NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-363

Impact Testing of Thermoelectric Hardware for Space Power Applications

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Contents

Tables

Figures

Abstract

As part of its overall thermoelectric failure-mode testing and analysis program, the Jet Propulsion Laboratory is carrying out a series of high-*g* impact tests to determine the effects of potential hard-landing missions on thermoelectric hardware. Two thermoelectric devices have been tested to date: Westinghouse tubular modules and RCA silicon–germanium couples. The Westinghouse module, an early high-efficiency prototype (HEP) series unit, successfully survived a 10,000-*g* impact shock with no apparent deleterious effects. A group of RCA couples successfully survived impact loads of up to 2000 *g* with no changes in their physical characteristics.

Impact Testing of Thermoelectric Hardware for Space Power Applications

I. Introduction

The thermoelectric failure-mode testing and analysis program was initiated at the Jet Propulsion Laboratory in mid-1966 with the impact testing of thermoelectric couples and modules. The program was expanded in late 1966 when the first couple tester became operational. This report describes the initial efforts of the impact testing phase of the failure-mode testing program.

II. Program Scope

The impact testing program has been established with two objectives in mind: first, to determine the effect of various high-g impact loads on thermoelectric generator performance; second, to determine the size and weight of impact attenuating mechanisms that might be required to reduce the transmitted loads to allowable levels. These are designated the Phase I and Phase II programs, respectively.

The Phase I program will evaluate thermoelectric hardware from Westinghouse, RCA, Minnesota Mining and Manufacturing, General Atomic, and the Martin Company. To date, only the Westinghouse and RCA devices have been tested.

III. Westinghouse Tubular Thermoelectric Modules

Five tubular thermoelectric modules have been acquired for impact testing, including all-surplus hardware from the Westinghouse high-efficiency prototype (HEP) series. The physical description of the modules at the time of delivery is shown in Table 1. Included are length-to-area ratios (L/A).

One aspect of the Westinghouse tubular concept is that the design does not lend itself to the fabrication of individual couples; the swaged (or isostatically pressed)

Table 1. Physical characteristics of HEP modules

ID No.	No. of couples	Type of contacts	Internal resistance, Ω[a]	Active length, in.	Overall length, in.	L/A, inner, per in.[b]	L/A, outer, per in.[b]	OD, in.
HEP-9	37	Pressure	0.1	7.91	12.11	0.182	0.0766	1.57
HEP-12	37	Pressure	0.1	7.78	12.99	0.182	0.0766	1.57
HEP-15	37	Pressure	3.7	7.86	12.22	0.182	0.0766	1.59
HEP-16	37	Pressure	1000	7.92	12.40	0.182	0.0766	1.58
HEP-17	37	Pressure	0.2	7.92	12.12	0.182	0.0766	1.75

[a] Internal resistance when fabricated.

[b] Length/area ratios are for single wafers of material only.

assembly fabrication process is currently feasible for full modules only. Since impact testing is ultimately a destructive experiment, the procurement of new, custom-made hardware for high attrition rate testing is prohibitively expensive. To minimize costs, tubular modules were obtained that had all experienced some environmental condition that was deleterious to performance, and were procured as used, surplus hardware. The internal resistances of the modules had increased greatly over their original "as-fabricated" values; in some cases by orders of magnitude.

A. Module Description

The tubular thermoelectric module is illustrated in Fig. 1a. The thermoelectric material is lead telluride doped with sodium or lead iodide for *p*- and *n*- material, respectively, and pressed into washers. The washers are alternately stacked *p*- and *n*- materials with 5-mil mica washers providing electrical inter-element insulation. Common hot-side and common cold-side electrical insulation is provided by thin-walled boron nitride tubes fitted between the washer-shaped elements and the hot and cold claddings. The electrical bridging of the elements is accomplished with the use of iron ring-shaped contacts on the inner and outer circumferences of the elements.

Preliminary assembly of the module is performed in an argon atmosphere. After assembly, the module is exposed to hydrogen-vacuum heat treatment cycle, seal-welded, and hydrostatically pressurized to approximately 50,000 psi in a cold fluid autoclave. This step reduces the outer diameter of the tube, closes the assembly gaps, and initiates densification of the lead telluride. Following cold compaction, the module is subjected to the final step of gas pressure sintering in a hot helium autoclave.

