike than would otherwise be possible.

III. THEORETICAL BACKGROUND

Although the JPL impact survival program has been primarily an experimental one, a few words of theory are necessary to furnish an appropriate background for the discussion of the design and test philosophy.

A significant amount of analytical and experimental work has been reported concerning the response of mechanical systems (particularly single degree of freedom) to impulse loadings (see Bibliography). Unfortunately, much of this information is of limited application to the calculation of the behavior of mechanical systems of practical interest because of their complexities, the lack of detailed knowledge of the dynamic properties of their component parts, and the difficulty in specifying and accurately simulating the service environment. The available information does permit the analysis of the behavior of some simple systems under idealized conditions and, what is perhaps more important, assists in the qualitative understanding of the behavior of mechanical systems subjected to impulsive loadings and of the consequences of particular types of shock pulses.

It has long been recognized that the specification of a "g-level" alone is insufficient to define an impact shock; additional information is required in the form of duration and pulse shape, or suitable equivalents. There are numerous ways in which the damage potential of a shock pulse or the damage sensitivity of a component may be presented. One of the easiest to understand qualitatively is a concept which is believed to have originated at the Naval Ordnance Laboratory (Ref. 6).

According to this concept, the conditions under which a specimen will or will not be damaged may be presented graphically on a plot of velocity change vs acceleration (as in Fig. 1), where the shape and location of the curve separating the regions of damage and no damage is dependent on the mechanical properties of the specimen (in the given direction of loading) and on the shape of the shock pulse (triangular, half-sine, etc.). Qualitatively, for a given pulse shape and direction of loading, there are two ways in which the specimen may escape damage. The peak acceleration may be so low that the component could withstand its steady application (representing an unlimited velocity change), or the velocity change may be so small that the maximum energy that can be supplied to the component is insufficient to produce damaging stresses, such that the applied acceleration could then be extremely high without causing damage. Under this concept (which can be verified by more sophisticated methods), one must be cautious in extrapolating shock test results to higher velocity changes (or greater durations). For example, while the results of a 1000-*g* 1-msec shock test on a transistor might be equally valid for longer durations, one would not expect the same comparison to be true for a large battery power supply.

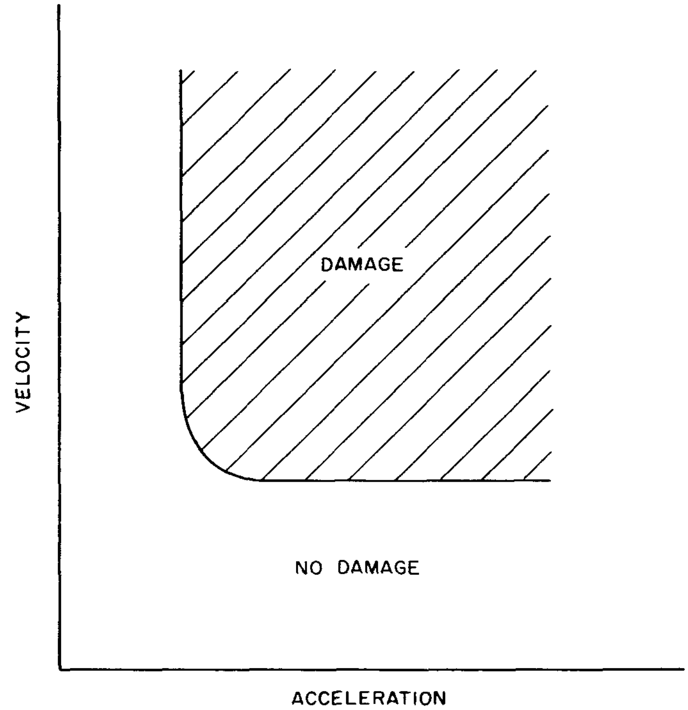

Fig. 1. Shock-damage sensitivity curve

It is also possible in principle to relate the damage potential of a shock pulse to the natural frequencies of the system by means of shock spectrum analysis. Little use of this tool has been made in the JPL experimental program, although there is an awareness of its existence and of some of the general implications that can be drawn from it regarding the significance of pulse duration and shape as related to component natural frequencies.

IV. IMPACT TEST FACILITIES

As explained earlier, the results of shock tests at low-velocity changes can not be readily extrapolated to higher velocity changes. Therefore, because of the need for testing with larger velocity changes than those obtainable from existing Laboratory shock testers, two new machines were constructed and used in this investigation. One is a 45-ft free-fall drop-tester (Fig. 2) and the other a bungee cord-propelled machine capable of producing impact velocities up to approximately 200 ft/sec.

The general method of producing test shocks is the same on both testers. The specimen is mounted on a carriage, a velocity is imparted to this carriage, and the carriage is then impacted against an expendable target to produce the test pulse. Low-level shocks (approximately 100 to 1000 *g* may be generated on the drop-tester by impacting the carriage directly against a suitably-sized block of a crushable material such as foamed plastic or aluminum honeycomb. High-level shocks are produced on both machines by attaching a "penetrating tool" to the carriage and impacting this against a plastically deformable target such as lead or annealed copper. The test acceleration is determined by the combination of target material, penetrating tool diameter, and carriage

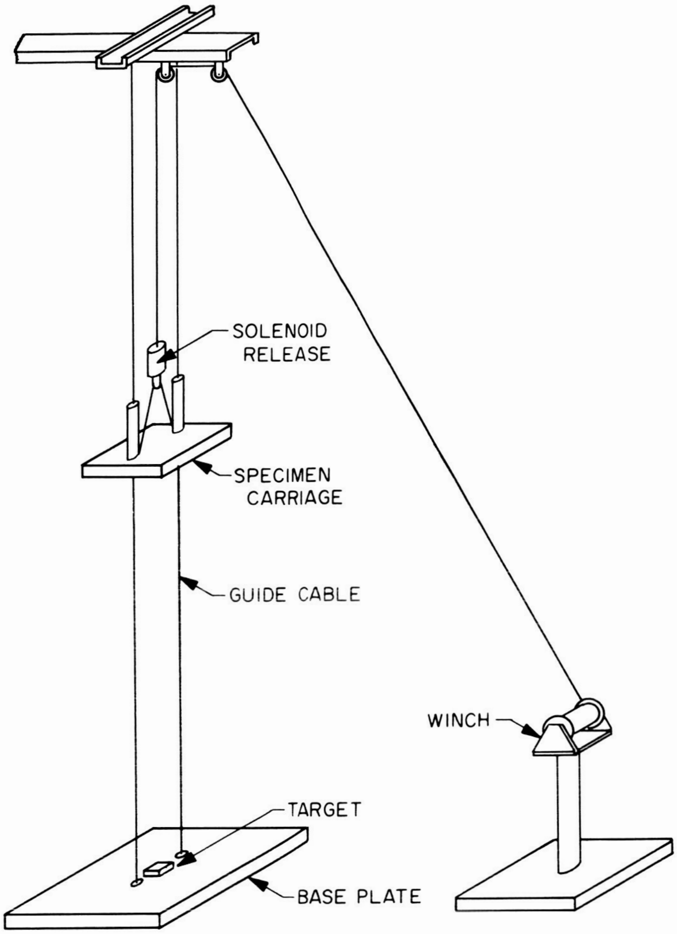

Fig. 2. Drop-test mechanization

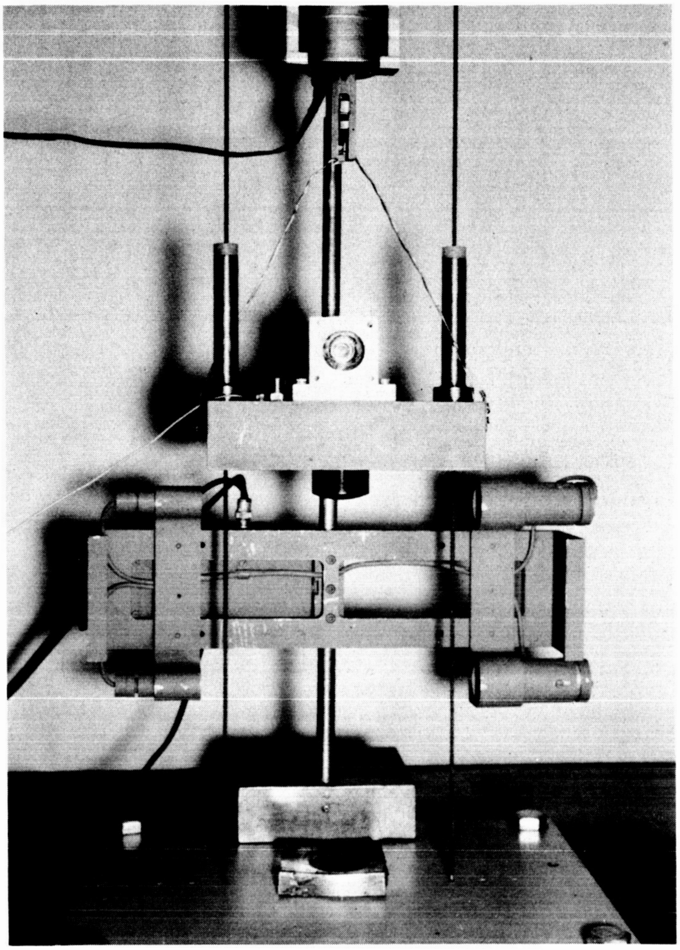

Fig. 3. Drop-tester impact area (following test)

mass (and is, of course, influenced somewhat by impact velocity). Pulse duration is directly proportional to impact velocity and inversely proportional to shock amplitude. No particular attempt is made to shape the shock pulse by contouring the penetrating tool, except in that the tools for the drop tester are "radiused" to provide a somewhat delayed rise. The tools for the other tester are cylindrical, with no "radiusing" of the tip (except for one concave tool which was used with balsa to simulate a lunar capsule impact).

Figure 3 illustrates schematically the 45-ft drop-tester. The elements of this tester are: a 2-in. thick steel impact plate which supports the target and is attached to a massive reinforced concrete block; the specimen carriage; a pair of taut vertical guide wires; and a hoist and release mechanism. Figure 3 shows the details of the impact area. With lead targets and tools from 1¼ to 2½ in. in diameter, the range of performance at full drop height is approximately 900- to 3000-g peak amplitude. Figures 4 and 5 are typical acceleration-time records for these impacts. The constraints which limit this range are: on the low end, the requirement for deep penetration by a small diameter tool; and on the high side, the point at which the pulse width becomes so small that it is no longer considered meaningful. It is possible (by using a material of lesser yield strength than lead, such as foamed plastic) to achieve accelerations as low as approximately 100 g at full impact velocity.

