Measurement Notes

Note 29

February 27, 1984

CHARACTERISTICS OF AMERICAN ROCKETS USED FOR TRIGGERING LIGHTNING

PART 1. ROCKETS FROM FLIGHT SYSTEMS INC., BURNS FLAT, OKLAHOMA

by

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ABSTRACT

The performance characteristics of small rockets - used for towing wires into regions with strong electric fields beneath thunderclouds - have been measured at Sandia National Laboratories. The thrust delivered by each type of rocket engine was determined by strain gages in static firings on the ground. Similar engines were fitted with nose cones and fins, then launched vertically. They were tracked by a distance-measuring, laser-theodolite that provided slant range, azimuth and elevation information from which location coordinates, vectorial velocities and accelerations were calculated.

Drag coefficients were estimated for these rockets using the position and velocity data after the end of thrust; the calculated coefficents ranged from about 0.8 to 1.1.

Other rockets of these types were used to deploy steel wires from bobbins. The data from these and the earlier tests were used to obtain estimates of the forces exerted on the rockets by the wire deployment and of the forces required to accelerate the wires.

The rocket engines used in these tests had thrusts measured between 47 and 200 N with impulses ranging from 123 to 207 Ns. The duration of thrust from these engines was from 1 to 3.5 sec. The forces exerted on the deployed wire often exceeded its 80 N breaking strength. A performance predictor program has been prepared from these studies to match the rocket engine performance with the requirements for optimum, high-speed wire deployment without breaking the conductor.

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Figure 33. Predicted forces that would be encountered in a vertical launch of a GR 80 Mod 1 rocket with a 7 mm venturi orifice with the thrust of the static test and a 440 gm mass. In this calculation it was assumed that a 400 gm wire dispensing bobbin was carried aloft beneath the rocket so that the wire deploying force was only twice the wire accelerating and weight force.

Figure 34. Plots of the predicted height above the launcher versus speed along the trajectory for various rocket configurations assuming the static thrust forces and the wire deployment force given in Figures 29 to 33.

Introduction

Several investigators have succeeded in triggering lightning by the rapid injection of grounded wires into the air beneath thunderclouds (Newman, 1965; Newman et al, 1968; Fieux and Hubert, 1976; Hubert, 1978 and others). The technology required, however, is not well described and recipes for triggering lightning are not readily available. Several interested groups have been unsuccessful in developing adequate methods of deploying wires rapidly but a French group (consisting of Dr. Pierre Hubert, MM. J. L. Boulay, P. LaRoche, A. Eybert Berard and others) has been quite successful with its approach. We have described the flight performance of the French rockets in Measurement Note 27 (Moore et al., 1983).

Our aim in preparing this report is to describe the behaviour of an American manufacturer's small rockets and to estimate the forces they exert on the wires that they tow.

Description of Flight Systems Inc.'s Rockets

The rockets that we first investigated were manufactured by Flight Systems, Inc. of Burnsflat, OKlahoma, USA, 73624, telephone 405-562-4296. Our technical contact was Dr. George Roos, President of the company. We obtained rocket engines of three different sizes from Dr. Roos. Their properties are shown in Table I.

The nominal burn time for the fuel in these engines is about 2.5 seconds. All of these rocket engines were encased in fiberglass epoxy cylinders about 28.6 mm in diameter with a 2.2 mm wall. The front end of each cylinder terminated in an epoxy plug; the exhaust

TABLE I
FLIGHT TESTS OF FLIGHT SYSTEMS INC. ROCKETS
AT
SANDIA NATIONAL LABORATORIES
January - May, 1983

Julian Date	Flight Number	Rocket Type	Nozzle Diameter (mm)	Initial Mass (g)	Maximum Velocity (m/s)	Maximum Height Tracked (m)	Length Wire Extracted (m)	Duration of Tracked Flight (s)
83047	Roos 1	GR-80	6.1	442.0	Blew up @ 5 m	0	0	0.15
83047	Roos 2	GR-20	6.1(?)	361.0	134	377	386	20.4
83047	Roos 3	GR-20*	6.1(?)	324.0	190	644	None	26.6
83047	Roos 4	GR-80	6.1	406.0	Blew up @ 10 m	0	0	0.3
83111	Roos 5	GR-80	6.1	447.0	313	947	210**	5.9
83111	Roos 6	GR-80*	6.1	567.1	319	1152	None	6.2
83111	Roos 7	GR-80	6.1	593.1	293	1386**	47***	26.4
83111	Roos 8	GR-80	6.1	570.0	Blew up @ 1 m	0	0	0.05
83111	Roos 9	GR-80	6.1	580.9	170	503	706	23.3
83139	Roos 10	GR-80* Mod 1	7.0	431.2	360	1497	None	32.4
83139	Roos 11	GR-80* Mod 1	7.0	439.8	279	1144***	325**	31.2
83139	Roos 12	GR-80* Mod 2	7.8	206.8	365	730	None	3.4
83139	Roos 13	GR-80* Mod 2	7.8	414.9	346	637	226***	3.2
83139	Roos 14	GR-40	6.1(?)	297.4	444	663	None	2.6
83139	Roos 15	GR-40	6.1(?)	339.2	182	489	516	22.2

*reinforced case
**wire untied
***wire untied broke

Mod 1 was a fiber glass reinforced case and an enlarged orifice
Mod 2 was a hexagonal grain and an enlarged orifice

venturi initially had an axial throat, 6.35 mm in diameter in a flame resistant material. The propellant was a high performance, solid fuel, cast around an axial perforation that extended from the exhaust nozzle to near the front of the engine. An inflammable mixture, a pyrogen, at the front end of the perforation could be ignited by an electric match to start the combustion of the main propellant.

Some of these engines were prepared for flight test by the symmetric installation of 4 tapered fins, each about 5 cm wide by 5 cm height at the fin root. These fins were expoxied to the engine body with the rear of each fin, 2 cm ahead of the exhaust orifice. Nose cones were supplied for those engines to be tested in flight and were epoxied in place. The characteristics of the rockets used in the flight tests are given in Table II.

Flight Test Procedure

Flight tests of various rocket configurations were performed at the Coyote Test Site of the Sandia National Laboratories during February, April and May, 1983. These tests consisted of automatically tracking vertically-launched rockets with a laser theodolite that provided slant range, elevation angle and azimuth once every millisecond. These data were recorded on magnetic tape then processed to yield x, y and z coordinates, displacement, velocity and acceleration information.

Each rocket was weighed before flight and when possible, after impact, so that the mass of fuel consumed could be determined.

TABLE II

ROCKET PROPERTIES AND ATMOSPHERIC CONDITIONS DURING FLIGHT TESTS AT SANDIA NATIONAL LABORATORIES

Flight Number	Rocket Type	Initial Mass (gm)	Fuel Mass (gm)	Final Mass (gm)	Burn Duration (s)	Surface Air Pressure (N/m^2)	Surface Air Temperature (^oC)	Rocket Cross Section ($10^{-4}m^2$)	Calculated Drag Coefficient
Roos 2	GR-20	361	96.1	265	2.45	83200	13	26.3	0.97*
Roos 3	GR-20	324	87.7	236	2.64	83200	13	26.3	0.97
Roos 5	GR-80	447	115.6*	331	1.87	83200	14	8.2	0.86*
Roos 6	GR-80	567.1	111.6*	456	1.78	83072	17.5	8.2	0.86
Roos 7	GR-80	593.1	115.6*	478	1.92	83072	17.5	8.2	0.86*
Roos 9	GR-80	580.9	115.6*	465	2.35	83072	21	8.2	0.86*
Roos 10	GR-80 Mod 1	431.2	115.6*	316	1.92	83241	17.8	8.6	0.78
Roos 11	GR-80 Mod 1	439.8	115.6*	324	2.02	83241	18	8.6	0.78*
Roos 12	GR-80 Mod 2	286.8	115.6*	171	2.1	83241	18	8.6	0.86
Roos 13	GR-80 Mod 2	414.9	115.6*	299	1.55	83241	18	8.6	0.86*
Roos 14	GR-40	297.4	93*	204	1.30	83241	18	8.6	1.08
Roos 15	GR-40	339.2	93*	246	2.35	83241	18	8.6	1.08*

*measurement borrowed from other tests

From the flight and mass information, aerodynamic drag coefficients were calculated for the rocket bodies of each type that was launched without wires. The procedure for these calculations used the difference between the kinetic energy loss and the geopotential energy gain as a measure of the work done against drag.

The energy balance on ascent is given by:

$$1/2\ mv_1^2 = 1/2\ mV_2^2 + mg\ \Delta z = F_d \Delta \ell.$$

where: m is the burnout mass of the rocket,

v_1 is the initial speed at the start of an interval,

v_2 is the speed at the end of the interval

Δz is the height interval traversed

$\Delta \ell$ is the path length traversed.

The drag force, F_d, is given by

$$F_d = 0.5 C_d A \rho v^2$$

where: C_d is the drag coefficient,

A is the measured cross sectional area of the rocket body and fins, and

ρ is the mass density of the air.

The mass density of the local atmosphere was estimated from the observed surface air temperatures and pressures with the use of an assumed, adiabatic thermal-lapse rate (but...this assumption is reasonable since all flight tests were made near noon on sunny days when the air was unstable.) The variation of air density with altitude, therefore, was assumed to be derivable from the hydrostatic relation and thus the density is described by:

$$\rho = \frac{MP_o}{RT_o}\left[(1 + \frac{\alpha z}{T_o}\right]^{-(Mg/R\alpha + 1)}$$

where M = molecular mass of dry air, 0.02896 kg/m^3

P_o = measured atmospheric pressure at the earth's surface in N/m^2

R = gas constant, 8.314 J/kelvin

T_o = measured surface air temperature, kelvins

z = height above launcher, m

g = gravitational force, 9.792 N/kg

α = adiabatic lapse rate of air temperature, -0.00975^o/m.

Accordingly, values for C_d were calculated from

$$C_d = \frac{2m[v_1^2 - v_2^2 - 2g\,\Delta z]}{\rho A\,\Delta \ell (v_1^2 + v_2^2)}$$

The computed drag coefficients and measured cross sectional areas are listed in Table II. Typical drag coefficient results obtained for the test identified as Roos 3 are shown later as a case study in Figure 5 for the rocket ascent and in Figure 6 for its descent.

In each set of the tests, a rocket of the type under study was used to pull wire from a military bobbin extracted from an ENTAC 58, anti-tank missile. This wire was steel, 0.20 mm in diameter and coated with a light varnish. It had a mass of 0.275 gm/m of length and a measured breaking strength of 81 N. The bobbins contain 2 km of single strand wire and have an initial mass of about 800 gm. Each of them was weighed, before and after, wire was pulled from them so that the length of wire extracted could be determined.

The flight results for these tests are summarized in Table I.

Static Firings

Ground measurements of typical rocket thrust were made in vertical static firings at Sandia National Laboratories in April 1983. The thrust was measured with a BLH load cell having a dynamic range in excess of 800 N and a resolution of about 0.1 N(?). The data were recorded on magnetic tape with a resolution of 1 millisecond. The engines were weighed before and after the firings so that thrust corrections could later be made for the weight of the burned fuel.

The results from these static and flight tests are presented here in sets showing (1) the thrust measured in the static firing of a given rocket engine (2) the flight results with height versus time, vectorial speed along the flight track versus time, (3) vectorial speed versus height. This last presentation is of great interest for our purposes for we need to select a rocket system that can propel an unbroken wire upward at speeds in excess of 150 m/s at heights above 150 m.

Flight Force Estimates

A composite plot of the flight forces involved in each test was prepared for each rocket engine type. The mass of fuel consumed in flight was often different from that used in the static tests even though the rocket engine types were the same. The instantaneously measured static thrust was multiplied by the ratio of flight fuel to static test fuel and the total flight impulse was thus scaled from that of the static test. For reasons that are not clear, the periods of thrust during the flight were significantly shorter than were the durations of static thrust. We assumed, therefore, that the fuel-adjusted total impulse was delivered in a shorter time period than in the static test. The assumed flight thrust was obtained by multiplying the fuel-adjusted static thrust by the ratio of static thrust duration to that found in the associated flight test so as to maintain the adjusted total impulse constant. In this manner, we estimated an appropriate rocket thrust performance that could be compared with the flight trajectory data obtained with a similar engine.

The aerodynamic drag forces were calculated from the measured velocities as previously described under the assumption that the mean drag coefficient determined from the unloaded comparison rocket was appropriate and invariant with height. The gravitational and acceleration forces were calculated from the initial mass of the rocket (decreased linearly during combustion), multiplied by the sum of the acceleration along the flight track and the related component of the gravitational force along the flight path.

The aerodynamic and the acceleration force terms were then subtracted from the rocket thrust to obtain a measure of the pull force that the rocket exerted on the trailing wire. In many of these flights with wires, the steel strand broke after lengths of

200 m or so had been deployed. It appears from these results that the breakage or untying of the wire from the bridle occurred as the pull on the wire exceeded 60 N or so when the rocket velocities were in excess of 150 m/s.

There are at least three forces developed as the rocket tows a wire upward:

1. the force F_a required to change the momentum of the wire and to support its weight. Let F_m be the force required to change the wire momentum:

$$F_m = \frac{d(mv)}{dt} = \frac{m\,dv}{dt} + \frac{v\,dm}{dt} .$$

Now, for an extended wire, $m = \ell(dm/d\ell)$

and $$dm/dt = v(dm/d\ell)$$

so that

$$F_a = (dm/d\ell)(v^2 + \ell(dv/dt).$$

2. the force, F_s, required to pull the wire from the spool in the bobbin. We were not able to measure this force in these tests but it can and should be measured in future tests.

3. the aerodynamic drag force, F_d, on the wire. This, too, we do not measure because it also requires a rocket-borne gage and a telemetry system that was beyond the scope of our study.

In the case studies that follow, it appears that the calculated pull forces exerted on the wires were about 5 times those inferred as being required to accelerate the wire and scaled reasonably well with the acceleration forces. Both the calculated pull forces and the acceleration forces reached their maxima near engine burnout, rather than at launch as had first been expected.

The calculated wire stresses and lengths pulled are listed in Table III.

Rocket Performance

GR 20 The first rocket engines of this series that we tested were identified as type GR 20. Their diameter was the standard 28.6 mm, their length was 7.0 inches (177.8 mm) and they delivered an impulse of about 125 Ns. These were of interest because we had previously succeeded in triggering lightning twice from South Baldy Peak out of about 10 tries with wire-trailing rockets having engines of this size.

A tranverse fiber-glass rod about 40 cm long and 6 mm diameter pierced the nose cone near the center of mass immediately ahead of the engine. The rod was epoxied in place perpendicularily to the line of flight and served as a anchor to spread a Y-shaped steel wire bridle to which was attached the wire to be towed. This arrangement was used both for lightning triggering experiments and for the Roos 2 and Roos 3 flight tests at Sandia.

The results of the tests of GR 20 rockets with static firings and flights Roos 2 and Roos 3 are given in Figures 1, 2, 3 and 4. The computed drag coefficients are shown in Figures 5 and 6. The forces are plotted in Figure 7. When loaded with a towed wire, this

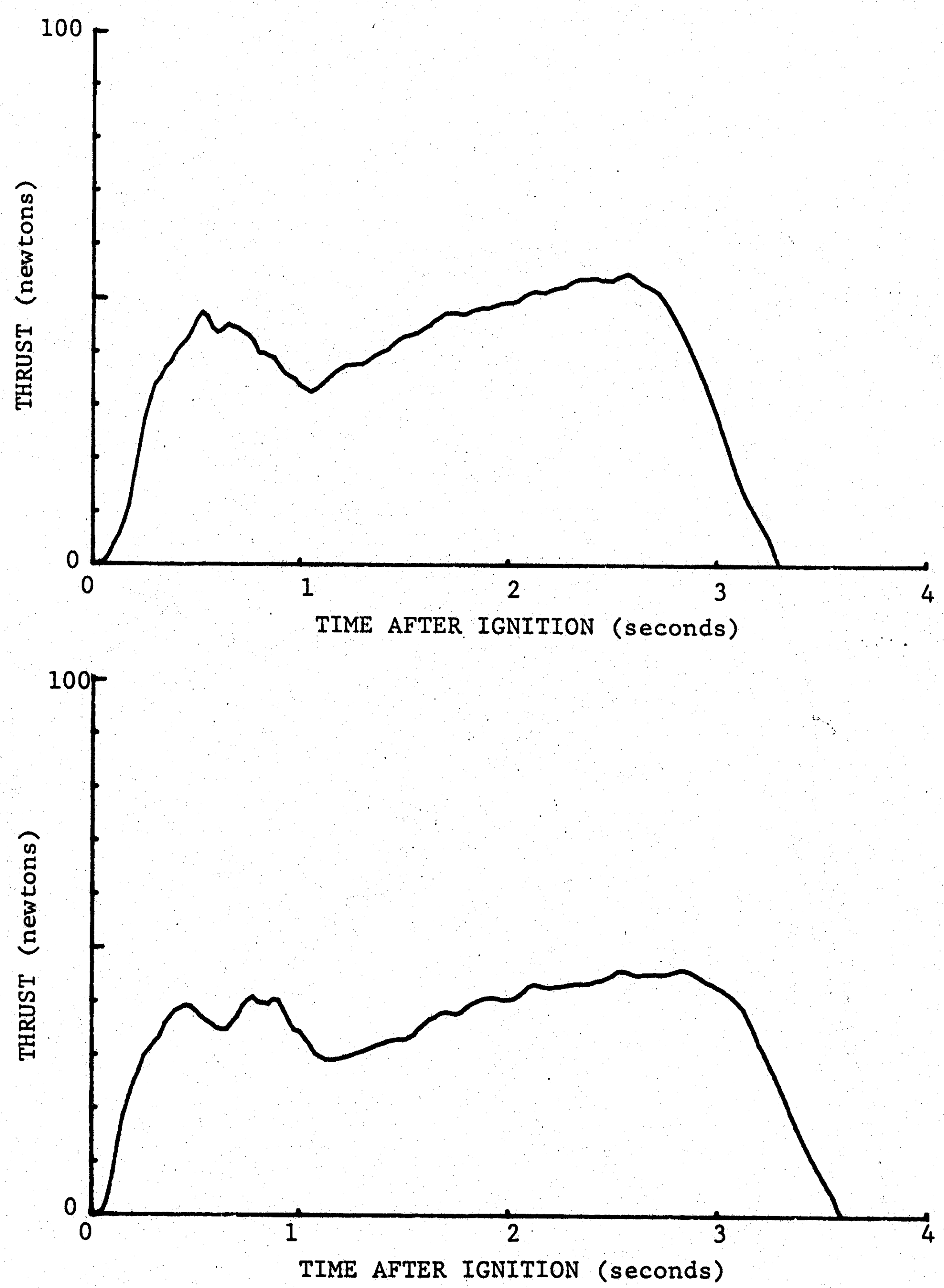

Figure 1. Static thrust measured for two standard GR 20 rocket engines at Sandia National Laboratories.

