Atmospheric Entry Test Facilities: Basic Limitations and Proposal for a New Technique

JULIUS LUKASIEWICZ*
Virginia Polytechnic Institute, Blacksburg, Va.

Theoretical and practical limitations of techniques which are being currently developed for atmospheric entry testing are examined in terms of velocity-altitude duplication, and it is concluded that they cannot provide low-altitude, orbital- to escape-velocity capability with sufficiently large models. It is suggested that this capability might be achieved by application of rocket propulsion to aeroballistic range type testing. A multi-stage rocket booster traveling inside a straight tube or tubes evacuated to a low pressure would launch the model into a variable-pressure tank instrumented for aerophysical, erosion, impact, stability, and drag studies. It is estimated that a 10-lb model/sabot package could be launched at 25 kft/sec; a 1-lb package, at 35 kft/sec. The proposed facility is not subject, in the range of interest, to any basic physical limitations, but only to economic constraints. Application of the proposed test technique to lower hypersonic speeds is discussed with particular reference to duplication of high Reynolds number conditions and to hypersonic ramjet testing.

Introduction

FOR many years now, considerable efforts have been underway to develop aerodynamic ground test facilities in which atmospheric entry phenomena could be adequately investigated. The techniques under development comprise wind tunnels of various types, aeroballistic ranges, counterflow facilities (which combine wind tunnel and range techniques), and rocket test sleds. However, each of these techniques has limitations,[1–5] as discussed below, and all of them may be reaching performance plateaus short of attaining the desirable goals of 25–35 kft/sec at densities corresponding to altitudes below 200 kft. Free, atmospheric flight, with full-scale or sub-scale models is at present the only other source of data. The usefulness of this technique, however, is severely limited because of excessive costs and difficulties of acquiring reliable measurements.

This paper suggests a new type of large, ground-based atmospheric entry test facility. It is, essentially, a small-scale (compared with full-scale flight hardware) free-flight facility of the aeroballistic range type in which the model is accelerated to the desired speed by a multi-stage rocket booster (rather than with a gun). The construction of such a facility would constitute a major undertaking, although it would not be necessarily more expensive than such past national aerodynamic facility projects as the post-war, U.S. Unitary Wind-Tunnel Program.

Limitations of Existing Atmospheric Entry Test Facilities

Wind Tunnels

Limitations of steady, isentropic flow expansion type wind tunnels are summed up in Fig. 1. This is a Mollier chart for air,[6] on which atmospheric conditions at altitudes from 150 to 350 kft (entropy s/R range from 30 to 39) are indicated. 10,000 and 5000 atm isobars are shown as corresponding to limiting stagnation pressures which may be in practice contained in the reservoir of the wind tunnel. A velocity† scale, included with the enthalpy H/R (°K) ordinate, indicates that the speeds attainable through isentropic expansion from 5,000 atm to ambient atmospheric conditions are limited to values between 16 kft/sec at 150 kft and 20 kft/sec at 250 kft. Based on pressure or structural limitations alone, these capabilities fall short of the atmospheric entry speeds of major interest, which span the range from about 23 kft/sec (ballistic missiles) to 36 kft/sec (lunar mission entry).

An additional limitation of the steady, isentropic expansion technique, caused by the relaxation processes in the nozzle, is also indicated in Fig. 1. Because of the finite relaxation rates, equilibrium air composition is not maintained in the course of expansion, and composition of the test section flow differs from equilibrium air composition.[7] It has been shown that, as the expansion reaches the "sudden freezing zone," Fig. 1, the flow composition becomes virtually "frozen," the actual composition being a function of the entropy only (to a good approximation). Since altitude conditions are also uniquely defined by entropy, there is a direct relationship between the flow composition and altitude attainable by isentropic expansion.[1] In the thermodynamic range of interest, the atomic (dissociated) oxygen is the most important species. In Fig. 1, the per cent fraction α_{fO} of atomic (frozen) to total oxygen is indicated for the case of a large facility having a scaling factor l = 10 cm, with $l = r^*/\tan\theta$, r^* = nozzle throat radius, and θ = conical nozzle half-angle. For l = 10 cm and $M \approx 20$, the test section core diameter would be on the order of 10 ft. It is evident that at velocities above 20 kft/sec, $\alpha_{fO} > 10\%$, and the test section flow composition differs substantially from that of the atmosphere; the correspondence between the test section conditions and the free-flight conditions becomes ambiguous. In Fig. 1, the bottom scale gives the altitude based upon matching of the free-stream density and frozen velocity of sound in the test section with the atmospheric values[8]; this results in a slightly lower altitude at a given entropy, but

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* Professor of Aerospace Engineering and Associate Dean, College of Engineering; also Consultant, ARO Inc. Fellow AIAA.

† Assumed equivalent to total enthalpy (i.e., neglecting static enthalpy after expansion to freestream conditions).