Figures 6 and 7 illustrate the horizontal shock machine, or slingshot, as it is commonly termed. It consists of a specimen carriage, a pair of I-beam guide rails, an impact block, a cocking mechanism, and a release device. It uses 40 ft of ¾-in. D elastic shock absorber cord (bungee), arranged as two parallel strands, for propulsion. Test shocks are produced by impacting the carriage nose (penetrating tool) against annealed copper targets attached to the impact block. The test level is adjusted by varying the diameter of the penetrating tool. Impact

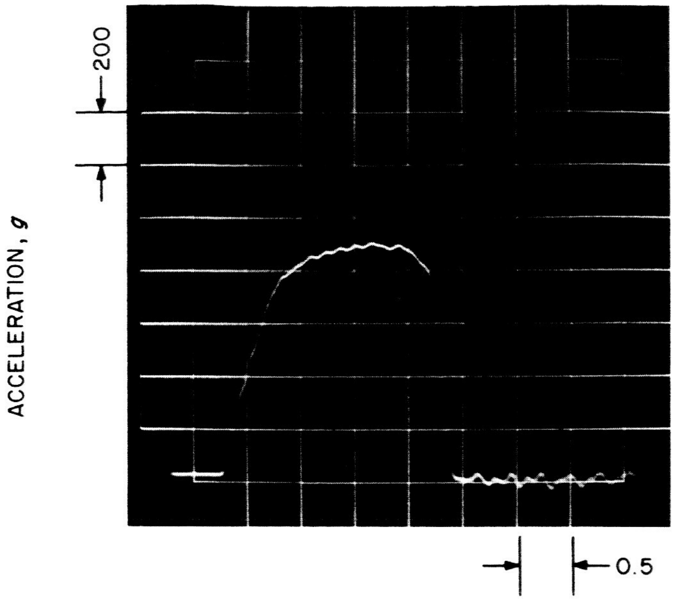

Fig. 4. Typical drop-test acceleration-time history, 1.25-in. D penetrating tool, 1 ⅓-in. lead target

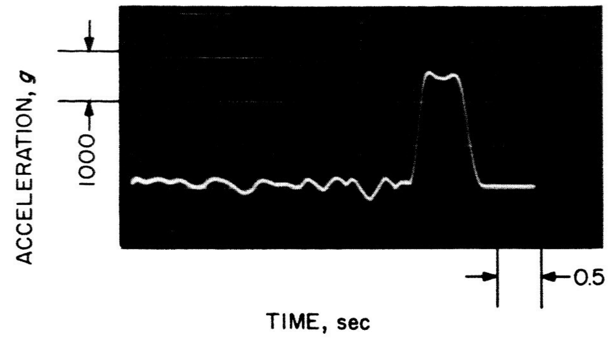

Fig. 5. Typical drop-test acceleration-time history, 2.5-in. D penetrating tool, ⅔-in. lead target

velocity may be varied downward to approximately 100 ft/sec by varying the point of release of the carriage.

The apparatus is supported on four individual concrete blocks. The impact block, which supports the target, is faced with a 2-in. steel plate which is attached to reinforcing rods set in the concrete. Two 4-in. D steel tubes

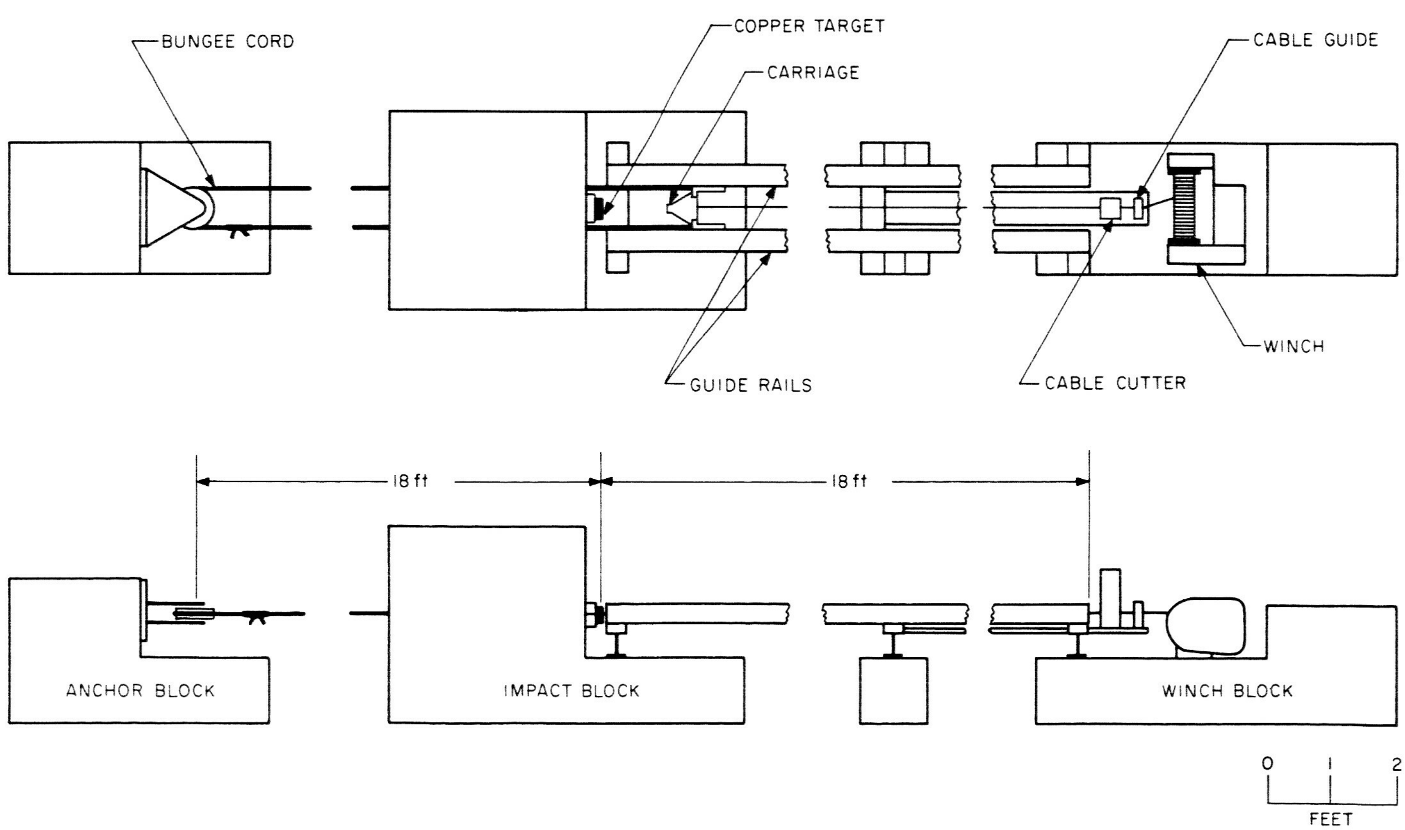

Fig. 6. General configuration of horizontal shock machine

Fig. 7. Horizontal shock tester

pass through the impact block to provide clearance for the bungee cord.

It should be noted that the shock absorber cord is actually a continuous loop passing through the carriage, through holes in the impact block, and around a tension-equalizing pulley attached to the anchor block. Other schemes were considered which would have avoided the requirement for holes through the impact block and which would have reduced the overall length of the apparatus. These were discarded because of complexity, the requirement for a number of unwieldy bungee cord terminations, or the need for pulleys which would have absorbed large amounts of the available energy. This system uses no such pulleys and requires only one simple cord termination, a knot.

The bungee cord weighs approximately 9 lb and is capable of storing (at 80% elongation) sufficient energy to impart a velocity of 200 ft/sec to a total mass of about 13 lb. Approximately ⅓ of the mass of the bungee cord should be deducted from this total to account for its kinetic energy at impact, leaving an allowable mass of about 10 lb for the specimen and carriage if a velocity of 200 ft/sec is to be achieved.

Figure 8 shows the specimen carriage that was designed to provide a specimen mounting area of about 4×5 in. and to possess adequate strength within the weight limitation cited. The main body is of aluminum to provide adequate rigidity without excessive weight. The nose, which must withstand impacts against copper, is of hardened steel. The aft portion of the nose is flared

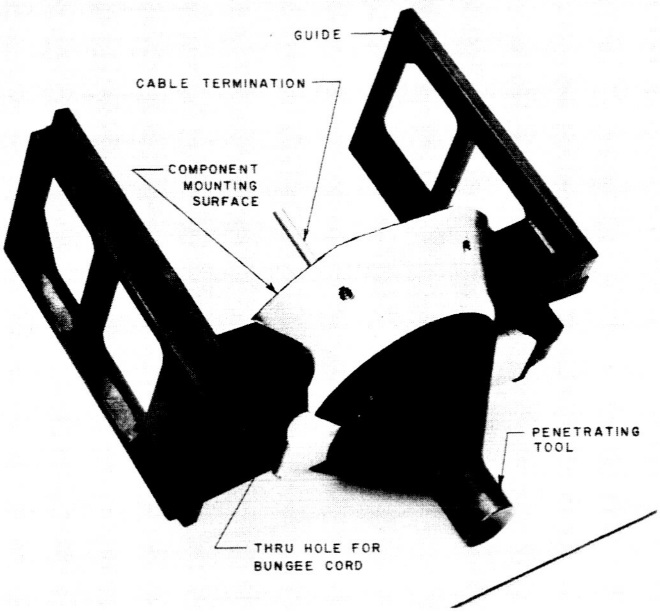

Fig. 8. Horizontal shock tester carriage

in order to distribute the load against the softer main body. Since it was not reasonable within the allowable weight limits to design carriage guides that would withstand the extreme impact loadings, expendable molded plastic guides (which shatter at impact) are used. The complete carriage weighs approximately 6.5 lb.

The hoist cable for cocking the device is fitted with a swedged-on threaded termination. This threaded end is screwed into the carriage (or on occasion, into the component or mounting bracketry). The carriage is then released by cutting the end of the cable, adjacent to the termination, with a commercial cable cutter actuated by a remotely released weight. In this manner, the portion of the release device which remains attached to the carriage is of minimal weight, absorbing very little of the available energy.

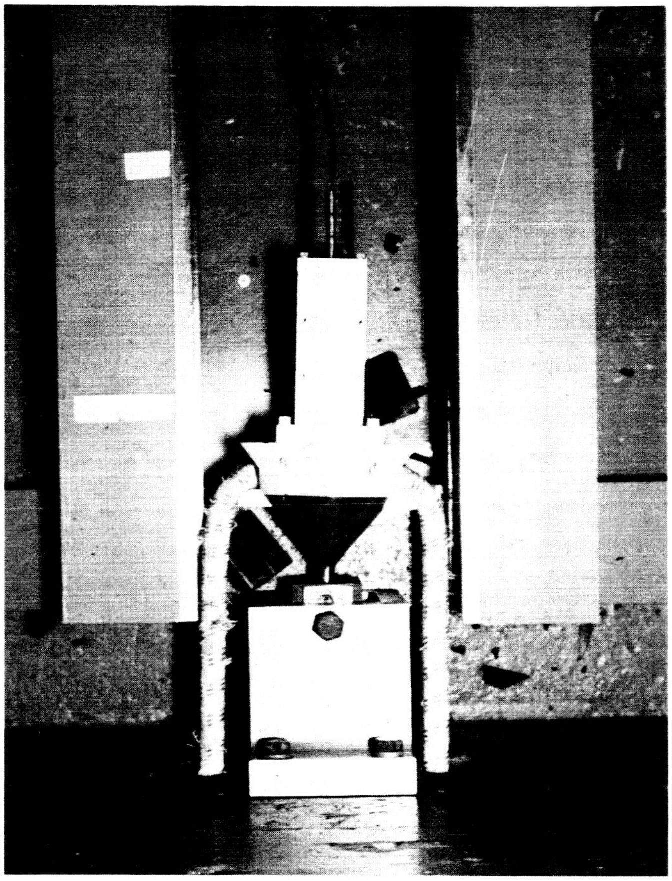

Fig. 9. Horizontal shock tester impact area

Figure 9 shows the impact area of the slingshot following a test. This picture shows the target support block, the copper target with the carriage nose embedded in it, the carriage with the remainder of the broken guides, the rails, and the bungee cord. Table 2 indicates the approximate range of performance of the machine for a fixed carriage mass (including specimen) of 10 lb. It will be noted that the maximum permissible impact velocity with the smallest tool is approximately 100 ft/sec

Table 2. Typical performance of horizontal shock machine*

Penetrating tool diameter, in	Impact velocity, ft/sec	$V^2/2g$, g	Peak acceleration, g	Duration, msec
3/8	100**		3,000	
1/2	100**	3,000	4,500	1.0
3/4	180	8,000	15,000†	0.75
1	180	10,000	20,000†	0.60
1 1/2	180	18,000	30,000†	0.40
2	180	25,000	40,000†	0.30

*Allowance should be made for variations in test conditions.
**Impact velocity with 3/8- and 1/2-in. tools is limited by permissible depth of target penetration.
† Peak accelerations of tests using 3/4-in. and larger tools based on calculated minima plus assumptions regarding relationship between peak and calculated minimum, aided by some partially satisfactory measurements in this region.

