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INTRODUCTION

The purpose of this paper is to discuss the rather unique application of a pyrotechnic device to solve a problem that was encountered in the design of the reentry package for Project Fire.

Project Fire was undertaken by the National Aeronautics and Space Administration to investigate the heating environment of vehicles entering the earth atmosphere at velocities slightly greater than lunar return velocities. The primary objective was to obtain onboard measurements that would define the hot-gas radiance and the total heating on a blunt-nosed body of fairly large scale. These results, on a firmly established basis, were needed to test various theoretical and empirical heat-transfer prediction techniques that had been proposed by individual research scientists, as well as others that would be proposed in the future.

BACKGROUND

The objective was met by lifting a powered spacecraft above the atmosphere with an Atlas launch vehicle and then propelling a reentry package in the spacecraft back into the atmosphere at a velocity of about 13 km/sec. Figure 1 illustrates the sequence of events by which the reentry package was placed in its high velocity return trajectory. The events of the experimental data period are not shown; they will be discussed later.

Figure 2 is a sectional view of the instrumented reentry package, the spacecraft adapter, and the separation system. The reentry package, at the left, had a blunt, spherical segment forebody and a conical afterbody, with a diameter of about 67 cm and a weight of 86 kg. The package is depicted in the act of separating from the powered spacecraft, under the action of a spring. As illustrated in the figure, there were three beryllium calorimeters, each of which was heavily instrumented with thermocouples and designed to provide total heating data until the surface melted. Under each calorimeter was a phenolic asbestos shield to provide heat protection for the next calorimeter. After the first calorimeter melted, the underlying heat shield was ejected on command, exposing the second calorimeter which then began to measure the total heating rate. This sequence of events was then repeated after the second calorimeter melted.

This complex calorimeter and heat-shield design was necessary because a single calorimeter could not survive the 13 km/sec reentry. The design not only provided heat protection for the underlying calorimeters, but also insured that the heating measurements would not be affected by ablation products. With the three calorimeters, there were three data periods at times that allowed a definition of the reentry-heating envelope. The sequence also provided solid, uncontaminated windows for the radiometers viewing the gas cap during the same data periods.

DESIGN PROBLEM

Vital to the practical realization of this experiment concept was the design of a suitable system to release and eject the heat shields promptly on command.

The following requirements (fig. 3) applied to the design of this system:

a. The system had to be compact enough to fit within the heat shield and calorimeter layers while leaving the center of the layers free to permit installation of a window for the stagnation-point radiometer.

b. The system had to attach and support the heat-shield system with sufficient strength and rigidity to withstand the force, vibration, and thermal environments produced by the launch vehicle and by reentry without damage or misalinement of the structure, windows, or sensors.

c. The system had to be suitable for programed release initiated by an onboard programer.

d. The system had to function in such a way as not to produce shocks which might damage the spacecraft instrumentation nor to produce unbalanced impulses which might perturb the attitude of the spacecraft.

e. The system had to function positively and with high reliability to insure that the required sequence of events would be performed in accordance with the necessary precise timing.

f. The system had to be compatible with installation during early stages of spacecraft assembly and not hazardous through the remaining stages of assembly, test, shipping, and field operations. Most conventional pyrotechnic release systems would fail to meet the requirements for low shock, low unbalanced impulse, and handling safety after installation. On the other hand, most purely mechanical systems would not be suitable for programed initiation.

EXOTHERMIC FUSE WIRE

The solution of this problem made use of a special fuse wire, which is available commercially. This wire is made of aluminum alloy with a palladium alloy jacket. When the wire is locally heated to a critical temperature, an alloying reaction occurs which is sufficiently exothermic as to be self-propagating, with the result that the wire melts and the melting propagates along the wire. There is no explosion, flame, or fire. Thus, this material inside a spacecraft would present no inherent hazard to handling personnel, and when initiated it would not produce objectionable shock loads. A heat-shield ejection system was designed which took advantage of these features and met the design requirements of Project Fire.

HEAT-SHIELD EJECTION SYSTEM

The heat shield was designed as four parts, held together by a multi-part link which, in turn, was held together by a wrapping of wire. The link was released on command by the melting of the wire.