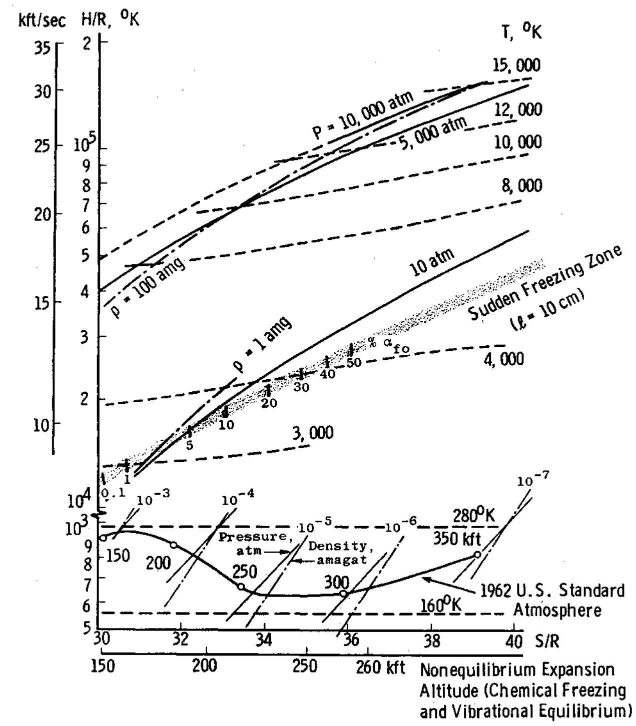

Fig. 1 Mollier diagram for air showing reservoir conditions in relation to flow velocity, duplication of atmospheric conditions, and amount of frozen atomic oxygen.

does not significantly change the duplication capability of steady, isentropic expansion.

A superior performance is possible under more restrictive conditions of simulation, or, theoretically, by other gas-dynamic means. For example, if Mach number duplication were dropped, as may be appropriate for blunt bodies, and only stagnation conditions duplicated, simple shock tubes[9,10] offer duplication at velocities up to 60 kft/sec, and at altitudes below 200 kft (e.g., 40 kft/sec at 100 kft). Theoretically, unsteady compression and/or expansion offer performance much superior to that obtainable with the steady, isentropic process[11–13]; however, because of practical difficulties, so far it has not been possible to utilize for aerodynamic testing the gas processed by an unsteady wave region.[14]

The performance attainable with steady, isentropic expansion can be augmented by electromagnetic acceleration. Optimization studies of a crossed-field (Faraday) type accelerator[8] gave the results shown in Fig. 2 in the velocity-altitude plane, where B is the applied magnetic field and L is the accelerator length. The accelerator is located in the initial, supersonic portion of a hypersonic nozzle, supplied from, e. g, a high-performance shock tunnel. The optimization involves maximization of test section velocity for a given final entropy or altitude.

Since for efficient operation of the accelerator (i.e., for a small entropy rise), a sufficiently large electrical conductivity is required, seeding of air with an easily ionized material is necessary. A seeding mass fraction of 0.0025 has been assumed; although a larger value would slightly improve accelerator performance, the resulting contamination would make the interpretation of some results more difficult.

The higher values of B^2L (500 and 2000 weber²/m³) may be unattainable in practice: they would correspond, for example, to an accelerator length of 5m and magnetic fields of 10 and 20 weber²/m³, respectively, with the electric fields of 100 kV/m and 200 kV/m. For B^2L of 100 weber²/m³, duplication for speeds > 22 kft/sec is possible only above 200 kft altitude.

The nozzle expansion nonequilibrium phenomena would not be alleviated by the accelerator; as before, freezing of chemical composition would occur in the nozzle expansion downstream of the accelerator, the frozen atomic oxygen fraction being again uniquely related to the altitude. The values of α_{fo} are indicated on the altitude scale in Fig. 2; the limit duplication lines are drawn for matching of density and velocity of sound, for chemically frozen and vibrationally equilibrated expansion.

A practical limitation of wind-tunnel type facilities relates to test-section energy flux and consequent power requirements. Duplication of ICBM and lunar flight (Apollo) atmospheric entry requires (Fig. 3) energy fluxes from 10,000 to 100 MW/m² of test flow cross section, the larger value exceeding 1% of the world's electrical generating capacity. Since large losses accompany acceleration of the fluid to the desired velocity and recovery of the kinetic energy is not possible, the actual power requirements would be much larger. Thus, only run times < 1msec in relatively small test sections could be obtained with the required, extremely high power levels being realized with some form of energy storage, e.g., capacitors or high explosives. Other factors, such as viscous effects and radiative losses also limit flow duration.