(due to limits on the permissible depth of penetration of the target). With the largest tools, the actual peak accelerations are not well known; there are difficulties in obtaining good measurements and these are estimates based on calculated minima and on the few partially satisfactory measurements that have been made. Figures 10 and 11 are typical acceleration-time records of the shocks produced by this tester.

Figure 12 indicates the instrumentation system which is used with both shock-testers. Impact acceleration is obtained from a piezoelectric accelerometer on the carriage via a trailing wire. This signal, taken through a cathode follower to minimize accelerometer loading and thus preserve good low frequency response, after suitable conditioning, is displayed on an oscilloscope. A photoelectric device triggers a single sweep of the oscilloscope just prior to impact and the acceleration trace is then photographed with a Polaroid camera on open shutter. Endevco Model 2215 accelerometers are used for accelerations up to about 2000 *g* and the Model 2225 for accelerations to 10,000 *g*. Calibration is based on the manufacturer's stated charge sensitivity, the shunt capacity across the accelerometer (which is adjustable for standardization), and the system voltage sensitivity. The low frequency response of the system extends to below 1 cps (which is adequate for all normal testing), and the transient response has been investigated with both positive and negative pulses and found to be excellent.

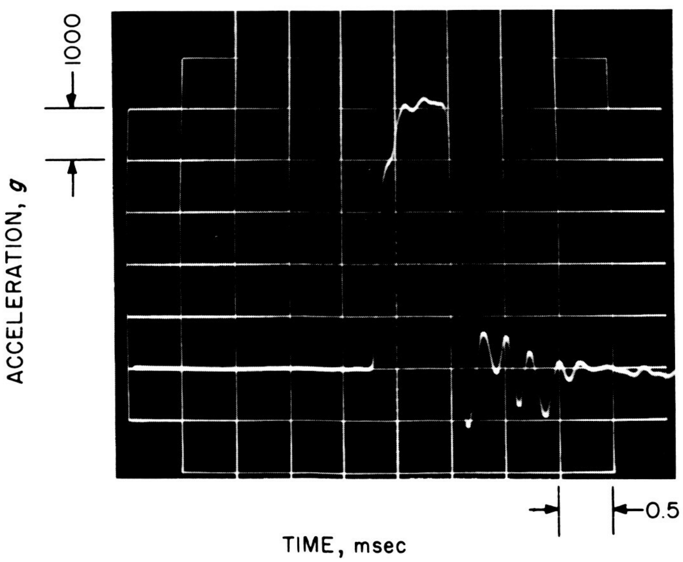

Fig. 10. Typical horizontal shock tester acceleration-time history, ½-in. D penetrating tool, 100 ft/sec impact velocity

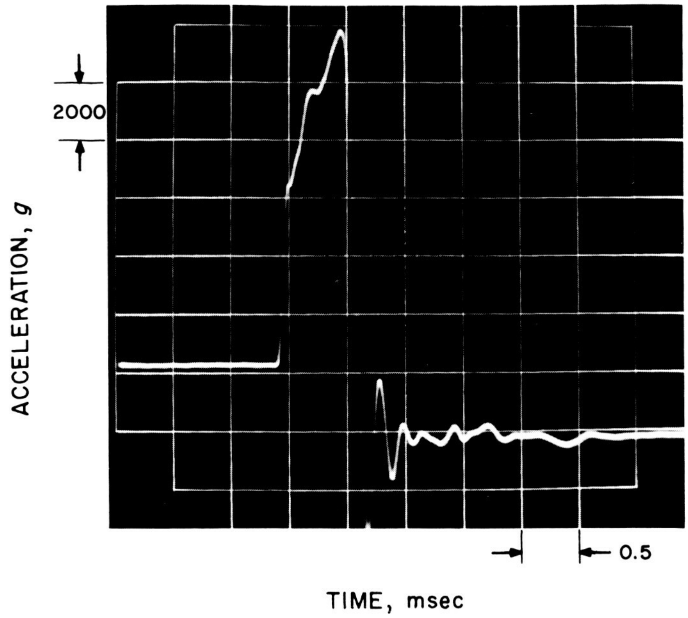

Fig. 11. Typical horizontal shock tester acceleration-time history, ¾-in. D penetrating tool, 1 ½-in. copper target

Impact velocity is determined by measuring the time of flight of the carriage over a 6-in. interval immediately before impact. If the rebound velocity is assumed to be zero, then the area under the acceleration-time curve should equal the impact velocity; this is used as a check on the validity of the acceleration measurement. Also, lacking a satisfactory acceleration measurement, one may establish a lower bound for the peak acceleration based on the measured impact velocity and the depth of target penetration (which is assumed to be the stopping distance of the carriage). The true peak can not be less than the calculated "average" value based on the equation for uniformly accelerated motion, $v^2 = 2as$.

Considerable difficulty has been experienced in obtaining good measurements of accelerations significantly in excess of 10,000 *g*, although various accelerometers with ratings to 40,000 *g* have been tried. The problems included large zero offsets, apparent changes in sensitivity, and accelerometer breakage. As a consequence, much of the information on high level tests has been deduced from impact velocity and depth of penetration measurements, together with assumptions about the relationship of the true peak to the "average" calculated therefrom. A few partially satisfactory measurements have been made in the vicinity of 20,000 g, and these are of assistance in the estimation.

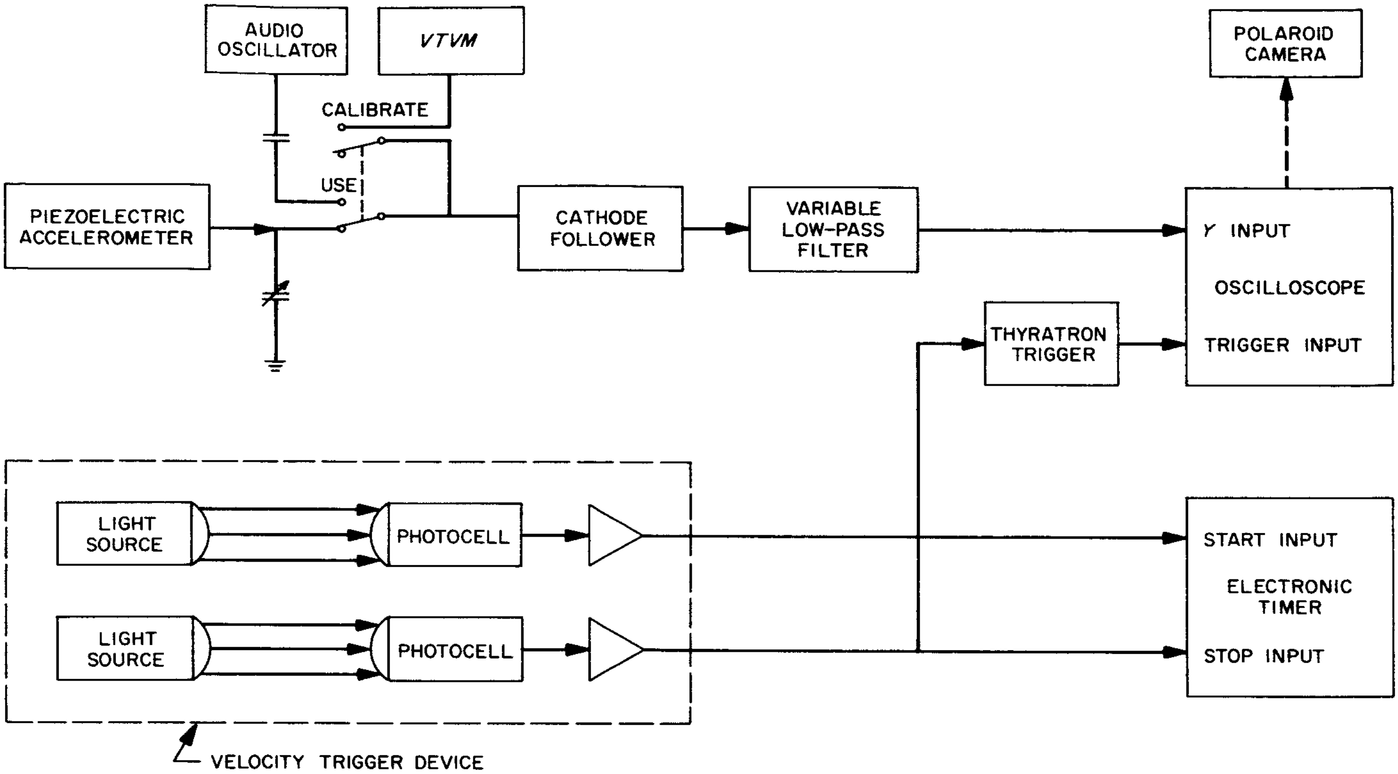

Fig. 12. Shock tester instrumentation diagram

V. DEVELOPMENT PHILOSOPHY

It should first be mentioned that the JPL impact survival program has been directed primarily toward survival only. The subject of the ability of equipments to operate during impact, although an interesting one, has not been investigated to any great extent. Impact survival has generally been construed to mean that the specimen will exhibit neither permanent deformation nor changed performance as the result of one or more impacts at the stated level. (It is recognized that in certain applications it might be possible and perhaps advantageous to accept small changes if they were sufficiently predictable, but this has been avoided).

Initially, there were no firm requirements regarding the magnitude of the shock accelerations and associated velocity changes that had to be withstood. As explained earlier, there are certain advantages in working toward survival of the highest possible accelerations and velocity changes consistent with other objectives. One of the objectives of the program was to define survival levels that could reasonably be achieved.

It was reasoned that the first step in the experimental program was to investigate the intrinsic impact survival capabilities of some of the types of electronic components that would be required. If one assumes that local impact mitigation would not be employed within the package, then the impact survival capability of the complete assembly could not be better than that of its weakest essential component. To the extent possible, components would be tested in hard mountings, such that the test shock would be neither amplified nor attenuated. Components which were particularly vulnerable to envelope damage resulting from concentrated loadings (such as vacuum tubes) would be uniformly supported by thin layers of resilient encapsulants.

As component survival information was accumulated, it became apparent that the range of shock conditions of interest could presently be confined between approximately 1000 or 2000 *g* and 10,000 *g* at impact velocities up to 200 ft/sec. A sufficiently large fraction of the components of interest have survival capabilities within this range that it seems trivial to set a lower goal. Additionally, there is sufficient work required to develop a well balanced technology within this range that effort can better be devoted to this task than to additional investigations at levels in excess of 10,000 *g*. A velocity change of 200 ft/sec is an equipment limitation and is, in addition, not an unreasonable order of impact velocity to expect for a partially-braked rough landing capsule.

With regard to component testing, failures may be categorized into two classes; those that are the result of inherent weaknesses within the component, and those that are the result of improper mounting. For example, consider the vacuum tube. If the tube is rigidly mounted so as to exhibit unity mechanical gain and one of the elements within the tube breaks or deforms such as to cause unsatisfactory performance, this represents a basic component limitation. Conversely, if the envelope breaks because of concentrated loading imposed by a poorly designed mount or because of collision with a nearby object, this does not represent a basic component limitation; it is amendable to correction without component redesign. In component testing, a test that results in envelope breakage from without is not considered satisfactory.