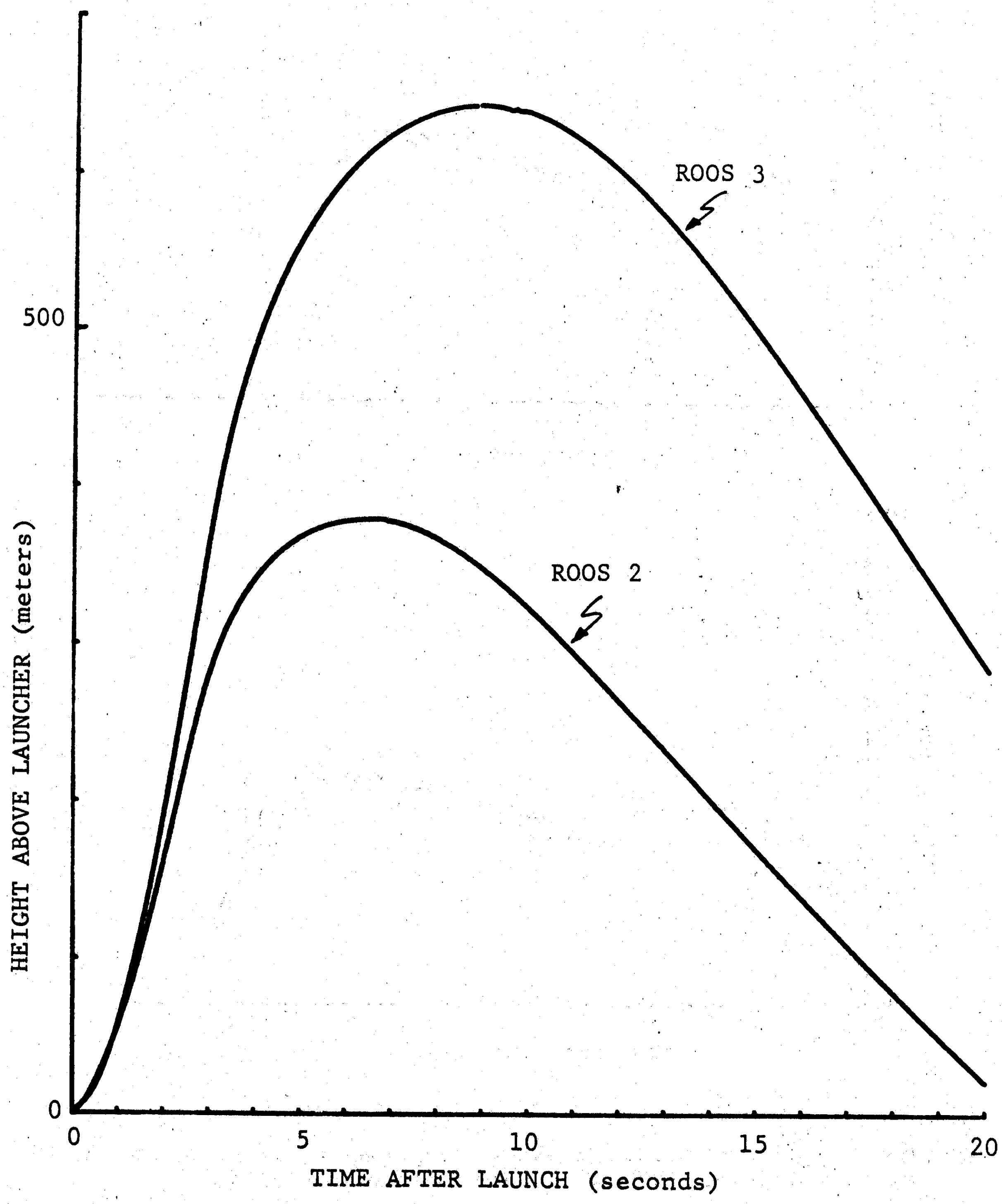

Figure 2. Plot of height vs time for GR 20 rockets launched on February 16, 1983 at Sandia National Laboratory. ROOS 2 pulled 386 m of wire from a grounded spool; ROOS 3 was a test of the rocket alone.

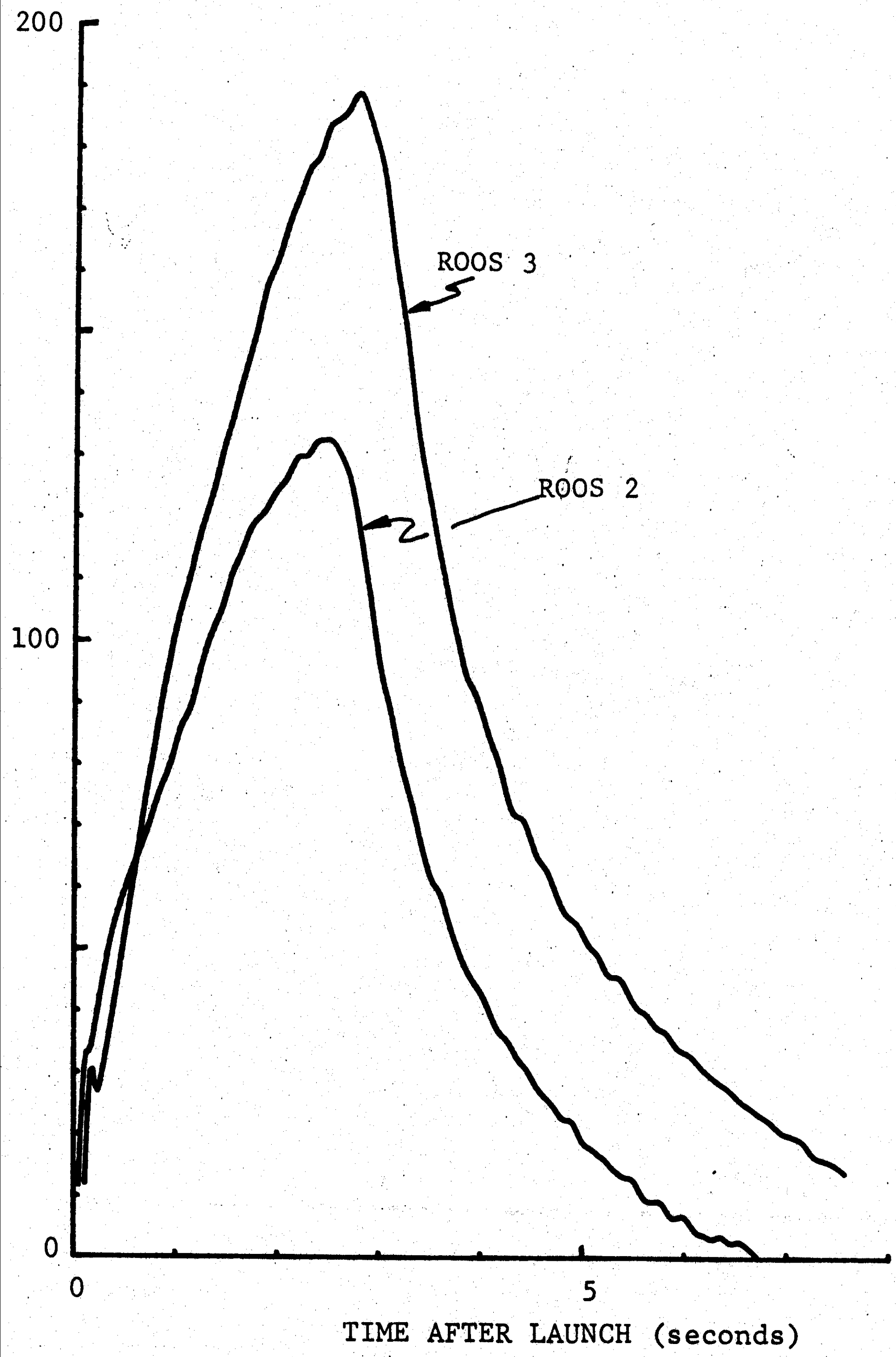

Figure 3. Plot of speed vs time for GR 20 rockets launched on February 16, 1983 at Sandia National Laboratory. ROOS 2 pulled 386 m of wire from a grounded spool; ROOS 3 was a test of the rocket alone.

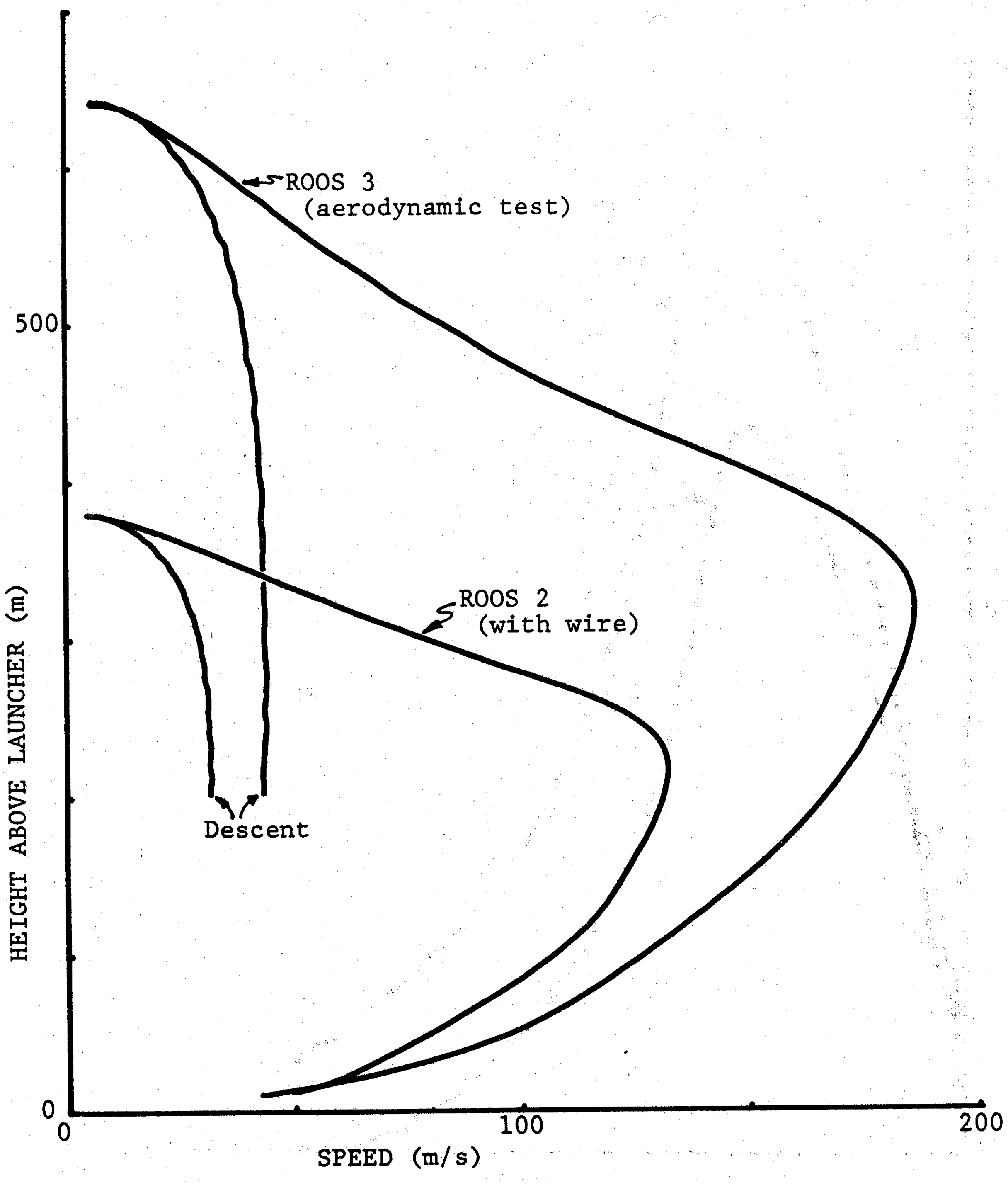

Figure 4. Plot of height vs speed along trajectory for GR 20 rockets launched on February 16, 1983 at Sandia National Laboratory. ROOS 2 pulled 386 m of wire from a grounded spool; ROOS 3 was a test of the rocket alone.

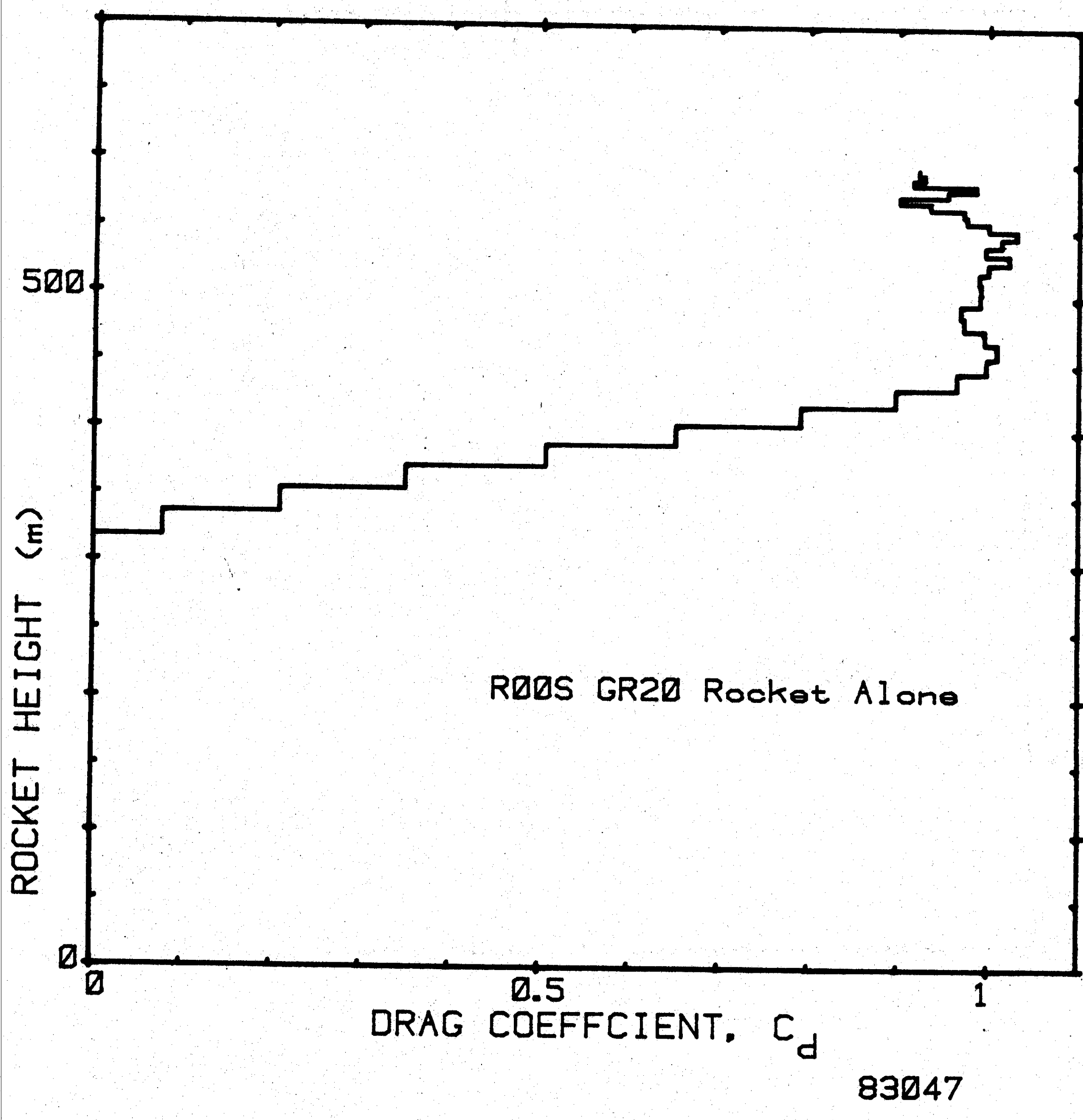

Figure 5. The drag coefficients calculated from the Roos 3 flight data for a GR 20 rocket during ascent.

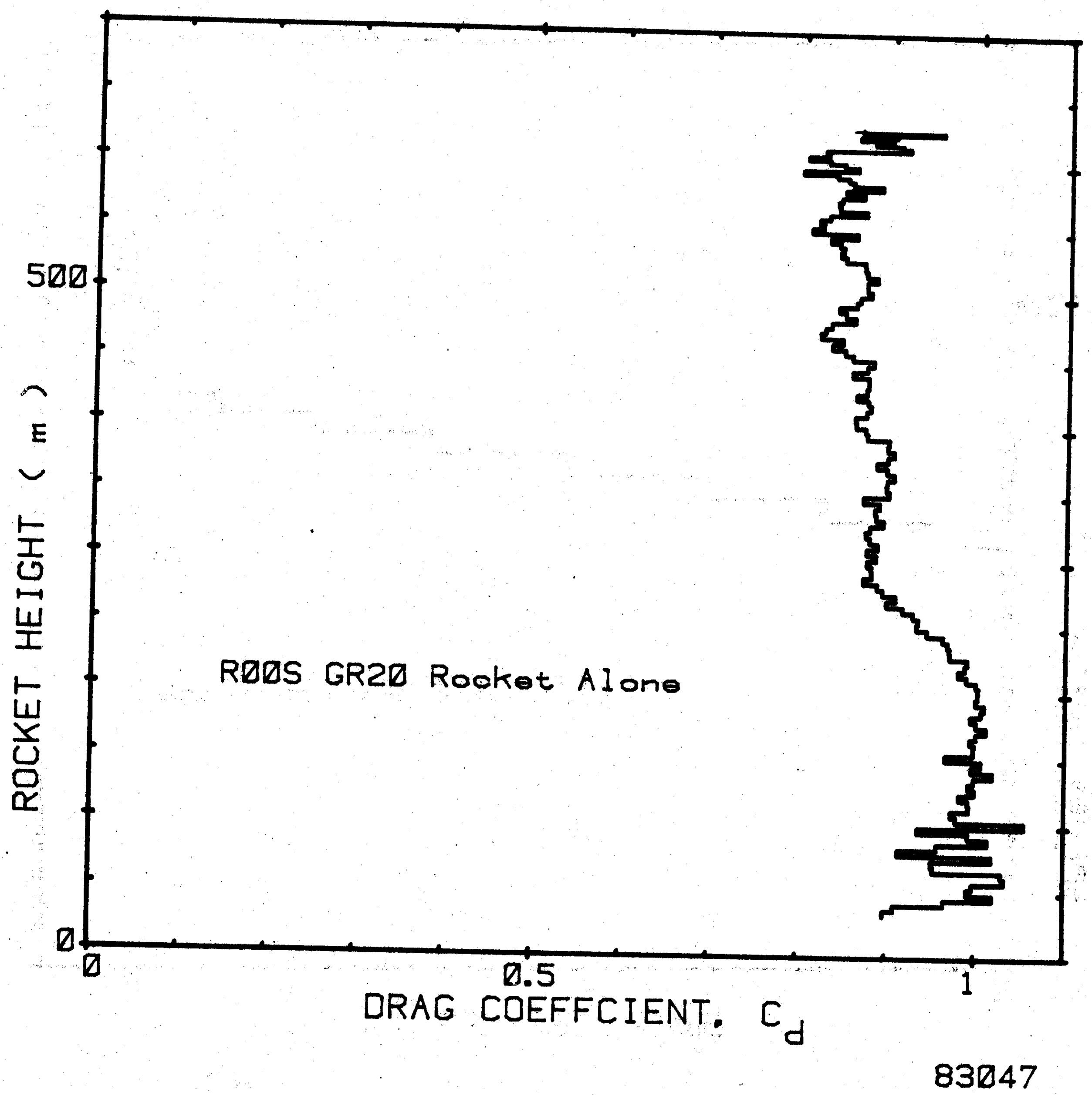

Figure 6. The drag coefficients calculated from the Roos 3 flight data for a GR 20 rocket during descent.