B. Test Procedure

The HEP-12 tubular module was X-rayed on a 2.5-MeV machine. Analysis of the X-ray films indicated no apparent internal abnormalities except for minor deformations resulting from processing of the module (Fig. 1b).

The module was checked on a high-sensitivity, precision milliohmmeter, and was found to have an internal resistance of over two orders of magnitude greater than the as-processed value. Because the internal resistance of the device, due to its history, was not a reliable standard, open circuit voltage, which is independent of resistance and purely a function of temperature for a given material, was selected as the reference output parameter.

To simplify the measurement of the Seebeck coefficient, a transient measurement test was selected. The module was inserted into a container to shield it against random air currents, and then instrumented with a chromel-alumel thermocouple on the outer cladding surface, midway along its length (Fig. 2). Electrical power input to the module was set at 200 W, and the resulting temperature of the module closely monitored. As soon as 200°F was reached on the outer cladding, the open circuit voltage was read. For the HEP-12 module, it was 103.6 mV.

The impact test was performed with a bungee cord "slingshot." The thermoelectric module was mounted laterally to the direction of impact in an impact fixture on a free rolling carriage (Fig. 3). The total weight of the module and fixture was 12.5 lb. A motor-driven winch drew the carriage into firing position and held it. Upon signal, the carriage was released, impacting its ¾-in.-diam leading edge into a 1.5-in.-thick copper block. The

