Multiple-Stage Solid-Propellant Sounding Rockets for Space Research

by

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Abstract

Aerodynamically stabilized sounding rockets with performance useful for space research can be constructed from existing solid-propellant motors. An appreciable portion of current high-altitude research is carried out with such vehicles. Three such systems, one capable of carrying 23 kg of payload to 160 km altitude, a second capable of sending 36 kg to 480 km, and a third which has sent 9 kg to 1770 km altitude, have been developed at The University of Michigan, and are described. All these systems have been characterized by low cost and high reliability. Design considerations, such as aerodynamic stability, interstage coupling, protection against aerodynamic heating, and launchers, are discussed. Also pointed out are future capabilities based on increasing availability of military solid-propellant rockets with considerably improved specific impulses and mass ratios.

Introduction

Small solid-propellant rockets were first used for upper-air research by Van Allen [1] in 1952 with the launching of the Deacon rocket from a balloon in the well-known "Rockoon" combination. The advantages of simplicity, reliability, and low cost which may be achieved with solids were effectively demonstrated, and efforts to realize these advantages in an all-rocket system resulted shortly in the Nike-Deacon [2] and later in the Nike-Cajun [2,3,4], Terrapin [2], Nike-Asp [2], Exos [5], Strongarm [6], and others. In many cases the solid units had been developed for military purposes and were available at moderate costs due to high production. This is a key factor in the ultimate low cost of the sounding vehicle combinations described below. Fortunately, many of the units may be obtained commercially.

In 1955 the High Altitude Engineering Laboratory of The University of Michigan, with the valuable aid of the Pilotless Aircraft Research Division of the National Advisory Committee for Aeronautics, began its rocket vehicle work with the Nike-Deacon two-stage combination. The Deacon was shortly superseded by the Cajun. The Nike-Cajun was developed for the purpose of carrying the falling-sphere experiment [7,8] for upper-air density. The Nike-Cajun carries 23 kg to 160 km. Since the sphere instrumentation was simple, small, and inexpensive, a rocket vehicle having the same qualities would permit the combination to be used frequently and independently of the support of a major missile base—two features required for synoptic work. Another important factor in achieving the low-cost objectives of the Nike-Cajun was that the scientific research group itself could, and did, assemble and fire the rocket. In the continuing work with staged solid rockets, which has led to a 480-km vehicle and a 1900-km vehicle, the capability of firing by university research personnel has been largely maintained. Thus even in the case of the 1900-km Strongarm, which is physically not a small rocket, assembling and launching the rocket are largely within the capabilities of a university group.

During the IGY about half the rockets fired in the U. S. program at Ft. Churchill, Canada, were Nike-Cajuns, and this type of medium-performance, two-stage rocket currently carries a significant portion of high-altitude payloads. The Nike-Cajun and Nike-Asp have been used to measure the pressure, density, temperature, composition, and winds to 100 km as well as to investigate cosmic rays, charge density, solar ultra-violet and X-rays, micrometeorites, auroral particles, magnetic field, and airglow.

The Nike-Cajun

The first stage of the Nike-Cajun (Fig. 1) is the booster from the Nike-Ajax anti-aircraft missile system and the second stage is the Thiokol Chemical Co. Cajun, a 15.2-cm-diameter, 244-cm-long motor which burns with a thrust of 3650 kg for 2.75 seconds. Both stages are fin-stabilized. The second stage simply sits on a cast coupling and separates by differential drag on burnout of the first stage. Ignition of both stages is accomplished on the launcher with an 18-second-delay squib allowing a suitable coast period following separation before the second stage begins to thrust. The simplicity of the Nike-Cajun is illustrated by the fact that in 1956 a group of five men from The University of Michigan took the vehicle and the falling-sphere experiment aboard the U.S.S. Rushmore (LSD-14) and fired five rockets at various latitudes between 39°N and 65°N. The group did virtually all the work of assembly and launching as well as servicing the instrumentation and manning the data receivers.

Most of the more than 100 Nike-Cajuns flown have been successful. In a few instances where the compatibility of the instrumented nose cone to the vehicle received insufficient study, the flights were spectacular if not successful. Some payloads were long, heavy, and somewhat flexible. In others the nose cone had a 50% increase in diameter over the diameter of the second stage. The failures generally resulted from aerodynamic and/or structural divergence [9] with consequent break-up near the end of the first-stage burning. The light payloads (20 to 23 kg) reached altitudes of just over 160 km. The heaviest payload flown (54 kg) reached an altitude of 116 km. Figure 2 is a plot of altitude and velocity versus time for a typical Nike-Cajun with a 23-kg payload launched at 75° elevation angle. Note that the peak velocity at second-stage burnout is about 1830 meters per second. The peak axial acceleration is about 70 times gravity. It was first thought that the problems of designing and constructing instrumentation that would operate under this acceleration would be very difficult. It has been demonstrated that, with thought and some ingenuity, these problems can be overcome. Transistorized circuits have helped greatly in solving the problems associated with high acceleration as well as the problems of making the instrumentation smaller. Most of the Nike-Cajuns have been launched from a modified Nike-Ajax system launcher. This is a rail-type launcher which provides about 3 meters of guidance, and has been used mainly because of its availability at numerous launching sites. The Nike-Cajun can be flown equally well from a zero-length launcher although the dispersion may be a bit larger. Only a modest amount of ground support equipment is required. A mobile crane, fork lift truck, or adjustable dolly is essential for loading the 544-kg first stage. The second stage with payload can be man-handled. The Nike-Cajun vehicle in general poses few problems from aerodynamic heating. With light payloads, say 23 kg, the fins (which are made from 14S-T4 aluminum alloy extrusion and are only 2.5 mm thick at the tip) are protected by adding a .78-mm Inconel—a nickel alloy with high melting temperature—leading edge cuff. This cuff is 5 cm wide and is riveted to the fin over a layer of Fiberglas cloth. An improved Cajun rocket called the Apache has recently been flight-tested. This rocket has virtually the same metal parts but with higher total impulse and longer burning time. The Apache has demonstrated in a single test flight its ability to take as a single stage a 16-kg payload to an altitude of 61 km. The Apache represents an increase in total impulse of 24% over the Cajun. Development work is continuing toward greater impulse and longer burning times in the same general size and configuration. In conjunction with the Nike booster, the Apache is predicted to carry 27 kg to 275 km.

