Vacuum-Tube Launchers and Boosters

L. D. Duncan* and W. L. Vechione†
U.S. Army Electronics Command,
White Sands Missile Range, N. Mex.

THE potential and feasibility of a vacuum-tube system to launch low-altitude meteorological probes was discussed by Kumar and Shieh.[1] Kumar also suggested the use of a vacuum-tube to impart initial velocities to meteorological rockets such as the ARCAS. This Note describes systems that the Atmospheric Sciences Laboratory will use to explore this technology.

The system consists of a partially evacuated tube with a breakable seal at the top and with the lower end sealed by the cup of a missile sabot. An expansion chamber near the top reduces the buildup of pressure ahead of the projectile as it moves up the tube. The principle of operation of such a system is the utilization of atmospheric pressure to impart an initial velocity to the rocket. When the sabot is released, atmospheric pressure accelerates the missile and sabot. The maximum acceleration is obtained at the instant of release and is given in g's by $PAW^{-1} - 1$, where W is the weight of the missile and sabot, A is the cross-sectional area of the tube, and P is the difference between atmospheric pressure and the residual pressure within the tube. The exit velocity thus depends upon the length and diameter of the tube, the weight of the missile and sabot, and the residual pressure inside the tube.

The following equation of motion for the projectile was derived by Kumar, Rajan, and Murray[2]:

$$\tfrac{1}{2}(m + \rho Ax)dV^2/dx + \tfrac{1}{2}A\rho V^2 + \tfrac{1}{2}A\rho f(x/D)V^2 + A\rho xg + mg(1 + s) - A(P - P_{sx}) = 0 \quad (1)$$

where m = mass of projectile, ρ = atmospheric density, A = internal cross-sectional area of tube, D = internal diameter of the tube, f = frictional factor for the tube, mgs = sliding or solid friction between the tube and the projectile, x = distance of the projectile from the breech end, V = velocity of the projectile, P = atmospheric pressure, P_{sx} = stagnation pressure in front of the projectile at position x.

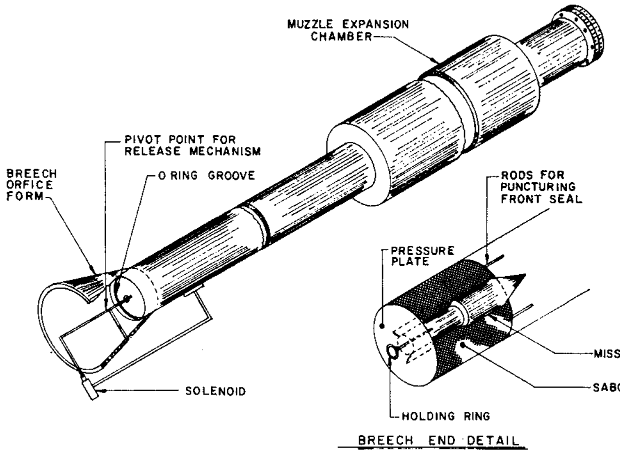

Fig. 1 Vacuum tube-general design.

Received December 3, 1970; presented as Paper 70-1393 at the AIAA Second Sounding Rocket Technology Conference, Williamsburg, Va., December 7–9, 1970; revision received February 1, 1971.

* Senior Research Mathematician, Atmospheric Sciences Laboratory.

† Electronic Engineer, Atmospheric Sciences Laboratory.

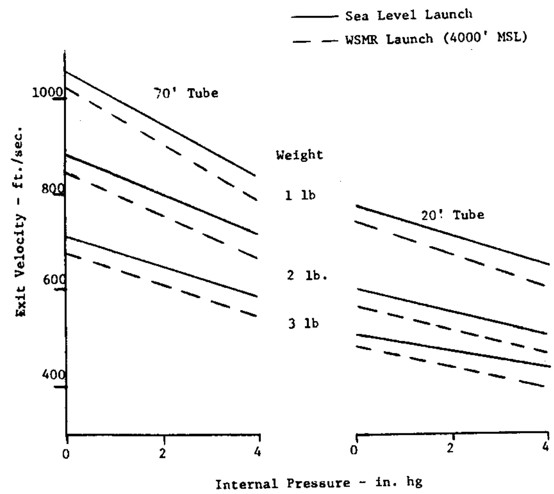

Fig. 2 Theoretical exit velocities for meteorological probe.

A numerical solution, assuming adiabatic compressible flow, and FORTRAN program of the solution were obtained by Lee,[3] who also showed good agreement between compared theoretical results with experimental results obtained at Duke University.