Aeroballistic Ranges

Testing in aeroballistic ranges constitutes essentially the miniaturization of free, atmospheric flight. As regards atmospheric entry testing, the main advantages of this technique are 1) decoupling of the production of relative velocity from provision of ambient conditions, which can be therefore easily controlled (usually by pressure level in the range tank), and 2) attainment of high velocities with small models launched from two-stage, light-gas guns. Compared to a wind tunnel, the main disadvantage is the difficulty of making many types of model measurements; on the other hand, the technique is particularly well suited to observation of some phenomena, such as wakes. At present, the limitations of the aeroballistic range technique rest with the gun.[2] The maximum launch velocity V_o available with current two-stage, light-gas guns is shown in Fig. 4 (see also Ref. 2), in terms of the total launched weight. Also included are two points for a 16-in. high-performance single-stage powder gun.[15] The calibers of the "record guns" are indicated in the graph, and the right-hand scale corresponds to a faired correlation of gun caliber-maximum velocity. For $V_o > 25$ kft/sec, the launched weight W (of which model constitutes only a fraction) is smaller than 100 g. Moreover, it decreases tenfold for every 4400 ft/sec velocity increase; for $V_o = 35$ kft/sec, $W \approx 0.2$ g. Ideally, scaling of a gun to any caliber

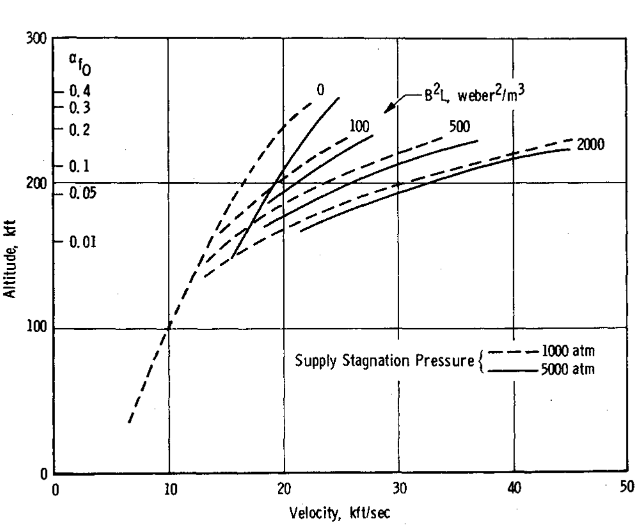

Fig. 2 Performance of MHD-augmented wind tunnels.

(and to any launched weight) is straightforward. In practice, the drastic decrease in launched weight with increasing velocity reflects the difficulties of containing very high pressures in large gun components. On the theoretical side, even for very small models, light-gas guns of conventional design do not offer much potential above the 35 kft/sec velocity level.[2]

One other limitation of the gun launching is the high base pressure (or acceleration) load to which it subjects models. With current guns, base pressures in excess of 50 kpsi are experienced for 20 kft/sec. The resulting stresses allow only simple model shapes to be launched, and, so far, prohibit inclusion of on-board telemetry for transmission of measurements from models in flight. At lower velocities, telemetry with gun-launched models has been successfully achieved.[16] Further progress may be expected from application of modern microminiaturization-integrated circuit techniques; however, difficulties might still be present due to acceleration loading of sensors. Scaling up of the launcher caliber by a large factor would relieve this problem (for a given launch cycle, model weight varies as the cube of the gun caliber while the base pressure remains constant, the time scale being proportional to the caliber) but, because of structural difficulties, appears impractical.[2]

Counterflow Facilities

A combination of the two foregoing techniques, in which models are gun-launched counter-current to tunnel test section flow,[17] can produce higher relative velocities. However, not only are the limitations of the two constituent techniques present, but also the time (or distance) of test is curtailed (as compared with aeroballistic ranges) because of inability of maintaining acceptable-quality, high-velocity flow over long distances and long times.

Rocket-Propelled Sleds

Sleds propelled with rockets on dual or monorail tracks have been used for a wide variety of developmental testing. This technique permits attainment of high Reynolds numbers at moderate hypersonic Mach numbers, with captive models. Good aerodynamic data have been obtained[5] on a monorail track up to V_o = 7430 fps (M = 6.53), resulting in a Reynolds number of 42 × 10^6/ft. The present velocity limitations of the sled technique are because of the severe pressure and thermal environment to which the sled package is exposed throughout its run, and to the difficulties experienced with the sled shoe performance.[5] With lift loads

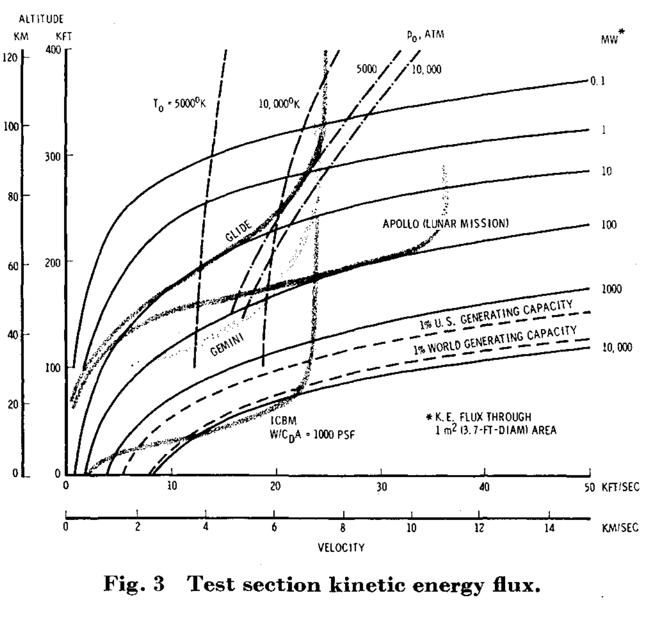

Fig. 3 Test section kinetic energy flux.