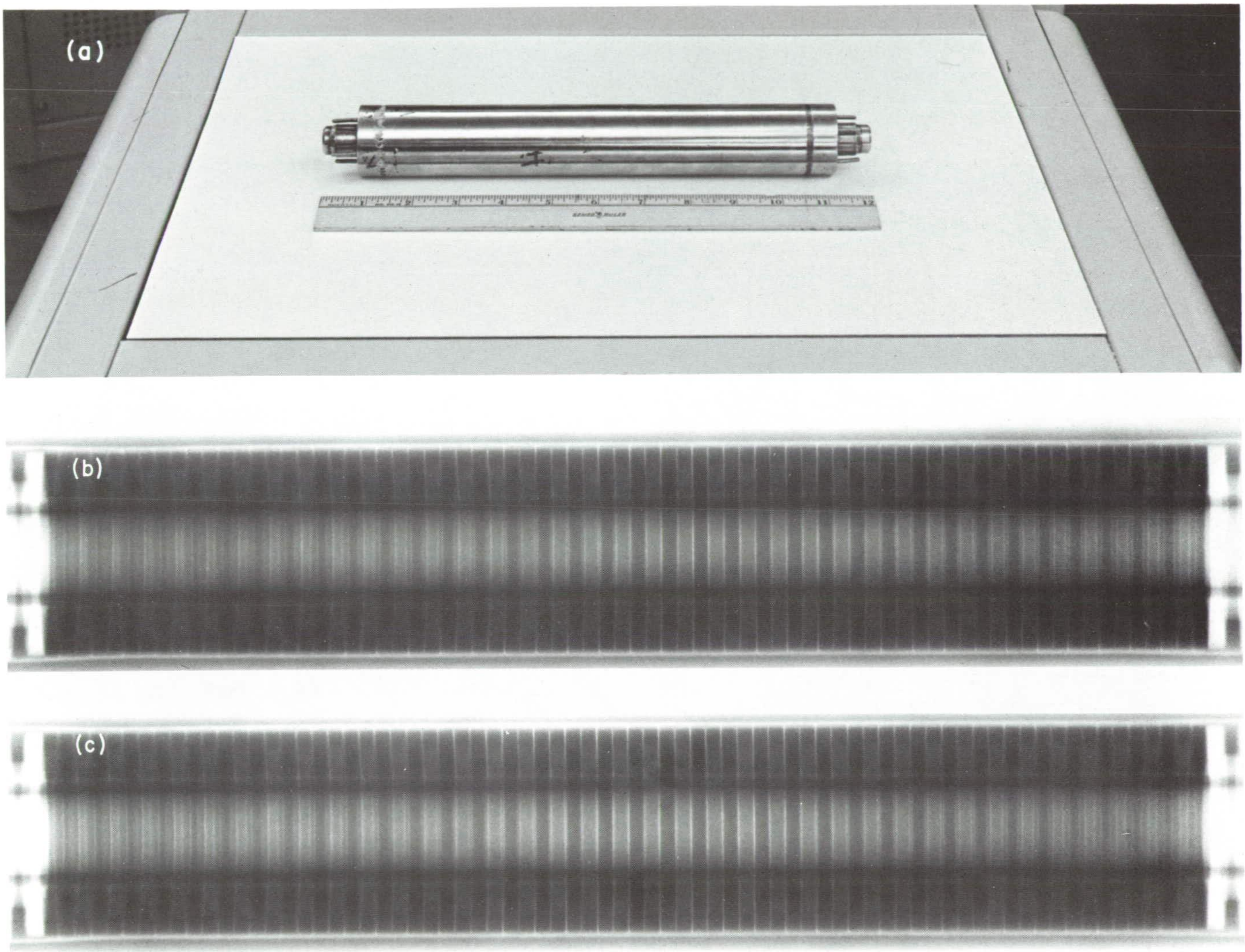

Fig. 1. Westinghouse tubular thermoelectric module: (a) external view, (b) X-ray of HEP-12 module before impact, (c) X-ray of HEP-12 module after impact

impact tool penetration depth measured 0.236 in. The impact velocity was calculated to be 91.3 ft/s, and the average impact load to be 6600 g, with a peak impact of greater than 10,000 g.

The tubular module was again X-rayed on a 2.5-MeV machine, and analysis of the post impact films revealed no discernible changes in the inner structure. No cracks in the material or dislocations in the element structure were observed (Fig. 1c). A second Seebeck test was performed, repeating the testing technique used for the pre-impact measurements. No change in Seebeck voltage was found.

IV. RCA Silicon–Germanium Air-Vac Couples

Individual Air-Vac thermoelectric couples were procured from RCA in groups of three different length-to-area ratios: 2, 4, and 8 cm^{-1}. Each of the couples had a threaded stud brazed to the cold side for easy mounting (Fig. 4). Two series of tests were performed: inclined ramp impact testing and drop tower impact testing.