Meteorological Probe Launchers

The vacuum-tube launcher should provide a reliable, low-cost system for wind and temperature measurement in the lower atmosphere. Two systems, each consisting of a vacuum-tube launcher and a meteorological probe, are being developed for wind and temperature measurements in the lower atmosphere. The launcher tube for each system has been fabricated from 8-in.-i.d. aluminum tubing. The general design for both tubes is as shown in Fig. 1. One has been designed as a mobile facility with a tube length of 20 ft, while the other will be a fixed installation with a tube length of 70 ft. The probe will be a small, fin-stabilized, reusable, instrumented missile which will deploy a parachute at or near apogee. The instrument will measure and transmit temperature data to a ground station, while wind data will be obtained by a radar track of the parachute.

The launch tube for the mobile system is mounted on a frame assembly which together with the tube weighs ~600 lb. The tube may be lowered for transport or during periods

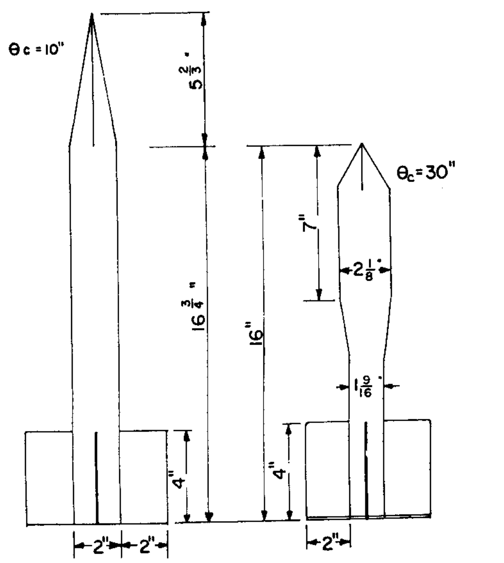

Fig. 3 Prototype meteorological probes.

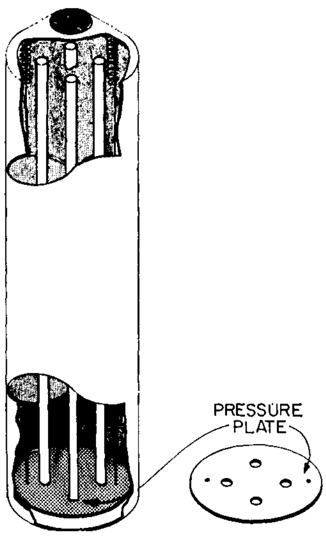

Fig. 4 Preliminary design.

when measurements are not required and raised to a desired elevation angle for firing. The elevation angle control allows for placement of the probe near a desired spatial point.

The tube for the fixed installation consists of three sections: a 24-ft section containing the breech and release mechanism; a 22-ft section containing the expansion chamber and muzzle; and a 24-ft center section. This system can be installed as a 46-ft tube by deleting the center section. A rigid structure, such as the side of a building or a telephone pole, is required for support of the tube. The latter will be used for test firings at White Sands Missile Range (WSMR), N. Mex.

Once the tube has been specified, the exit velocity [from Eq. (1)] is a function of the weight of the projectile, the residual pressure inside the tube, and the altitude of the launcher. Theoretical values of exit velocity for projectile weights of 1, 2, and 3 lb, tube lengths of 20 and 70 ft, and various values of internal pressure are shown in Fig. 2 for sea level and WSMR (Z_0, initial altitude = 4000 ft) launches.

The primary forces acting on the projectile after it exits the launcher will be those of gravity and aerodynamic drag:

$$m\, dV/dt = -(\tfrac{1}{2}C_d \rho V^2 A + mg) \tag{2}$$

The maximum height obtained by the projectile may be obtained by numerical integration of Eq. (2), using the exit velocity as an initial condition.

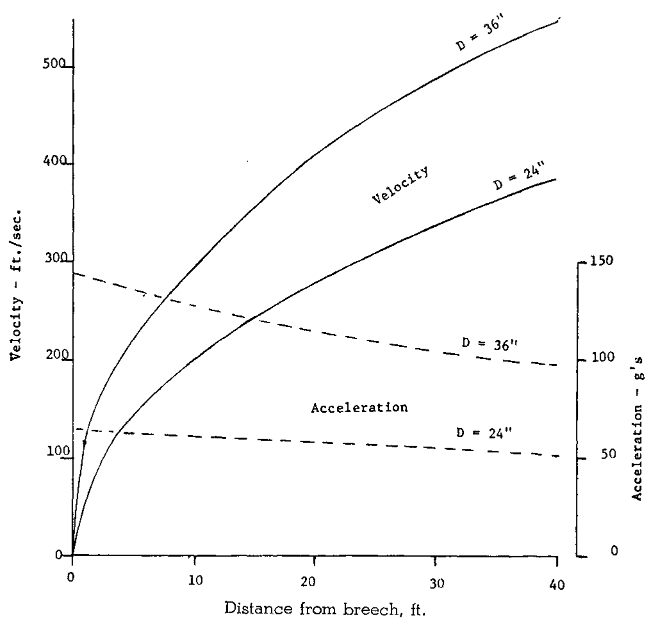

Fig. 5 ARCAS theoretical velocity and acceleration time history.