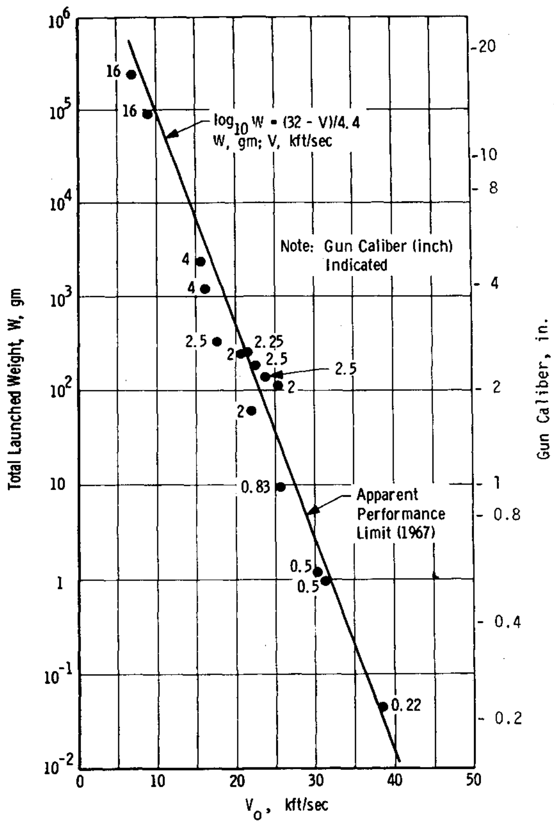

Fig. 4 Maximum launch velocity versus total launched weight and gun caliber.

present, extreme rates of shoe surface erosion are experienced, and yet elimination of lift loads through the entire velocity range is difficult to achieve. While development of the rocket sled technique is proceeding, an upper speed limit of ≈ 10 kft/sec is envisaged.

Rocket Launcher Facility

General Description

The proposed facility is essentially an aeroballistic range in which multi-stage rocket propulsion is used to accelerate the model to the desired velocity. The envisaged rocket booster travels inside a straight, cylindrical tube (or series of tubes of decreasing number or diameter) evacuated to a low pressure. The tube provides guidance, and its evacuation eliminates aerodynamic drag. These two essential factors distinguish the proposed system from free-flight testing in the atmosphere and from rocket sled testing. The absence of atmospheric resistance reduces the distances required for acceleration and minimizes aerodynamic heating, and the "built-in guidance" simplifies the booster stages. On attainment of the desired velocity, the model proceeds into the test range, and the booster stages are decelerated and, most likely, destroyed, each on completion of its propulsive run. Recovery of booster stages could be effected in downstream tube sections, separated by diaphragms and pressurized to increasingly high levels. Rather than arrange for recovery, for operational simplicity it would be preferable to deflect booster stages, allow them to exit into atmosphere through expendable diaphragms, freely decelerate and impact. This mode of operation would be possible with the launcher configuration described in the next section and Fig. 7. The test range consists of a suitably sized vacuum tank instrumented for aerophysical, stability, drag, erosion, impact, etc. studies and equipped to provide an atmosphere of desired pressure and composition. Within the test tank,

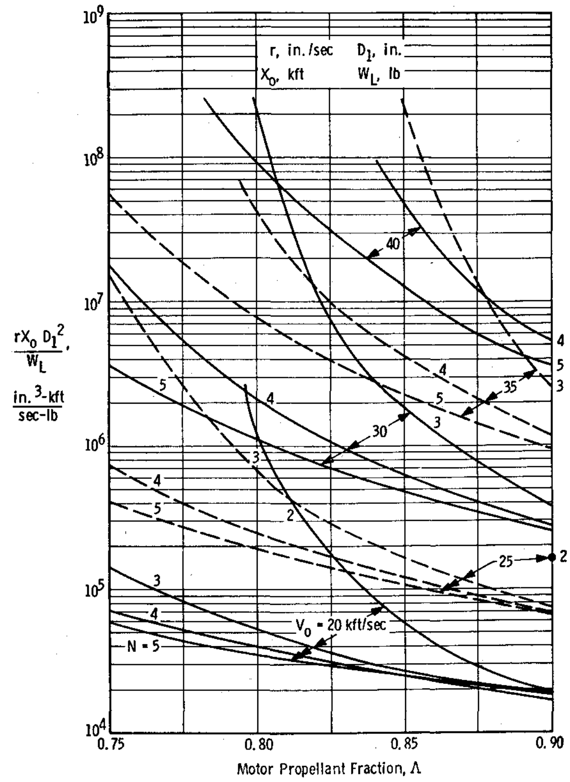

Fig. 5 Performance of multistage rocket propulsion systems.