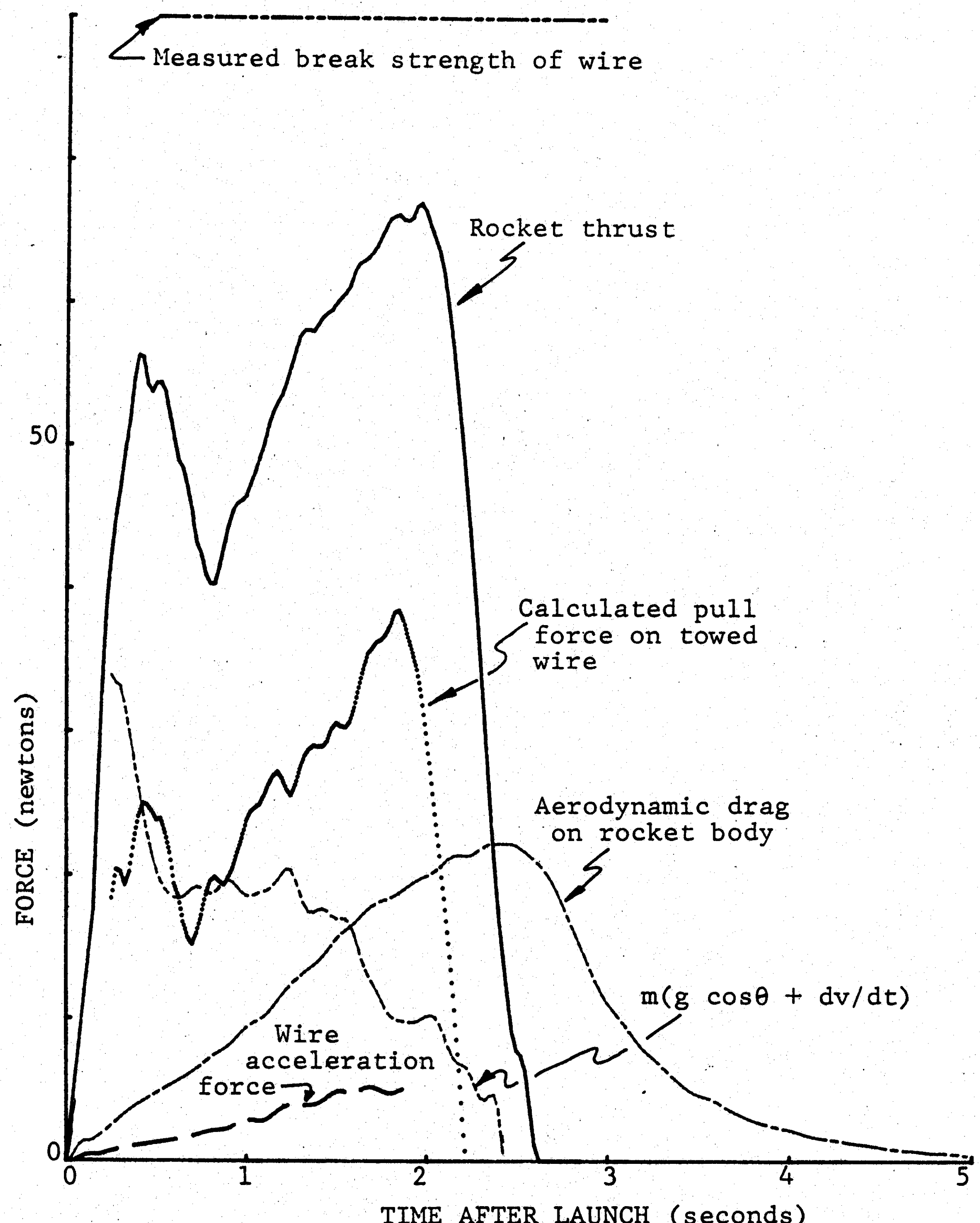

Figure 7. Forces associated with the deployment of a steel wire, pulled from a grounded spool by a small, vertically-launched rocket on February 16, 1983 at Sandia National Laboratory. The rocket was a Flight Systems type GR 20 and this test was identified as "ROOS 2".

TABLE III

WIRE STRESSES AND LENGTHS TOWED IN ROCKET TESTS

Wire Pull Flight Number	Rocket Type	Estimated Maximum Force on Wire (N)	Length of Wire Extracted (m)	Slant Range, Bobbin to Rocket, at Wire Failure (m)	Rocket Velocity at Wire Failure (m/s)	Time After Launch (s)
Roos 2	GR-20	58 (check)	386	No Failure	-	-
Roos 5	GR-80	74	210	120	184	1.025
Roos 7	GR-80	?	47	39	103	0.575
Roos 9	GR-80	68	706	No Failure	-	-
Roos 11	GR-80 Mod 1	80	325	187	216	1.425
Roos 13	GR-80 Mod 2	70	226	177	162	1.725
Roos 15	GR-40	62	516	197	165	1.85

maximum velocity of this rocket was about 130 m/s and therefore, it appears marginal for our purpose. A 386 m length of wire was deployed, without breakage and, if the velocity had been higher, this length would have been satisfactory.

GR 80 In an effort to obtain more thrust, an 9" (22.86 cm) engine, identified as a GR 80, was tested. It was found to have an impulse of about 205 Ns. As can be seen in Figure 8 and 9, it develops a very large initial thrust immediately after ignition. The high internal pressure associated with this initial thrust caused four or more of these engines to fracture and fail prematurely. [We subsequently learned that this difficulty arose from an excess ignition mixture at the top of the fuel grain perforation. After this finding, Dr. Roos suggested that the venturi area be enlarged by 25%.] The venturis used on later tests were drilled out with a "J" letter drill (0.277" or 7.04 mm diameter). When this was done, the premature failures ceased and these rockets performed well in flight.

Four successful flight tests of the unmodified GR 80 engines were made; the results from these are shown in Figures 8 through 14. Three of these flight tests involved wires that were were deployed more or less successfully in two attempts. In Roos 9, the wire apparently withstood a force of 70 N with more than 700 m being deployed. On Roos 7, the wire broke almost immediately with only 47 m being extracted. In Roos 5, a length of about 200 m was deployed before the wire untied from the bridle at a velocity of 200 m/s.

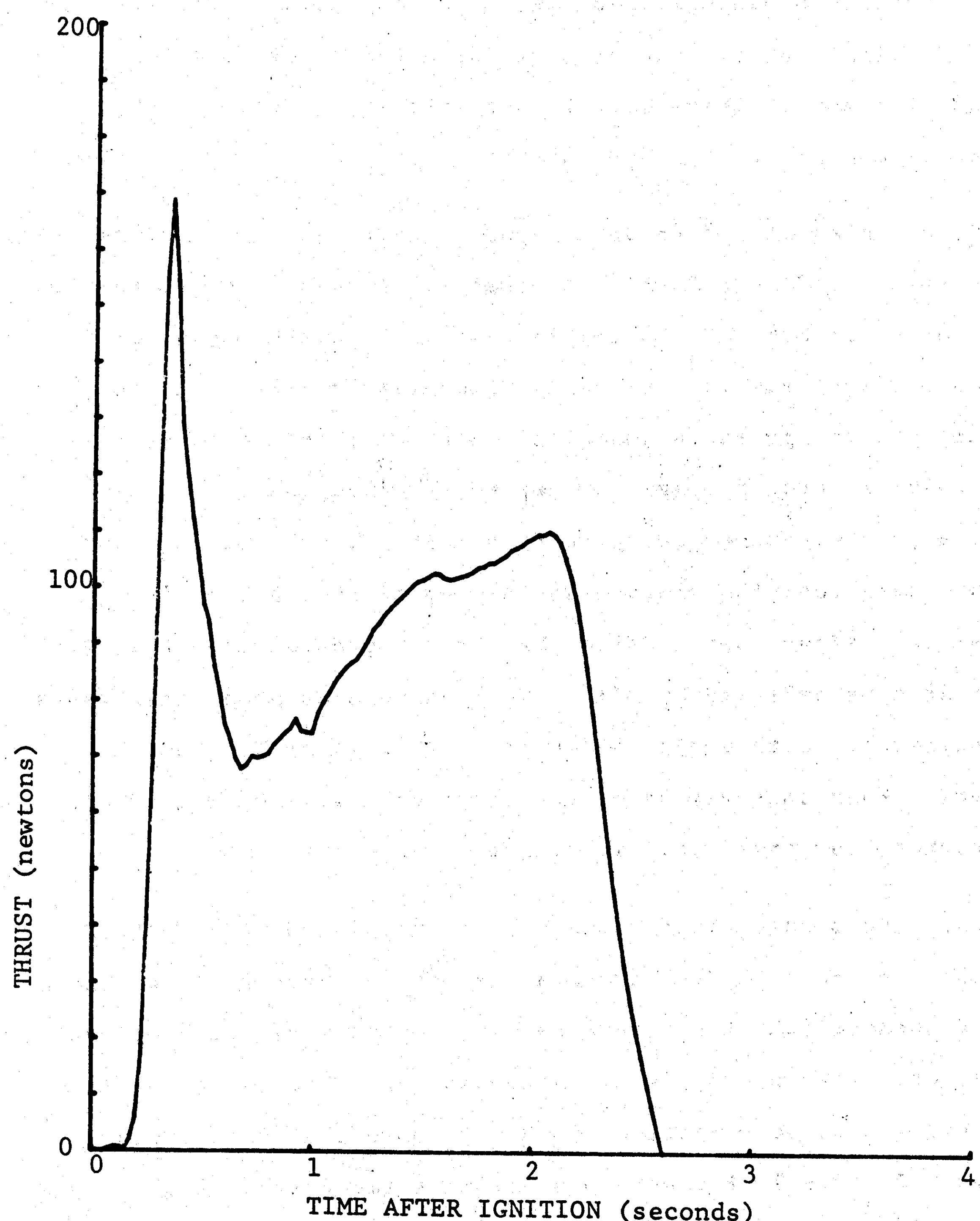

Figure 8. Static thrust measured for a standard GR 80 rocket, engine with a 6.1 mm venturi orifice at Sandia National Laboratories.

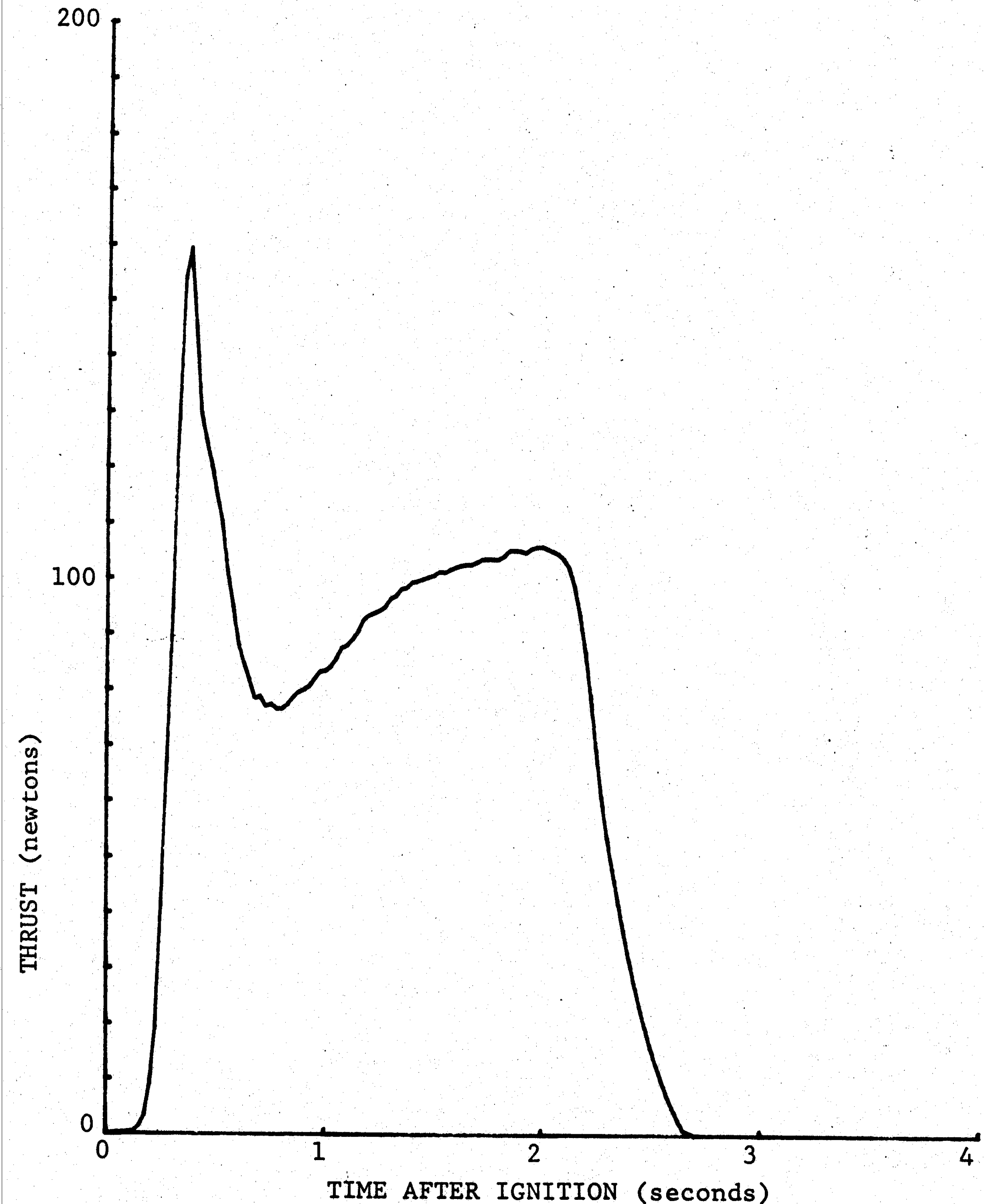

Figure 9. Static thrust measured for a standard GR 80 rocket, engine with a 6.1 mm venturi orifice at Sandia National Laboratories.

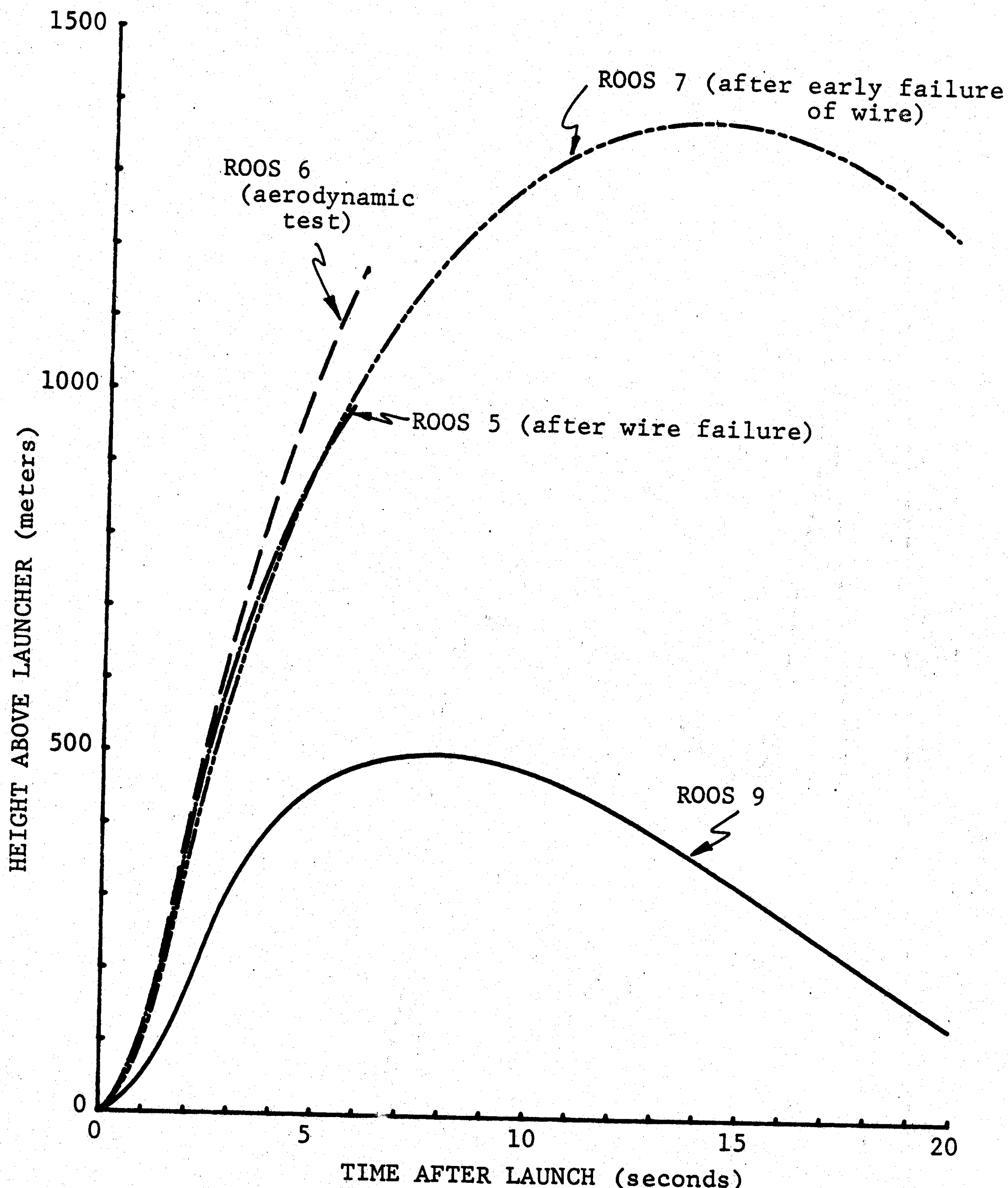

Figure 10. Height versus time plots for four standard GR 80 rockets launched vertically at Sandia National Laboratories.

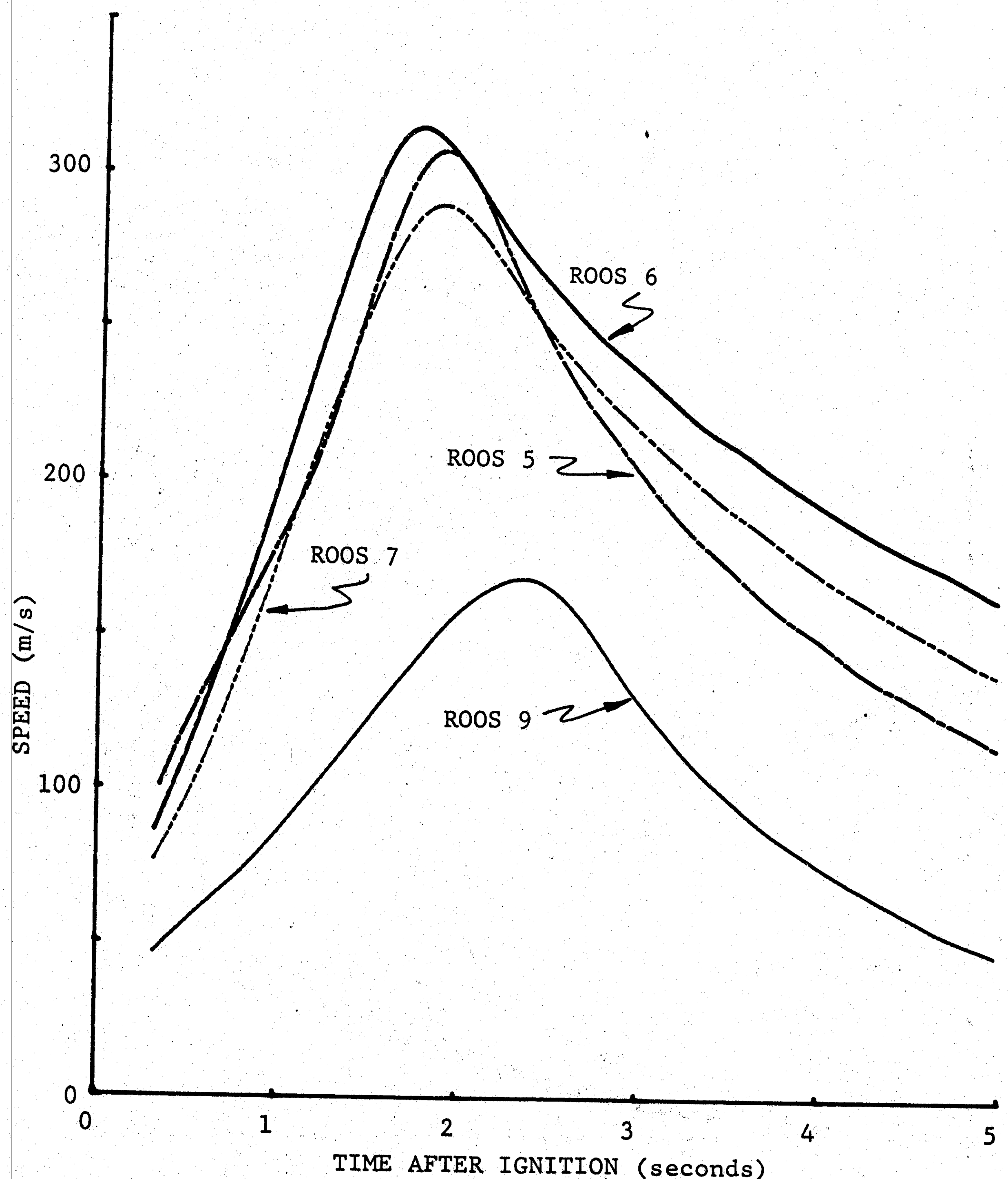

Figure 11. Plots of speed along flight trajectory versus time after ignition for four standard GR 80 rockets launched vertically at Sandia National Laboratories.