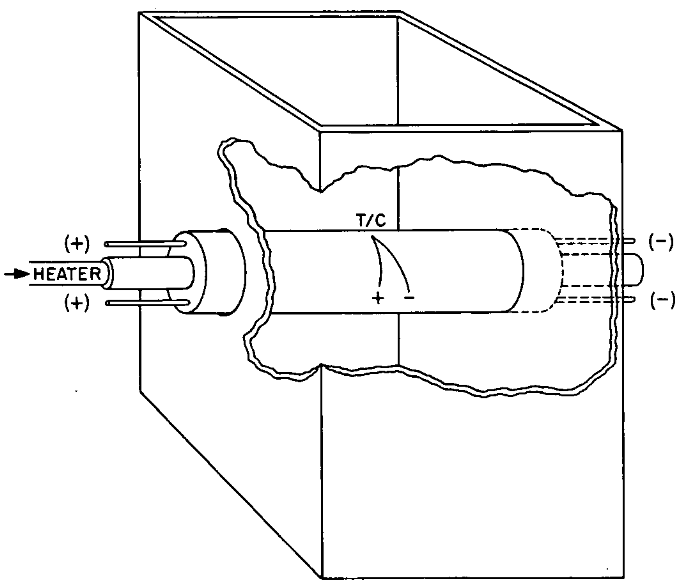

Fig. 2. Test setup for Seebeck measurement

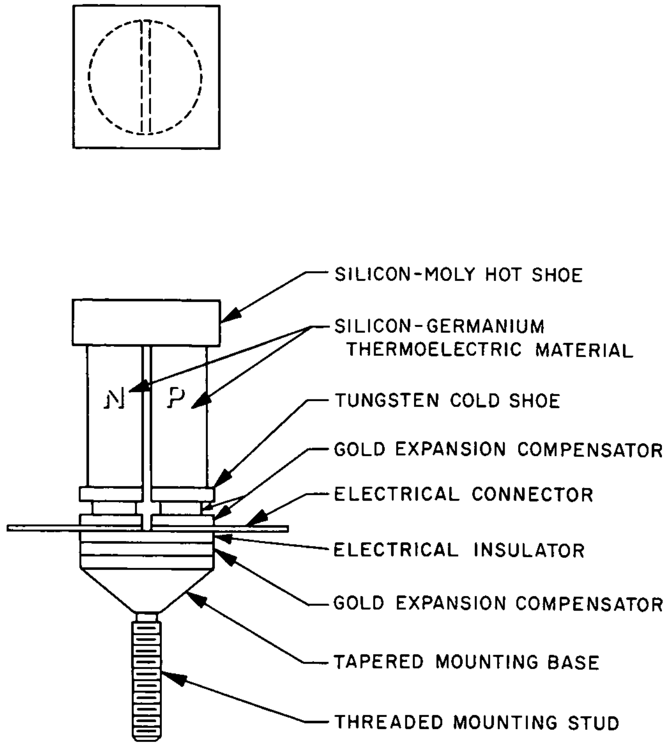

Fig. 4. Silicon–germanium Air-Vac thermoelectric couple

A. Thermoelectric Couple Description

The RCA name of Air-Vac designates the couple's ability to operate effectively in air or vacuum. The RCA Air-Vac couples were prepared from silicon–germanium material that had been cast and zone refined. The hot shoe, made of silicon–moly alloy, and the cold shoes, made of tungsten, were bonded to the elements by an RCA-developed process. The supporting stack, composed of gold expansion compensators and an electrical insulator, was attached to the basic couple by diffusion bonding. The couple, with the expansion compensating stack, was then brazed to a stainless steel mounting base stud.

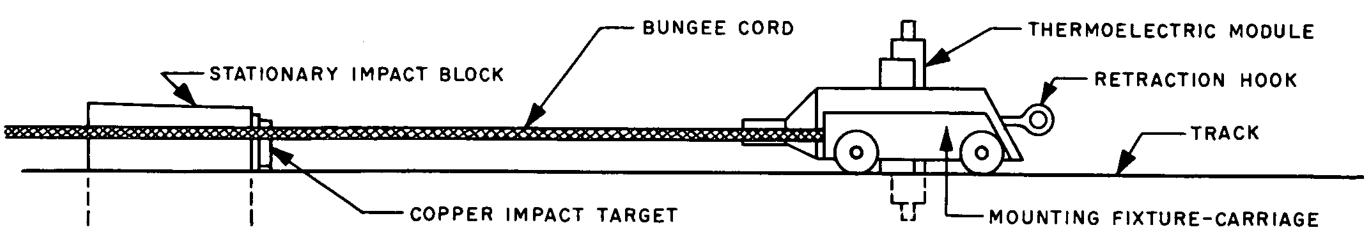

Fig. 3. Bungee cord impact test

B. Inclined Ramp Testing

Six Air-Vac couples were mounted to a circular holding fixture which was bolted to the floating support bed shown in Figs. 5 and 6. An electrically hoisted impact block was pulled up the incline and held at a fixed distance from the support bed (Fig. 6). Upon a given signal, the block was released, impacting into the support bed and transferring the impact energy to the mounting block and the thermoelectric couples.

A series of four tests was performed on the inclined ramp, starting at 100 g and ending with 475 g, the capacity of the ramp. Electrical resistance checks of each of the six couples were made prior to and following each test. The results are shown in Table 2.