the model is allowed to fly freely, or its mechanical guidance can be continued with small aerodynamic interference by, e.g., three slender rails, supported radially along the length of the test tank. The latter, "captive" mode of operation may be particularly suitable for nose heating, erosion, air-breathing propulsion and impact testing, but would be subject to some of the difficulties and limitations experienced at high speeds with the existing rocket sleds.

We shall focus our attention on the $25 \leq V_o \leq 35$ kft/sec, the approximate range of entry speeds from Earth ballistic, orbital, and lunar missions.

Performance of Multistage Rocket Propulsion Systems‡

Using standard equations of rocket propulsion, and assuming constant values of stage mass ratio R, motor propellant fraction Λ, stage payload ratio α, and specific impulse I for each of N propulsive stages, the performance of a multistage system can be obtained in terms of parameters shown in Fig. 5, where r = equivalent, constant propellant burning velocity ($r = r_b A_b / A$, where r_b = linear burning rate, A_b = surface area, A = motor cross-sectional area), X_o = total propulsive distance (all stages), D_1 = diam of 1st stage, W_L = weight of payload stage, V_o = final velocity. Values of 200 sec and 0.06 lb/in.^{3} have been taken for I and the specific propellant weight γ, respectively. From curves of Fig. 5 the powerful effect of the motor propellant fraction Λ, particularly with smaller numbers of stages, is evident.

To interpret these results, meaningful assumptions must be made concerning several rocket parameters, including the stage burn time t and the maximum acceleration a_{max}. As regards limitations on the thrust loading f ($= \gamma I r$) and the equivalent burning velocity r, these can be obtained from consideration of thermodynamic properties of the propellant gas.

For a given propellant, thrust coefficient C_F is mainly a function of chamber pressure p_c and nozzle expansion ratio ϵ, and may take values between 1 and 2; a value of 1.5 may be taken as representative. Typically, for $C_F = 1.5$, $p_c = 2000$ psi and assuming a minimum nozzle expansion ratio $\epsilon = 2$, we find $f_{max} = 1500$ psi. With $I = 200$ sec and $\gamma = 0.06$ lb/in.^{3}, this corresponds to $r_{max} = 125$ in./sec.

As regards the base pressure to which the payload is subjected during acceleration, it would not exceed the thrust loading of 1500 psi, i.e., it would be an order of magnitude smaller than encountered in high velocity guns.

Rocket motors with performances approaching the aforementioned limits have been developed for propulsion of sleds. Characteristics of one motor, developed in 1966 by the Atlantic Research Corp. under contract to Sandia Corp.,[19] are $\Lambda = 0.715$, $I_{ave} = 237$ sec, $\epsilon = 3$, $f_{ave} = 760$ psi and $f_{max} = 1000$ psi (or $r_{ave} = 53$ in./sec and $r_{max} = 70$ in./sec) based on outside nozzle diameter of 5.5 in.; maximum motor case diameter = 5.2 in., $t = 1.08$ sec, $p_{c_{ave}} = 1920$ psi, $C_{F_{ave}} = 1.29$, and $a_{max} = 315\ g$ (sustained in test). Thus, high I and f have been achieved. As regards Λ it has been suggested[19] that it could be increased by the use of higher strength/density ratio case materials. In fact, a motor of similar performance, with a maraging steel case and having $\Lambda = 0.8$ has been available from the Thiokol Chemical Corporation. Other multistage designs of high-performance rocket motors (solid and liquid) are mentioned in Ref. 15; Λ's from 0.8 to 0.85 were estimated for these designs.

Based on these considerations, calculations were performed for a number of multistage systems with $I = 240$ sec and $f = 1000$ psi. The over-all length X_o was taken to correspond to a mean acceleration of about 2000 g, giving $X_o = 5$ kft for $V_o = 25$ kft/sec, and $X_o = 10$ kft for $V_o = 35$ kft/sec. Each case was calculated for $\Lambda = 0.7$ and $\Lambda = 0.8$. The results are summarized in Table 1 and Fig. 6. It is evident that the stipulated performance is attainable under the assumed realistic conditions with reasonable numbers of stages and initial weights. The powerful influence of Λ on these parameters is apparent.

Additional performance data are obtained by considering not only the last rocket stage, but each of the preceding stages in a system. This gives plots shown in Fig. 6, covering a range of weights and velocities. Comparison with the limit performance of guns shows large gains in weight, by a factor of over 1000 at $V_o = 35$ kft/sec. Also, very worthwhile launch capabilities are indicated at subescape velocities.