Exos

A second sounding vehicle developed by the Michigan group is Exos. This design resulted from a requirement to take an 18-kg payload to an altitude of from 320 to 480 km. A three-stage combination was selected, starting with the Honest John, a ground-to-ground artillery rocket yielding very high thrust for over four seconds. It is presently being produced in quantity and hence its cost is relatively low. The standard Honest John fins are used in the Exos. The second stage is again a Nike booster with cruciform fins having an area of .23 square meter per fin as in the Nike-Cajun. The third stage was originally a Thiokol Recruit rocket of high impulse and short duration. The instrumentation at time of Recruit burnout experienced an axial acceleration of nearly 175 times gravity. By the time the third Exos vehicle was fired, a new version of the Recruit, called the Yardbird, was substituted and the acceleration was reduced to approximately 80 times gravity. Figure 3 shows the Exos on a rail type launcher. The vehicle takes off with 14-1/2 times gravitational acceleration and is suitable for zero length launching. The flight parameters are shown in Table I. The values given were calculated for a 90° launch angle. Table II gives the peak altitude reduction factor for various launch angles between 75° and 90°. The vehicle is fairly insensitive to changes in payload weight. Peak altitude loss for added weight is about .73 km per kg. Exos, with a burnout velocity in excess of 3000 meters per second at 19.2 km altitude, does present some aerodynamic heating problems. Figure 4 shows calculated skin temperatures versus time at two places on the third stage. The upper curve shows temperatures of the 1.27-mm Inconel nose cone at station 15 just aft of the solid nickel nose tip, and the lower curve shows temperatures on the case magnesium flared skirt. In this instrumentation we used a heat sink approach to the nose-cone-heating problem. The tip itself was a 3.6-kg nickel casting separated from the nose cone by a porcelain insulator. The tip then was one side of a dipole telemeter antenna. The cone itself was a 1.4-mm Inconel sheet rolled, welded, and spun. A light-weight, bright-surface, aluminum reflective shield was placed around the instrumentation. The skirt serves the dual purpose of providing aerodynamic stability and acts as part of the coupling to the second stage. Figure 5 shows the construction of the blast diaphragm type of coupling. The flared skirt on the forward stage and the coupling casting bolted to the aft stage are both threaded on the outside of the blast diaphragm. When the forward stage is ignited, the pressure of the exiting gas bows the diaphragm so that the threads become disengaged from the flared skirt, and a clean, rapid separation occurs. This system is generally used between stages which are fired in succession without a coast period. The large diameter of the skirt and the burned out preceding stage would cause large drag losses during a coast period. The flight tests in two of three cases have demonstrated that the vehicle more than meets the design specifications. The first shot launched at 75° elevation angle carried a nose-cone weight of 36 kg to 386 km, while the second carried the same weight to 476 km. The latter was launched at 80° and exceeded the prediction by about 13 km. The third test was a failure due to some malfunction during third-stage burning. It is believed that either the nozzle came off or that the case burned through at the aft end. The second-stage hardware has proved to be very reliable through more than 100 firings as Recruits. The longer-burning Yardbird propellant caused nozzle failure in static firings. Corrective measures were taken and successful static firings and a single flight test were accomplished prior to the failure.

The Exos perhaps does not fall into the category of a small rocket; yet it can be handled, assembled, and flown by a crew of modest size. The launcher shown in Fig. 3 is one of the first experimental Honest John launchers. Originally elevation of the loaded launch rail was accomplished with a crane. When the desired elevation angle was reached, the A-frame strut was pinned to rails attached to the concrete launch pad. The launcher was modified by shortening the launch rail to a guided travel length of 3.6 meters and adding a motor-driven pump and hydraulic rams to elevate the launching rail. The launcher is not trainable in azimuth, which is a disadvantage at some firing ranges.

Strongarm

A third sounding rocket, Strongarm, has been developed and assembled by our group. Insofar as possible, this too uses high-production, military rocket engines as a means of keeping the cost down. Strongarm was designed to take a 9-kg payload to an altitude of over 1600 km. Figure 6 shows Strongarm on the launcher. Like Exos, its first stage is the Honest John and its second stage is the Nike booster. The third stage is also a Nike booster with .185 square meter fins. The fourth stage is the Yardbird and the fifth is Jet Propulsion Laboratories' Scale Sergeant. The last stage is the same engine, with minor hardware modification, as that used in the Explorer series of satellites. Table III shows selected flight parameters. The burnout of the final stage occurs at 35 seconds at an altitude of 53 km and velocity of approximately 5300 meters per second. Because we depend entirely on aerodynamic forces for stability the powered portion of the flight must take place at altitudes where sufficient dynamic pressure can be obtained. With velocities well over 3000 meters per second, this means that the heat-input rates will be considerable. In the case of Strongarm, not only did the nose cone have to be considered and protected, but the fifth-stage motor as well. The wall thickness of this motor is only .58 mm and the propellant grain is cast in after the inner surface has been coated with a bonding thermoplastic liner. Because the case would be subjected to extensive heating for 30 seconds prior to ignition of the motor, it was feared that the liner would become liquid and the grain would be loose, thus causing burning over too much of the grain surface with subsequent over-pressure and rupture. The maximum allowable temperature prior to ignition was 120°C. The problem was solved by using an ablative coating. Sheet Teflon (E.I. Dupont's Tetrafluoro Ethylene) 1.27 mm thick was glued to the entire exposed surface. The Teflon ablates at approximately 600°C and provides heat protection in three ways. First, Teflon is a moderately good insulator and delays the heat transfer by conduction. Secondly, considerable heat is dissipated in the ablation process, thirdly, the gas product of ablation increases the boundary-layer thickness.