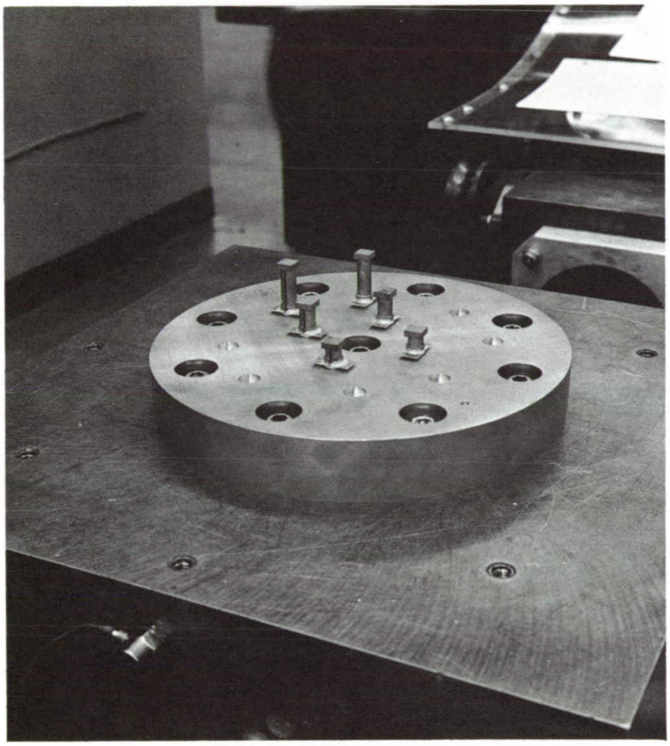

Fig. 5. Air-Vac couples mounted on impact block

Fig. 6. Inclined ramp impact testing device

Table 2. Electrical resistances of Air-Vac couples before and after impact tests

ID No.	L/A, cm^{-1}	Test No. 1, 100 g		Test No. 2, 200 g		Test No. 3, 300 g		Test No. 4, 475 g	
		Resistance, Ω		Resistance, Ω		Resistance, Ω		Resistance, Ω	
		Before	After	Before	After	Before	After	Before	After
17	2	0.0062	0.0062	0.0062	0.0062	0.0062	0.0063	0.0062	0.0062
65	2	0.0061	0.0061	0.0061	0.0061	0.0061	0.0065	0.0063	0.0063
03	4	0.0099	0.0099	0.0099	0.010	0.010	0.010	0.010	0.010
63	4	0.012	0.012	0.012	0.0105	0.0105	0.012	0.012	0.012
13	8	0.020	0.020	0.020	0.0195	0.020	0.020	0.020	0.020
16	8	0.0215	0.0215	0.0215	0.0215	0.0215	0.0215	0.0215	0.0215