Heat Shields

The heat shields were molded of a high-density phenolic asbestos, a material selection based on mechanical strength as well as heat-protection considerations. Figure 4 is a photograph, from the back side, of one set of the ejectable shields in an assembly test fixture. Each shield was molded in four quadrants. A tension link, which was called the ejection link, tied quadrants A and C together and a "jigsaw" configuration retained quadrants B and D. The mating edges of the quadrants were machined for an overlapping seal joint; the rim of the assembly was arranged to hook over the rim of the succeeding beryllium calorimeter dish. The numerous pads that can be seen were bearing points; each was covered with teflon to reduce the sliding friction on the beryllium during ejection. Two semielliptical springs were mounted in the rim of each quadrant; at assembly, they were compressed to a preload of about 1000 N each to provide the ejection force. The tongue on quadrant A extended across the center line to provide material for mounting the stagnation radiometer window; the hole for the window had not been drilled when the photograph was made.

Ejection Link

The ejection link can be seen bolted to quadrant C in figure 4. Figure 5 shows how the link was built. The parts of the link are shown in the lower photograph. The right end of the link was made with a slot and the left end had a mating tongue. When these parts were mated, they were locked by the two wedge-shaped detents which were positioned by the keepers. After the keepers were installed, this assembly was tension wrapped with the previously described stranded exothermic fuse wire. When this wire was locally heated to the melting point by an electrical current, an exothermic alloying reaction took place and the remaining wire rapidly disintegrated. This action freed the detents and allowed the links to separate under the action of the springs in quadrants A and C (fig. 4). The impulse from these springs was sufficient to rapidly eject quadrants A and C from the reentry package. Meanwhile, as soon as the link ends had separated, quadrants B and D were free to move and they were rapidly ejected under the action of their springs.

Ignition Circuit

Initiation of the fuse-wire action was accomplished electrically with a dual-igniter system for redundancy. Two short loops of fuse wire were inserted under the load-bearing wrap of wire which held the keepers in place. These loops were brought out as lead wires. One end of each lead was reduced to a single strand to provide an electrical "hot spot" as an igniter when current was passed through the loop. The exothermic action started at the igniter, propagated along the fuse wire, and was thermally transferred to the load-bearing wrap. The igniter was designed for a 1.0-ampere "no fire" current to meet range safety requirements; the "sure fire" current was about 3.0 amperes. A dual silver-zinc battery was used for redundant firing of the igniters through silicon-controlled rectifier switches which were initiated by the reentry event timer in the reentry package. Magnetic latching relays were used to provide protective shorting of the pyrofuse circuits; these relays were placed in the "ready" condition just prior to launch. The deceleration-started reentry event timer was held in a disabled condition until just before reentry began.

QUALIFICATION

Both qualification testing and development testing were conducted on the ejection link. The development tests verified design capabilities and structural adequacy. They also uncovered one severe ignition problem. Qualification testing was conducted to demonstrate the adequacy of the design for conditions and environments more severe than those expected in flight.

Eight ejection links were subjected to development tests. These tests are listed in figure 6. Two links were tested to ultimate load, and they broke at about 18,000 newtons, which is well over the flight load of 6000 newtons. Two other links were subjected to a separation force test. At the initial test force of 44.5 newtons, these links failed to separate after ignition; however, both did separate by the time the force had been increased to 130 newtons, which is still only a small fraction of the force provided by the ejection springs in flight. One link was subjected to a sustained load of 6000 newtons for more than 800 hours with no significant creep. This link was ultimately fired in the qualification vacuum separation test. One was accidentally fired by a test setup short circuit. One fired successfully on one igniter and one failed to fire at -18° C and 1.3×10^{-2} N/m^2 vacuum on either igniter.

Qualification testing was performed on 42 igniters and on 15 ejection link assemblies containing dual igniters. The environmental tests and their sequence are shown in figure 7.

All igniters were subjected to a 1-ampere "no fire" current. Eighteen were then fired at 10° C in air. The remainder were fired at 10° C in a vacuum of 1.3×10^{-2} N/m^2. In qualification testing of the complete ejection links, each was preloaded to 6000 newtons during exposure to the test environments. All firing tests were conducted by applying firing current to one igniter. Figure 8 shows a link inside the vacuum chamber ready for test and figure 9 shows the link coming apart. In this photograph the fuse wire has melted, the keepers and detents have flown out, and the two halves of the link are pulling apart. Separation was considered to be complete when 3 mm of motion had resulted under the 6000-newton load. Three firings were made with the links at 150° C in the vacuum; 12 firings were made with the links at 10° C in the vacuum. One link failed to fire on one igniter and had to be fired on the second igniter.