The instrumentation flown in Strongarm for the measurement of ion density requires two fairly large loop antennas. The antennas were mounted within the nose-cone shell so the nose cone had to be made of a material which would be transparent to the radiofrequency transmission. Molded Fiberglas has this property and is structurally more than adequate. However, Fiberglas will char if subjected to sufficient heat and the charred surface is opaque to the frequencies used. Teflon sheet 1.78 mm thick was applied over the Fiberglas to prevent charring. The effectiveness of this approach was demonstrated in the first test when signals were received throughout the entire 25-minute flight. Figure 7 shows the calculated and measured temperature versus time at station 28 on the nose cone. The second- and third-stage fins had Inconel leading-edge cuffs for heat protection and the fifth-stage flared skirt was cast from a rare-earth magnesium alloy which exhibits better high-temperature properties than the common alloys.

Strongarm requires the same launching and handling equipment as Exos. All its flight tests to date have been made from the versatile zero-length boom-type launcher shown in

Figure 6. In fact, this single launcher is easily adapted to all vehicles discussed in this paper.

A fourth vehicle is now being designed which will take payloads of 34 to 57 kg to the 220- to 320-km altitude range. It is a two-stage vehicle called the Nike-Yardbird and is expected to have all the simplicity and ease of handling of the Nike-Cajun system. The first test flight will be made this fall.

Conclusion

The University of Michigan program of staging solid-propellant units in sounding rocket combinations for use in our upper-atmosphere program has been an interesting and useful exercise. We hope that our experience will encourage university groups in other countries to undertake high-altitude research.

Acknowledgment

The considerable aid given us by the Pilotless Aircraft Research Division of the National Advisory Committee for Aeronautics is acknowledged. We are also indebted to the U. S. Air Force Cambridge Research Center for financial support and cooperation in the development of Nike-Deacon, Nike-Cajun, and Exos. Financial support for Strongarm and Nike-Yardbird development was supplied by Ballistic Research Laboratories of the U. S. Army Ordnance Corps.

References

1. Boyd, R. L. F., and Seaton, M. J., Rocket Exploration of the Upper Atmosphere, Pergamon Press, Ltd., London, 1954.

2. Newell, H. E., Jr., Sounding Rockets, McGraw-Hill Book Co., Inc., New York, 1959.

3. Annals of the I.G.Y., Vol. VI, Part II, Pergamon Press, Ltd., London, 1958, p. 82.

4. Hansen, W. H., and Fischbach, F. F., The Nike-Cajun Sounding Rocket, The University of Michigan Research Institute Report 2453-1-F, Ann Arbor, March, 1957.

5. Hansen, W. H., and Fischbach, F. F., The Exos Sounding Rocket, The University of Michigan Research Institute Report 2595-1-F, Ann Arbor, December, 1958.

6. Hansen, W. H., and Fischbach, F. F., The Strongarm Sounding Rocket, The University of Michigan Research Institute Report 2816:004-1-F,Ann Arbor, May, 1960.

7. I.G.Y. Rocket Report Series, No. 3, National Academy of Sciences, Washington, 30 September 1959.

8. Jones, L. M., et al., "Upper-Air Density and Temperature: Some Variation and an Abrupt Warming in the Mesosphere, Journal of Geophysical Research, 64, 2331-2340 (1959).

9. Arbic, R. G., White, G., and Gillespie, W., Jr., Some Approximate Methods for Estimating the Effects of Aeroelastic Bending of Rocket-Propelled Model Booster Combinations, NACA RM L53A08, Washington, March 27, 1953.

TABLE I

FLIGHT PARAMETERS OF EXOS
(37-kg nose)

Action	Time (sec)	Weight (kgf)	Drag (kgf)	Altitude (m)	Velocity (m/sec)	Acceleration (g's)
1st Ignition	0	2640	0	0	0	14.5
1st Burnout	4.4	1753	5443	1,524	725	19
Separation	4.45	789	1762	--	--	- 3
2nd Ignition	29.4	789	66	13,707	316	27
2nd Burnout	32.6	430	494	16,401	1409	48
3rd Ignition	32.6+	207	166	--	--	41
3rd Burnout	35.9	86	195	23,827	3369	100
Peak	393	86	0	645 km	0	- 1

TABLE II

PEAK ALTITUDE REDUCTION FACTORS

Launch Angle, °	Peak Altitude Reduction Factor
90	1.000
87.5	.995
85	.981
82.5	.957
80	.918
77.5	.883
75	.834

TABLE III

FLIGHT PARAMETERS OF STRONGARM
(9-kg nose)

Action	Time* (sec)	Altitude (m)	Velocity (m/sec)	Weight (kgf)	Mach No.	Dynamic Pressure (kgf/m^2)	Reynolds No. per Meter (millions/meter)	Drag (kgf)	Acceleration (g's)
1st Ignition	0	20	0	3220	0	0	0	0	12
1st Burnout	4.375	1,260	588	2291	1.75	18,776	35.9	3220	16
Separation	4.425	--	--	1398	--	--	--	2578	- 3
2nd Ignition	6.375	2,368	535	1398	1.62	13,787	29.5	1534	14
2nd Burnout	9.375	4,670	1002	1038	3.12	37,582	45.0	2960	18
Separation	9.425	--	--	805	--	--	--	2957	- 5
3rd Ignition	23.375	15,700	656	805	2.22	3,769	7.9	257	28
3rd Burnout	26.375	19,177	1721	446	5.83	14,993	11.8	735	50
4th Ignition	26.375+	--	--	212	--	--	--	259	40
4th Burnout	29.625	27,450	3559	90.8	11.88	17,360	6.6	250	90
5th Ignition	29.625+	--	--	40.4	--	--	--	81	18
5th Burnout	35.875	54,494	5325	17.7	15.92	932	.16	4.5	- 1.3
Peak	818	1,958,000	0	17.7	0	0	0	0	- .6

*Time is taken to nearest 1/8 sec for computer solution.