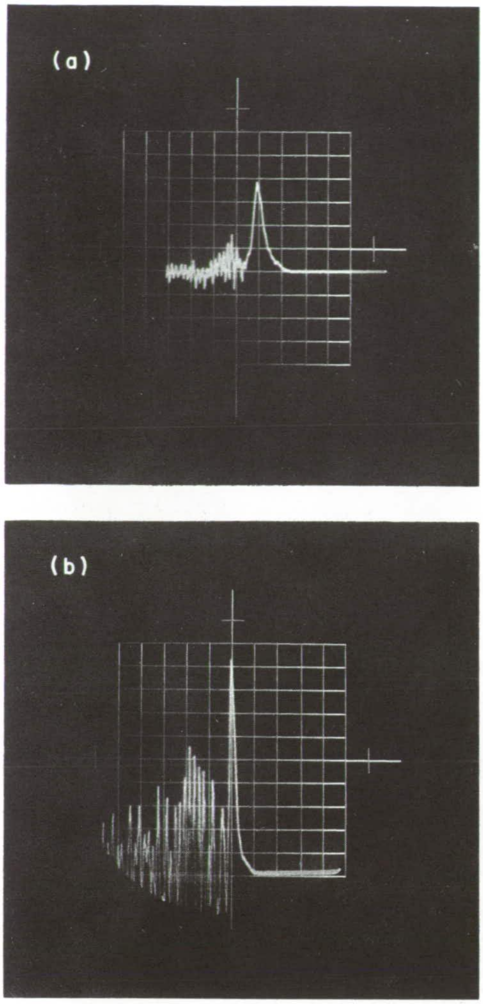

Fig. 7. Oscilloscope measurement: (a) 200-*g* impact, (b) 475-*g* impact

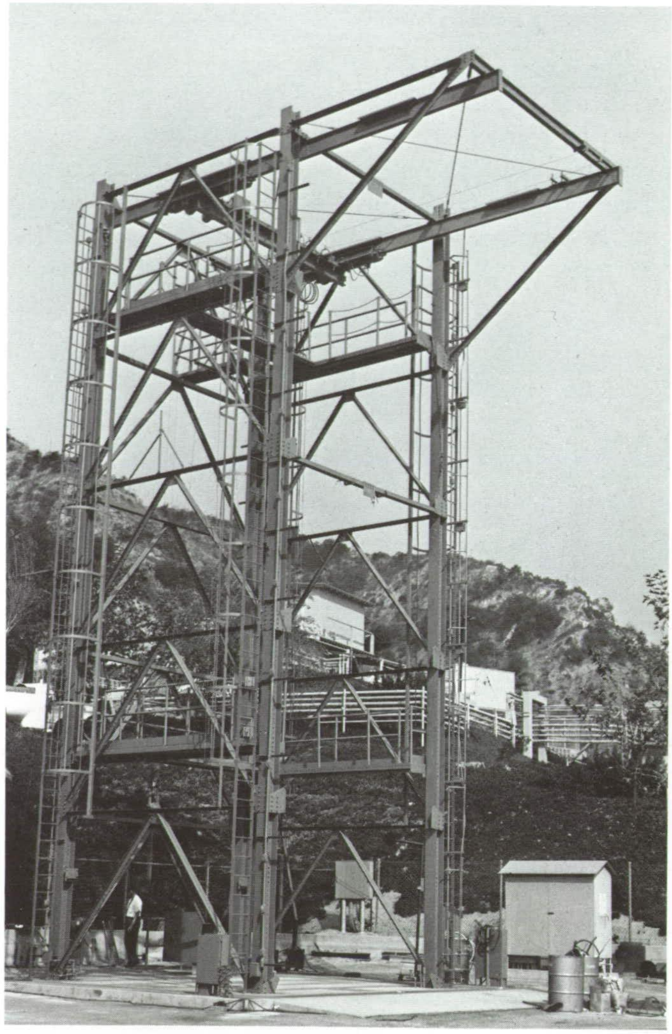

Fig. 8. Fifty-foot drop tower

The *g* load, as measured on a Hughes Memo-Scope oscilloscope Model 105AR, is shown in Figs. 7a and 7b. With the scope calibration set at 50 *g* per division, Fig. 7a shows an impact of 200 *g* and Fig. 7b of 475 *g* (peak value in both cases). Velocities of less than 20 ft/s were obtained in these tests.

C. Drop Tower Tests

The drop tower (Fig. 8) tests were established to obtain impact data at load levels above the 475-*g* capability of the inclined ramp. Although the impact velocity of the drop tower test fixture was fixed by the tower height and was fairly low (51 ft/s), the *g* level could be widely varied by changing the target material and geometry.

The test basically involved the free fall of the test specimen from a predetermined height onto a specific target material. The impact velocity was measured by a differential photocell-timer circuit, and the peak *g* measured with an accelerometer attached to the test specimen mounting fixture. Six Air-Vac thermoelectric couples were attached to a mounting fixture (Fig. 9) which was, in turn, attached to the impact carriage (Fig. 10).

The couples were mounted in three different orientations: cantilevered, with the slot between the elements aligned parallel to the direction of impact; cantilevered, with the slot between elements aligned normal to the direction of impact; and vertical, with the cold shoes of the couples in the direction of impact (Fig. 11). Each orientation included three different lengths of couples, representing couples with length-to-area ratios of 2, 4, and 8 cm^{-1}.