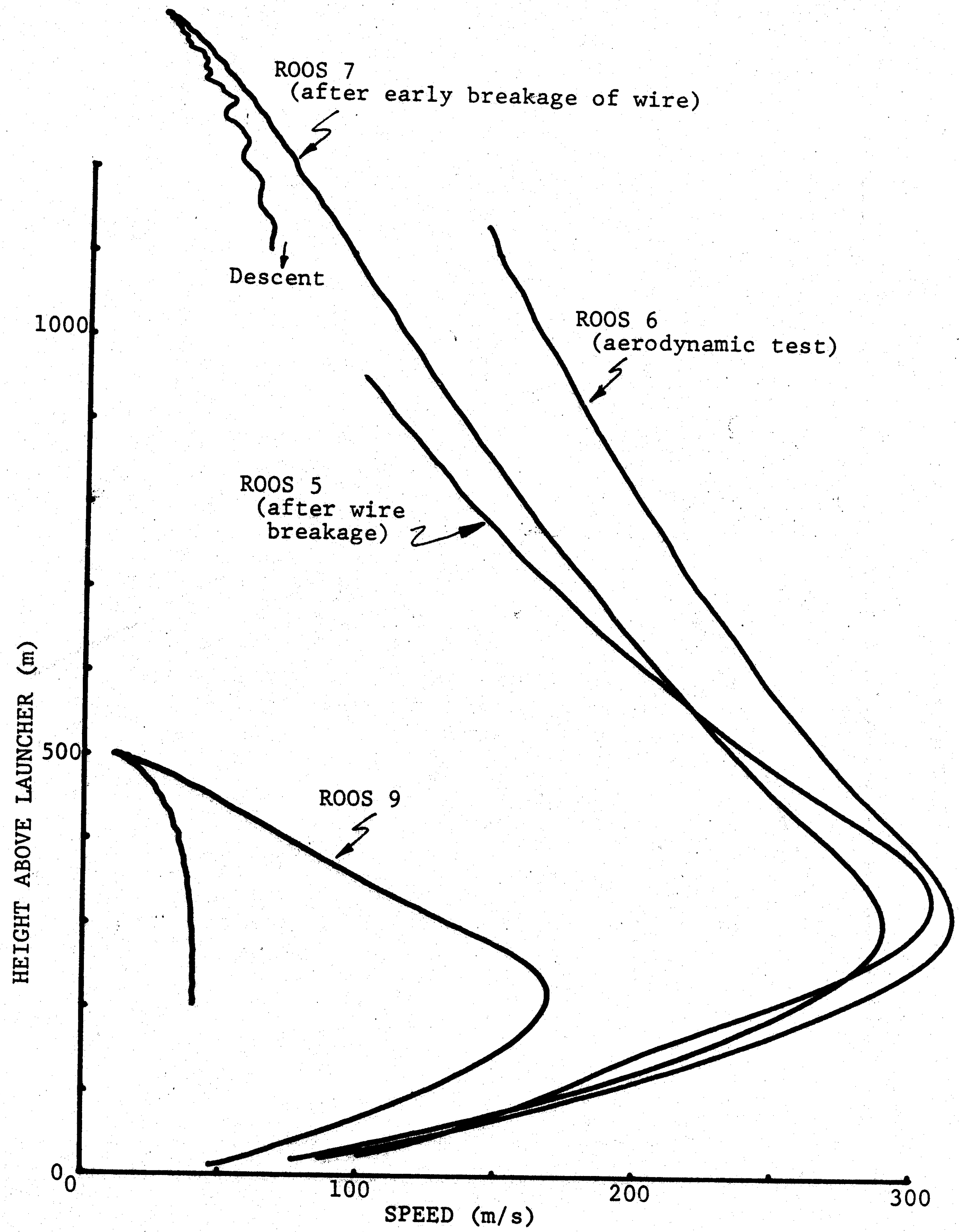

Figure 12. Plots of height above the launch versus speed along the trajectory for four standard GR 80 rockets launched vertically at Sandia National Laboratories.

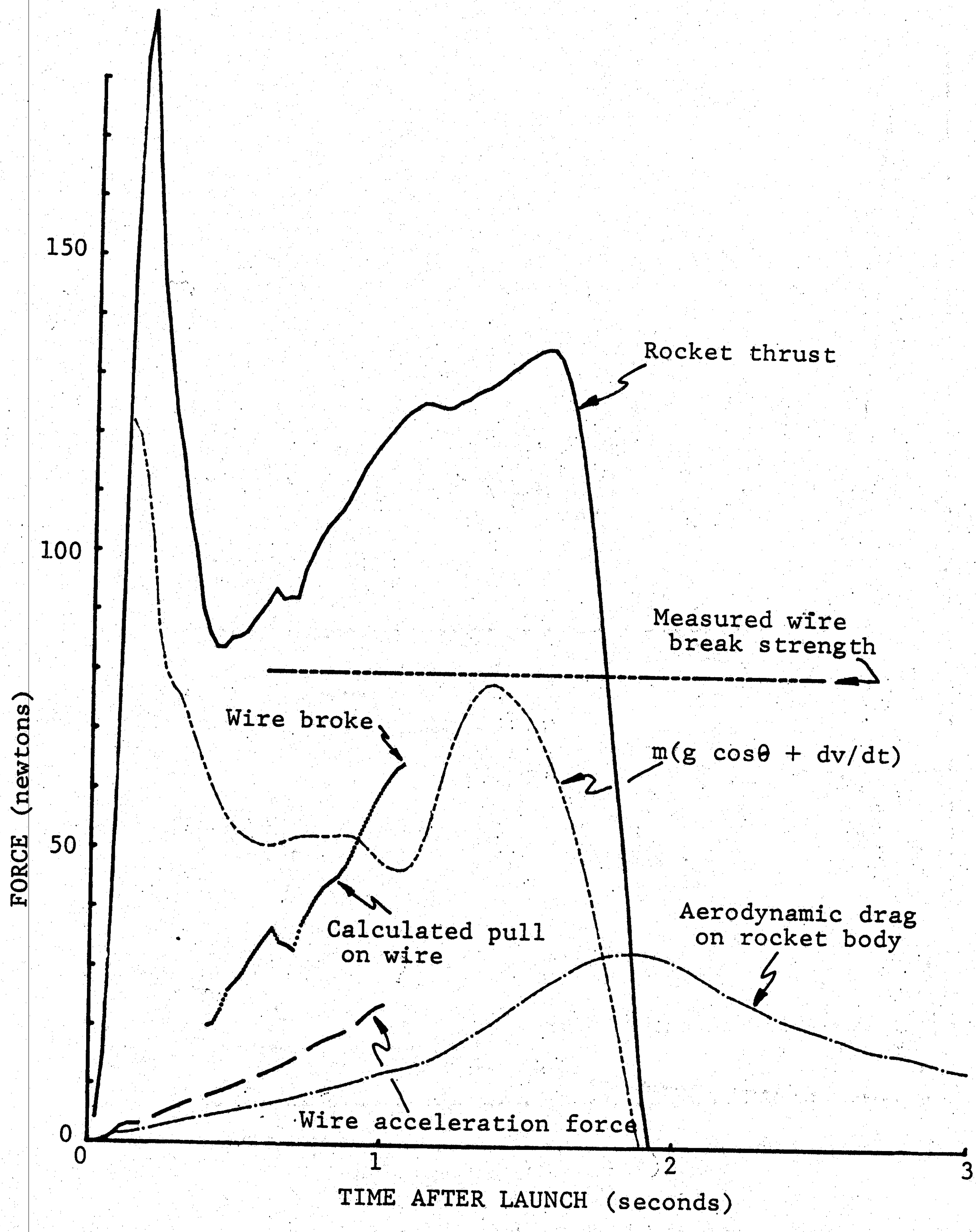

Figure 13. Forces associated with the deployment of a steel wire, pulled from a grounded spool by a small, vertically-fired rocket on February 16, 1983 at Sandia National Laboratory. The rocket was a Flight Systems type GR 80 and this test was identified as "ROOS 5".

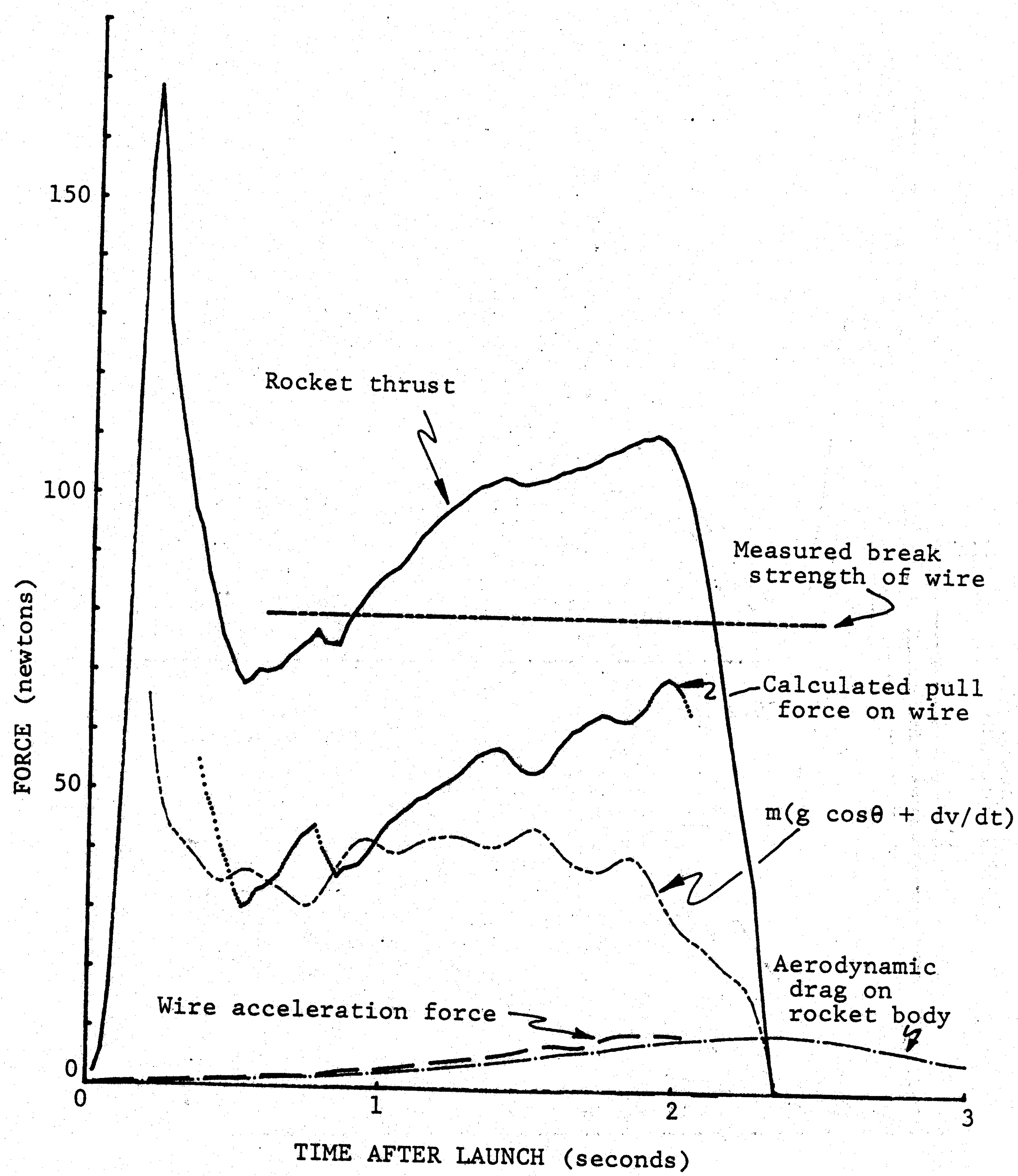

Figure 14. Forces associated with the deployment of a steel wire, pulled from a grounded spool by a small, vertically-fired rocket on April 21, 1983 at Sandia National Laboratory. The rocket was a Flight Systems type GR 80 and this test was identified as "ROOS 9".

GR 80 (with enlarged venturi) After enlargement of the GR 80 venturis, the large initial over-pressures were relieved with no significant reduction in impulse. The performance of two of the engines in static firing was a bit variable as can be seen in the thrust plots shown in Figure 15.

A successful flight test towing a wire was achieved in Roos 11 with an enlarged venturi. In this flight with more than 200 m of wire were deployed at speeds in excess of 220 m/s before the wire broke under a force in excess of 80 N.

From these tests shown in Figures 15 through 19, it appears that the modified GR 80 is useable but needs either more drag or more mass in the nose cone if greater lengths of wires are to be deployed reliably.

GR 80 (hexagonal perforation, enlarged orfice) Dr. Roos supplied a variation of the GR 80 engine with a hexagonal perforation of the fuel grain and a 5/16" (8.65 mm) venturi orifice. This engine performed well and, in a static test, provided an impulse with a good initial thrust that continued at a nominal 90 to 100 N level. In flight with a wire, about 150 m of wire were deployed at speeds of up to 260 m/s before the wire became untied from the bridle under forces in excess of 70 N.

The static test result is shown in Figure 22 and the flight results in Figures 22 through 24.

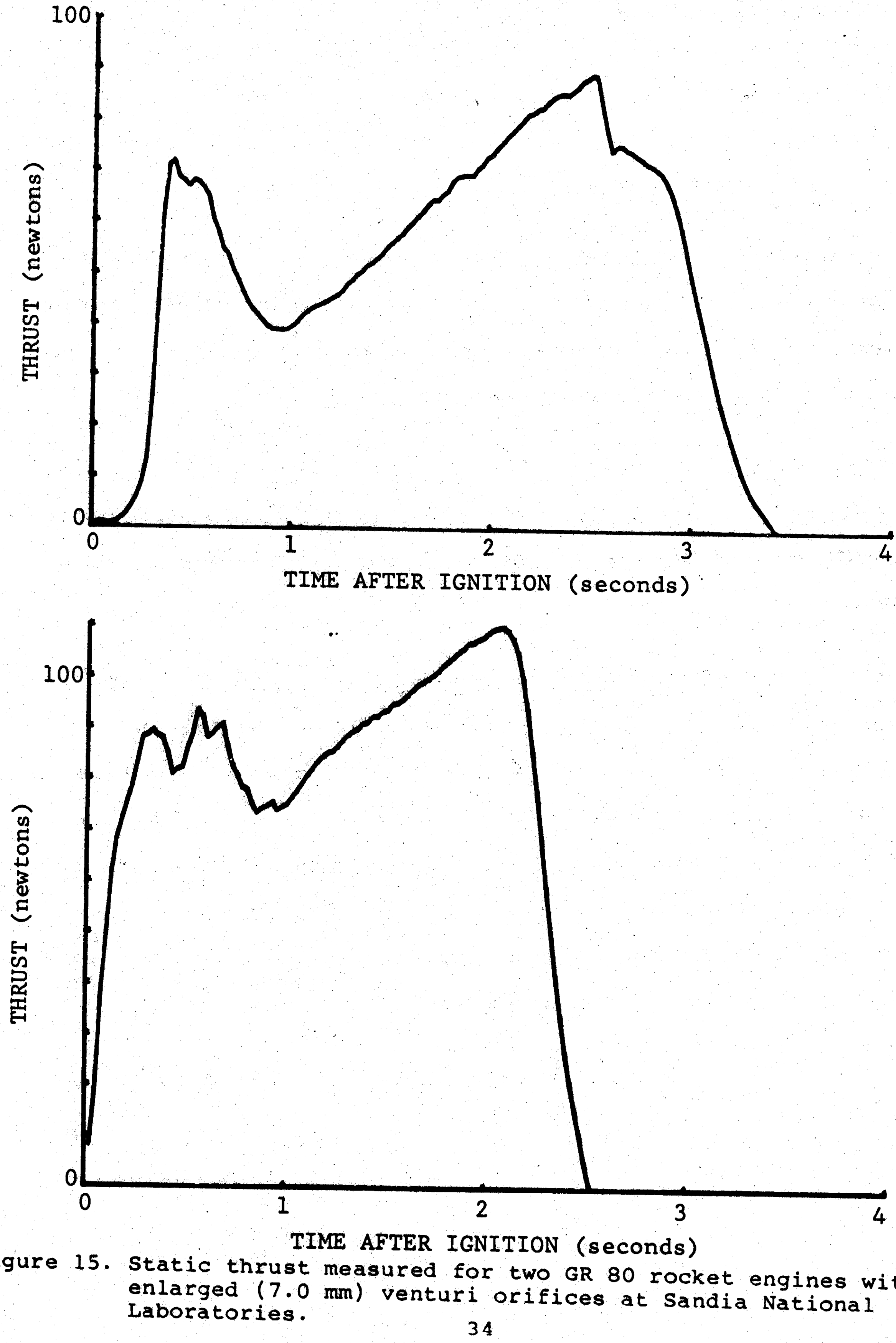

Figure 15. Static thrust measured for two GR 80 rocket engines with enlarged (7.0 mm) venturi orifices at Sandia National Laboratories.

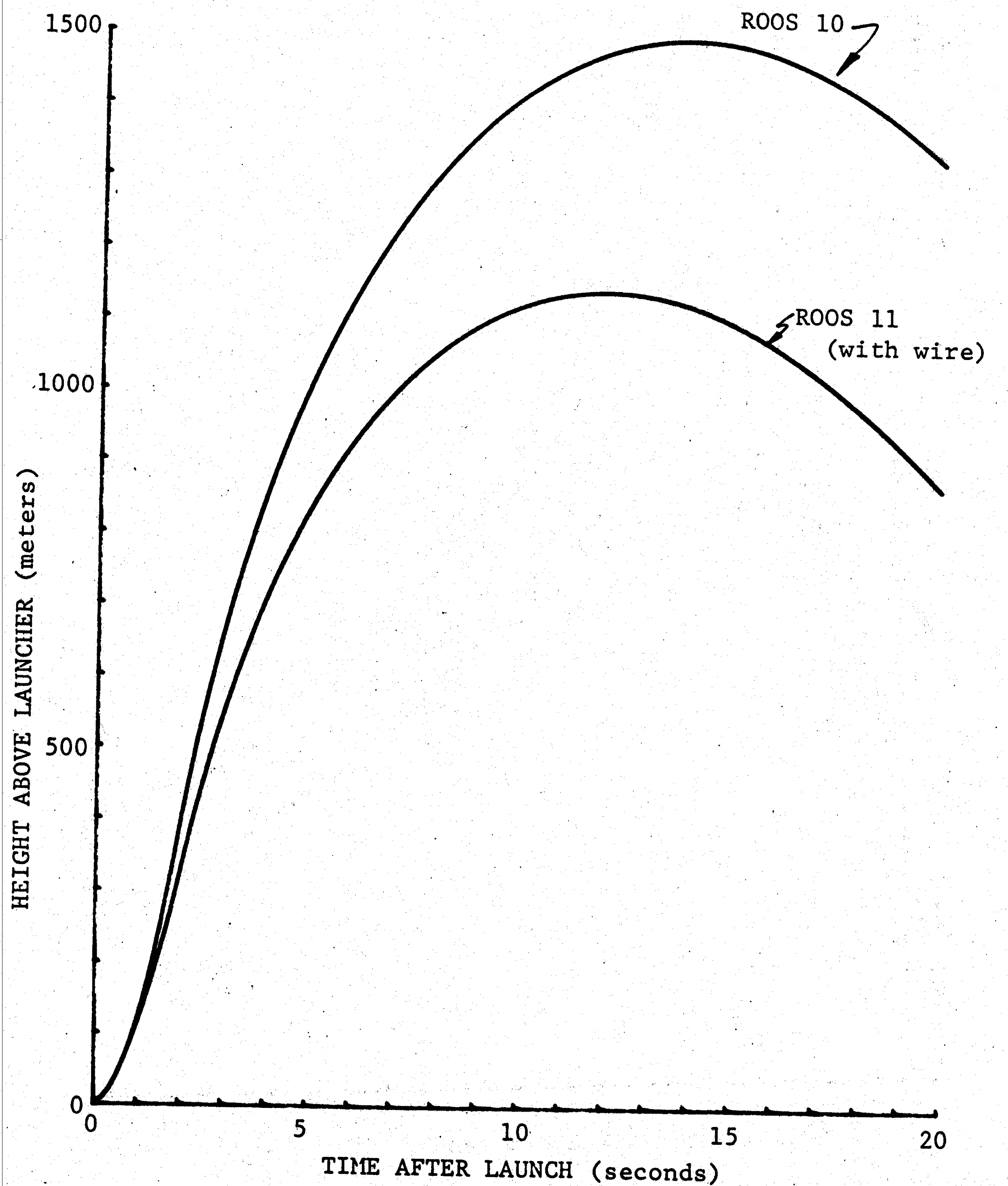

Figure 16. Plots of height above launcher versus time for two GR 80 rockets with 7 mm venturi orifices launched vertically at Sandia National Laboratories.