The subject of component selection should also be mentioned. As survival information is accumulated, it should be possible to develop lists of preferred components, such that circuit designers could employ these wherever possible. For example, it is known that certain types of alloy junction transistors have very poor survival capabilities, whereas (as a rule) the mesa and planar types are much better. (Interestingly, it appears that as the planar types are developed for higher power handling capabilities, the impact survival capabilities become better. Apparently, the changes in internal lead construction and attachment necessary for performance reasons are also beneficial in improving shock resistance.) It is expected that in some instances, mechanical considerations will dictate circuitry. One would expect that high impact circuitry would not employ electromechanical relays; that solid state switching would be used.

VI. PACKAGING

The basic requirement of the equipment package is to suitably contain and support the components and interconnections such that the impact survival capability of the complete equipment is not degraded below that of the weakest component. In designing the package, consideration must also be made for other general requirements, e.g., providing for heat dissipation and for accessibility for adjustment and repair. Regardless of the packaging scheme employed, there are certain basic guidelines that should be followed if extreme impact is to be withstood.

There must be structural integrity of the complete package. Components must be suitably supported so as to avoid the imposition of concentrated loadings. This is particularly true of components having glass envelopes, such as vacuum tubes. Large unsupported structures, such as long cantilever beams, should be avoided. Since the accelerating forces will generally be applied locally at discrete points on the external package, case distortions will possibly occur. These should not cause damaging stresses to be transmitted to the internal components.

Figures 13 and 14 illustrate the packaging of the high-impact 2-w L-band transmitter referred to earlier in this Report. Particular care was exercised in the selection of shockworthy components and in certain areas of the mechanical design for impact. Otherwise, the general

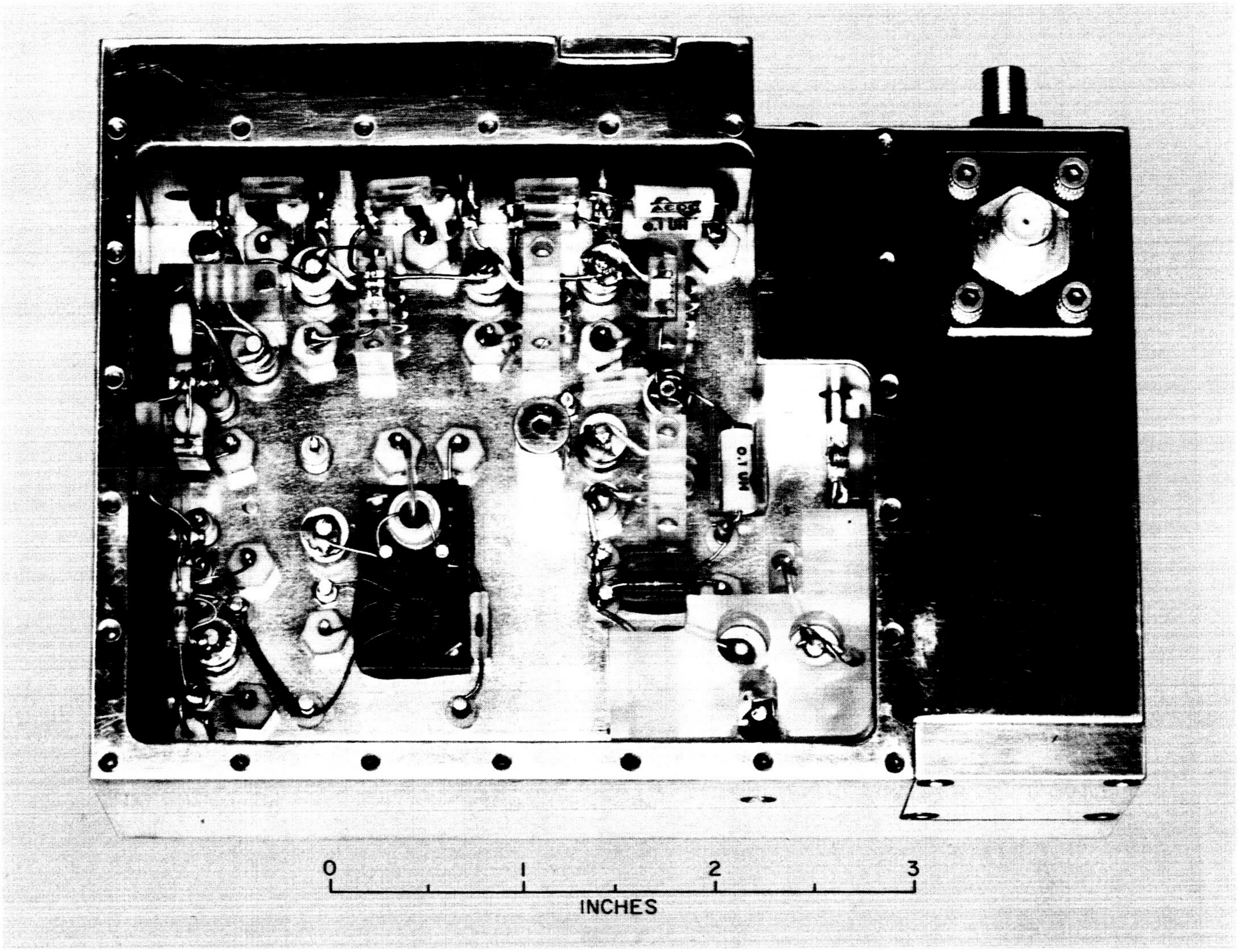

Fig. 13. High-impact L-band beacon (top view)

packaging method employed is a time honored one at JPL for the design of rugged flight equipment. Complete encapsulation was not used, since it was not only unnecessary, but would have caused severe power losses at these frequencies and would have very seriously interfered with the required tuning adjustments. Instead, a rigid one-piece chassis incorporating an integral output cavity resonator (seen on the right side in Fig. 13) was used, and all components were secured to this chassis. The chassis could be described as a box incorporating a floor parallel to, and approximately midway between, the two faces of largest area. Two deep webs on the lower side (Fig. 14) reinforce the floor and support the bottom cover plate; a support post for the top cover can be seen in Fig. 13. The RF components were mounted on the upper side of the floor; the lower side is used primarily for the dc returns. To provide adequate heat dissipation, the power transistors are operated with grounded collectors and are imbedded in the thick wall at the top of Fig. 13.

Small, rugged by-pass and trimming capacitors were screwed into the chassis floor. Fixed-glass capacitors and composition resistors were bonded either to the terminal boards (which are in turn bonded to the chassis) or directly to the chassis. The photographs (Figs. 13 and 14) of this transmitter were taken prior to component bonding. Small signal transistors were bonded into alumina ceramic heat sinks, which, in turn, were bonded to the terminal boards.

Tank coils were wound on special forms made from low-loss Rexolite plastic. These forms are small blocks

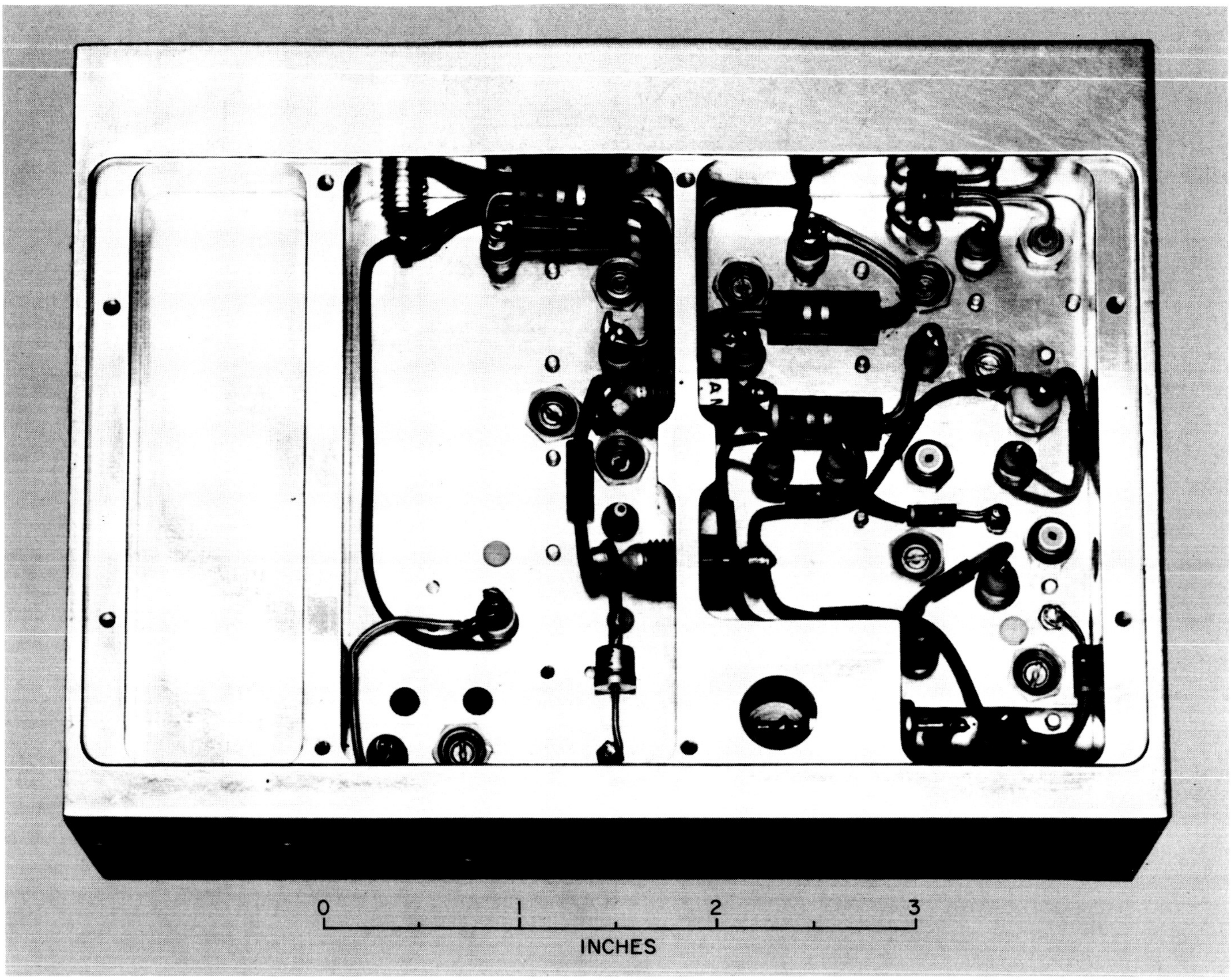

Fig. 14. High-impact L-band beacon (bottom view)

with mounting holes and with two parallel rows of holes through which the wire is served. This assures dimensional stability of the coils under high-impact loadings. One large block of Rexolite supports several of the tank coils and tuning capacitors associated with the frequency multiplier stages. It is quite possible once the basic dimensions for these special forms have been established, that they could be advantageously replaced with custom ceramic parts.

One of the critical features of the output cavity is a tuning rod which is cantilevered from one end. While it would have been possible to employ a low-loss plastic support for the outboard end of this rod, this would have reduced the efficiency somewhat, due to additional losses. An analysis based on static loads indicated that if this tuning rod were of tubular form (which is quite as good as a solid rod at these frequencies), there would be ample margin over the design shock loading; this was confirmed by test.

The complete transmitter has survived impacts of 3000-*g* peak amplitude at 200 ft/sec in three mutually perpendicular directions. It was damaged slightly when subjected to impacts of 10,000-*g* peak at 200 ft/sec. The tuning capacitors which were damaged at this level have been redesigned. It is believed that the only obstacle in the way of demonstrating a 10,000-*g* impact survival capability is the completion of the development of a ruggedized quartz frequency control crystal unit.