Table 1 Peak altitude for various tube lengths (L) and projectile weights (W_O)

Z_o, Kft	W_o, lb	$Z_{max} - Z_o$ ft, L = 20 ft	46 ft	70 ft
0	1	3655	4759	4883
	2	3511	5194	5889
	3	3035	4946	5739
4	1	3707	4802	5216
	2	3361	5132	5806
	3	2791	4768	5677

Designs for two prototype missiles are shown in Fig. 3. The estimated drag coefficient for each of these projectiles is approximately 0.2. Computed values of peak altitude for tube lengths of 20, 46, and 70 ft and projectile weights of 1, 2, and 3 lb are shown in Table 1. In each case, the exit velocity for an internal pressure of 1 in. Hg was used, since experience has shown that such a residual pressure is readily obtainable. From the data shown in Table 1, it appears that an optimal projectile weight is near two lbs.

Vacuum Booster for the ARCAS

The ARCAS rocket is one of the principal vehicles used by the Meteorological Rocket Network for measurements in the upper atmosphere. It is fired from a closed-breech launcher approximately 15 ft long. A gas generator is used as a "booster assist." With this system the rocket exits from the launcher at 0.16 sec with a velocity of 221 fps. (These are average figures; there appears to be considerable round-to-round variation.)

The ARCAS is fairly wind sensitive, having a unit wind effect of 2.2 miles/mph. This necessitates meteorological support for prelaunch impact predictions. Excessive wind speed and/or wind variability sometimes causes cancellation of planned launches.

A vacuum-tube launcher would provide a "booster assist" for the ARCAS, yielding exit velocities well in excess of that provided by the present system. A schematic for a proposed tube design is presented in Fig. 4. The muzzle end is partially capped. This cap serves two purposes; it supports the vertical rods and simplifies the problem of sealing the end of the tube since a much smaller area must be sealed. The opening in the cap is, of course, large enough for passage of the missile. This cap, together with the sytem of vertical rods, allows for a simple sabot or carrier system.

The carrier system (sabot) would consist of the styrofoam packing used with the current ARCAS launcher and the pressure plate shown in Fig. 4. The styrofoam would be placed between the rocket and the vertical rods to maintain proper alignment of the rocket prior to and during the launch. Atmospheric pressure would act upon the pressure plate which would push the rocket down the tube. The pressure plate would also serve as the breech-end vacuum seal. An "O" ring seal would be used to seal the pressure plate and the tube itself. Smaller "O" rings would be used to seal the openings for the vertical rods. The styrofoam will exit the tube with the rocket. The pressure plate will be caught by the springs near the breech-end and then will fall back down the tube. One of several techniques employed by conventional launchers could be used with the vacuum-tube for supporting the tube and providing azimuth and elevation angle control.

The nominal launch weight of the rocket including payload is approximately 77 lb. With the carrier system described above, it should be possible to achieve a gross missile and sabot weight of near 80 lb. Figure 5 depicts a time history of velocity and acceleration for two tube diameters. It is easy to see that an exit velocity in the range 300–500 fps is readily achievable.

Other calculations show that the vacuum-tube launcher will provide an increase of 10% to 20% in altitude, with a simultaneous decrease of 35–60% in wind effect is obtained.

References

[1] Kumar, S. and Shieh, S. C., "Vacuum-Air Tube System for Low Altitude Meteorological Probes," Project Mountainwell Interim Report 7, July 1968, U.S. Army Research Office—Durham, Durham, N.C.

[2] Kumar, S., Rajan, J. R. N., and Murray, J. J., "Vacuum-Air Missile Boost System," *Journal of Spacecraft and Rockets*, Vol. 1, No. 5, Sept.-Oct. 1964, pp. 464–470.

[3] Lee, E. E., "Further Studies of the Vacuum-Air Missile Boost System," M. S. thesis, 1964, Duke Univ., Durham, N.C.

Solar Array Degradation due to Meteoroid Impacts during Extended Planetary Missions

A. J. Richardson* and J. W. Warren*

North American Rockwell Corporation, Space Division, Downey, Calif.