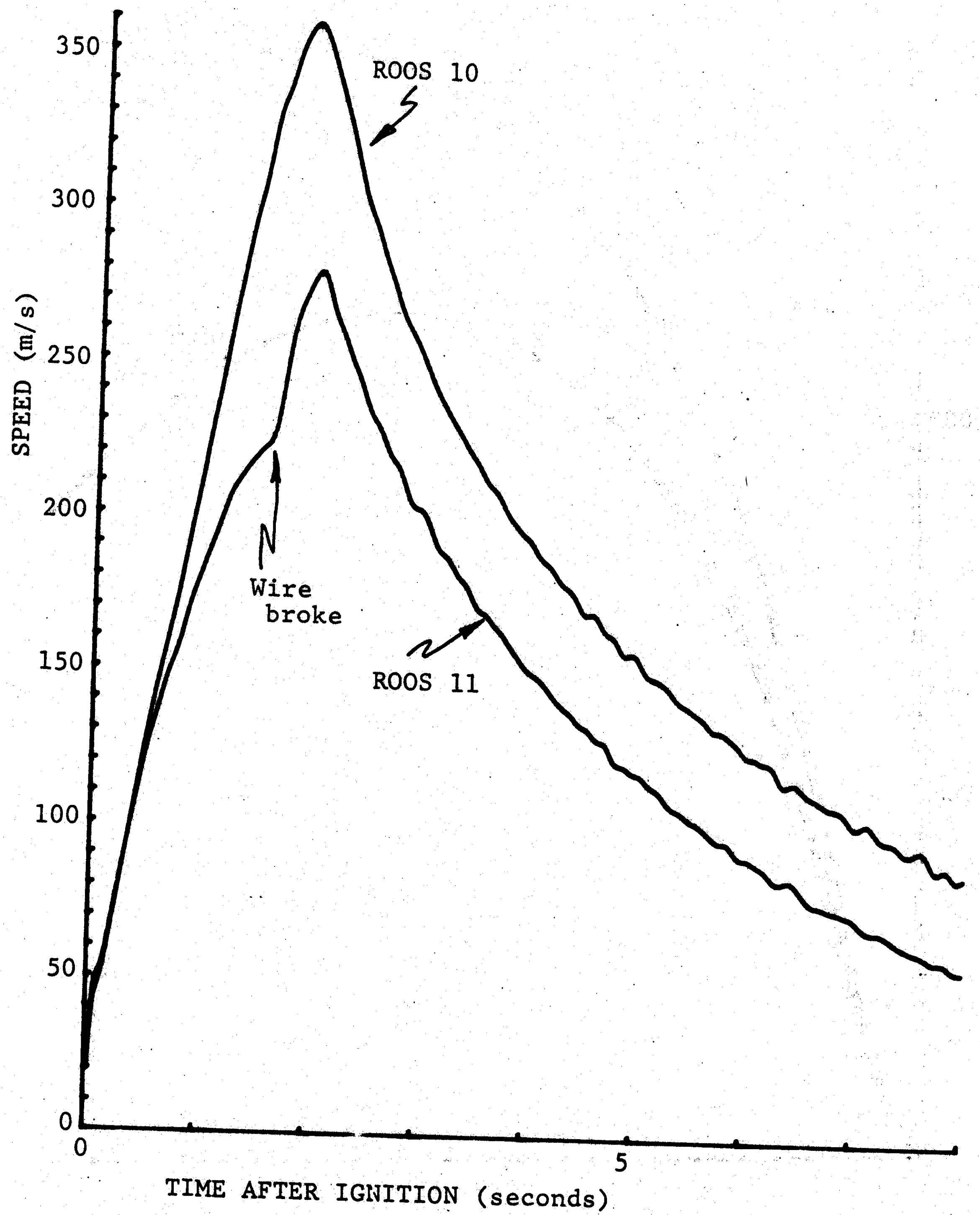

Figure 17. Plots of speed along the trajectory versus time for two GR 80 rockets with 7mm venturi orifices launched vertically at Sandia National Laboratories.

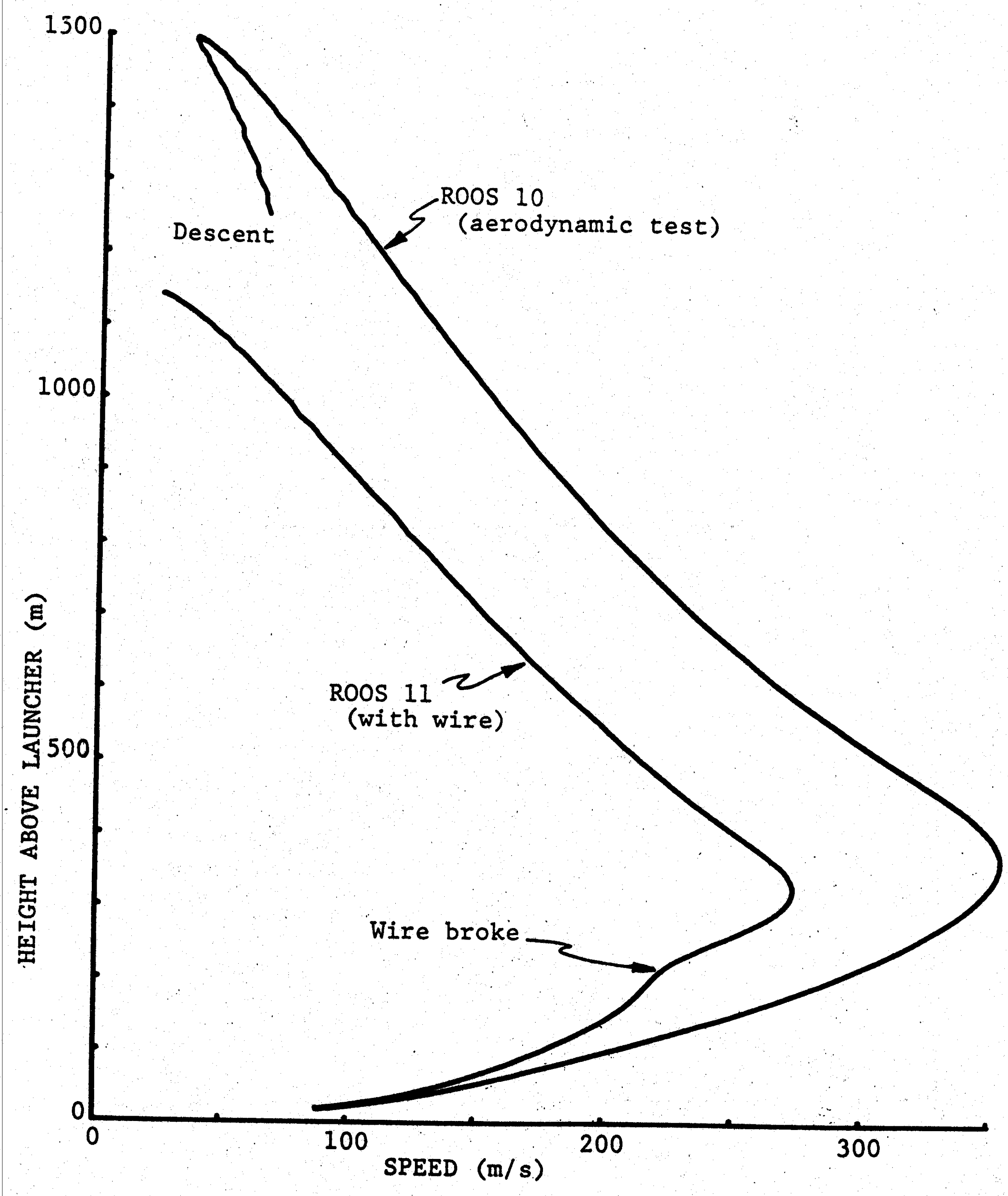

Figure 18. Plots of height above launcher versus speed along the trajectory for two GR 80 rockets with 7 mm venturi orifices launched vertically at Sandia National Laboratories.

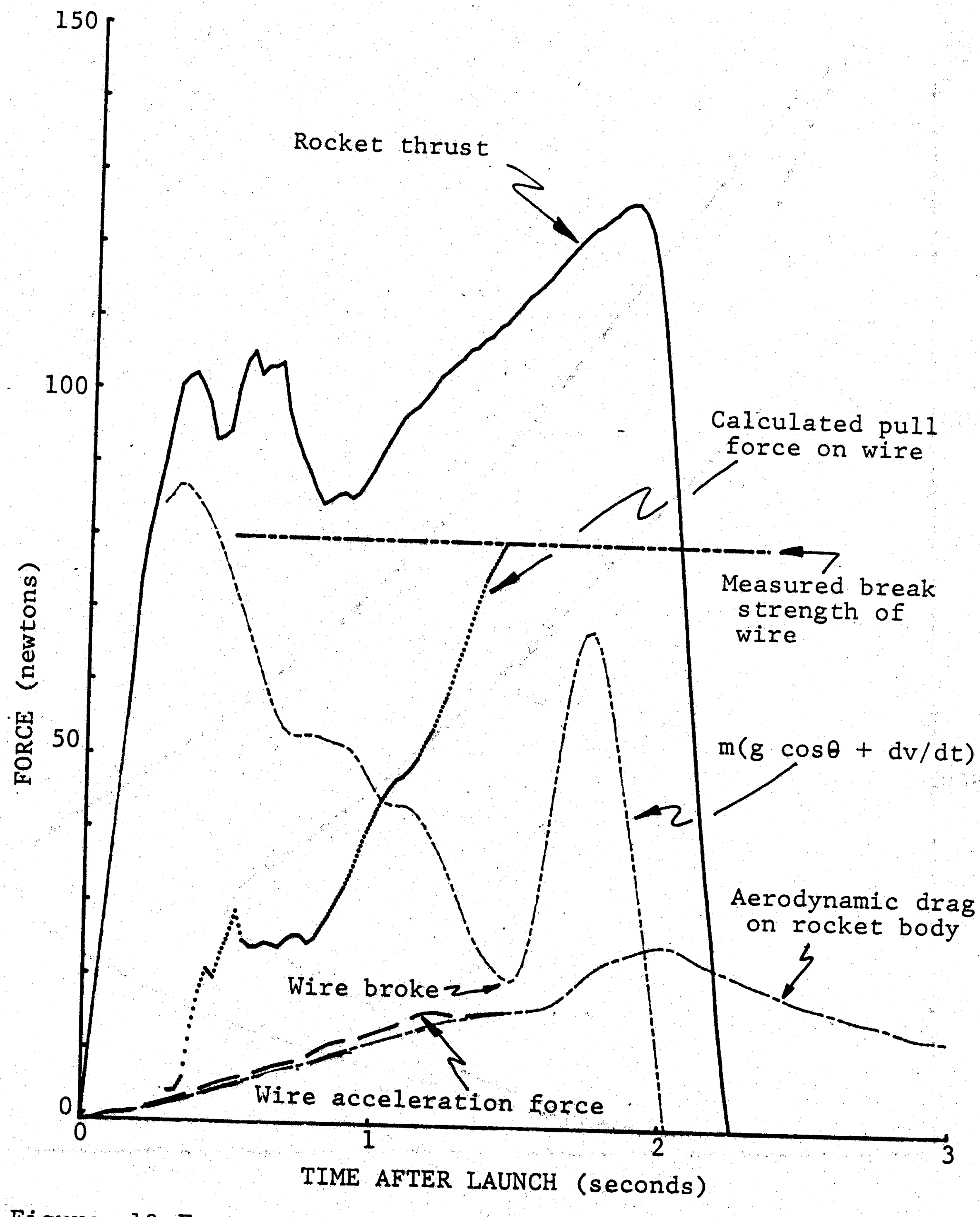

Figure 19 Forces associated with the deployment of a steel wire pulled from a grounded spool by a small, vertically-launched rocket on May 19, 1983 at Sandia National Laboratory. The rocket was a Flight Systems type GR 80 with an enlarged venturi (diameter: 0.704 cm) and this was identified as "ROOS 11".

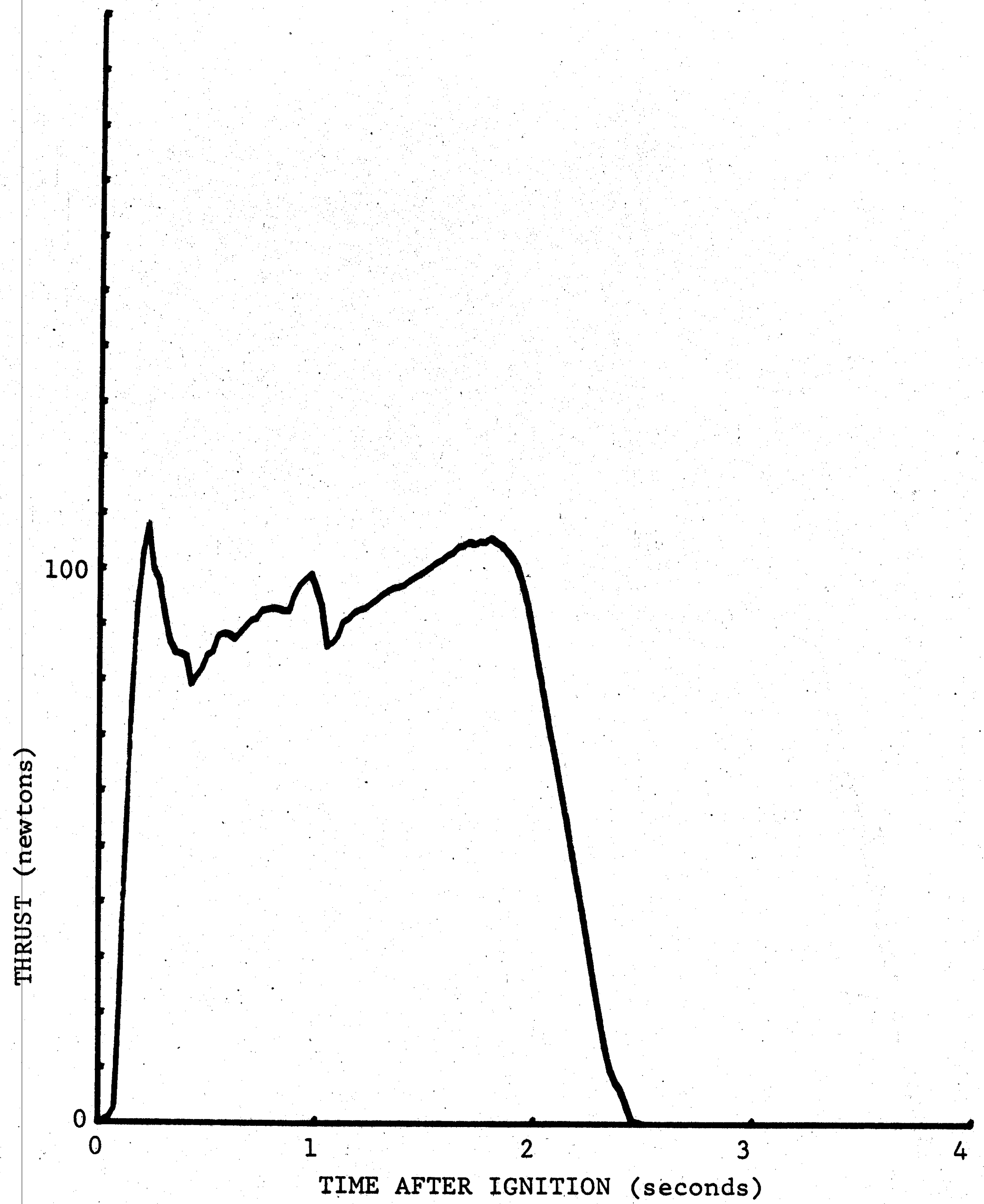

Figure 20. Static thrust measured for a GR 80 Mod 2 rocket engine with a hexagonal grain and a 7.8 mm venturi orifice launched vertically at Sandia National Laboratories.

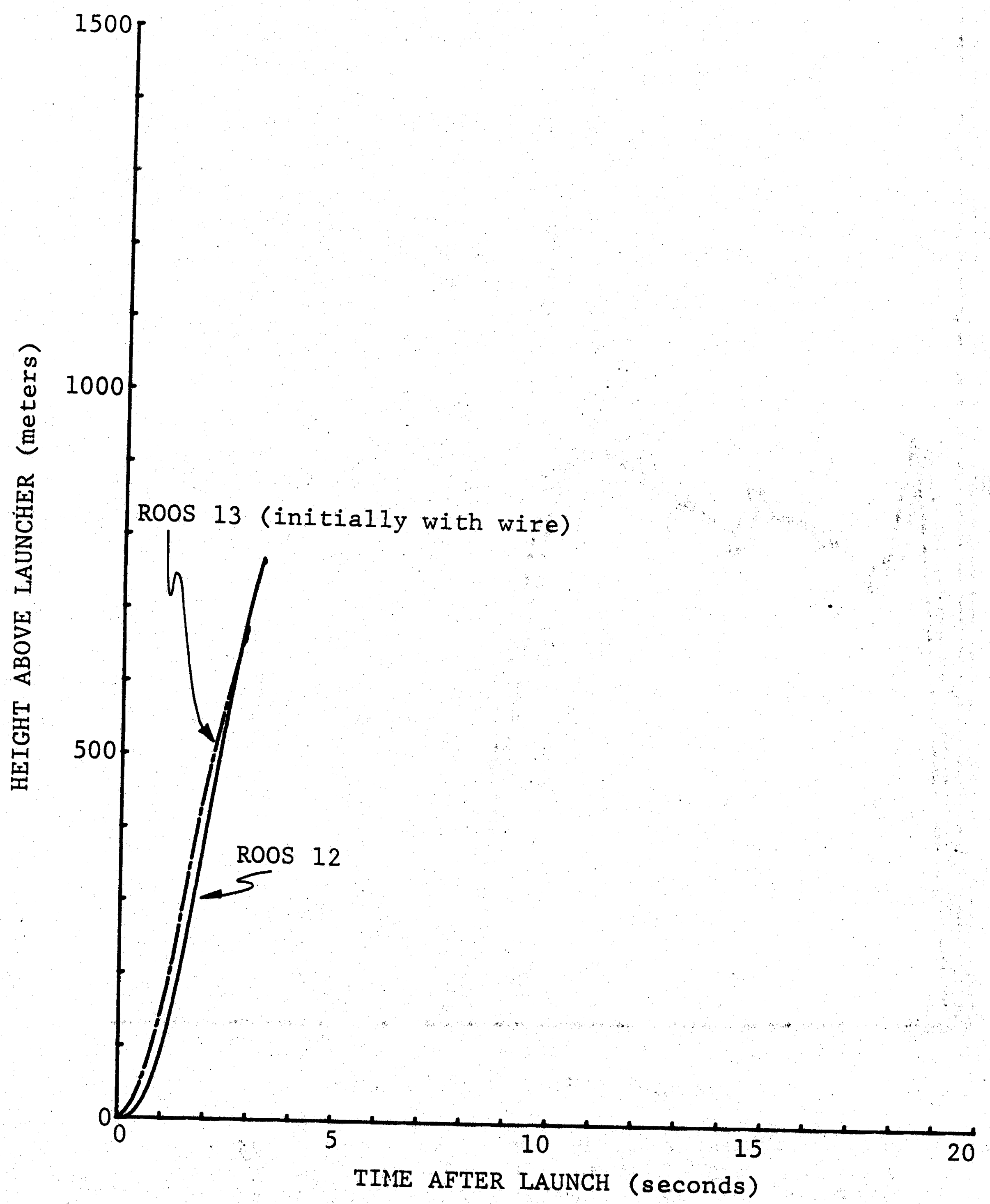

Figure 21. Plots of height above the launcher versus time after ignition for two GR 80 Mod 2 rocket engines with a hexagonal grain and a 7.8 mm venturi orifice launched vertically at Sandia National Laboratories.