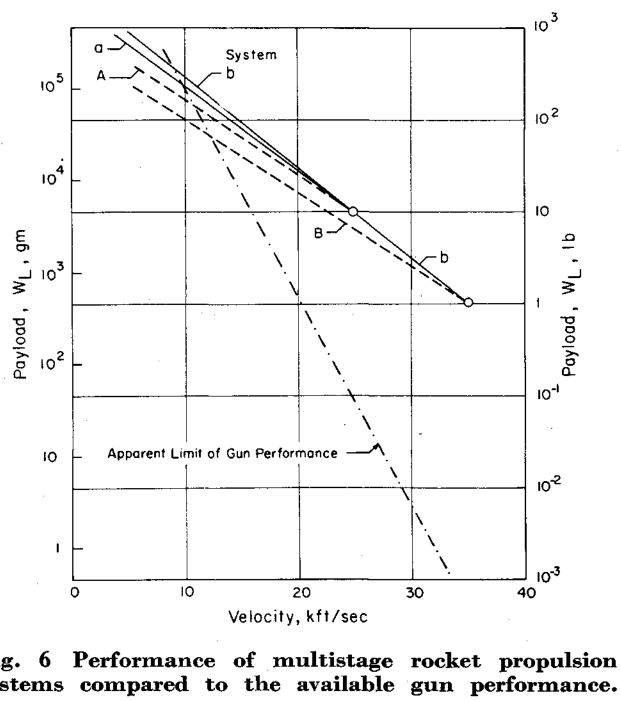

Fig. 6 Performance of multistage rocket propulsion systems compared to the available gun performance.

‡ See Ref. 18 for details of derivations and computations.

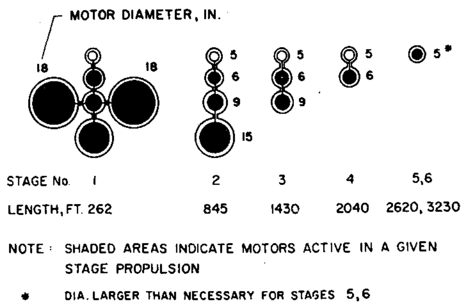

Fig. 7 Conceptual configuration of system B (see Table 2).

We shall focus our attention on the 35-kft/sec, $\Lambda = 0.8$, 1-lb-payload system B; more detailed data are given in Table 2 and Fig. 7. As regards mechanical design, one could envisage a more or less conventional multistage booster and payload being guided during propulsion by suitable rails inside an oversize vacuum tank. An alternative geometry is shown schematically in Fig. 7; the booster stages and the payload are guided inside tubes and are interconnected by radial members enclosed in longitudinal channels which run the length of each tube (except for stages 5 and 6, which require a single tube only). Guidance similar to that provided by a gun barrel is achieved, and the total volume of the vacuum tank is minimized. In Fig. 7 the cross-sectional configuration of the launcher as required by each stage is shown, and the motors used in each stage's propulsion are indicated by the shading. Thus, for example the second stage launcher configuration includes 5-, 6-, 9-, and 15-in.-diam motors. Another 15-in.-diam motor is also used in the 1st stage propulsion and the 15-in. tube extends over a minimum length of 1107 ft. The last two stages use each one 5-in.-diam motor, and the 5-in. tube extends the whole length of the launcher. The volume of all the tubes amounts to 5300 ft^3.

Gun-Augmented Rocket Propulsion

The obvious complication in the proposed rocket propulsion system is the mechanics of staging. It is therefore of interest to estimate performance attainable with a gun used as the first stage of propulsion, and to determine the extent of rocket propulsion system required in conjunction with the gun. The tradeoff could involve elimination of staging or reduction in the number of stages, at the penalty of high-acceleration loading during the gun launch.

Such systems of propulsion have been proposed before mainly for the purpose of augmentation of gun performance. Early, unsuccessful and abandoned efforts[20–22] were concerned with the so-called travelling charge gun, an arrangement in which some propellant was carried on the base of the projectile. Only very small and erratic (hence useless for artillery applications) increases in muzzle velocity were observed using this technique. No throat or nozzle was provided to accelerate the propellant gases and to maintain combustion pressure, which was progressively decreasing because of rarefaction accompanying the projectile travel. Clearly, only a small specific impulse could have been realized with this primitive technique.

More recently, the use of gun-launched rockets was being considered as a means of increasing the range of guns[23,24] and for atmospheric sounding, flight testing, and satellite launching[15] applications. Except for some aspects of the design of rocket motors, these systems, inasmuch as they involve atmospheric flight, are not comparable to the system here considered.