FIGURE CAPTIONS

Figure 1. Nike-Cajun on launcher.

Figure 2. Trajectory of Nike-Cajun launched at 75° elevation angle.

Figure 3. Exos on launcher.

Figure 4. Skin temperature as a function of time.

Figure 5. Blast diaphragm coupling.

Figure 6. Strongarm on launcher.

Figure 7. Calculated and measured temperature versus time.

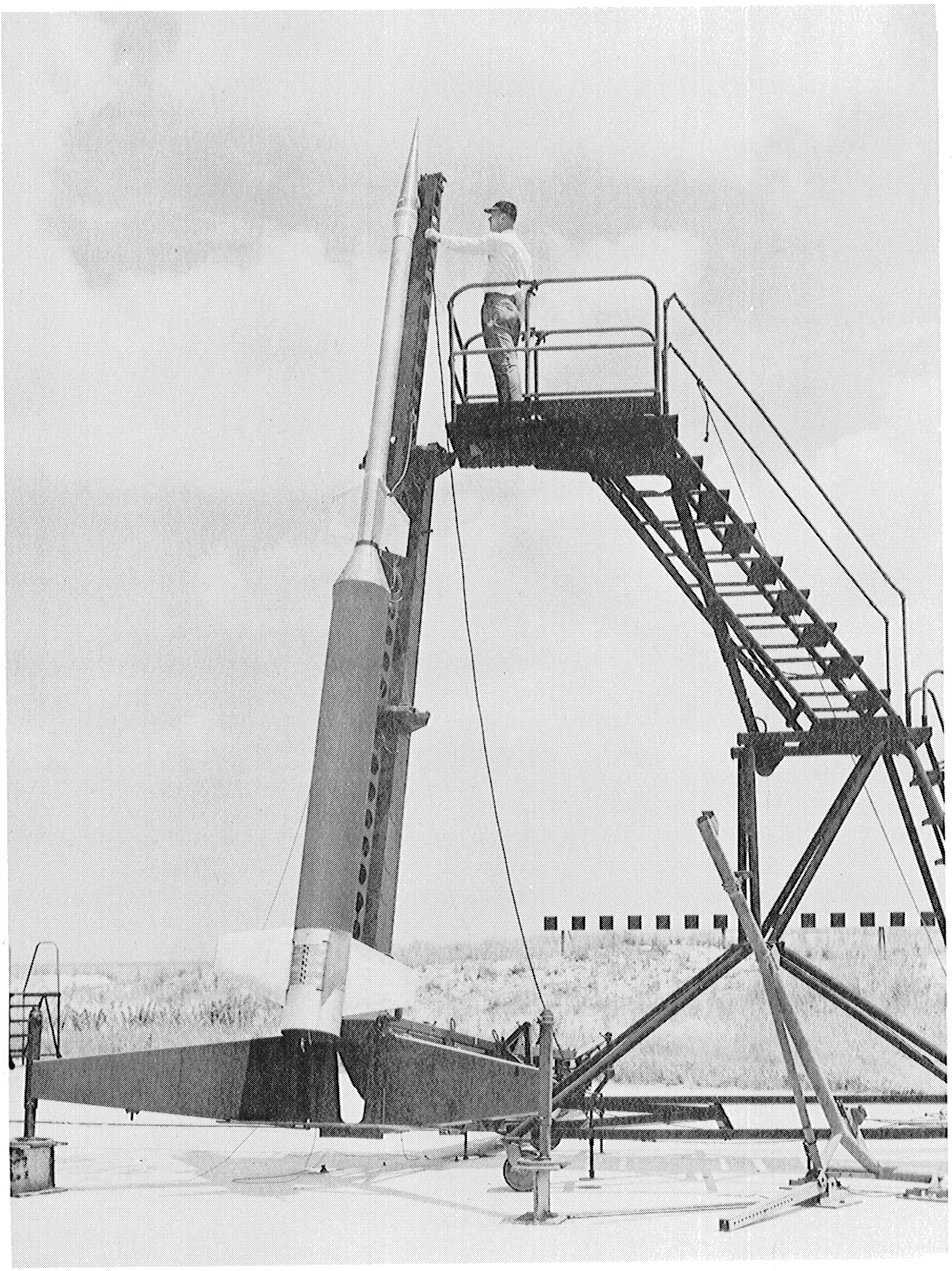


Figure 1. Nike-Cajun on launcher.