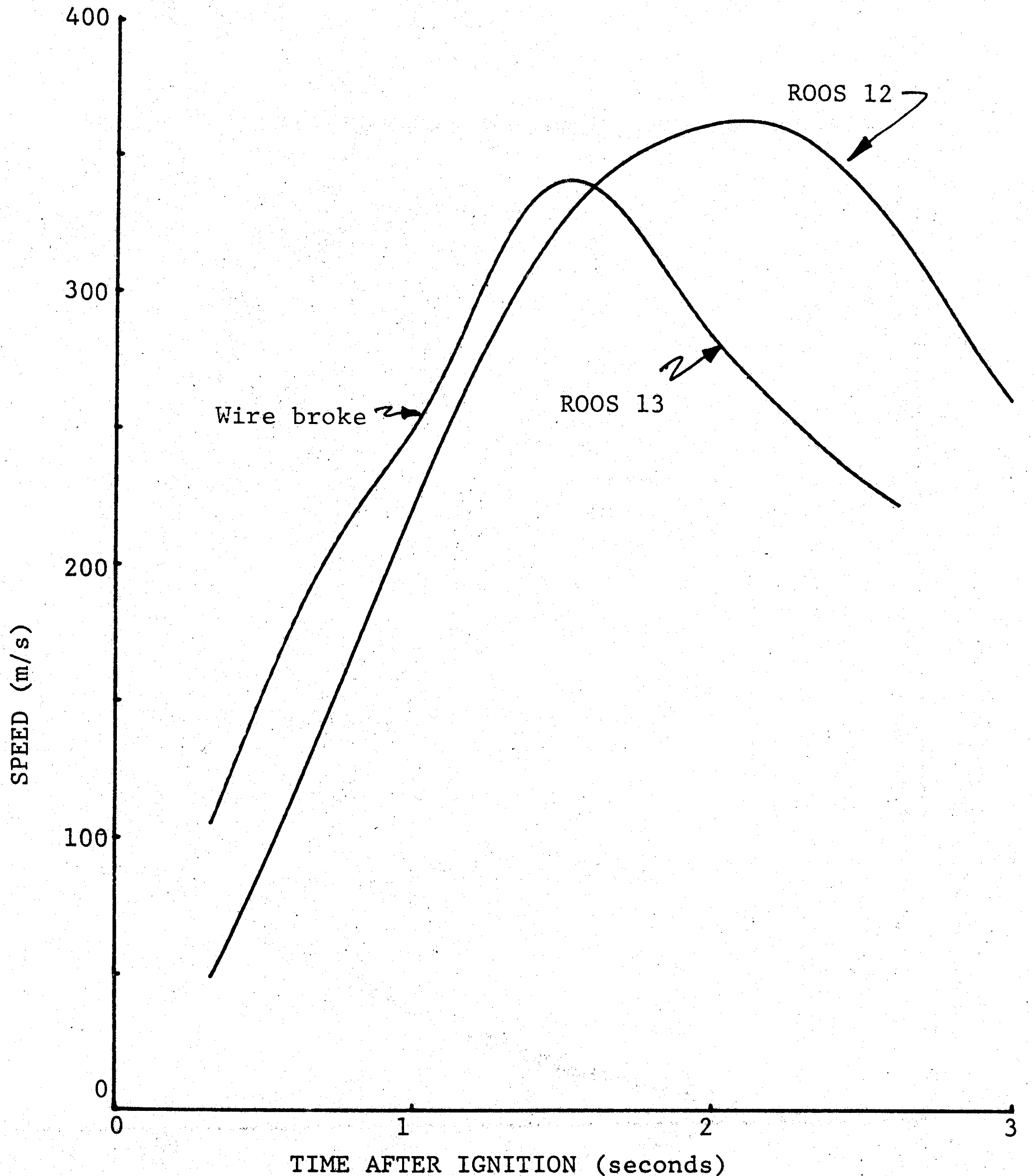

Figure 22. Plots of height above launcher versus time for two GR-80 Mod 2 rocket engines with a hexagonal grain and a 7.8 mm venturi orifice launced vertically at Sandia National Laboratories.

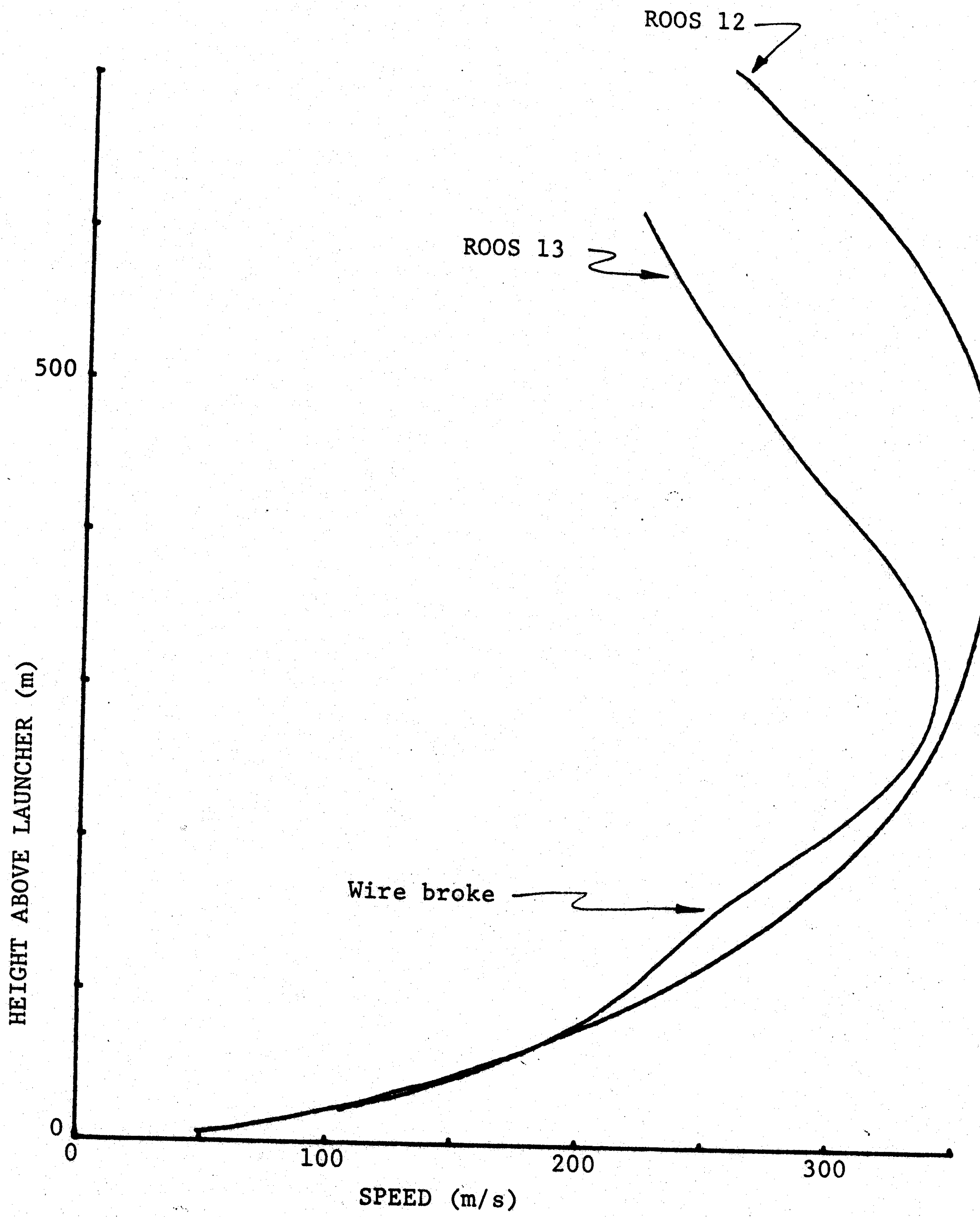

Figure 23. Plots of height above the launcher versus speed along the trajectory for two GR 80 Mod 2 rocket engines with a hexagonal grain and a 7.8 mm venturi orifice launched vertically at Sandia National Laboratories.

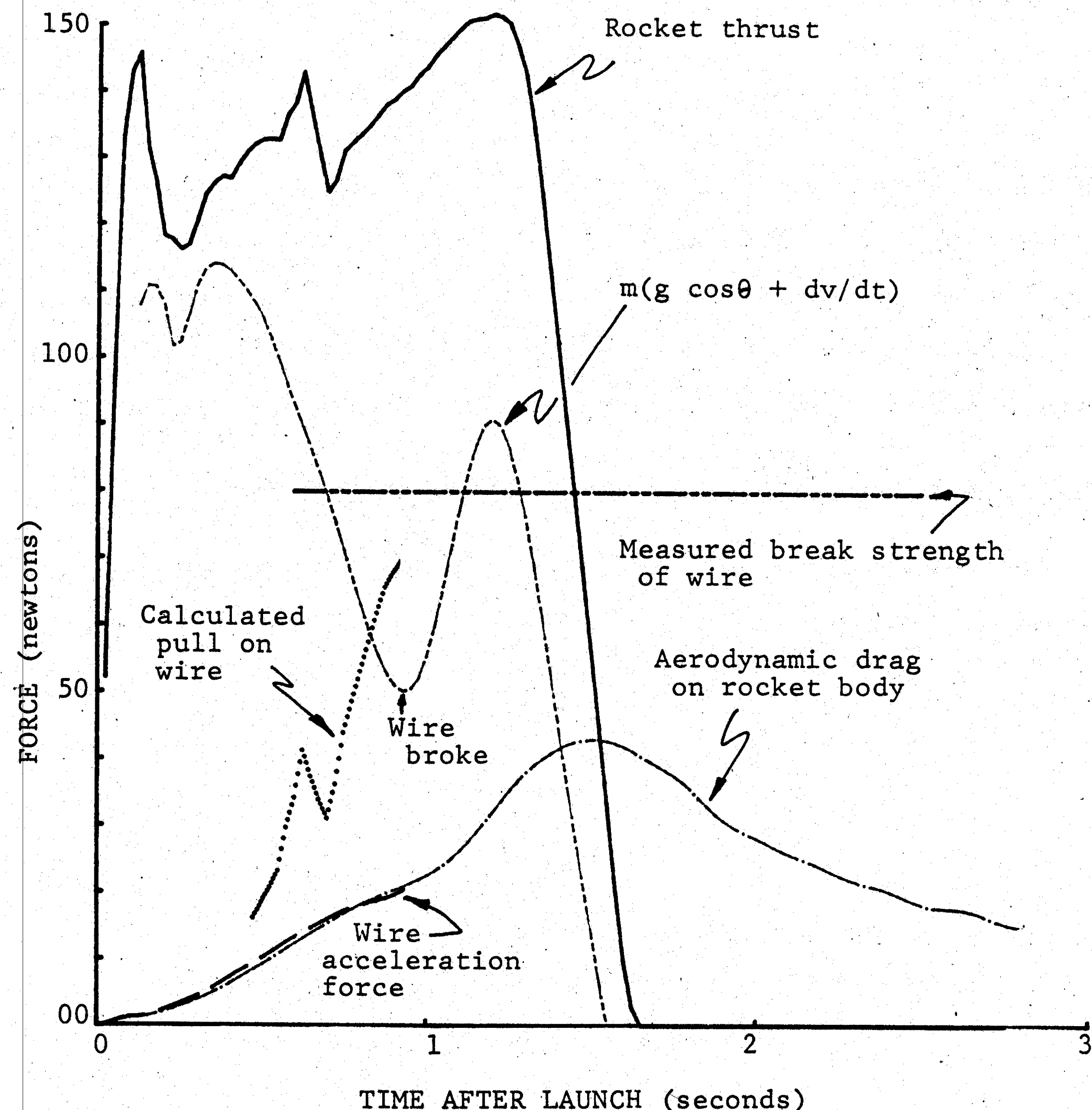

Figure 24. Forces associated with the deployment of a steel wire, pulled from a grounded spool by a small, vertically-launched rocket on May 19, 1983 at Sandia National Laboratory. The rocket was a Flight Systems type GR 80 with a hexagonal grain and an enlarged venturi (diameter: 0.78 cm). The test was identified as "ROOS 13".

GR 40 Flight Systems Inc. also supplied two intermediate thrust rockets identified as type GR 40 that were 8 inches (203 mm) in length for flight tests. (No engines of this type were available for static firing but such tests are needed.)

The rockets behaved well in flight. In Roos 14, using a rocket with an unloaded GR 40 engine, vertical velocities in excess of 440 m/s were achieved. A wire was towed during Roos 15 in which velocities of 160 m/s were observed before the wire became untied at an altitude of 200 m. under estimated forces in excess of 60 N. These results are shown in Figures 25 through 28.

Rocket Exhaust Velocity and Thrust Impulse Calculations

The mean rocket exhaust velocity, v_{ex}, was calculated using the derivation in Measurement Note #27 from which:

$$\bar{v}_{ex} \leqslant \frac{v_f + \int_{\substack{\text{burn}\\\text{period}}} (g\cos\theta + F_{drag}/m)\,dt}{\ln(m_f/m_i)}$$

where

v_f = velocity at fuel burnout,

$\cos\theta$ = direction cosine between rocket acceleration direction and the upward vertical,

g = the magnitude of the gravitational force/unit mass,

m = the instantaneous rocket mass during thrust,

m_f = rocket mass after fuel burnout,

m_i = initial mass of rocket with fuel.

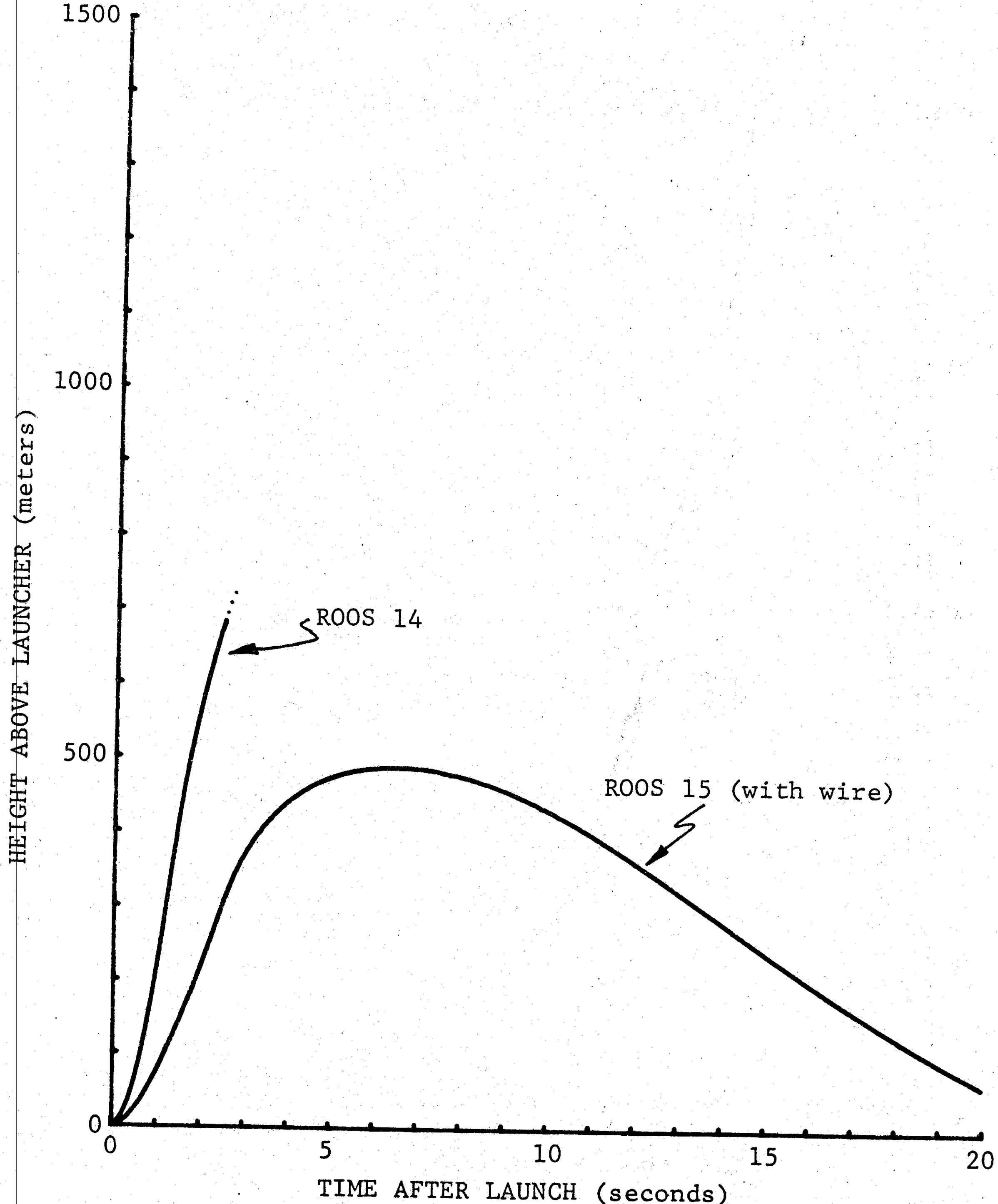

Figure 25. Plots of height above launcher versus time after ignition for two GR 40 rockets launched vertically at Sandia National Laboratories.