Nomenclature

A_{L1},A_{L2}	= total area lost due to particle impacts by front or rear surface, m²
A_{L1}',A_{L2}'	= area lost per impact by front or rear surface, m²
A_{sp}	= solar cell area of the solar array, m²
A_{spe}	= effective solar cell area of the solar array, m²
C_1,C_2	= meteoroid flux constants
D_{fz}	= fracture zone diameter, cm
d_p	= meteoroid particle diameter, cm
$f(R)$	= meteoroid flux spatial distribution function
H_s	= substrate hardness, Brinell
K,K_s	= penetration equation constants (0.64 and 1.38, respectively)
m	= meteoroid particle mass, g
n	= number of particle impacts
N	= meteoroid flux, impacts/m²-sec
P	= total penetration depth, cm
P_r	= probability of a particle impact
P_{sc}	= penetration into solar cell from rear, cm
P_s	= penetration into substrate, cm
t_s	= substrate thickness, cm
t_3	= thickness of a glass substrate equivalent to the actual substrate, cm
T_a	= mission duration, sec
T_R	= effective exposure time, sec
V	= particle impact velocity, km/sec
α	= ratio of fracture zone diameter to penetration depth in glass (20.0)
ρ	= meteoroid particle density, g/cm³
ρ_s	= substrate density, g/cm³

Introduction

Very little degradation has occurred in near-Earth solar array applications, but an asteroid belt or other deep space mission may pose a major problem. Because of current interest in the use of solar electric spacecraft with large solar arrays for future interplanetary scientific investigations it is necessary to define the meteoroid hazard for them. The problem is not the puncture damage caused by chance encounter with a single large meteoroid, but the errosive type damage caused by continually impacting micrometeoroids. Evaluation of this problem requires adoption of a mechanism to describe the solar cell power reduction associated with individual particle impacts, followed by treatment of factors that determine the number of impacts.

Presented as Paper 70-1139 at the AIAA 8th Electric Propulsion Conference, Stanford, Calif., August 31–September 2, 1970; submitted October 6, 1970; revision received January 27, 1971. The work described in this paper was performed for the California Institute of Technology, Jet Propulsion Laboratory under Contract NAS7-100.

* Staff Engineer, Structural Systems and Mechanisms Department.

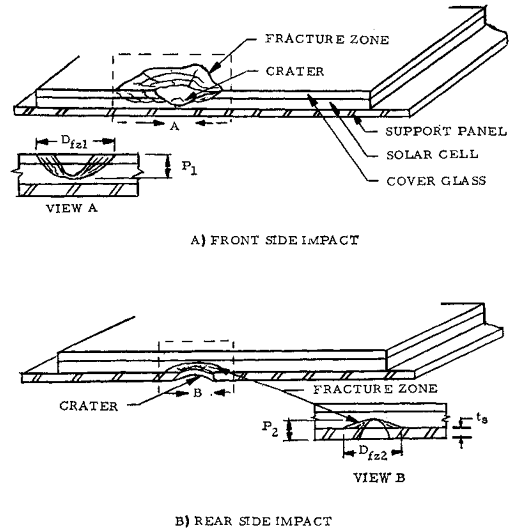

Fig. 1 Solar cell damage modes as a result of micrometeoroized impacts.

Power Loss due to Particle Impact

The results of experimenters, particularly Bowman,[1] provide data on the solar cell power loss resulting from cumulative hypervelocity impacts. However, a method was needed which would account for the difference between laboratory particles and meteoroid particles, i.e., velocity, size, and density. Hypervelocity impacts on glass produce a crater, surrounded by a large fracture zone.[2] These fracture zones will reduce solar cell output by restricting light energy reaching the solar cell rear surface. Figure 1 represents the fracture zone formed by meteoroid impacts on both the front and rear side of the solar panel, and it was assumed that particles impacting the rear side must perforate the substrate before damaging the solar cell. It was also necessary to establish the amount of light reflected by each fracture zone. Evaluating the damaged test articles from the standpoint of optical mechanics, it was concluded that even damage to solar cells by extremely small micrometeoroid particles would produce back-scattering of light. Because of the complex nature of the fissures formed in the damage area, available theoretical methods were judged to be inadequate to establish the exact

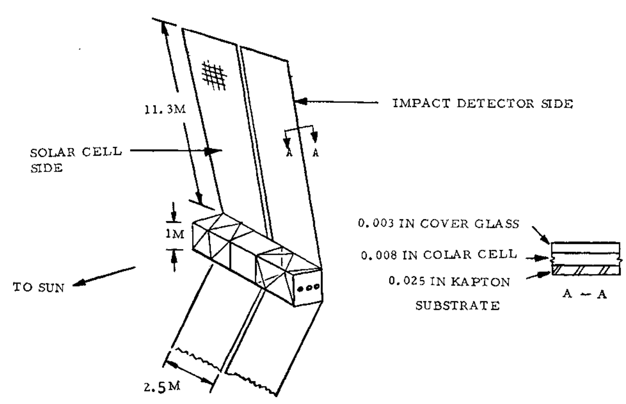

Fig. 2 Spacecraft configuration.