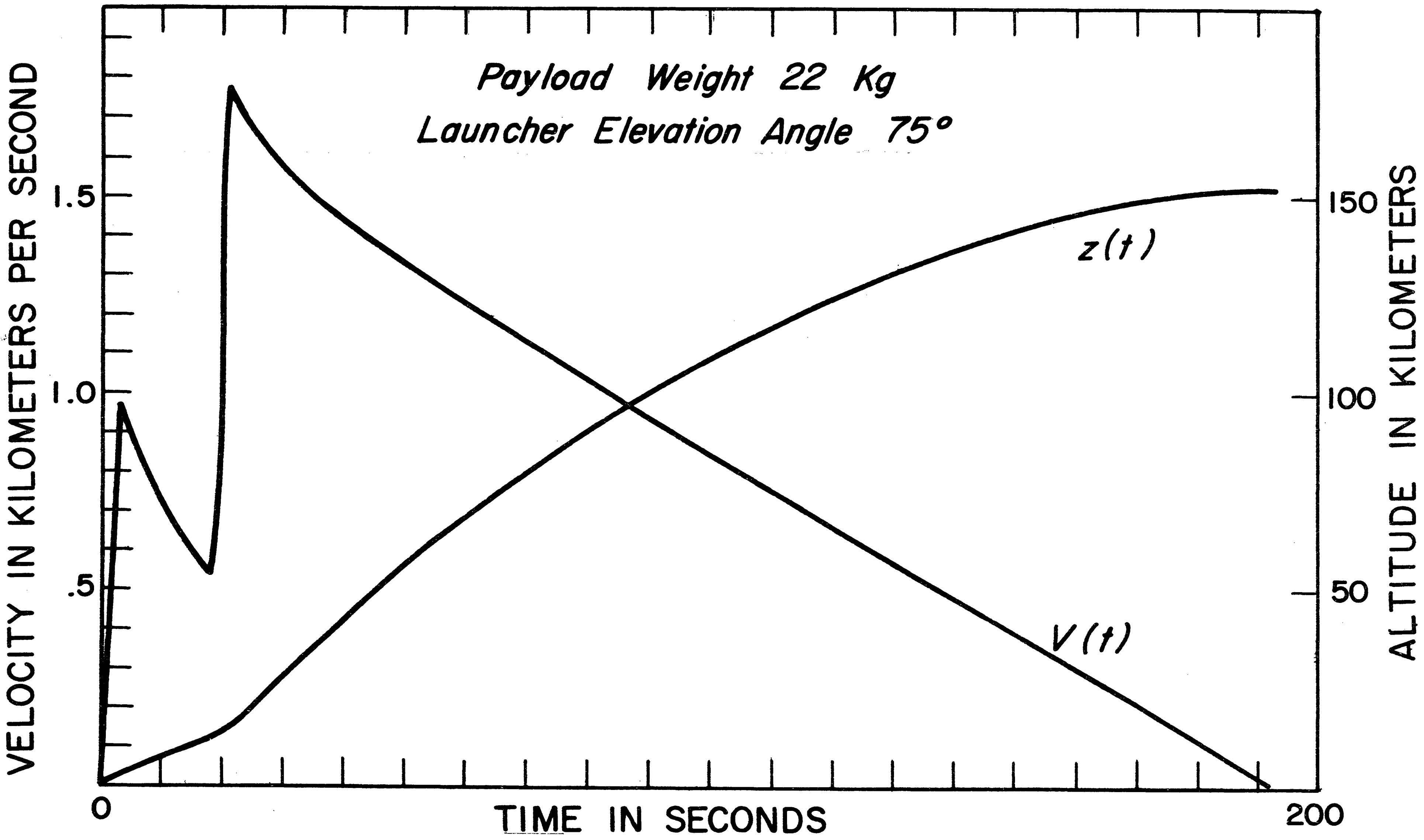


Figure 2. Trajectory of Nike-Cajun launched at 75° elevation angle.