In order to determine optimum performance of gun-rocket systems, the maximum gun performance as indicated by the 1967 limit in Fig. 4 was assumed, and, for a given N, I, and Λ, maximum W_L was calculated. The results are summarized in Fig. 8; in all cases $\Lambda = 0.85$ has been assumed, as well as a gun muzzle velocity not smaller than 5 kft/sec. It is apparent that, with a single-stage rocket, although a very significant improvement over the unassisted gun can be obtained for the high-I case, at 35 kft/sec the available payload is small, ≈ 50 g. Two stages are required, with $I = 250$ sec, to increase W_L to 500 g. The 25 kft/sec case is more interesting, a single stage with $I = 250$ sec gives $W_L = 2000$ g, more than tenfold the weight which can now be launched with an unassisted gun. The optimum gun-launch velocity in this case is 11.9 kft/sec, and the corresponding gun-launched weight 37 kg. A two-stage gun of about 10-in. caliber (see Fig. 4) would be required; the length of the rocket

Fig. 8 Performance of rocket-augmented guns.

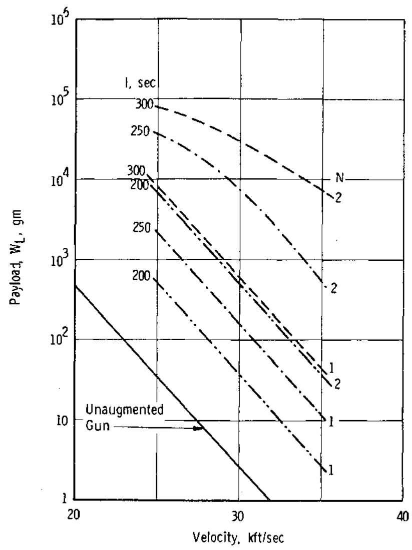

Table 1 Design characteristics of multistage rocket propulsion systems (I = 240 sec, f = 1000 psi, mean acceleration ≈ 2000 g; W_1 = initial weight of all stages including payload, A_1 = total cross-sectional area of first stage motors)

System	*a*	*A*	*b*	*B*
V_o, kft/sec	25	25	35	35
W_L, lb	10	10	1	1
D_L, in.[a]	10	10	5	5
X_o, kft	5	5	10	10
Λ	0.7	0.8	0.7	0.8
N	6	4	7	6
R	1.71	2.25	1.91	2.12
t, sec	0.07	0.1	0.08	0.1
a_{max}, g	2420	2840	2660	2560
W_1, lb	2080	1120	2780	650
A_1, in.^{2}	2930	1410	3860	785

[a] Payload caliber D_L is based on the scaling from the present practice with light gas guns.

Table 2 Six-stage rocket system B for W_L = 1 lb at 35 kft/sec with Λ = 0.8, f = 1000 psi, I = 240 sec, t = 0.1 sec, $X_o \approx$ 10 kft. The ith stage of a multistage rocket configuration is characterized by V_i = final velocity attained on burn-out of the ith stage, X_i = distance taken by the ith stage propulsion, A_i = total cross-sectional area of the ith stage motors, W_i = initial weight of all stages higher than and including the ith stage

i	1	2	3	4	5	6	Total
V_i, kft/sec	5.8	11.7	17.5	23.3	29.2	35	...
X_i, ft	262	845	1430	2040	2620	3230	10,427
A_i, in.^{2}	785	268	92	31	10.5	3.6	...
W_i, lb	650	222	76	25.6	8.7	2.95	...

Table 3 Single-stage rocket performance[a]

X, kft	5		5		10		10	
D, in.	24		48		24		48	
r, in./sec	20	50	20	50	20	50	20	50
W_L, lb	65	162	260	650	130	325	520	1,300
W, lb	910	2275	3640	9100	1820	4550	7280	18,200

[a] In all cases: $R = 4.73$, $\Lambda = 0.85$, $\alpha = 14$, $\gamma = 0.06$ lb/in.^{3}; $I = 200$ sec, $V_o = 10$ kft/sec or $I = 300$ sec, $V_o = 15$ kft/sec.

run would be $\approx$ 4700 ft (assuming $f = 750$ psi). However, even with a barrel 150 calibers long (125 ft), the in-gun package would have to be subjected to an equivalent, constant base pressure of $\approx$ 17.5 kpsi, or to an actual peak pressure§ of some 35 kpsi. Thus, the rocket motor and payload would be subjected to relatively high stresses.

Performance at Lower Hypersonic Speeds

The $10 \leq M \leq 15$ regime may be of interest in terms of duplication of flight Reynolds numbers and heating rates, or for air-breathing propulsion. In the lower portions of the ballistic entry trajectory, Fig. 3, or for trajectories of other payloads, Reynolds numbers on the order of 30×10^6/ft are developed (10 kft/sec at 30 kft altitude, or 15 kft/sec at 40 kft altitude). Comparable magnitude of the Reynolds number may be available only in impulse-type wind tunnels, at much smaller actual flow velocities, i.e., with lower heating rates.