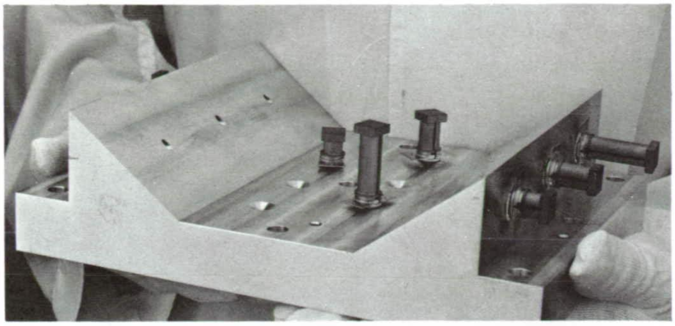

Fig. 9. Air-Vac couple mounting fixture

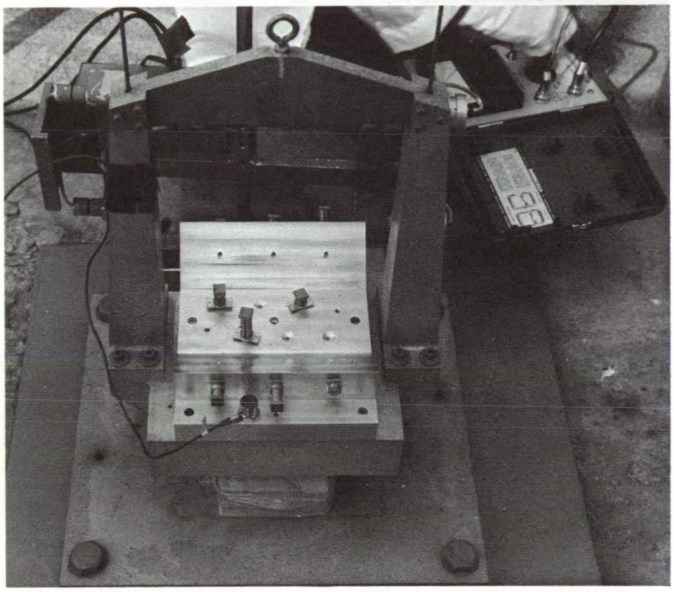

Fig. 10. Mounting fixture attached to drop carriage

Electrical resistance measurements were taken of all the couples, both before and after each test. Four tests were performed, the peak *g* level for the series being 700 *g*, 800 *g*, 1400 *g*, and 2200 *g*. An electrically-driven winch raised the couple mounting fixture to a height of 42 ft each time.

It was expected that a discrete failure, rather than a gradual increase in electrical resistance, would result from the stresses induced by the high-impact loads. This expectation was borne out by the drop tests, as two couples broke apart and no evidence of resistance increase could be detected for the remainder of the couples, all of which survived.

The two couples that broke were the ones that logically would be expected to experience the greatest internal stresses: they were the two longest couples (L/A = 8/cm), oriented in the cantilever position. The couple with the interelement slot in the horizontal position failed at 700 *g*; the couple with the vertical slot failed at 800 *g*.

A summary of the test results is given in Table 3. The letter A after couple number indicates a vertical couple orientation; B indicates cantilevered with a horizontal slot; and C indicates cantilevered with a vertical slot.

The *g* loads were obtained by the following variations in the impact target:

(1) 700 *g*: untaped balsa wood, 2 in. thick, hit with impact area of 4¼ × 4¼ in.