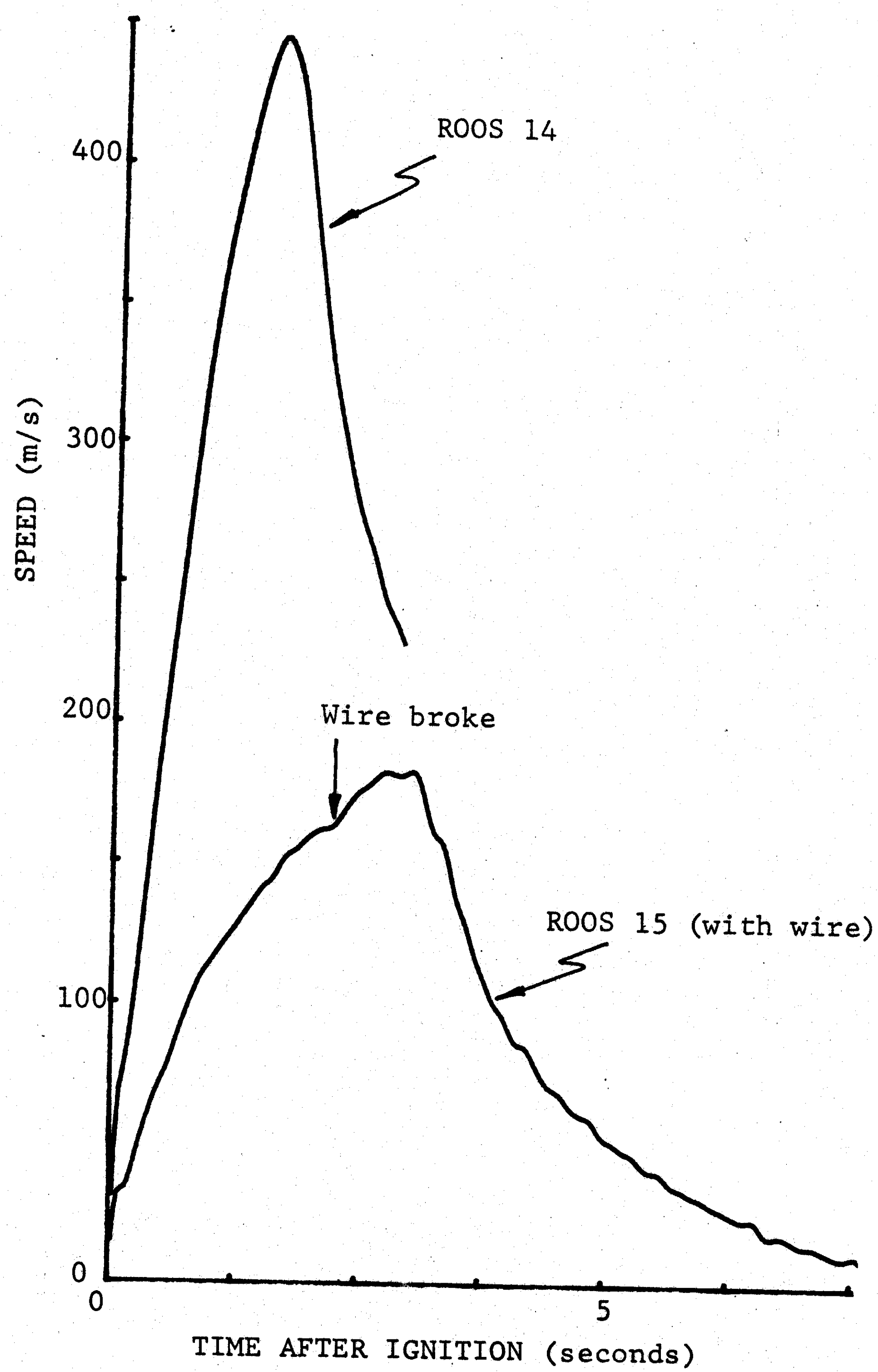

Figure 26. Plots of speed along trajectory versus time after ignition for two GR 40 rockets launched vertcially at Sandia National Laboratories.

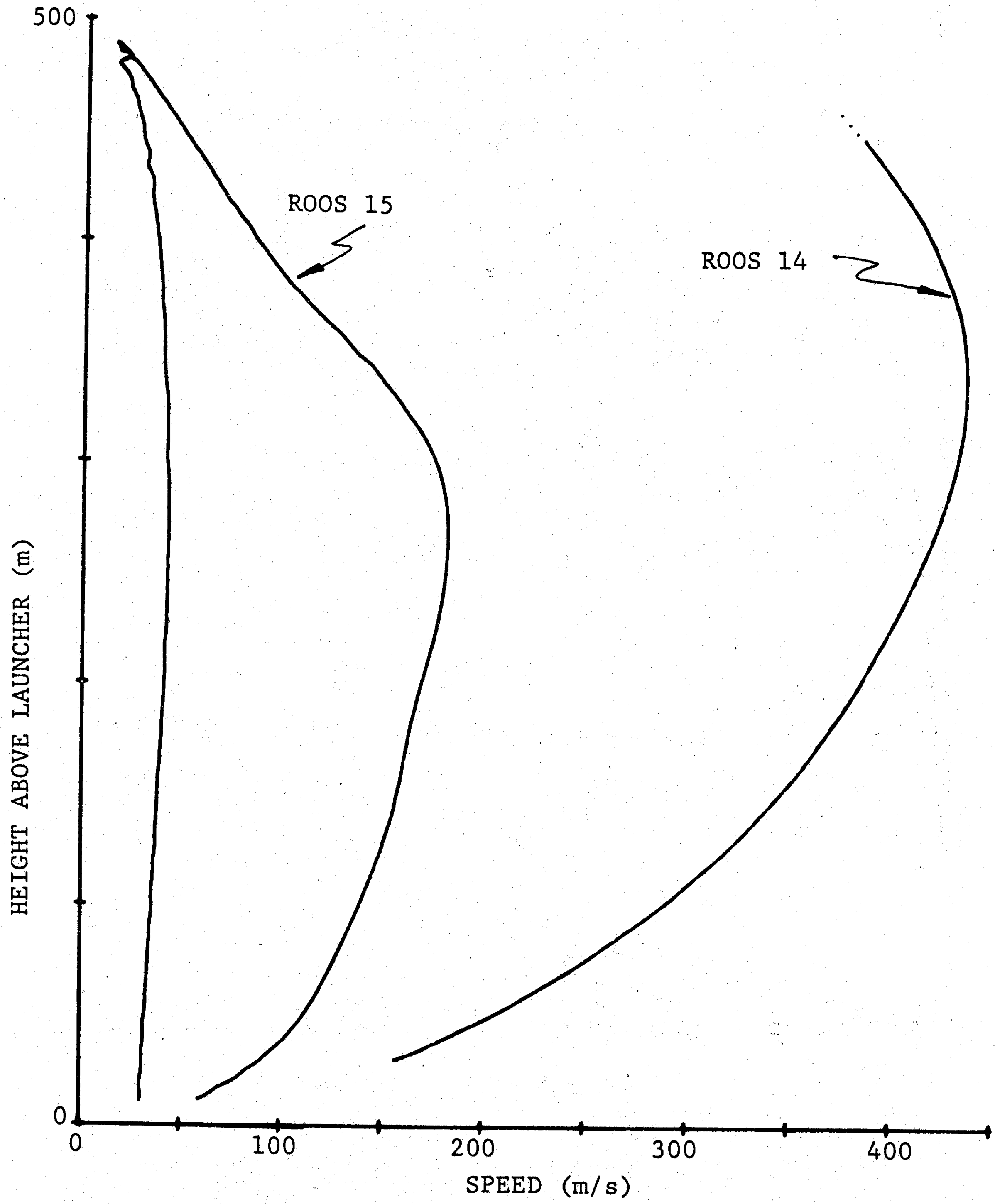

Figure 27. Plots of height above launcher versus speed along trajectory for two GR 40 rockets launched vertically at Sandia National Laboratories.

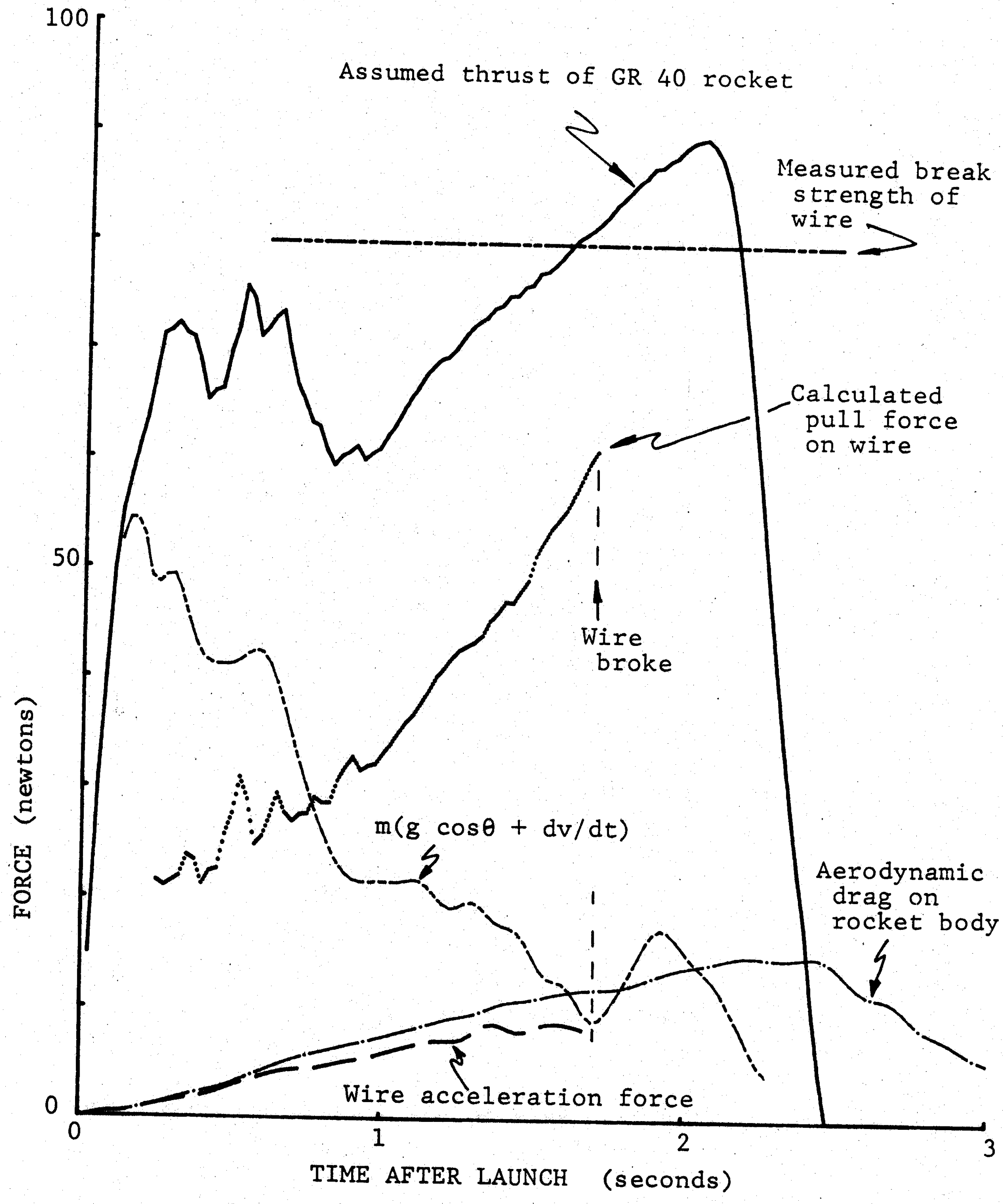

Figure 28. Forces associated with the deployment of a steel wire pulled from a grounded spool by a small, vertically-launched rocket on May 19, 1983 at Sandia National Laboratory. The rocket was a Flight Systems type GR 40 and this test was identified as "ROOS 15". The thrust data were scaled from the static test of a GR 80 with an enlarged venturi (diameter: 0.704 cm).

The total impulse I_f delivered by the fuel combustion in

$$I_f = \bar{v}_{ex}(m_i - m_f).$$

The specific impulse I_{sp} is given by

$$I_{sp} = \bar{v}_{ex} / g$$

and, from these results, is about 150 sec for the Flight Systems Inc. rockets. A comparison of the measured static thrust impulses to those calculated for thrust in flight for these rockets is shown in Table IV.

Flight Force Predictions

If we assume flights made with rockets having the same thrust in flight as measured statically for rockets of these types and, if we scale the wire pull force in terms of the calculated force required to change the wire momentum, we can predict how various rocket configurations might perform when launched vertically upward. These assumptions produce some feedback into the predicted rocket accelerations and velocities but the computations so far have been stable.

Our algorithm is

$$F_T - F_d - F_w - mg = m\ dv/dt$$

where F_T = rocket engine thrust as a function of time

$F_d = 0.5\ C_d A \rho v^2$

$F_w = \gamma(v^2 + z(dv/dt + g))$

γ = wire mass/unit length

TABLE IV

COMPARISON OF MEASURED STATIC THRUST IMPULSES TO THESE CALCULATED FOR THRUST IN FLIGHT FOR FLIGHT SYSTEMS INC. ROCKETS

Aerodynamic Test Number	Rocket Size	Fuel Mass (gm)	Calculated $\bar{v}_{ex}$ (m/s)	Calculated Flight Impulse (Ns)	Mean Static Impulse (Ns)	Static Thrust Duration (s)	Flight Thrust Duration (s)
Roos 3	GR-20	87.7	1364	120	124	3.2	2.64
Roos 6	GR-80	111.6	1710	191	206	2.5	1.78
Roos 10	GR-80 Mod 1	115.6	1565	180	195	2.7	1.92
Roos 12	GR-80 Mod 2	115.6	1254	145	-	-	2.10
Roos 14	GR-40	93(?)	1860	173	-	-	1.30

Mean: 1550 m/s

$m = m_o - (dm/dt)t$

dm/dt = fuel burn rate, assumed to be constant during the period of thrust

dv/dt = upward acceleration

In Figures 29, 30, 31 and 32, we show the predicted behaviour of four assumed, wire-towing, GR 80 rockets having the flight thrust characteristics of the static firing given in Figure 15b. For these calculations, a wire drag force of $5\gamma(v^2 + z(dv/dt + g))$ was assumed, from the earlier flight results. The assumed rocket masses after burnout for these four calculations were:

Figure 29:	440 gm
Figure 30:	840 gm
Figure 31:	940 gm
Figure 32:	1440 gm

The predicted excessive pull on the wire in Figure 29 (440 gm) rocket mass) agrees well with that estimated for Roos 11 (Figure 19) where the wire separated from a rocket of similar mass.

The addition of mass to the rocket in Figures 30, 31 and 32 reduced significantly the inferred pull force on the towed wire. From this, it appears that the addition of 300 to 400 grams would reduce the pull force adequately without limiting the rocket velocity at burnout excessively.

The effects of carrying a bobbin behind the rocket in the French fashion for the deployment of a wire aloft was then considered. We assumed a bobbin mass of 400 gm and, because the

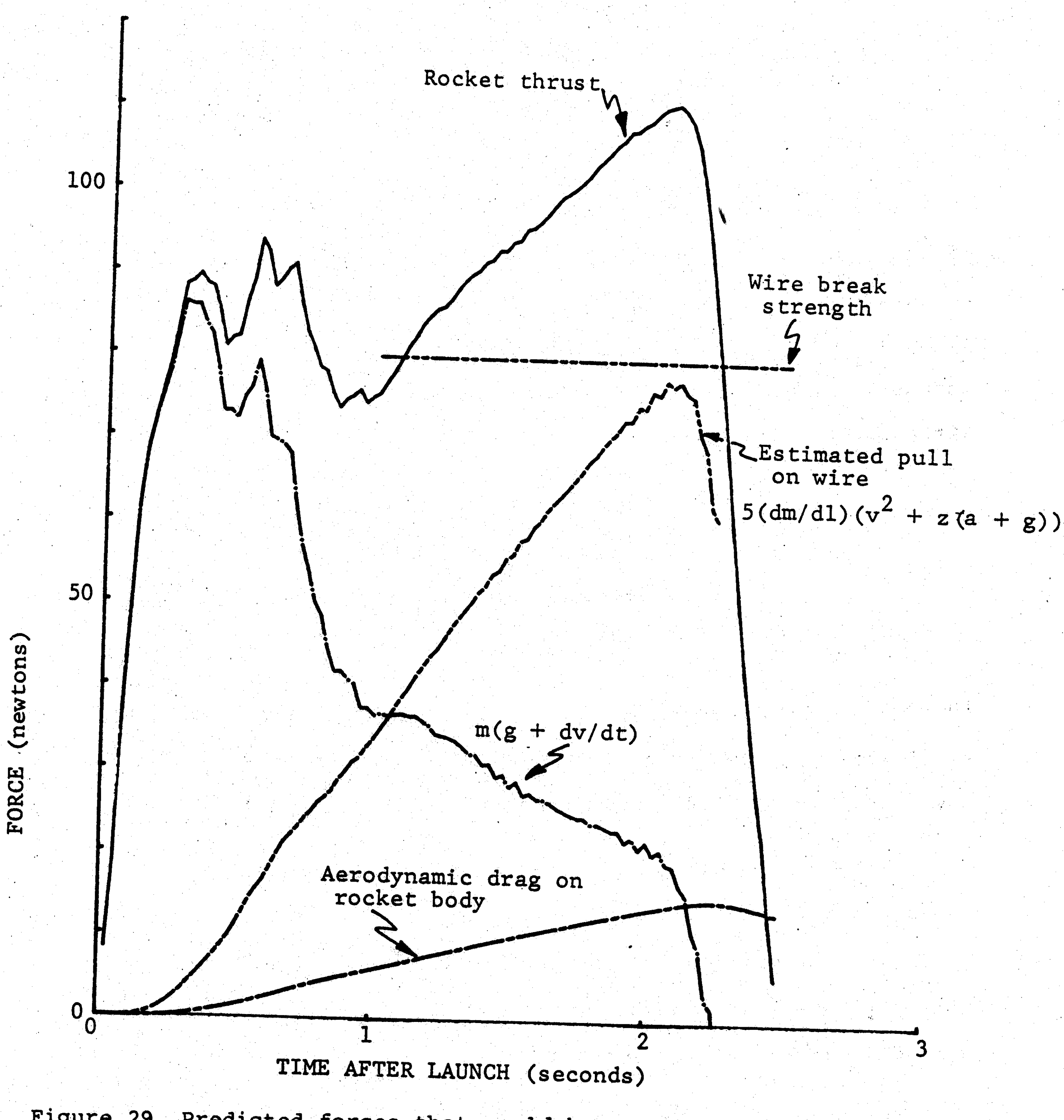

Figure 29. Predicted forces that would be encountered in a vertical launch of a GR 80 Mod 1 rocket with a 7 mm venturi orifice with the thrust of the static test and a 440 gm mass. The wire deployment force is assumed to be 5 fold that of the wire acceleration and weight force.