As regards air-breathing propulsion (hypersonic ramjets), because of a high degree of aerodynamic coupling of engine components (intake, combustor, exhaust nozzle), it has been most difficult to achieve realistic test conditions in conventional facilities. These could be provided by the facility here proposed; moreover, as already mentioned, the mechanical guidance present in the rocket acceleration phase could be continued, with small aerodynamic interference, in the hypersonic ramjet test phase (e.g., by three slender rails located along the length of the test tank and swept-back, radial, model-supporting struts).

In Table 3 some typical single stage data are given, for two equivalent conditions; $V_o = 10$ kft/sec with $I = 200$ sec, and $V_o = 15$ kft/sec with $I = 300$ sec. Values of $\Lambda = 0.85$ and $\gamma = 0.06$ lb/in.^{3} have been taken. With a 5-kft long, 2-ft-diam launcher, a payload of 65 lb is possible (taking a conservative $r = 20$ in./sec); this increases to 260 lb for a 4 ft-diam launcher. Thus, in the lower hypersonic range, significant performance is possible with a single stage. Moreover, aerodynamic scale can be further increased by pressurization of the test tank.

Again, it is pertinent to compare the single-stage rocket and gun performances. At 10 kft/sec the maximum gun-launched weight for a 16-in. gun is about 220 lb (see Fig. 4), i.e., in the order indicated for single-stage rocket propulsion (260 lb for a 48-in.-diam, 5 kft-long launcher, $I = 200$ sec). The major difference lies, as before, in loads experienced during launching. For the above 260-lb payload case, the rocket thrust pressure is only 240 psi. For a 16-in., 75-caliber-long gun (100-ft barrel), a constant base pressure of about 17 kpsi is required to accelerate a 220 lb payload to 10 kft/sec, but because of imperfections of the actual launch cycle, a peak pressure at least twice as large would be estimated. Thus, although the gun offers the velocity performance at the 10 kft/sec level, it subjects the payloads to base pressures high enough to pose structural and instrumentation problems.

§ Because of imperfections of the actual launch cycle, a peak pressure about double the ideal, minimum value would be expected.[2]

Conclusions and Recommendations

Results presented here indicate that the proposed facility would be capable of testing much larger models than is now possible in the velocity range of major interest; in the examples considered, model/sabot weights range from 10-lb for 25 kft/sec to 1-lb for 35 kft/sec.

For specified performance (payload weight and velocity), the facility size depends critically on the propulsive performance attainable. Except for the very short (0.1 sec) burn times required, rocket motors whose characteristics approach those here stipulated are already commercially available, and further development of specialized, light, fast-burning motors can be envisaged.

No obvious physical, as opposed to economic, limitations on performance of such facilities are apparent. Through decoupling of velocity and atmosphere duplication, such facilities offer freedom of environmental simulation. Although a full-scale (in terms of flight hardware) facility could not be in general considered practical, the relatively large model scale offered by the proposed facility would allow a significant range of scaling experiments to be performed. In view of relatively small launch accelerations, telemetry of model data (subject to model flow field interference) would be practical. Model telemetry coupled with external range observations would provide experimental data comparable in variety and quality to data available with the conventional wind-tunnel technique.

The use of a high-speed gun as the initial propulsion stage was investigated, but, multistage rocket propulsion is required in conjunction with the gun to reach velocities near 35 kft/sec with payloads of interest. Thus, since the simplicity of single-stage rocket operation is lost, and the multistage rocket and launcher design must be developed, it seems desirable to favor pure, multistage rocket systems, which, moreover, are free from high accelerations.

Beyond the geometry of a conceptual configuration, the mechanical design is not considered in this paper. The motion of rocket stages in long tubes at very high speeds, and the staging technique are problems which will undoubtedly require much developmental work. However, compared to the rocket sled shoe situation, the high-speed motion of rocket stages in evacuated tubes is quite different and probably less critical. The fact that no difficulties have been encountered with launching of cylindrical Lexan® projectiles by light gas guns at velocities in the 25–35 kft/sec range is encouraging in this connection. With rocket motors there would be no requirement for a seal with the tube wall, and gas lubrication may effectively eliminate friction and increase allowable tolerance on tube wall finish and waviness.

It is recommended that, on the basis of the above feasibility study, development of a rocket-propelled, multistage facility should be undertaken in several stages. First, experiments should be performed in a long tube attached to a high-speed gun muzzle, and terminated by a recovery section (consisting, for example, of tube sections containing an inert gas at suitable pressures and light plastic foam). With such set up, high-speed motion of a cylindrical slug could be investigated as a function of tube straightness, surface finish, alignment at joints, projectile stagnation pressure, etc., to provide design data for a rocket launcher facility.

Concurrently, a design investigation of multistage, rocket-propelled aeroballistic range facility should be conducted to examine critically the main technical problems, such as rocket motor design, dynamics of motion inside the launch tubes, exhaust flow in launch tubes, staging technique (including stripping and disposition of burnt-out stages), absorption of model impact, operational and maintenance aspects, etc. Then, following detailed cost estimates, a pilot, multistage facility should be designed and built to serve as a test bed for full-scale facility design and operation.

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