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ADVANCED AERODYNAMIC TEST FACILITIES AND THE "SLINGSHOT" CONCEPT

by

Robert W. Perry

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POLYTECHNIC INSTITUTE OF BROOKLYN

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71

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9. Sodickson, L., Carpenter, J., and Davidson, C.: A New Method of Producing High Speed Molecular Beams. AFCRL Report 65-337 (ASE 933), March 1965.

FOREWORD

This is the final report prepared under Contract No. Nonr 839(25) Project No. NR 061-107. In addition to the analyses and results presented herein, two Master's theses were generated under partial support of this program; these are:

1) A. Donow: A Second Order Theory for the Performance of the Quasi-Isentropic Compressor. Thesis for the Degree of Master of Science (Astronautics) June, 1967.
2) J. Genovese: Acceleration of Encapsulated Gases.* Thesis for the Degree of Master of Science (Astronautics) June, 1967.

In addition to these students, the following personnel have contributed significantly to this project and their assistance is gratefully acknowledged:

Mr. Morton Cooper of ONR, the contract monitor;

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ABSTRACT

Mechanical acceleration of an encapsulated relatively dense, neutral gas is suggested for the gas supply of a non-conventional wind tunnnel. Design considerations for such a novel aerodynamic test facility, christened "Slingshot", are discussed. Particular attention is concentrated upon the possibility of shock formation within the confined gas during acceleration.

The relationship of the widely-used "shock compressor" within the general class of adiabatic compressors and its limitation for the production of increased temperatures of dense gases are also explained. The potential advantage of "kinematic staging" for advanced aerodynamic test facilities is stressed.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS(Contd)

LIST OF SYMBOLS

A		cross-sectional area of the piston or barrel
a		sonic speed
a_o		sonic speed of the undisturbed gas
E		energy
G		specific heat ratio of the propellant
n	$\equiv$	$(\gamma + 1)/2(\gamma - 1)$
R		ratio of sonic speed in propellant to sonic speed in capsule
r	$\equiv$	$(\frac{2a}{\gamma-1} + u)/2a_o$
s	$\equiv$	$(\frac{2a}{\gamma-1} - u)/2a_o$
t		time
V		relative velocity between model and test gas
v_o		optimum gas velocity for minimum overall energy
v		gas velocity
x		coordinate along the barrel
α_i		initial acceleration of the piston
Δp		initial pressure difference across the piston
ϵ		relative efficiency
γ		specific heat ratio
λ		capsule length
μ	$\equiv$	$\epsilon_G m_G/\epsilon_B m_B$
ρ		density
ℓ		piston stroke

Subscripts

B	refers to model
G	refers to test gas
p	refers to piston

Superscripts

$'$	denotes differentiation with respect to v

SECTION I

INTRODUCTION

The development of aerodynamic test facilities has quite obviously failed to keep pace with the advancement of flight capability during the recent part of this decade; yet, both flight and ground equipment are subject to similar limitations imposed by thermodynamics and available materials. The big difference is that the advanced flight vehicles use "kinematic staging", in which successive relatively small velocity increments are provided with respect each time to the local (generally already moving) coordinate system; whereas what is called staging in ground equipment is really "thermodynamic staging", which does not take advantage of Newtonian relativity, but merely transfers and necessarily degrades available energy. Thus, the designers of test facilities have been seeking to obtain an increasingly large velocity increment in a single kinematic state with, understandably, little success. Rather than a continued proliferation of increasingly complex devices, all essentially derivatives of existing devices, what seems really needed is a re-examination of the basic problem.

An exact copying of flight technology would surely not be desirable, since the principal attraction of ground testing is its usual economy, although convenience and reproducibility are also advantages. The relative economy of ground testing versus flight testing normally derives from the use of simplified and scaled-down vehicle models, which is generally justifiable when the Navier-Stokes equations are known to be applicable. When energy-dependent effects are considered and binary chemical reactions are not dominant, scaling apparently cannot be justified and ground testing may lose attractiveness. However, direct energy-dependent effects upon a flow field have not yet been shown which are at all comparable to those caused by transition and separation of boundary layers. So, the gross nature of the flow field about a particular vehicle seemingly directly involves the classical problems of transition and separation, but is only indirectly influenced by the energy-dependent effects. The question of the sensitivity of the boundary layer profile to the physico-chemical effects is then apparently of fundamental importance. Since all available evidence indicates a remarkable insensitivity, presumably then the classical "cold" (Navier-Stokes) wind tunnels are adequate for general aerodynamic investigations. There is seemingly very little to be gained through reproduction of the actual energy level of flight in a ground test facility, since an ultimate flight test is anyhow unavoidable and must be the final arbiter. Also, the chemical concentrations in a flow field, which are frequently considered as suitable for determination in "hot" tunnels, are generally so sensitive to impurity levels that much of the data must be doubted.