The development and qualification tests that have just been described resulted in the discovery of the following problems:

a. One development fuse link failed to fire on either igniter at -18° C and 1.3×10^{-2} N/m^2. The igniter strand melted open but ignition did not continue to the full wire. Subsequent inspection of other igniter wires revealed small nicks caused by tools during assembly. These constituted high resistance areas that caused premature ignition with too little energy for propagation when the wire was cold. A review of the expected flight temperature showed that the qualification temperature of -18° C was unnecessarily low. It was, therefore, raised to +10° C.

b. After raising the qualification temperature, one pyrofuse link failed to ignite at 10° C on one igniter and had to be fired on the second igniter.

c. The time from electrical initiation to fuse link separation ranged from 322 milliseconds to 567 milliseconds. This time lag was acceptable for the application under discussion, but it does represent a limitation to the application of this exothermic fuse wire.

Qualification of the ejection links installed in the spacecraft was accepted since the one complete ignition failure encountered in the tests had occurred at an unrealistically low temperature. It would have been desirable to at least reinspect the installed links for igniter wire nicks but this was not possible without extensive disassembly which would have caused irreparable damage to the spacecraft. A decision to proceed with the flight was therefore made.

For the second flight spacecraft a modified ejection link was fabricated, qualification tested, and installed. In the modified link, the fuse wire was re-routed so that fuse wire from both ends of the igniter passed under the wrap on the link. Thus, if the fuse action propagated in either direction from the igniter, it would reach and ignite the main wrap. No test failures were encountered with the redesigned link.

OPERATIONAL EXPERIENCE

Wind-tunnel tests, under simulated dynamic-pressure conditions, indicated a time from first motion to full clearance of the package of about 20 msec. The flight performance of the system was excellent for both flights with rapid ejections and no significant disturbance in either case. Telemetry data from the radiometers and calorimeters indicated that each ejection occurred within the expected time after the command was made.

CONCLUDING REMARKS

A special fuse wire which functions by an alloying reaction with no flame and gives off no smoke or gaseous products was a key element in the design of a heat-shield ejection system for an important flight experiment. Two such systems were commanded to function on each of two flights in Project Fire, and in all four cases they functioned properly.