It was previously mentioned that certain components (such as glass vacuum tubes) are susceptible to damage resulting from concentrated loadings. Although no ruggedized equipments have been designed which use them, several such objects have been successfully mounted for test purposes. Vidicon camera tubes encapsulated with thin layers of resilient materials (such as RTV Silastic or Thiokol modified epoxy inside aluminum test fixtures) have been tested up to 3000 *g* without envelope breakage.

Thus far, essentially no work has been done with completely encapsulated circuitry. Future tests are planned for such equipment, however (e.g., cordwood modules). Complete encapsulation has been used by others in the construction of equipments for survival of extreme accelerations. Information received from Aeronutronic Division of the Philco Corporation indicates that complete encapsulation can be beneficial in the damping of high-frequency components of the shock spectrum. An example was cited where certain transistors were being damaged when hard mounted to the chassis; the same transistors survived when they were isolated by encapsulation in a somewhat resilient material. It is not reasonable to believe that the encapsulant permitted sufficient excursion of the transistors to materially reduce the amplitude of the shock envelope; the result was attributed to high-frequency damping.

VII. SUMMARY OF ELECTRONIC COMPONENT SURVIVAL CAPABILITIES

An attempt is made in this Section to summarize the results of component impact survival testing that has been performed over a period of several years. Occasionally, information is included that is based on the experiences of others (this is noted as such).

Because of the generally small number of samples involved and also because in many instances, the functional tests that were performed did not constitute a complete evaluation, these tests should be regarded as being exploratory rather than component qualifications. In addition, it should be recognized that even with components having identical registered type numbers, there may be differences in construction for units from different manufacturers which affect the impact survival capability. No attempt was made to compare manufacturers.

In general, components were hard-mounted for these tests. For example, small components (such as resistors and glass diodes) were bonded to terminal boards, which in turn were bonded to metal fixtures. Some components (such as transistors and metal cased capacitors) were inserted in close fitting holes in the test jigs and held in place by cover plates. Others having fragile envelopes (such as vacuum tubes) were potted into metal fixtures with very thin layers of RTV silastic rubber for load distribution.

Components were checked for survival only. They were checked functionally before and after impact, but were not operated during impact. They were generally shocked in each distinguishable direction. For example, a tube or transistor would be tested in three directions; two axial and one lateral.

A. Batteries

Nine Mallory RM-12 primary mercuric oxide/zinc cells were each subjected to six impacts of 3000-*g* peak amplitude and approximately 0.6-msec duration (65-ft/sec impact velocity); one shock being in each of the two directions along each of three orthogonal axes. Based on open circuit voltage and 10-Ω load voltage, there was no indication of damage. Six of these same cells were then subjected to six impacts each at 6000-*g* peak amplitude and 0.3-msec duration. Two of the six began leaking electrolyte and a third suffered a failure of the pressure contact between the zinc electrode and the external negative terminal.

Four RM-12 cells were mounted in each of two free-fall capsules; two oriented laterally and two axially with the bottom (+) terminal toward the nose of the capsule. The capsules impacted into soil at approximately 300 ft/sec. Calculated "average" accelerations were about 1000 and 2000 *g* with estimated peak values of about

3000 and 5000 *g*, respectively. All eight cells exhibited normal output voltage, internal resistance, and discharge capacity.

A power supply composed of ten RM-12 cells was impacted with the acceleration directed from the bottom (+) toward the top (−) of the cells and with the voltage under load monitored during impact. One of the cells open-circuited during a 6000-*g*, 0.3-msec shock and did not recover. A similar pack employing nine RM-4 cells performed satisfactorily during and after a 3000-*g*, 1-msec shock in the same orientation.

Five CG 10-180 sealed nickel/cadmium battery packs were procured from C. G. Electronics Corporation (a subsidiary of Gulton Industries) for evaluation. Each pack consists of a stack of ten series-connected 180-ma-hr button cells potted into a rectangular configuration. These battery packs were reputed to be very impact-resistant.

The results of the investigation of the CG 10-180 battery packs may be summed up as being only partially satisfactory. Two packs were tested in free-fall capsules which impacted at approximately 2500-*g* peak at 300 ft/sec. These batteries then gave approximately 240-ma-hr capacity on a charge/immediate discharge cycle. Approximately six months later, another pack was shocked on the drop-tester and the slingshot machine. This pack was subjected to one axial and one lateral impact of 2000-*g* peak at approximately 1-msec duration (50-ft/sec impact velocity) and then given a charge/immediate discharge cycle which indicated no loss in capacity. Following one axial impact each at approximately 15,000, 20,000, and 30,000-*g* peak amplitude a charge/immediate discharge cycle indicated no loss in capacity. Following one additional axial impact at an estimated 40,000 *g*, the capacity was reduced by about 75%, becoming worse with additional cycling.

There were two problems involved with these battery packs, neither of which was inherent in the cells. One was that the potting material apparently did not adhere to the intercell connectors, with the result that it was possible for electrolyte to leak between cells, causing loss in charged shelf life and eventually causing failure of the copper conductor extending from the bottom of the cell stack to the terminal on the top of the case. The other was that the individual cells were not supported sufficiently well, such that the potting material between cells fractured when the pack was subjected to axial impacts, allowing additional electrolyte leakage between cells. As a result of the electrolyte leakage, all of the five battery packs were so badly deteriorated that no further testing was accomplished.

Although not based on work at JPL, it is known that very small mercury cells have survived accelerations of approximately 200,000 *g* (Ref. 1). Also, the Electric Storage Battery Company has developed, for the Aeronutronic Division of Philco for use on the *Ranger* lunar landing capsule, a sealed silver oxide/zinc battery of approximately 1000-whr capacity capable of surviving a 3000-*g* peak impact at 250 ft/sec. An investigation of the basic impact survival limitations of the silver oxide/zinc cell is now in progress, since this system is extremely desirable on the basis of energy density.

Summary

RM-12 mercury cells have survived 3000-*g* tests; some have failed at 6000 *g*. Very small mercury cells have been tested by others at 200,000 *g*. A special purpose silver/zinc battery is known to have withstood impacts of approximately 3000 *g*.

B. *Capacitors, Fixed*

Three units of each of the following capacitor types were subjected to controlled impact testing:

1. Ceramic, Vitramon VK30CW103M, 0.01 μf, 200 v.
2. Ceramic, Aerovox Cerafil HMC80, 0.1 μf, 100 v.
3. Paper, metallized, Aerovox P323ZN, 1 μf, 200 v.
4. Paper, Sprague CPO8A1KC103K, 0.1 μf, 200 v.
5. Tantalum, solid, General Electric 7K163G3, 47 μf, 35 v.
6. Tantalum, wet slug, Fansteel HP40B50D1, 40 μf, 50 v.
7. Tantalum, wet foil, General Electric 5K112AA2, 10 μf, 50 v.

The capacitors were mounted in close tolerance holes in an aluminum test fixture and were held in place by cover plates. They were so oriented that two units of each type could be impacted axially (one in each direction) and the third would receive a lateral shock. Capacitance and dissipation factors were measured at 1000 cps with an ESI 250DA impedance bridge. Leakage current was measured at rated voltage using an adjustable dc power supply and a Simpson 260 multimeter (or for the very low currents, a 20-μamp panel meter).

After one impact of 5000-*g* peak amplitude and 0.6-msec duration, the only discernible evidence of failure or gross parameter change was an increase in leakage current from 4.5 to 40 μamp through one of the GE 7K units.

Following one impact at an estimated 10,000-g peak (7650 calculated average) at 200 ft/sec, this same GE 7K had a broken seal but otherwise showed nearly unchanged parameters. The leakage current in another GE 7K had increased from 3.5 to 500 μamp. One of the 5K capacitors was ac open-circuited and showed an increase in leakage current from 0.1 to 95 μamp. A special test was then run with the two remaining (apparently good) GE 5K and 7K capacitors only, mounted so that they received a 5000-*g* peak shock directed from the positive toward the negative terminal. The glass seal on one of the 7K capacitors broke and its leakage current increased from 3.5 to 40 μamp. The leakage current on the 5K units increased from 0.01 to 25 and 50 μamp. Capacitance values remained unchanged.

To obtain additional information from these test units, the fixture containing all of the test units except the types 5K and 7K was then impacted once in each of the other two orthogonal axes at an estimated peak acceleration of 10,000 *g* (7400-*g* average) at 200 ft/sec. There was no apparent damage.

Although they were not tested in this evaluation, the following capacitors have been successfully employed in prototype equipment subjected to shocks of 10,000-*g* peak (estimated) at 200 ft/sec: El Menco type CM-15 silver mica; Corning Glass type CY; Maida Development Co. ceramic by-pass and stand-off; and Sprague 150D (15 μf, 20 v only). Figure 15 shows the various capacitors mentioned, including those not tested.

Summary

All mica, glass, ceramic, and small paper units tested have survived 10,000 *g*. Difficulties have been experienced with large solid tantalum and wet foil tantalum units at 5,000 *g*.

C. Capacitors, Variable Trimming

A number of trimmer capacitors (Fig. 16) were tested for application in RF circuits. Because of the sensitivity of such circuits to the close proximity of metallic conductors or lossy dielectrics, these capacitors were in general not potted nor hard mounted, but were mounted by the usual methods. Because of the small capacitances involved, no attempt was made to measure capacitance changes resulting from impact. The failures noted were catastrophic, generally glass breakage.

As would be expected, the JFD piston capacitors are most sensitive to impact in the lateral direction, where the body is cantilevered. One each of types VC-5 and VC-11 so mounted survived free-fall capsule impacts at an estimated 3000-*g* peak acceleration (1000-*g* calculated average) at 300 ft/sec. One each of the same two types broke when impacted in the same manner at an estimated 5000-*g* peak (2000-*g* calculated average). Similar failures were noted at 3000-*g*, 0.6-msec duration on the drop tester. Several JFD type VC9GWB2 capacitors were tested to and failed lateral impacts of 4500-*g*, 1-msec duration on the slingshot machine.

The one glass piston trimmer capacitor which consistently withstood all impacts to which it was subjected was JFD type VC-21G, a small unit having a capacitance range of 0.8 to 4.5 pf. A total of about 20 of these units were tested, both as components and as elements of functional circuits at test levels from 3000 g to in excess of 10,000 g at 200 ft/sec impact velocity with no catastrophic failures. Some detuning of an L-C tuned beacon, of which this capacitor was a part, was noticed at a test level of about 6000 *g*. However, this did not occur after the rotor was locked with cement.