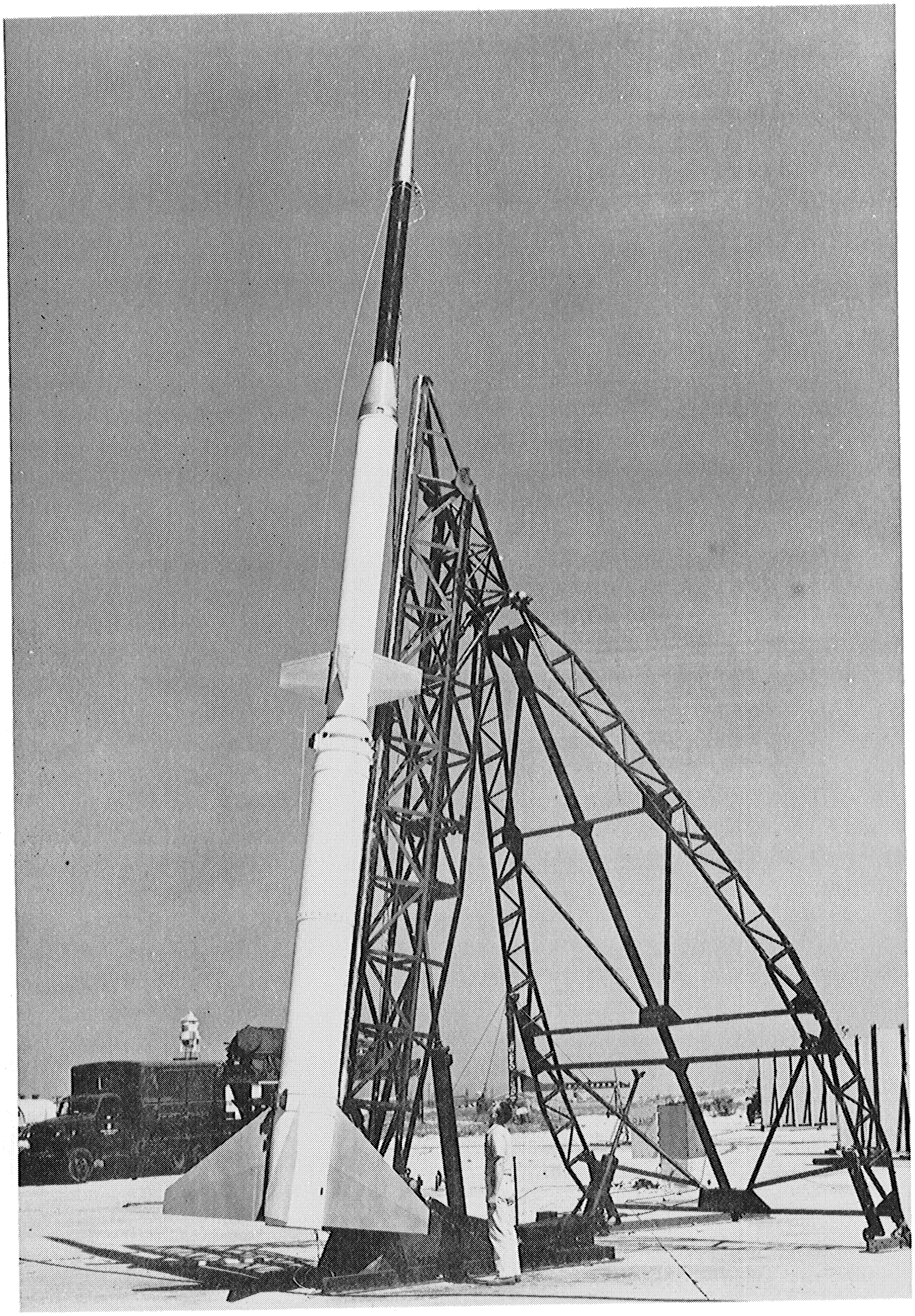
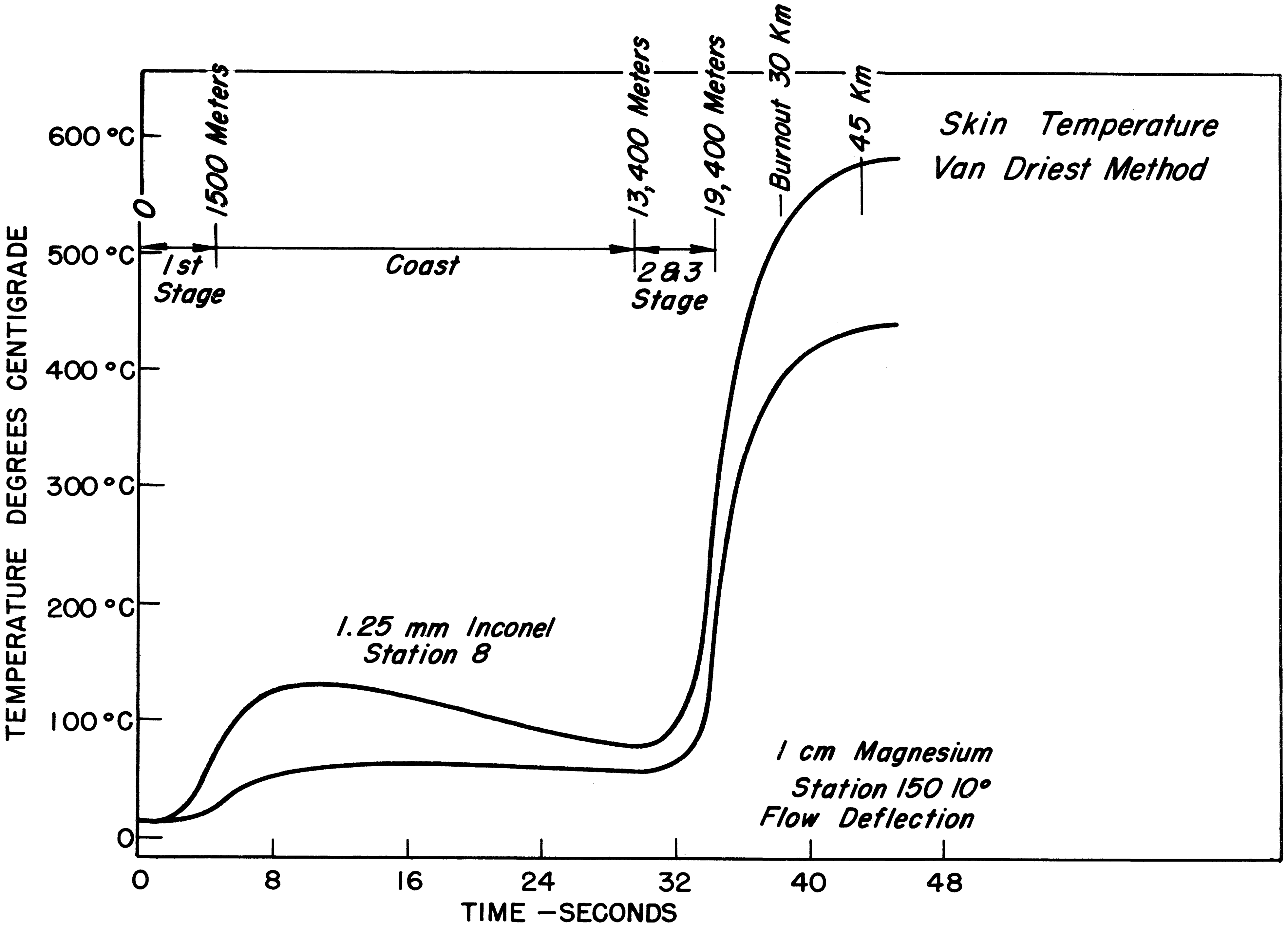


Figure 3. Exos on launcher.