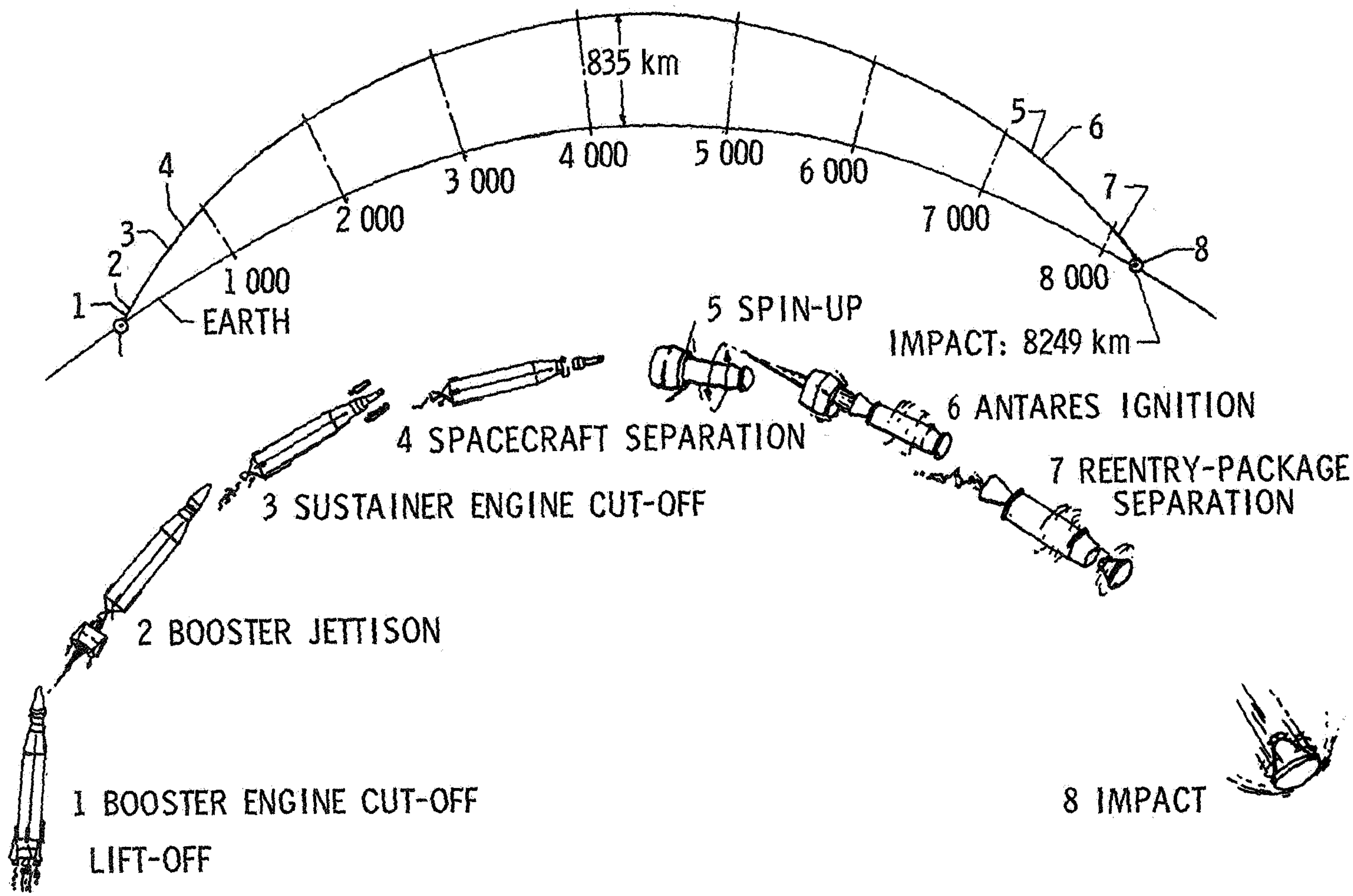

Figure 1.- Project Fire flight-plan sequence of events.