For electrical reasons, the radio development group decided to employ in the ruggedized transmitter described elsewhere in this Report a Johanson Manufacturing Company type 2954 trimmer capacitor. Four of these units survived a 3000-*g*, 2-msec impact. Two were cantilevered and two were mounted axially (one in each direction). Of four units tested at approximately 7500 *g* in like orientation, the two which were axially oriented broke, and one of the two in the cantilever mounting broke. The failure involved both separation of the solder joint between the ceramic body and the brass base and fracture of the ceramic adjacent to this joint. At JPL's request the manufacturer made the following changes and issued the part as type 4364: Changed the Steatite body to a high alumina ceramic with a thicker wall section; changed from a silver-copper-tin plate to a molymanganese metallized coating on the ends of the ceramic body; changed to a higher melting point solder for assembly; and increased the bond area between the ceramic and the two ends of the unit. Through an error, the first lot of 15 units (five each in tension, compression, and cantilever) was subjected to an impact of approximately 20,000-*g* peak at 200 ft/sec. Three of these failed

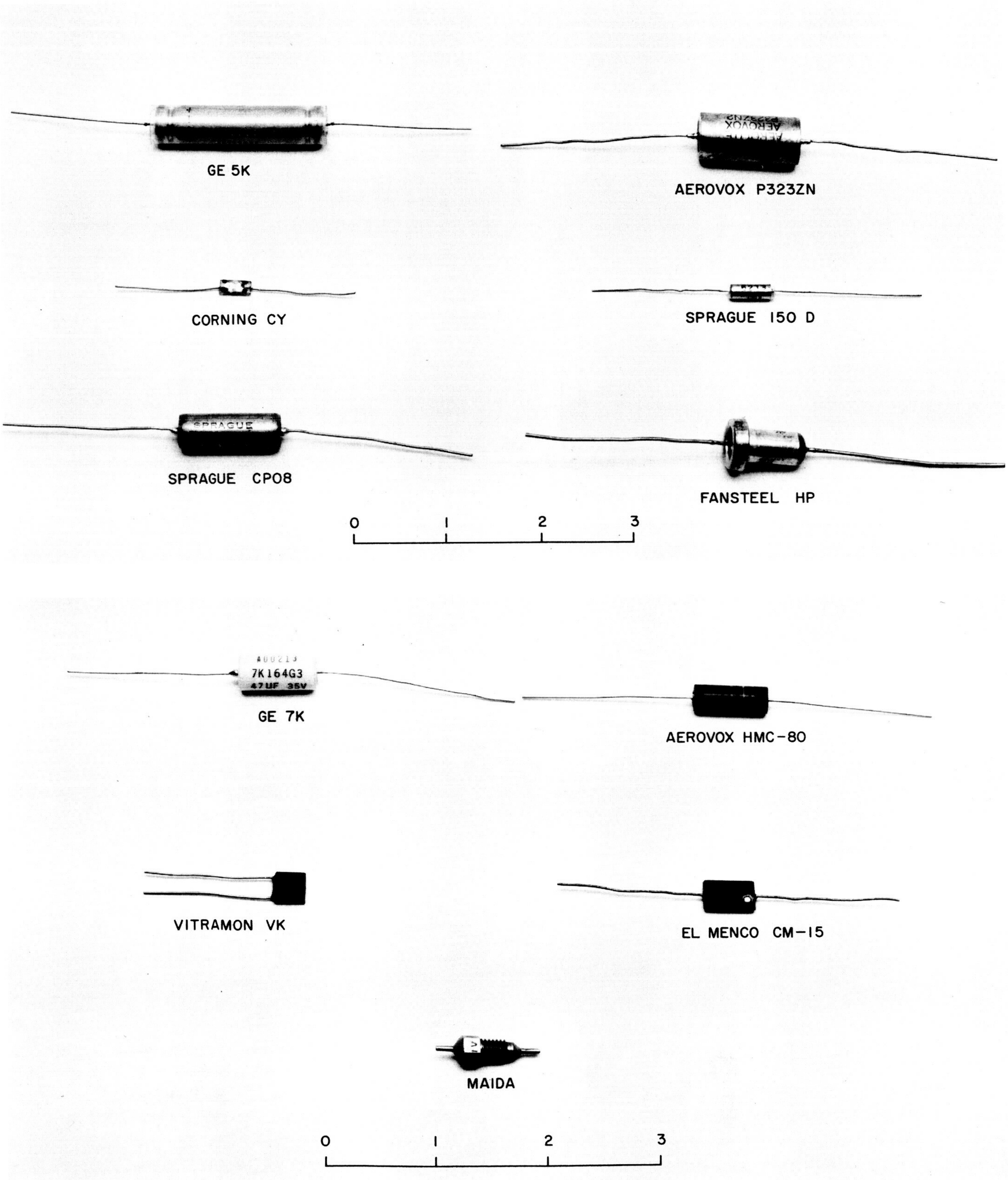

Fig. 15. Capacitors, fixed

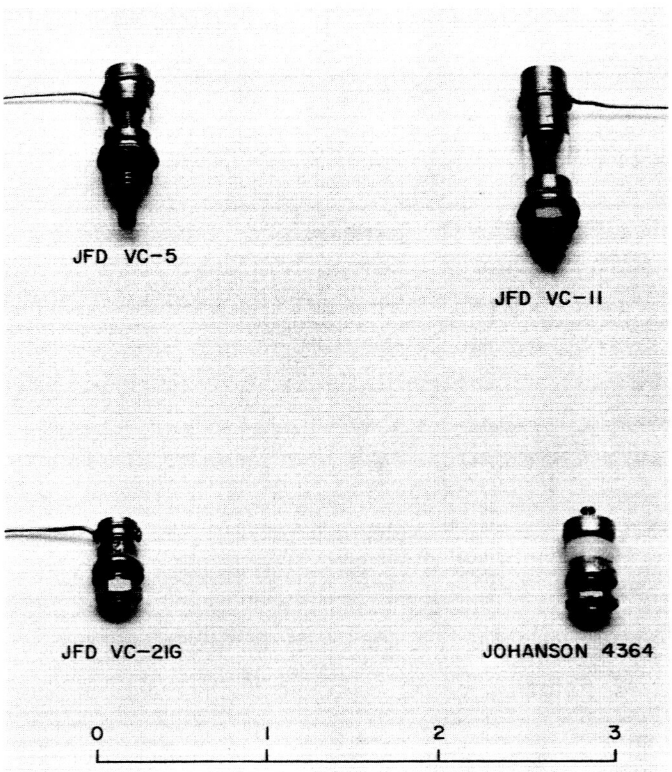

Fig. 16. Capacitors, variable trimming

in cantilever, two in tension, and one in compression; the remainder survived. The failed units were replaced and retested at an estimated 15,000-*g* peak. All units survived, although some change in capacitance took place (which was still within specification).

Summary

JFD type VC-21G and Johanson Manufacturing Co. type 4364 are capable of surviving shocks in excess of 10,000 *g*.

D. Crystals, Quartz Frequency Control

Four 20-Mc wire-mounted crystal units, Midland Manufacturing Company type ML-6J, were subjected to two shocks of 3000-*g* peak amplitude and 0.6-msec duration in each of four directions (one normal to and three in the plane of the wafer). No attempt was made to check electrical performance; the units were merely inspected for mechanical damage. The crystal wafers in two of the units broke; the other two apparently survived. These two were then found to be broken following two impacts of 6000-*g* peak amplitude and 0.35-msec duration. One 20-Mc wire-mounted crystal unit, Monitor Products Co. type MC-6AV was impacted (normal to the plane of the

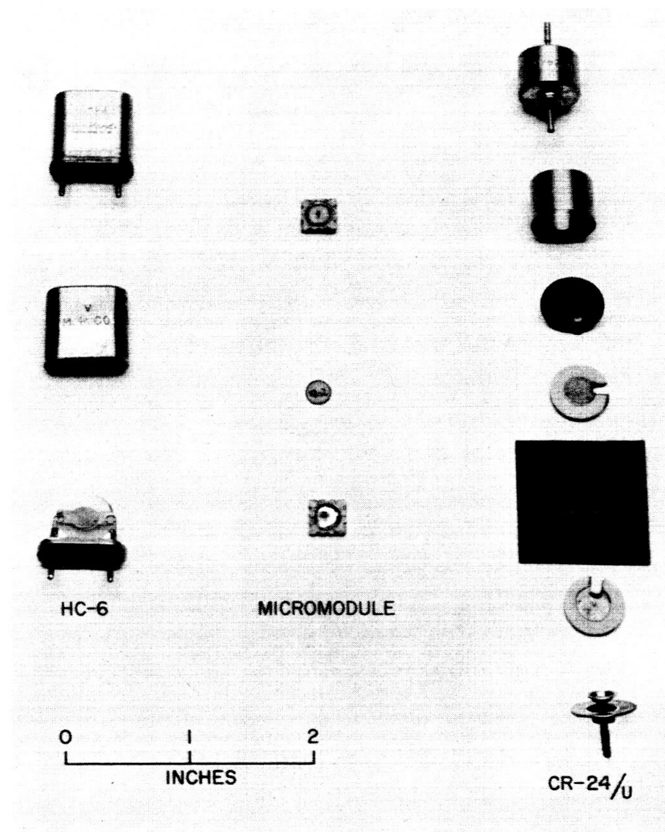

Fig. 17. Crystals, quartz frequency control

wafer) in a free-fall capsule at an estimated 3000-*g* peak amplitude (1000-*g* average) at 300 ft/sec impact velocity. It remained functional following impact, although no preimpact data was available for comparison.

Eight coaxial pressure-mounted crystal units, Monitor Products Company type CR-24/U (Fig. 17), were shock tested. Four were 20-Mc third overtone units; the others were fifth overtone units having resonant frequencies from 35 to 40 Mc. The test was conducted such that each crystal unit was shocked once at each test level, with the acceleration either parallel to or normal to the plane of the crystal wafer. Resonant frequencies were checked at the beginning of the test series and following each impact, using a Radio Frequency Laboratories Model 531 crystal impedance meter and a Hewlitt Packard 524A frequency counter and a 512A frequency converter. The results of these tests are shown in Table 3. In summary, all units survived one shock of 4500-*g* peak amplitude and 1-msec duration. Six units failed at estimated peak accelerations from 15,000 to 30,000 *g* at an impact velocity of 200 ft/sec. Two units, mounted so that the acceleration was parallel to the wafer, survived six tests at peaks from 4500 *g* to an estimated 30,000 *g*. In almost

Table 3. Impact data for CR-24/U crystal units

Number	Orientation*	Resonant Frequency, Mc						
		Initial data	Drop test			Slingshot		
			3000 g	6000 g	4500 g	15,000 g	20,000 g	30,000 g
1	Perpendicular	20.2584	20.2581	20.2583	20.2583	open		
2	Parallel	20.2581	20.2582	20.2586	20.2589	20.2580	20.2585	20.2589
3	Parallel	20.2582	——	——	20.2581	20.2581	20.2581	open
4	Perpendicular	20.2584	——	——	20.2584	open		
5	Perpendicular	35.6310	35.6322	35.6317	35.6314	35.6315	35.6321	open
6	Parallel	37.6878	37.6882	37.6876	37.6877	37.6874	37.6873	37.6882
7	Perpendicular	40.6371	——	——	40.6371	40.6371	40.6372	open
8	Parallel	37.6874	——	——	37.6873	37.6872	37.6874	open

*Crystal wafer with respect to applied acceleration

every case, a resonant frequency shift was noted following impact. The shifts were approximately evenly distributed in sign, having an average magnitude of 240 cps for the 20-Mc units and 360 cps for the 35 to 40-Mc units, or roughly 1 in 10^6 for all units.

Eight 60-Mc fifth overtone CR-24/U crystal units manufactured by Midland Manufacturing Company were tested for possible application in the ruggedized L-band beacon. Four were subjected to a 4500-*g* 1-msec shock (two with the acceleration normal to the wafer and two with it parallel to the wafer). The two subjected to the normal acceleration failed. Four more were subjected to a 3000-*g*, 2-msec impact. Again, the two with wafers normal to the acceleration failed.

Four 40-Mc fifth overtone CR-24/U crystal units obtained from Wright Manufacturing Company were subjected to a 3000-g, 2-msec shock. All four units survived. These were then subjected to a shock having an estimated peak amplitude of 10,000 *g* (7700-g calculated average) at 200 ft/sec; again, all four survived.

It was apparent from this testing that there was a marked variation in impact resistance of CR-24/U crystal units obtained from various sources. Post mortem examinations of both failing and surviving units revealed significant variations in internal construction, particularly in the quality of the spring hardware and in the closeness of the fit between the case and the electrode assembly. To insure against any undesirable variations, a supplemental specification was drafted for use with MIL-C-3098B in the procurement of CR-24/U crystal units for high-impact applications.

Several subminiature (0.312 × 0.312 × 0.060 in.) ceramic encased crystal units (Fig. 17) developed for the Signal Corps micromodule program were shock tested. Approximately half of those tested at 4000 *g* failed, with no preferred axis. Only one passed a 10,000-*g* impact (normal to the plane of the wafer).