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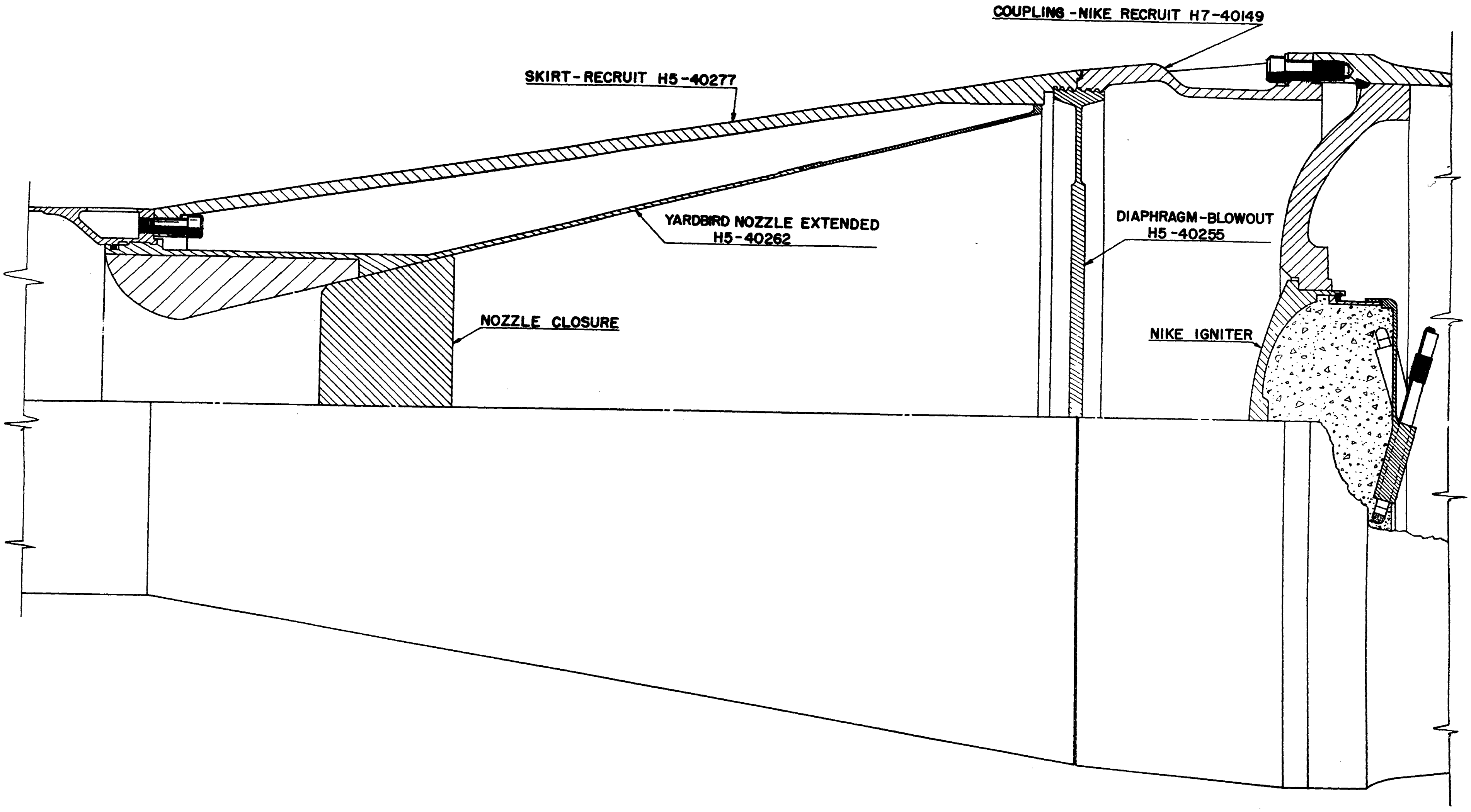

Figure 5. Blast diaphragm coupling.