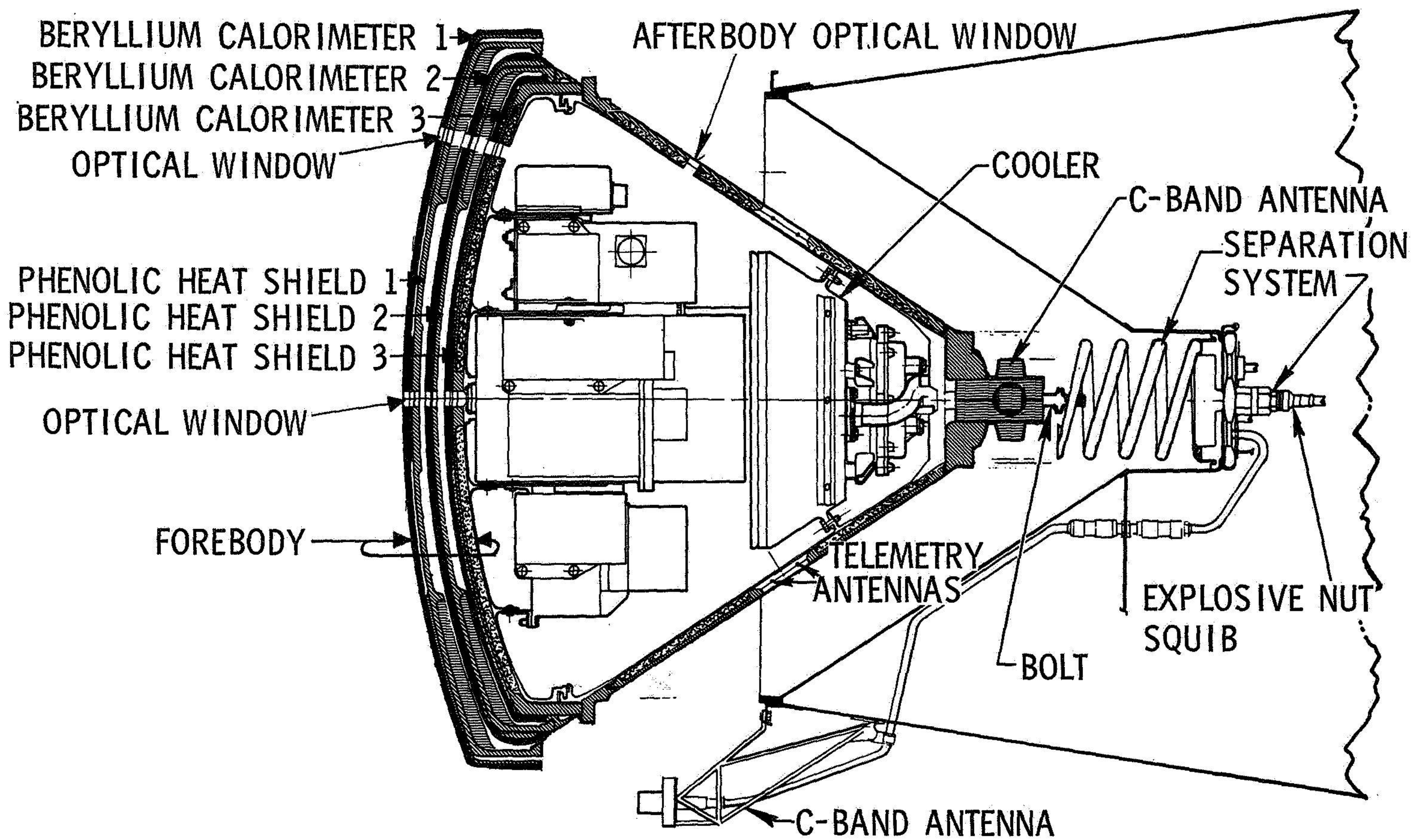

Figure 2.- Sectional view of reentry package and adapter.

COMPACTNESS

STRENGTH AND RIGIDITY

PROGRAMMED RELEASE

MINIMUM SHOCK AND NO UNBALANCED IMPULSE

RELIABILITY

ASSEMBLY MONTHS BEFORE LAUNCH

NO HAZARD IN HANDLING

Figure 3.- Release and ejection system requirements.