Summary

Wire mounted units in the HC-6 holder are marginal at 3000 *g*. Some CR-24 pressure-mounted crystal units have survived shocks of 10,000 *g*. A ruggedized crystal unit is being developed.

E. Diodes, Semiconductor

Impact survival evaluation tests were performed on the following silicon diodes:

1. 6 ea. 1N459, Fairchild Semiconductor, glass, general purpose.
2. 6 ea. 1N647, Pacific Semiconductor, glass, general purpose high conductance.
3. 6 ea. 1N754, Pacific Semiconductor, glass, 400-mw zener regulator.
4. 6 ea. 1N916, Texas Instruments, glass, subminiature computer.

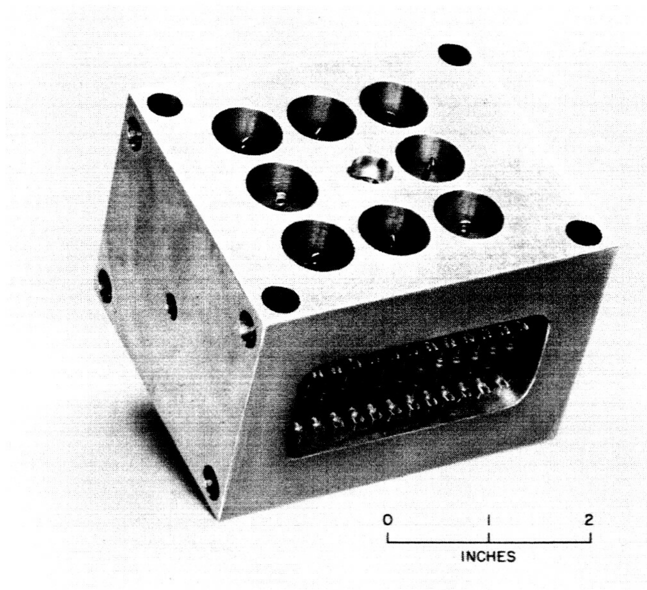

Fig. 18. Diodes, semiconductor in test fixture

5. 6 ea. 1N1126, Texas Instruments, 3-amp stud mount rectifier.

6. 2 ea. 1N1361 and 1N1368, Hoffman, 10-w stud mount zener regulator.

7. 1 ea. 1N2041, 1N2042, 1N2044, 1N2045, 1N2046, Transition, 10-w stud mount zener regulator.

The diodes were mounted in an aluminum block (Fig. 18) such that they could be shocked simultaneously. The longitudinal axes were aligned, with half of the specimens of each type (or family) oriented in each of the two directions along this axis. The stud mount units were screwed into tapped holes in the block; the glass units were bonded with epoxy to terminal boards which were rigidly attached to the fixture. The test levels, in order of performance, were 3000, 4500, 10,000, and 15,000 *g*, the latter two being estimated peak values. The diodes were shocked three times at each test level; in the two axial directions and the one lateral direction. Electrical performance was checked at the beginning of the evaluation and following each series of three impacts. Forward voltage drop and reverse voltage breakdown were measured at specified currents and the characteristic curves were observed on an oscilloscope.

The test results are given in Table 4. Some of the variations in measurements can be explained on the basis that they were made by different operators using different Simpson 260 multimeters. All units passed the 3000-*g* tests and all except one 1N754 (which exhibited a significant increase in forward conduction drop) passed the 4500-*g* test. One 1N459 and one 1N916 failed in reverse breakdown following the 10,000-*g* tests. In addition, several of the 1N459 units exhibited seemingly significant increases in forward conduction drop following the 15,000-*g* tests. One 1N647 was broken following the 15,000-*g* tests. This was a result of the mounting, not the diode. It is believed that the high reverse breakdown voltage recorded for three of the 1N916 diodes following the 10,000-*g* tests may be attributable to a measurement error.

Several special purpose silicon diodes were also evaluated for possible use in the ruggedized L-band beacon. Six Pacific Semiconductor PC 137 Varicaps (variable capacitance diodes) were subjected to one shock at each of the following peak accelerations: 3000, 4000, 10,000, and 20,000 *g* (the latter two being estimated). They were so oriented that two units were shocked in each of the two axial directions and the remaining two units were subjected to a lateral shock. Capacity and "Q" were measured at fixed bias and frequency before the test series was begun and following each impact. Within experimental error, there was no variation in these two parameters; the diodes are presumed to have passed all tests.

Five Microwave Associates MA4348F and three Sylvania D4274-1 varactor diodes were shock tested. Three units (one in each direction along one axis and the third perpendicular to this axis) of each type were potted with RTV 881 Silastic in slightly oversized cavities in an aluminum test fixture (which was made in sections, bolted and doweled together for ease of removal of the diodes). The group of diodes survived one shock of 4500-*g* peak amplitude and 1-msec duration. The same six units were subjected to one shock at an estimated 10,000-*g* peak amplitude at 200-ft/sec impact velocity. All of the MA4348F varactors survived, but two of the D4274-1 diodes (the one subjected to a lateral shock and one of the two impacted axially) were damaged. The two units which failed were replaced in the fixture with MA4348F units and the test was repeated at an estimated 15,000 *g* at 200-ft/sec impact velocity. All the MA4348F diodes survived, but the remaining D4274-1 was damaged.

Summary

Most of the diodes tested have survived 10,000 *g*.

Table 4. Shock test data for diodes

Diode	V_{fwd}, v						V_{BR} or V_z, v						Remarks
	@ I_f, ma	Initial data	3000 g	4500 g	10,000 g	15,000 g	@ I_R, ma	Initial data	3000 g	4500 g	10,000 g	15,000 g	
1N459 1	100	0.88		0.90	0.88	1.0	1.0	280		300	4.8	0.34	Failed
2		0.90		0.90	0.90	1.0		270		290	282	290	
3		0.89		0.90	0.89	0.94		200		207	207	210	
4		0.89		0.90	0.89	0.90		300		320	315	320	
5		0.89		0.90	0.89	0.90		285		310	300	300	
6		0.92		0.92	0.92	0.85		340		365	360	360	
1N647 1	100	0.88		0.88	0.88	Broken	0.5	750		790	770	Broken	Not a failure
2		0.86		0.86	0.86	0.87		>780		>800	>800	>800	
3		0.87		0.88	0.88	0.88		>780		>800	>800	>800	
4		0.88		0.89	0.90	0.88		>780		>800	>800	>800	
5		0.88		0.89	0.88	0.88		>780		>800	>800	>800	
6		0.88		0.90	0.88	0.88		>780		>800	>800	>800	
1N754 1	100	0.84		0.84	0.86	0.84	25	7.0	6.8	6.9	6.9	7.0	
2		0.84		0.85	0.85	0.85		7.0	6.8	6.8	6.9	7.0	
3		0.88		1.07	1.2	0.96		7.0	6.8	6.9	7.0	7.0	Failed
4		0.90		0.91	0.92	0.86		7.1	6.9	7.0	7.0	7.1	
5		0.86		0.85	0.86	0.85		6.9	6.8	6.8	6.8	6.9	
6		0.88		0.89	0.86	0.86		7.1	7.0	7.0	7.0	7.1	
1N916 1	10	0.84	0.82	0.84	0.85	0.84	0.5	150		160	158	155	
2		0.83	0.81	0.83	0.84	0.83		150		150	152	152	
3		0.84	0.81	0.84	0.84	0.83		145		150	0.42	0.54	Failed
4		0.85	0.82	0.85	0.86	0.85		125		130	155	127	
5		0.84	0.81	0.82	0.84	0.83		120		125	145	120	
6		0.71	0.71	0.71	0.72	0.71		123		130	150	125	
1N1126 1	200	0.84		0.86	0.86	0.84		>780		>800	>800	>800	
2		0.84		0.86	0.86	0.84		>780		>800	>800	>800	
3		0.85		0.86	0.87	0.86		>780		>800	>800	>800	
4		0.84		0.86	0.86	0.84		>780		>800	>800	>800	
5		0.85		0.86	0.85	0.84		>780		>800	>800	>800	
6		0.85		0.86	0.86	0.85		>780		>800	>800	>800	
1N1361 1	200	0.79	0.78	0.79	0.80	0.78	50	25.5	26	27	27	26.5	
2		0.78	0.78	0.78	0.79	0.78		26.5	26	27	27	26.5	
1N1362 1	200	0.78	0.78	0.79	0.80	0.77		49.2	49	55	50	50	
2		0.78	0.78	0.79	0.79	0.78		47.0	47	49	48	48	
1N2041	200	0.80		0.82	0.81	0.80	200	4.4	4.3	4.2	4.2	4.2	
1N2042		0.79		0.80	0.80	0.78		6.0	5.9	5.9	5.9	6.0	
1N2044		0.78		0.80	0.79	0.78		8.8	8.7	8.7	8.6	8.6	
1N2045		0.77		0.79	0.79	0.79		9.5	9.4	9.4	9.2	9.2	
1N2046		0.77		0.79	0.78	0.76		13.1	12.8	12.7	13.0	12.5	

F. Inductors

It is difficult to generalize, but it should be mentioned that the impact resistant L-band beacon employs a number of RF inductors both on small toroidal cores and on special Rexolite plastic forms that are capable of surviving impacts of 10,000 *g* at 200 ft/sec. Power components have not been tested.

G. Lamps, Incandescent

Four each of Sylvania type ML 202A and Kay Electric type 15-15, and two Kay Electric type 30-30 subminiature incandescent lamps (Fig. 19) were shock tested. The leads were attached to terminals on a Micarta block and the envelopes were cemented to the block with Duco (for ease of removal). Half of the sample of each type was shocked in the direction parallel to the leads and the other half perpendicular to the leads. The lamps were shocked in the nonoperating condition and checked for operation afterward (although measurements of light output were not made). The lamps withstood all tests up to and including one at an estimated 7500-*g* peak (calculated average 6500 *g*) at an impact velocity of 160 ft/sec. Following one impact at an estimated 10,000-*g* peak acceleration at 200 ft/sec, one ML 202A and one axially oriented 30-30 were open-circuited. Through inadvertent omission of the copper target, the next impact at 200 ft/sec resulted in a peak acceleration in excess of 25,000 *g*. One more ML 202A and two laterally oriented 15-15 lamps were then found to be open-circuited. Two types ML-202A, two types 15-15, and one type 30-30 were still operable. Failures of the Sylvania ML 202A's were by breakage of the platinum lead wire where it is flattened in the area of attachment of the tungsten filament loop. Failures of the Kay Electric lamps were by breakage of the helical tungsten filament near the center.

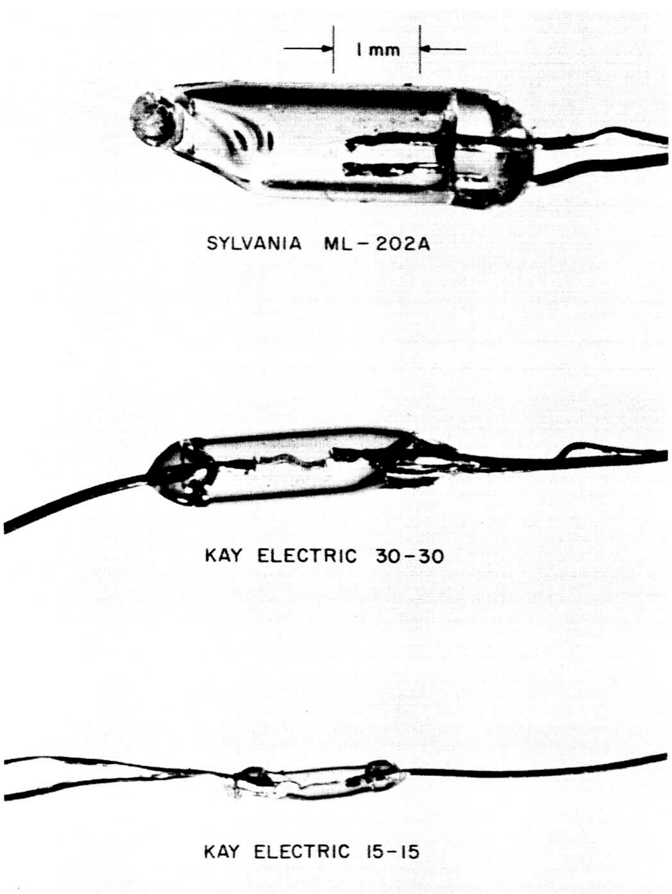

Fig. 19. Lamps, incandescent

Summary

Several types of subminiature incandescent lamps have survived shocks of 7500 *g*; some have withstood in excess of 10,000 *g*.