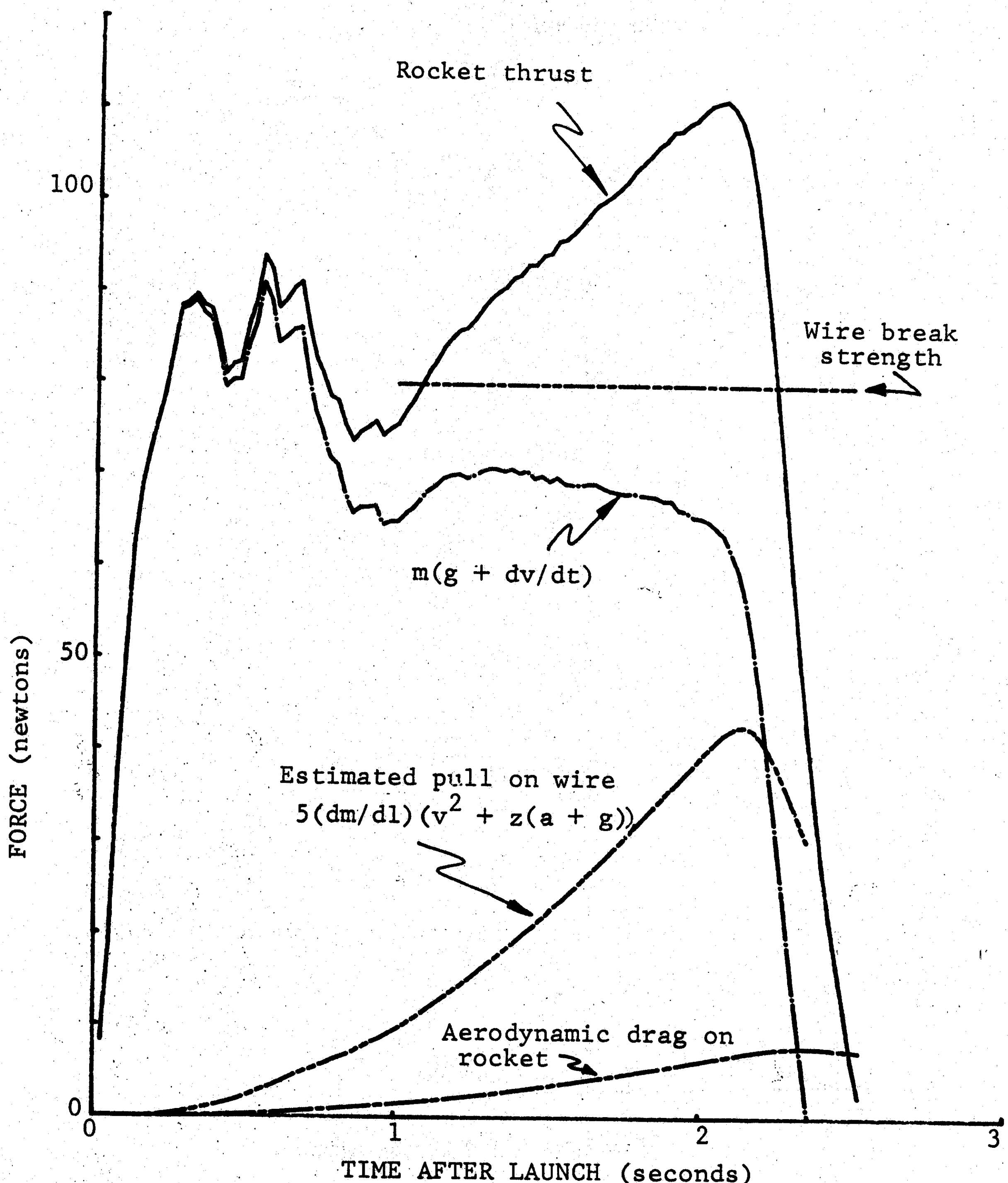

Figure 30. Predicted forces that would be encountered in a vertical launch of a GR 80 Mod 1 rocket with a 7 mm venturi orifice with the thrust of the static test and a 840 gm mass. The wire deployment force is assumed to be 5 fold that of the wire acceleration and weight force.

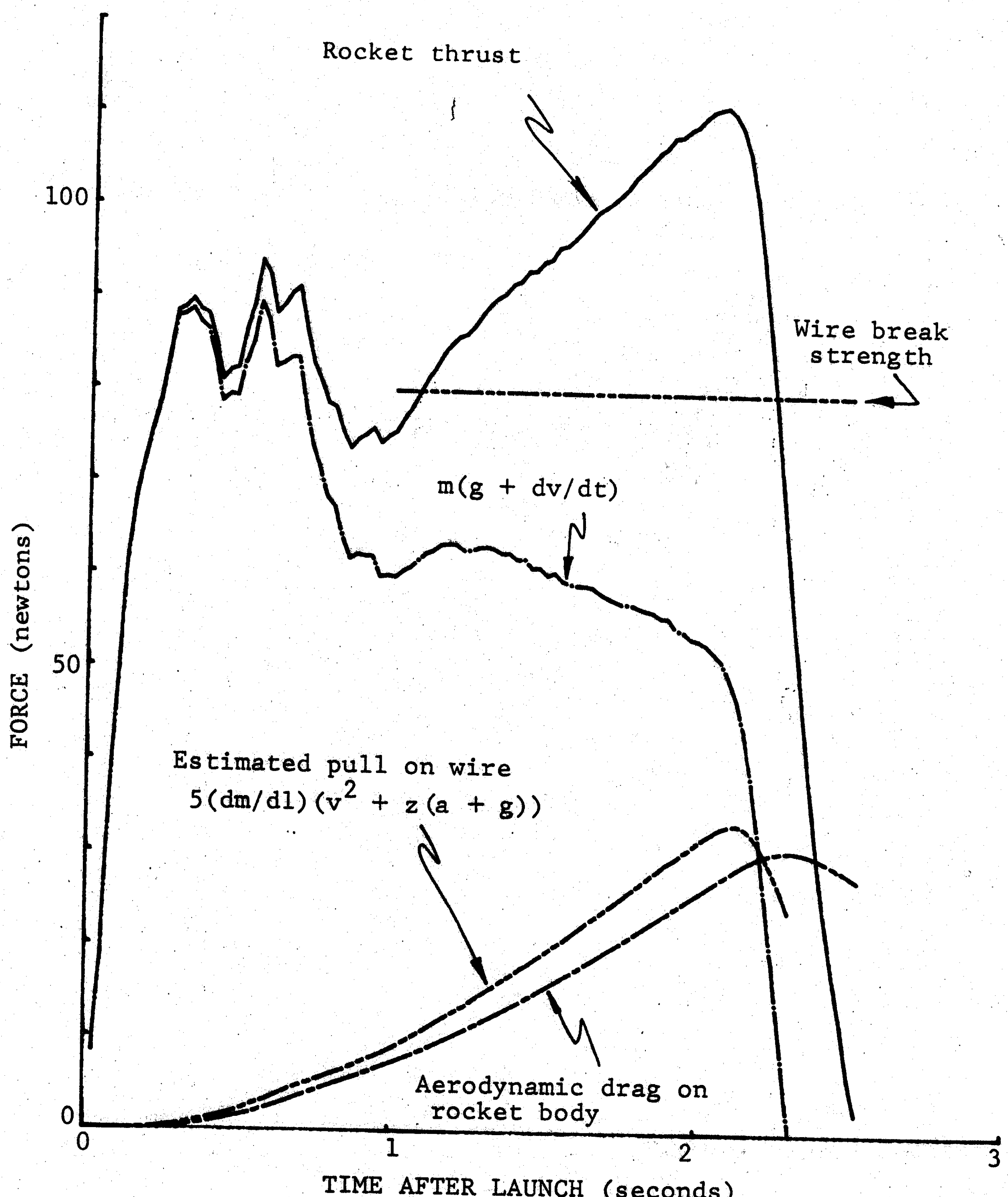

Figure 31. Predicted forces that would be encountered in a vertical launch of a GR 80 Mod 1 rocket with a 7 mm venturi orifice with the thrust of the static test and a 940 gm mass. The wire deployment force is assumed to be 5 fold that of the wire acceleration and weight force.

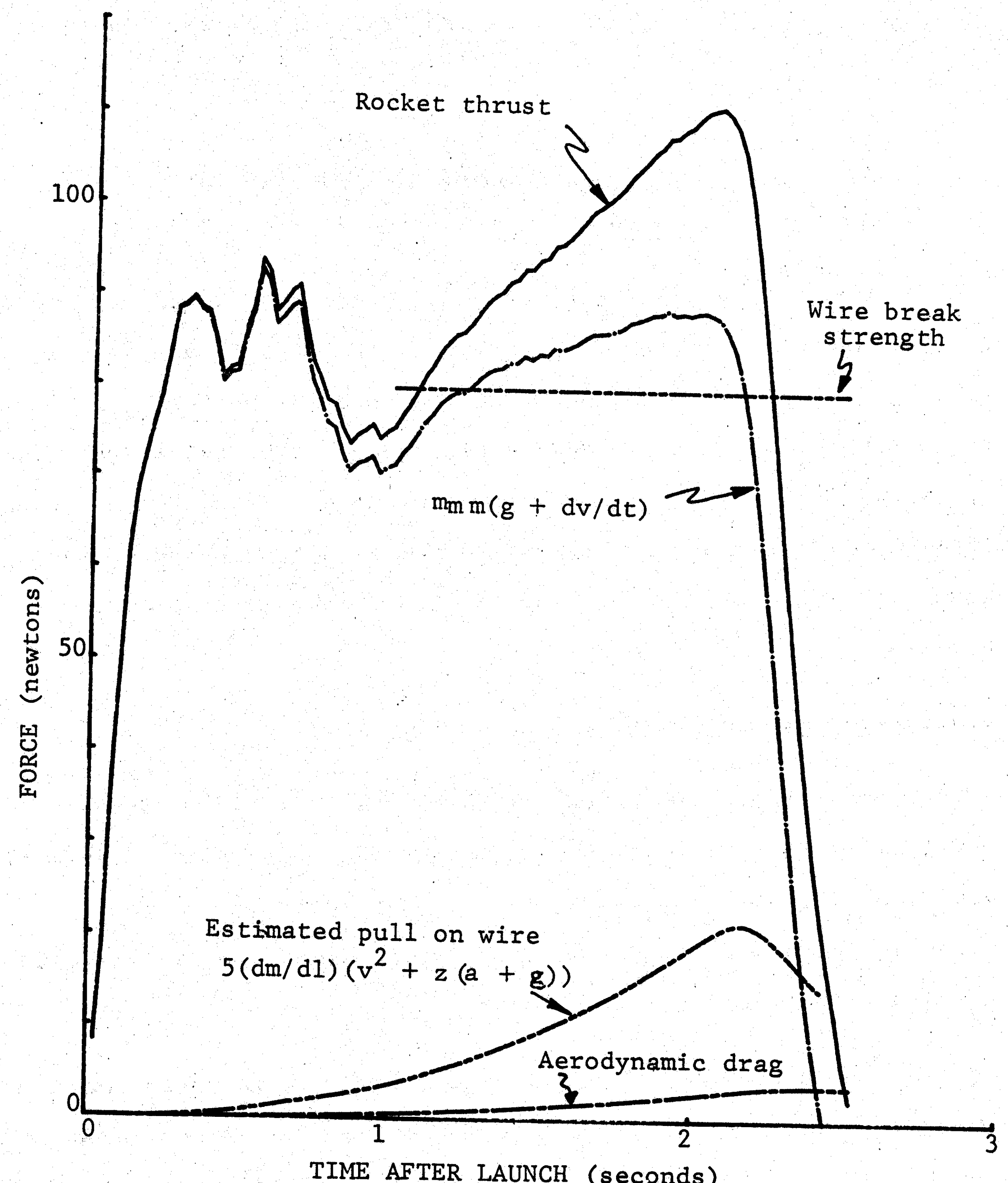

Figure 32. Predicted forces that would be encountered in a vertical launch of a GR 80 Mod 1 rocket with a 7 mm venturi orifice with the thrust of the static test and a 1440 gm mass. The wire deployment force is assumed to be 5 fold that of the wire acceleration and weight force.

deployed wire would be stationary in the air, we further assumed that the wire pull would be less. For this calculation we used a sealed wire force of

$$2\gamma(v^2 + z(dv/dt + g))$$

The results of this calculation are shown in Figure 33.

A plot of the calculated vertical velocities versus the height of the various rocket configurations is shown in Figure 34. Here it can be seen that an unloaded GR 80 produces the best flight performance (neglecting the wire breakage possibilities) while less desirable velocities result as the rockets are loaded down. From these preliminary calculations it appears that carrying a light weight bobbin aloft may provide the best lightning triggering results.

Conclusions and Recommendations

These Flight Systems Inc. rockets seem worthy of further development for use in lightning triggering experiments. Attention needs to be given to matching the venturi orifice size to the internal pressures developed during combustion so as to minimize premature failures.

If GR 80 rockets are to be used for deploying wires, more mass should be placed in the rocket nose cone. Calculations based on the static firing indicate that the rocket mass (after burnout) should be between 750 gm and 900 gm if stresses on the wires are to be

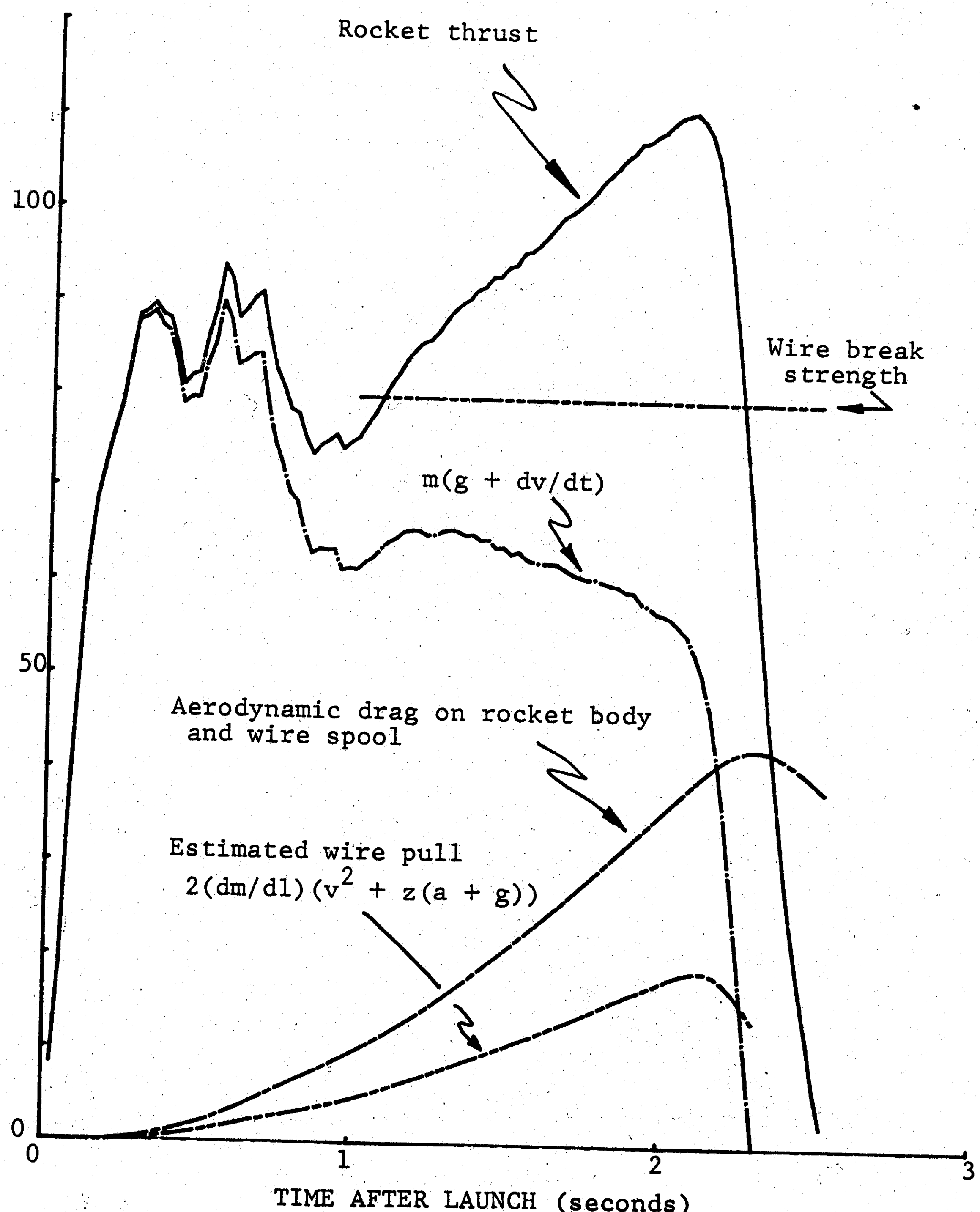

Figure 33. Predicted forces that would be encountered in a vertical launch of a GR 80 Mod 1 rocket with a 7 mm venturi orifice with the thrust of the static test and a 440 gm mass. In this calculation it was assumed that a 400 gm wire dispensing bobbin was carried aloft beneath the rocket so that the wire deploying force was only twice the wire accelerating and weight force.

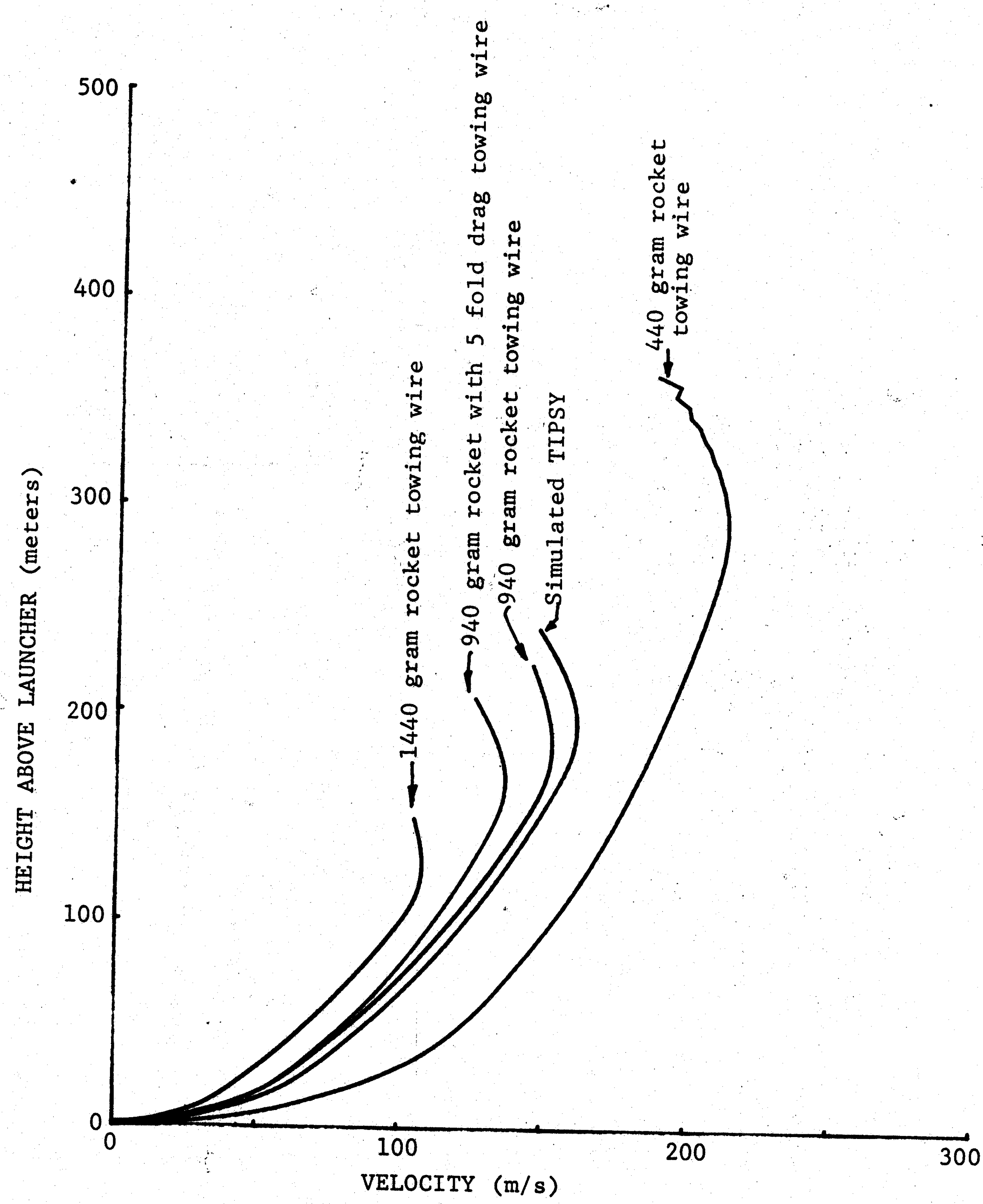

Figure 34. Plots of the predicted height above the launcher versus speed along the trajectory for various rocket configurations assuming the static thrust forces and the wire deployment force given in Figures 29 to 33.

tolerable with an injection speed sufficient for triggering lightning.

These results further suggest that the GR 80 rockets might be suitable for a variation of the French Tipsy system of wire deployment. In this system, the bobbin is carried aloft by the rocket. The lower end of the wire is tethered to earth by an insulating fiber. The lower portion of any triggered lightning, therefore, simulates natural lightning somewhat more closely than does lightning triggered by a grounded wire.

A static thrust measuring instrument should be used at the launch site of rockets used in lightning triggering experiments so that optimum configurations of rocket engines, nose cone masses and wire deploying bobbins can be designed and utilized. The wire-deployment forces exerted on ground based bobbins and on dielectric tethers should be routinely measured and recorded in efforts to improve our understanding of the wire breaking forces.

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