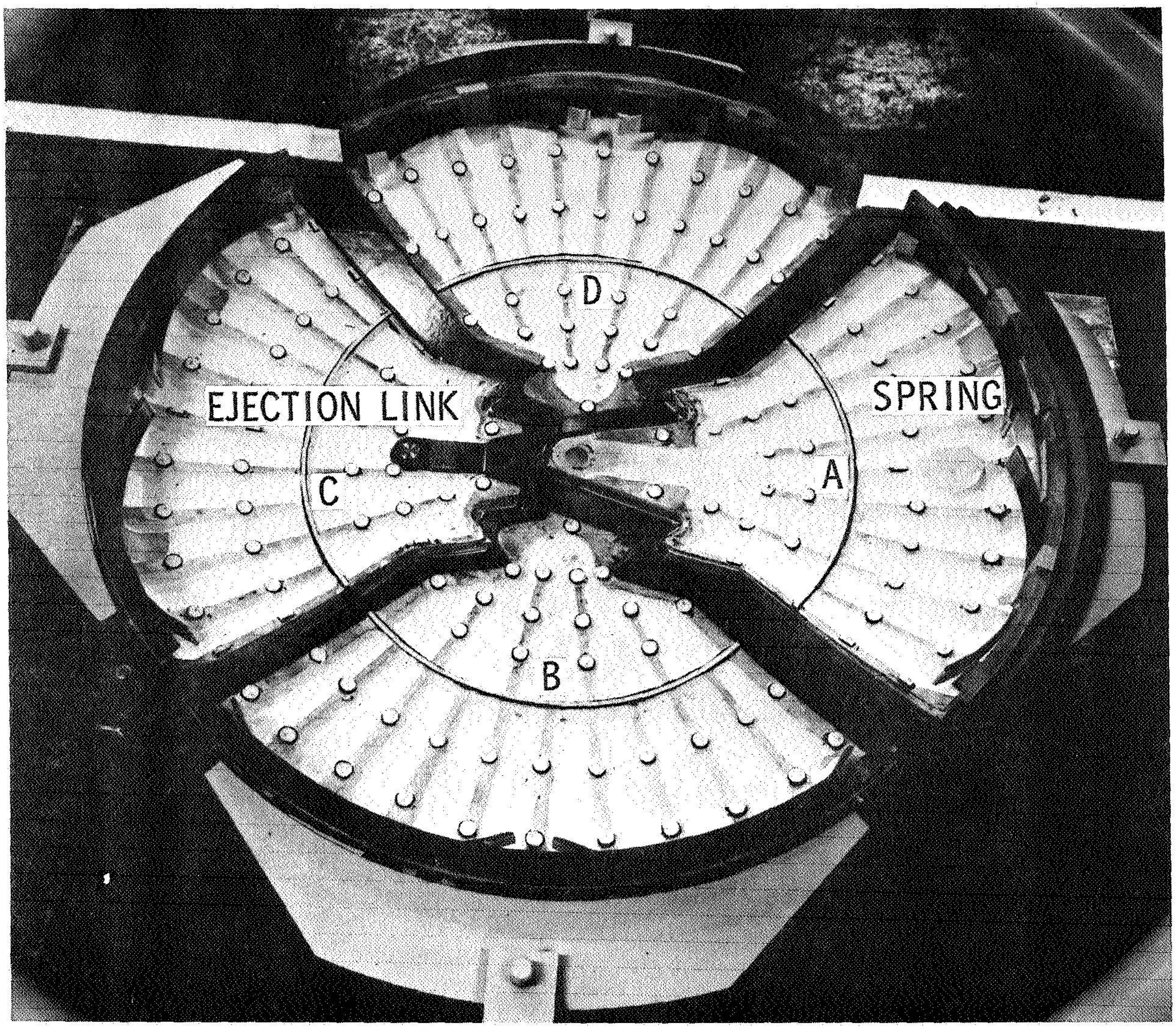

Figure 4. Phenolic-asbestos heat-shield quardrants in assembly test fixture.

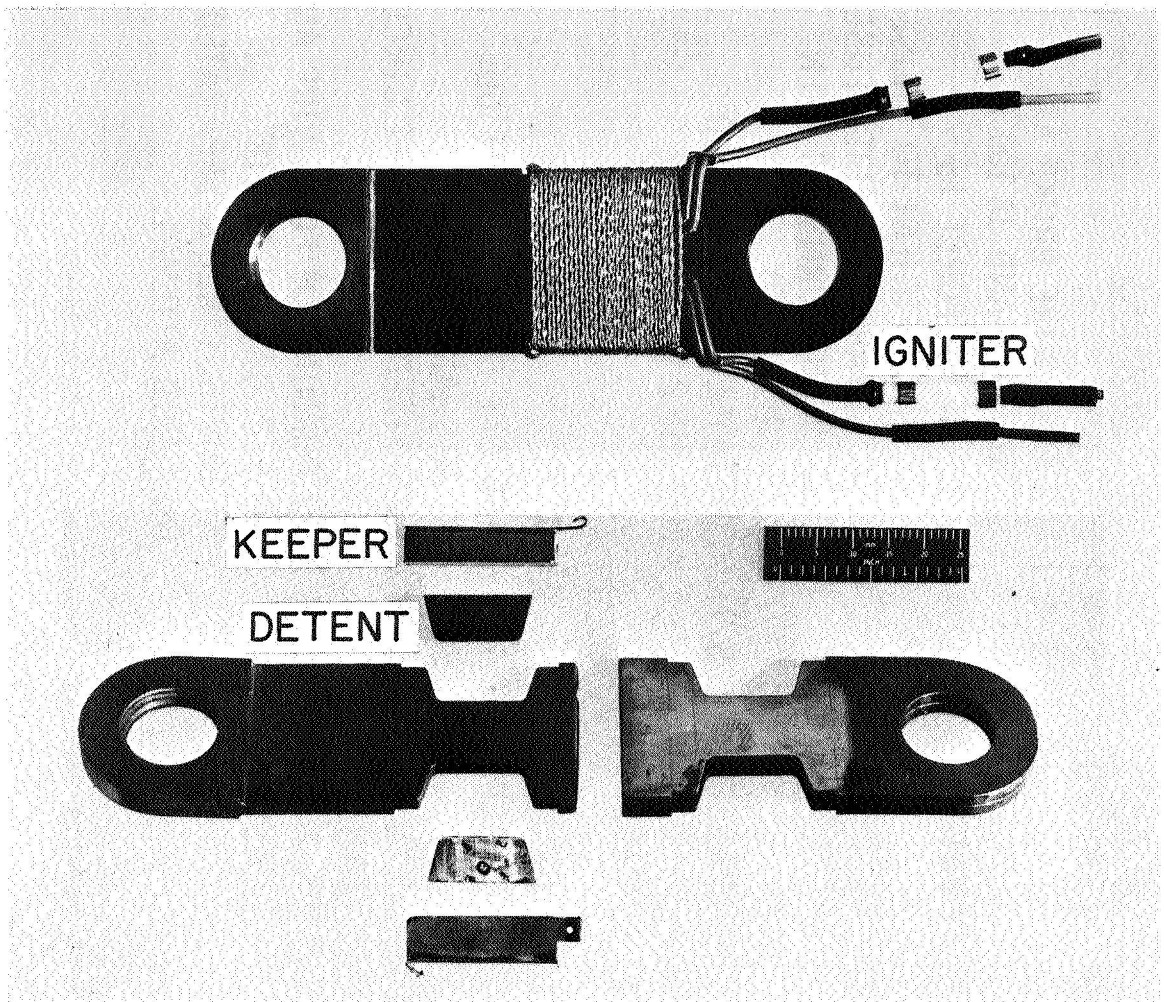

Figure 5.- Photographs of assembled heat-shield ejection link and parts.