H. Resistors

Molded deposited carbon resistors have been tested to 3000 *g* at 50 ft/sec, and fixed composition resistors in ½-w and smaller sizes have been tested to levels in excess of 10,000 *g* at 200 ft/sec. These shock loadings have produced no observable failures.

I. Transistors

Impact survival capabilities of the following transistor types were investigated in early 1960, using the 50-ft drop-tester:

1. 2N270, PNP Germanium Alloy, RCA
2. 2N328, PNP Silicon Alloy, Raytheon
3. 2N334, NPN Silicon Grown Junction, General Electric (fixed bed)
4. 2N336, NPN Silicon Grown Junction, Texas Instruments
5. 2N700, PNP Germanium Mesa, Motorola
6. 2N706, NPN Silicon Mesa, Fairchild
7. 2N1131, PNP Silicon Mesa, Fairchild

The transistors were mounted in close fitting wells in an aluminum fixture, and clamped by a cover plate which gripped the flange of the transistor case. The dc Beta was measured and the characteristic curves were observed on a Tektronix curve tracer. Each transistor was subjected to six shocks (one in each direction along each of three orthogonal axes) of 3000-g peak amplitude and 0.6-msec duration and of 6000-g peak amplitude with 0.35-msec duration. In addition, certain of the transistors were subjected to four shocks (directed as above except only one in each of the two axes parallel to the mounting base) of 10,000-g peak amplitude and approximately 0.2-msec duration. In general, the transistors surviving the lower test levels were retested at the higher levels.

The results of the tests are summarized in Table 5. No degradation of parameters was observed; the failures were all catastrophic. All units passed the 3000-g tests with the exception of one type 2N328, which failed by breakage of the bond between the internal base lead and the large cantilevered silicon wafer. The 6000-g tests confirmed the weakness of the 2N328 design and indicated a difference in impact resistance between the different internal constructions used by two companies in the manufacture of a family of silicon-grown junction transistors. It was observed that the mesa transistors were generally superior to the other types in impact resistance. The failures that did occur with these units were generally of the bond between the internal base lead and the wafer (it was elsewhere observed that the early 2N706 units were particularly erratic in this respect). It was also noted that although the 2N270 and 2N328 are both alloy junction units, the former was much stronger due to the internal encapsulation employed.

Four Western Electric type 2N1195 germanium mesa transistors were employed in a development type transmitter which was subjected to three impacts of 4500-g peak amplitude and 1-msec duration and to three impacts each at estimated peak accelerations of 15,000 and 20,000 g at 200-ft/sec impact velocity. One unit failed at 15,000 g and was replaced; all the others survived.

A number of VHF power transistors were evaluated for possible use in the L-band beacon. These were tested in a VHF amplifier circuit before and after impact. In general no degradation of parameters was noted; the only failures were catastrophic. Three RCA type TA 2084, six RCA type TA 2267, and nine Clark Transistor type SN 101 were subjected to and survived one impact at approximately 10,000-g peak amplitude and 1-msec duration. They were oriented such that equal numbers of each type were shocked in each of three directions; two directions perpendicular to the mounting base and one lateral direction. Three each Pacific Semiconductor types 2N1506 and 2N1709, oriented as above, were subjected to and survived one impact of 4500-g peak amplitude and 1-msec duration. The test was repeated at an estimated peak acceleration of 15,000 g with a duration of about 0.75 msec, with one 2N1506 and two 2N1709's failing.

Table 5. Summary of results of transistor shock tests*

Transistor**	Manufacturer	Number failed/number tested at peak g of 600	3000	6000	10,000	Direction of failure
2N270	RCA	0/2	0/6	0/6	0/4	
2N328	Raytheon	0/2	1/6	3/4		No record on three units; fourth failed with acceleration transverse (normal to wafer)
2N334†	GE	0/2	0/4	0/4	1/2	Acceleration toward top of transistor
2N336†	TI	0/2	0/6	2/4	2/2	Three failed with acceleration along axis of transistor, fourth with acceleration transverse (in all cases, acceleration normal to semiconductor bar)
2N700††	Motorola	0/2	0/4	0/4	1/2	Acceleration toward top of transistor
2N706††	Fairchild	0/2	0/4	1/6	0/2	No record
2N1131††	Fairchild	——	——	0/4	0/2	

*Tests performed on drop-tester at impact velocity of approximately 50 ft/sec.
**Transistors were in all cases subjected to acceleration in at least one direction along each of three mutually perpendicular axes; in most cases, acceleration was in both directions along each axis. In several instances, transistors that passed lower levels were retested at higher levels.
†GE type 2N334 has "fixed bed" construction; TI type 2N336 has silicon bar supported by emitter and collector leads. In both cases, failures were due to fracture of silicon bar.
††Types 2N700, 2N706, and 2N1131 are mesa transistors. Failures were due to internal emitter or base leads pulling loose from wafer.

Summary

Several types of mesa and planar transistors have survived shocks of 10,000 *g* and more. Some grown junction and unencapsulated alloy junction units failed at levels as low as 3000 *g*.

J. Tubes, Special Purpose

Impact survival tests were performed on a ½-in. D (RCA 4427) and two 1-in. D (RCA 72621 and GEC 7226A) vidicon tube types. These tubes were potted in clearance holes in aluminum test fixtures (Fig. 20) using thin (approximately 0.025 in.) sections of resilient potting materials (RTV Silastic or an epoxy/polysulfide rubber blend). The purpose of the encapsulant is not to provide a cushion, but to conform to the irregularities of the tube envelope, providing as nearly uniform support as possible, so that the tube and not the envelope mounting method is evaluated. The RCA tubes were checked for visible damage and for cathode emission following each test. The GEC tubes were removed from the test fixture and tested in an operating camera chain.

The ½-in. D tube survived axial and lateral impacts to and including 2000 *g* at 50 ft/sec with no evidence of damage. After one 3000-*g* impact at 50 ft/sec, the heater was open and the glass rods which support and space the electron gun assembly were broken. The 1-in. D RCA tube survived axial and lateral impacts of 100 and 300 *g* at 50 ft/sec and failed an axially applied 700-*g* shock. The heater was open and the gun support rods were broken; the envelope was intact and the decelerator mesh appeared to be in satisfactory condition.

Axial shocks as low as 900 *g* caused slight shifts of the electron gun in the GEC 7226A, but there was no apparent picture degradation; axial shocks in excess of this level caused failure. These tubes survived lateral shocks to and including 1700 *g* at 50 ft/sec. One tube subjected to a 2500-*g* shock at 50-ft/sec impact velocity in the lateral direction survived, but with a slightly deformed gun structure; another failed at 4000 *g* and 110 ft/sec in the lateral direction (apparently due to a broken heater lead).

A photomultiplier tube (Fig. 21), Ascop type 541A-01-14-03900, was subjected to nine impacts of 1500-*g* peak amplitude and approximately 1-msec duration (50-ft/sec impact velocity). Three of the impacts were in each of the three significant orientations; one lateral and both axial directions. This tube was supplied by the manufacturer, Electromechanical Research Inc., in their normal potted configuration (tube and voltage divider chain encapsulated in silicone rubber in a cylindrical epoxy-glass case). The encapsulated tube was mounted in an aluminum test fixture in the same manner as the vidicons.

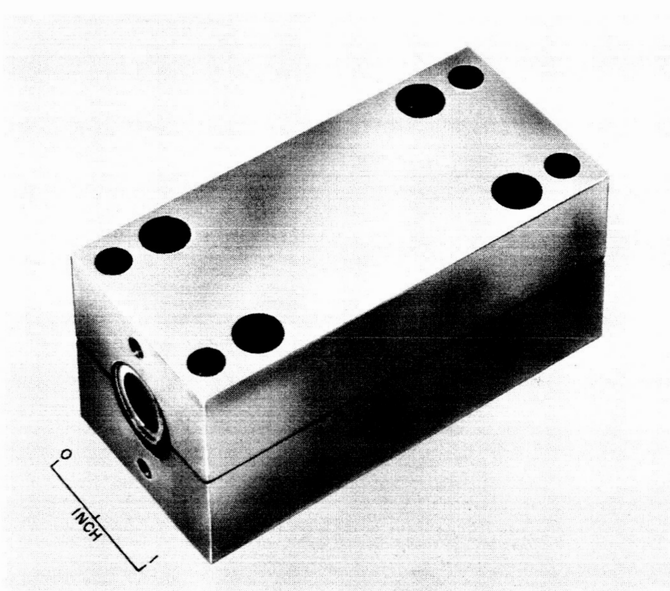

Fig. 20. Vidicon tube in test fixture

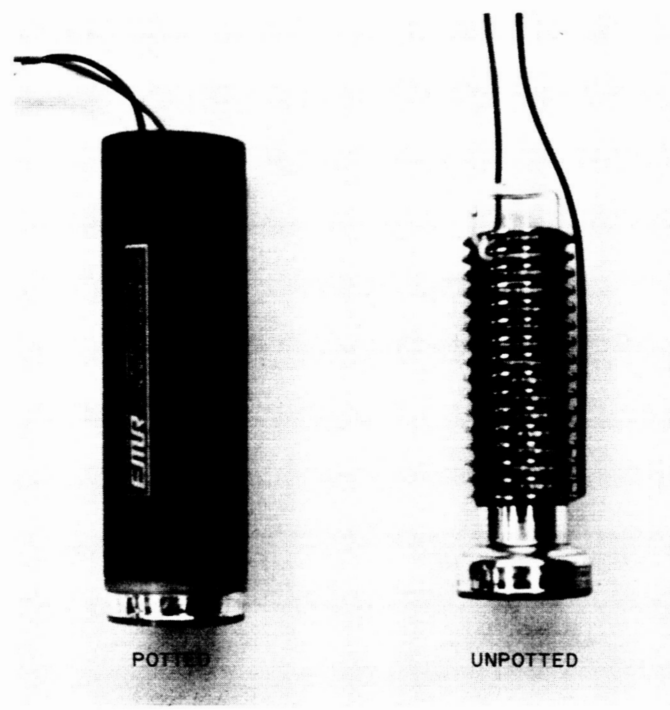

Fig. 21. Photomultiplier tubes

The photomultiplier tube was checked before and after impact for dark current and for signal current under fixed illumination (at the stated supply voltage for 10^5 gain). After the first three impacts (one in each axis), the sensitivity appeared to be down about 15%; however, no further reduction was noted after six additional impacts and it is possible that the test conditions might have varied sufficiently to cause this apparent sensitivity change.

The tube was then subjected to three impacts of 2000-g peak amplitude and approximately 1.5-msec duration (100-ft/sec impact velocity). It was found that the glass envelope had shattered in the flared region adjacent to the cathode window and that there was internal damage which might have resulted from the broken glass being loose within the tube. This test is considered unsatisfactory and further tests are planned.

Summary

Certain vidicon camera tubes have withstood impacts of 2000 to 3000 *g*. A photomultiplier tube has been successfully tested to 1500 *g*.

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