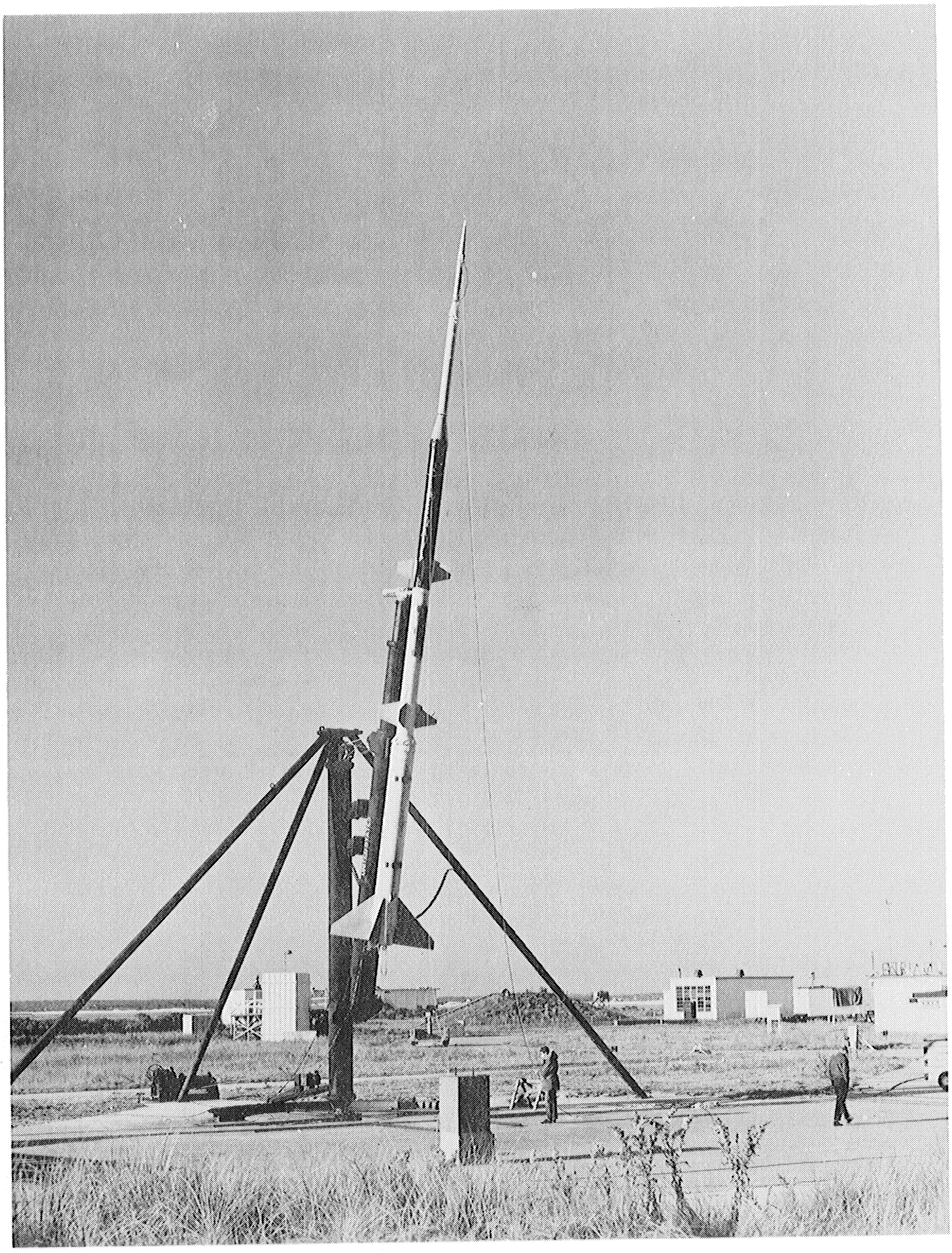

Figure 6. Strongarm on launcher.

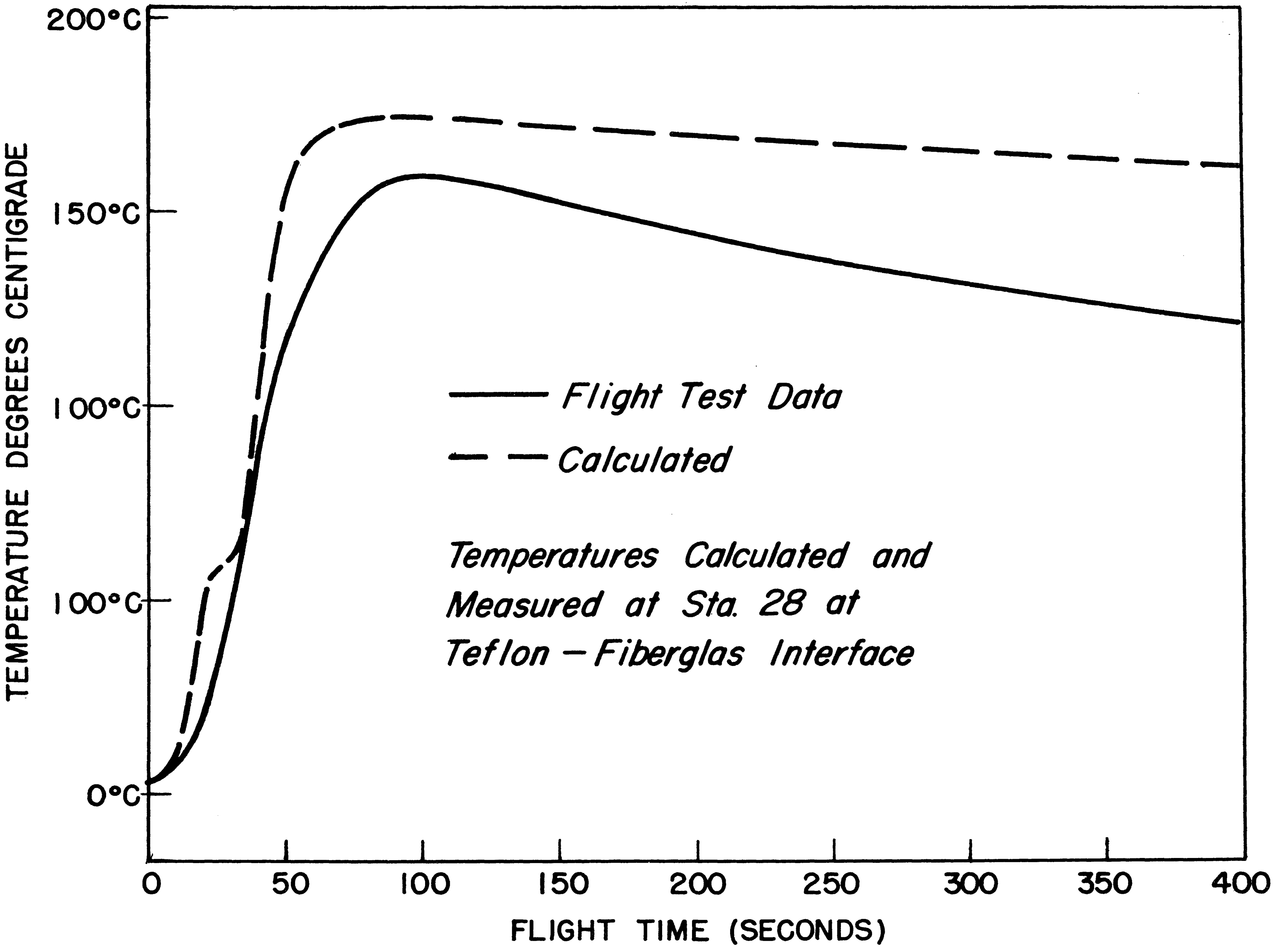

Figure 7. Calculated and measured temperature versus time.