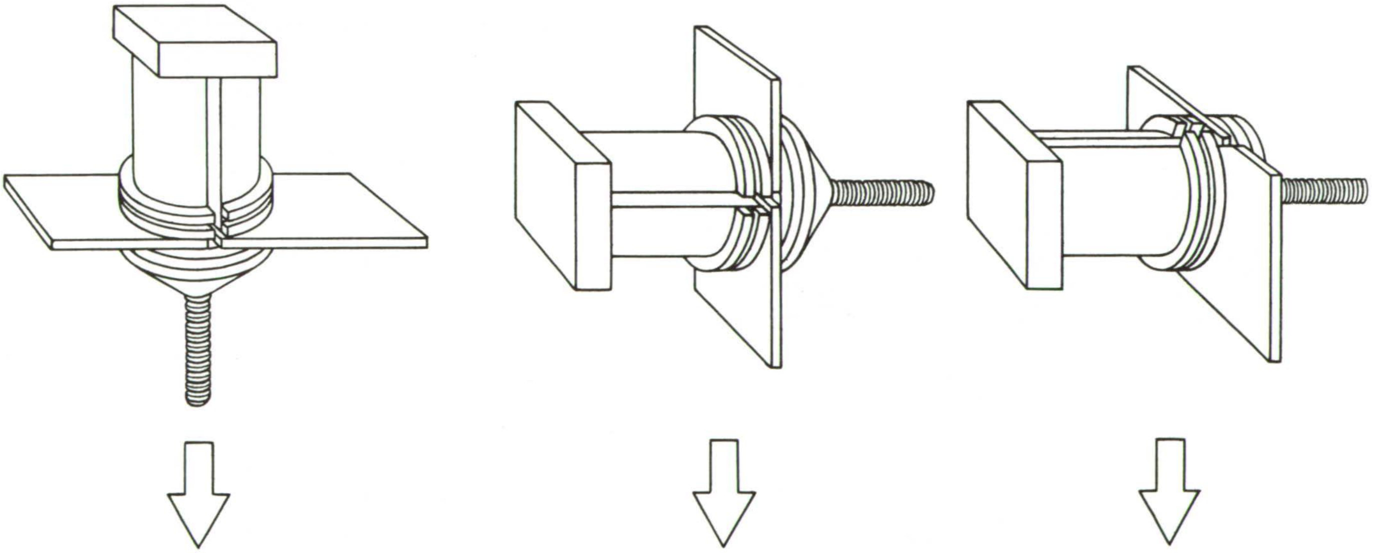

Fig. 11. Air-Vac couple impact orientation

Table 3. Drop test results on Air-Vac couples

ID No.	L/A, cm^{-1}	Initial test resistance, Ω	After 700-g drop test, Ω	After 800-g drop test, Ω	After 1400-g drop test, Ω	After 2300-g drop test, Ω
N 52A	4	0.0100	0.0100	0.0100	0.0100	0.0100
N 13B	4	0.0095	0.0095	0.0096	0.0095	0.0096
N 8C	4	0.0095	0.0092	0.0092	0.0094	0.0094
N 20A	2	0.0050	0.0050	0.0051	0.0051	0.0050
N 40B	2	0.0050	0.0050	0.0049	0.0050	0.0049
N 2C	2	0.0050	0.0049	0.0049	0.0050	0.0050
N 56A	8	0.0188	0.0188	0.0183	0.0181	0.0185
N 27B	8	0.0187	0.0188	Broke	—	—
N 22C	8	0.0193	Broke	—	—	—

(2) 800 g: untaped balsa wood, 2 in. thick, hit with impact area of 4½ × 5 in.

(3) 1400 g: taped balsa wood, 2 in. thick, impact area 4½ × 8 in.

(4) 2200 g: lead cone, truncated, ½ in. thick, 3-in.-diam base, ½-in.-diam tip.

Figure 12 shows the nature of the failure for couple No. 27. It will be noted that the couple failed not at the contact, but on a nearly 45-deg plane through the material near the hot shoe.

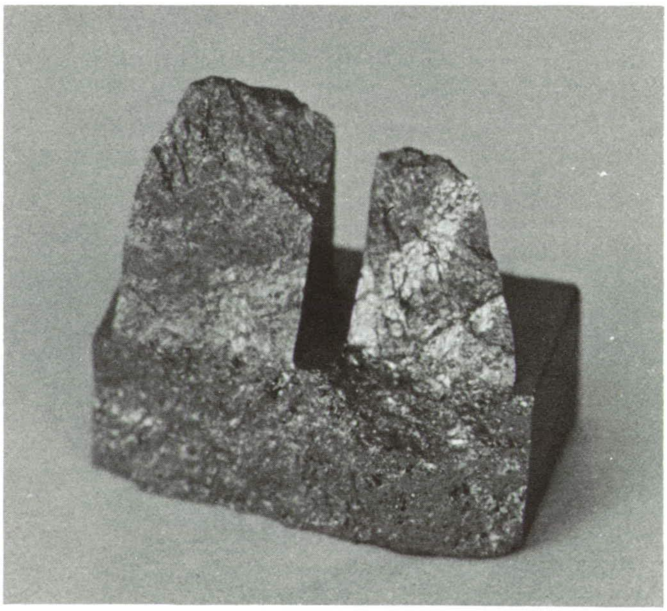

Fig. 12. Impact fractured Air-Vac couple

V. Conclusions

From the limited impact testing performed to date, it appears that at least two thermoelectric concepts, the tubular lead telluride module and the silicon–germanium Air-Vac couples, are capable of successfully surviving most impact loads that may be encountered in handling, shipping, and nominal space flight operations. To directly translate test results into a determination of the capability of the two thermoelectric concepts to survive either earth reentry or planetary entry impacts would be unrealistic from two standpoints.

First, the total number of tests performed was statistically too small to permit a broader interpretation of results. Second, the impact velocities obtained were far below the 350-ft/s number that has been generally accepted as representative of expected reentry or entry conditions. The latter factor is the reason why only one tubular module and a portion of the silicon-germanium couples were used; testing is being shifted to a facility that will provide higher velocities.

Further impact testing at JPL will be performed in compressed air guns which are currently committed to flight programs. The silicon–germanium thermoelectric couples will be tested in a 6-in.-diam gun which is capable of accelerating a mass of 24 lb to 500 ft/s. The tubular thermoelectric modules will be tested in a 22-in.-diam device which is capable of accelerating approximately 400 lb to 500 ft/s.