TEST DESCRIPTION	TEST RESULTS	REMARKS
PHYSICAL EXAMINATION	PASSED	S/N 1-5
ULTIMATE LOAD TEST		S/N 1 & 2 FUSE WIRE BROKE AT 17 700 N AND 18 100 N
SEPARATION TEST	FAILED	S/N 3 & 4 - 44.5 N FORCE IS INSUFFICIENT TO CAUSE SEPARATION AFTER FUSE WIRE BURNS. 90-130 N REQUIRED
SUSTAINED LOAD TEST	PASSED	S/N 5 SUSTAINED 6 000 N LOAD FOR 815.2 hr
TEMPERATURE HUMIDITY TESTS	PASSED	
SHOCK TESTS	PASSED	
VIBRATION TESTS	PASSED	S/N 5 HAD ONE OPEN CIRCUIT DUE TO MISHANDLING
LOW TEMP SEPARATION	S/N 7 FAILED	S/N 6 WAS FIRED BY A SHORT CIRCUIT
	S/N 8 PASSED	S/N 7 NO BURNING OF FUSE WIRE AND NO SEPARATION AT -18^{0}C ON TWO ATTEMPTS. FIRED & SEPARATED ON THIRD ATTEMPT.

Figure 6.- Test results summary-development ejection links.

TEST NO.	DESCRIPTION	IGNITERS NO.1-18	IGNITERS 19-42	EJECTION LINKS SPECIMEN NO. 1,2	3	4	5	6,7,8 (6R, 7R, 8R)	9-17
1	PHYSICAL EXAMINATION	X	X	X	X	X	X	X	X
2	ULTIMATE LOAD			X					
3	SEPARATION TEST				X	X			
4	SUSTAINED LOAD TEST				—		X		
5	LOW TEMPERATURE - HUMIDITY				X*	X*	X	X	X
6	HIGH TEMPERATURE - HUMIDITY				X	X	X	X	X
7	SHOCK				X	X	X	X	X
8	VIBRATION				X	X	X	X	X
9	STEADY STATE ACCELERATION							X**	X**
10	CONTINUITY - NO FIRE TEST	X	X		X	X	X	X	X
11	LOW TEMP. SEPARATION	X							
12	LOW TEMP. - VACUUM - SEPARATION		X					X	X
13	HIGH TEMP. - VACUUM - SEPARATION				X	X	X		

* S/N 3 & 4 REWOUND TO 3R AND 4R

** SN 6R, 8R AND 10 WERE EXPOSED TO 120g's IN ALL 6 DIRECTIONS FOR 1 MINUTE. SN 12 AND 14 WERE EXPOSED TO +45g's, -120g's IN LINE OF THRUST AXIS PER SPEC.

Figure 7.- Test sequence.

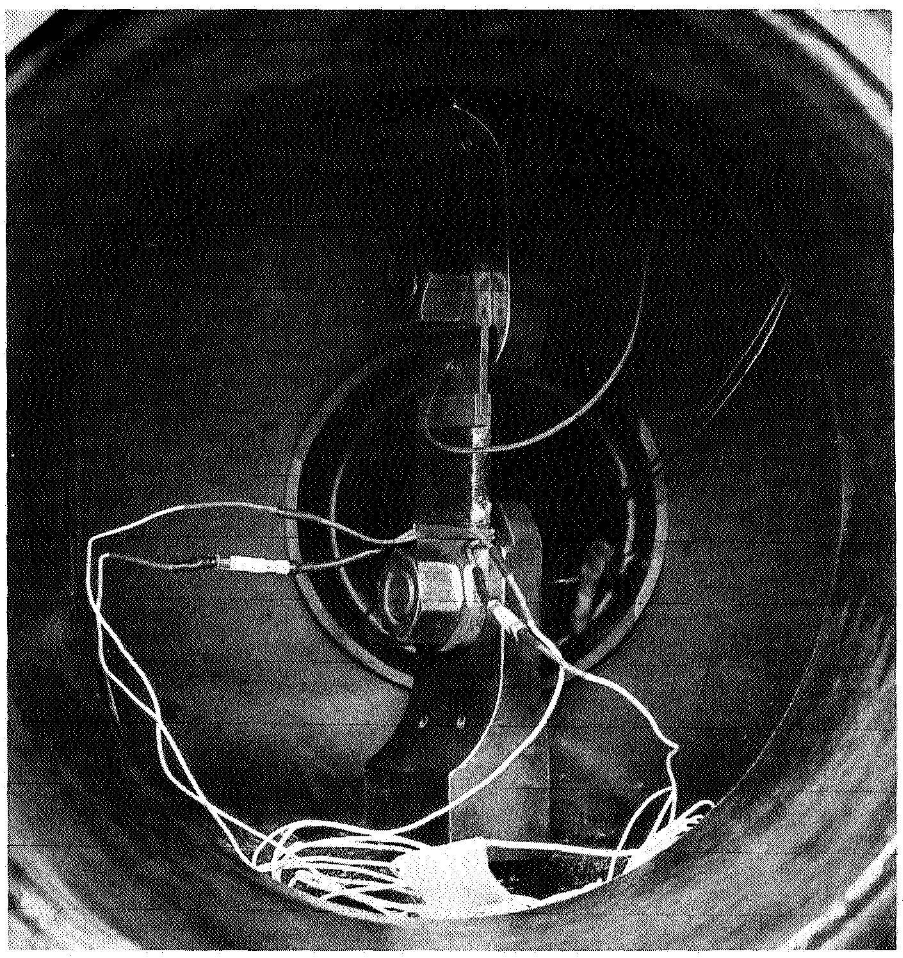

Figure 8.- Ejection link in vacuum chamber.

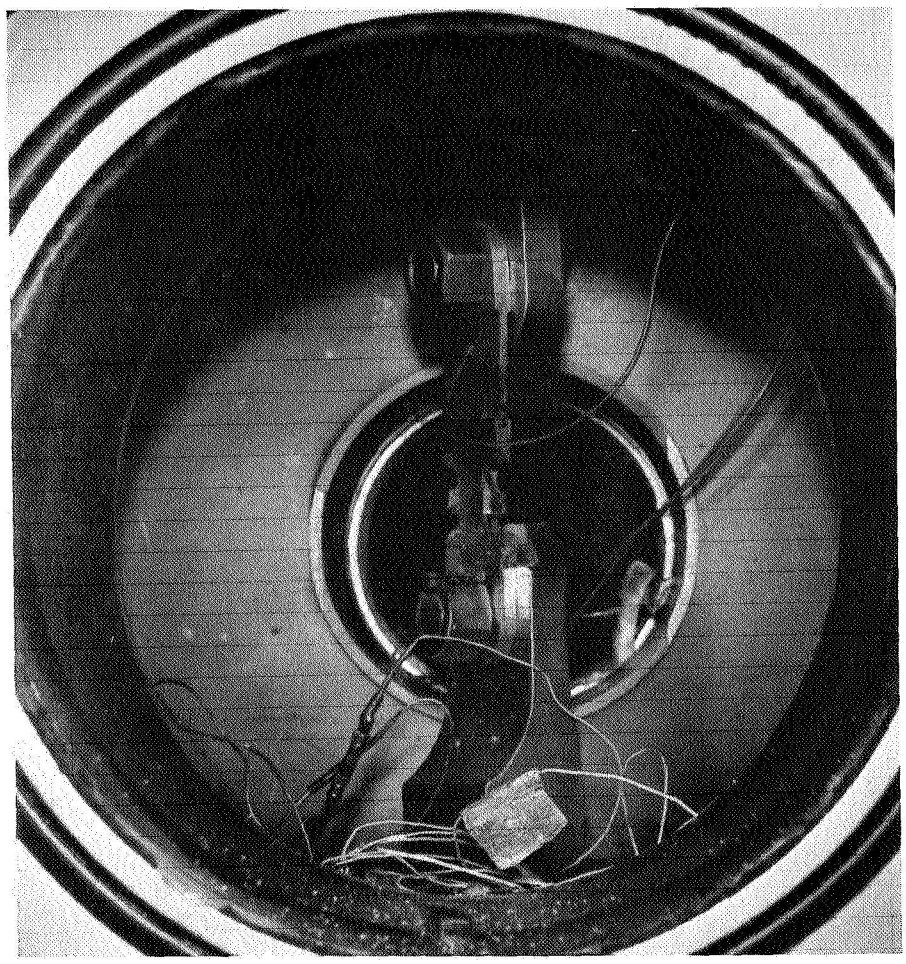

Figure 9.- Ejection link separating.

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