Regardless of whether it is desired to reproduce the full relative velocity of flight, though, there are three possible Galilean permutations: the vehicle model may be forced through a stagnant gas; the model may be held stationary in a moving stream; or both model and gas may be in motion. The former type of test facility is commonly called the "ballistic range", the second is called the "wind tunnel", and the third has been known as the "counter-flow" type of facility. Of course, the first two are really just special cases of the latter. Since there are conflicting claims for each of these configurations, it is of interest here to consider their comparative energy requirements. If the desired relative velocity is taken as V, the mass of the model as m_B, and the mass of the minimum "test slug" of gas as m_G, then the net energy requirement of a range is $\frac{1}{2}m_B V^2$, of a tunnel is $\frac{1}{2}m_G V^2$ and of a comparable counter-flow facility is $\frac{1}{2}m_B(V-v)^2 + \frac{1}{2}m_G v^2$, where v is the gas velocity. To determine the gross energy requirements, the efficiency of accleration of the body, ε_B, and the efficiency of heating and utilization of the gas, ε_G, must be introduced, so the overall requirement in the general case must be $2E=\varepsilon_B m_B(V-v)^2 + \varepsilon_G m_G v^2$. The most efficient configuration can be readily determined by differentiating E with respect to v, thus finding:

$$(\varepsilon_G' m_G - \varepsilon_B' m_B) v_o^2 + 2(\varepsilon_G m_G - \varepsilon_B' m_B V + \varepsilon_B m_B) v_o + \varepsilon_B' m_B V^2 - 2\varepsilon_B m_B V = 0$$

where v_o is the optimum gas velocity to minimize the overall energy requirement and primes denote differentiation with respect to v.

Generally, the efficiencies will be functions of the scale of the equipment, as well as of the velocity level, but this is surely a smaller effect. If it were not for the velocity dependence of the efficiencies, the above equation would merely reduce to $(\frac{v_o}{V})_\epsilon = \frac{1}{1+\mu}$, where $\mu \equiv \epsilon_G m_G/\epsilon_B m_B$. If the test slug of gas is taken $10^{3/2}$ times as long as the model, its cross-sectional area is taken $10^{3/2}$ times that of the model, and 10% of the gas heated is actually used, then $\mu=10^4 \epsilon \rho_G/\rho_B$, where ϵ is the relative efficiency of accelerating a gas or a solid and the ρ are respective densities. So, commonly $\mu<<1$ and $v_o \approx V$; that is, it is undesirable usually to accelerate the model, because of the orders-of-magnitude greater density of solids compared to gases at desired test section conditions. It is only when the efficiencies become rather steep functions of velocity, as they do near a natural limit, that the wind tunnel configuration, with its ease of instrumentation, becomes clearly less attractive.

Whether the gas or the body, or both, are to be accelerated, though, there are only relatively few types of forces or original sources of energy to be considered. In a laboratory situation of this type, nuclear forces are generally considered too strong and gravitational forces as too weak, so only the short-range repulsive "mechanical" forces and the long-range Coulomb forces seem suitable. Hence, there may be distinguished six classes of accelerators useful for present purposes: the mechanical, the electromagnetic, and possible mixed types; each either for acceleration of a body or a gas. Devices for acceleration of a body are variously referred to as "launchers", "boosters", or "guns". The single-kinematic-stage, purely mechanical "gun", which uses the repulsive forces between the neutral molecules of a moderate density, heated gas, has already been well-developed to about its natural limit in velocity, although it could still be scaled-up to launch larger bodies at present velocities. The electromagnetic gun, in contrast, has reached only moderate velocities yet, but seems far from any natural limit. One possible example of a single-kinematic-stage, "mixed" type of gun is the "Pot-Shot" design[1], in which electromagnetic energy is added to a confined gas as thermodynamic "heat", followed by unsteady expansion of the gas; but this may also be regarded as a basically mechanical type with thermodynamic staging, and the original source of the energy for heating the propellant is really of secondary importance provided the desired temperature level is attainable. Perhaps it would be best to reserve the "mixed"class for the possible multiple-kinematic-stage devices in which the same type of force is not used in all stages.

Although the acceleration of a gas is of equal or greater importance than the acceleration of a body for the present application, as discussed earlier, the corresponding technology is definitely less advanced. The concept of kinematic staging, for instance, apparently has never been applied to the acceleration of gases. Electromagnetic acceleration has been commonly used for ionized gases and is being developed for relatively-rarefied neutral gases, but not for the moderately-dense neutral gases of interest for aerodynamic testing. For this purpose, until recently, only a single type of mechanical device was commonly used - the adiabatic Laval nozzle, in which the test fluid was permitted to accelerate itself. Because of the increasingly obvious deficiencies of this device, non-adiabatic expansions have received increasing attention; however, the addition of thermodynamic "heat" to a flowing stream is clearly undesirable because of the resultant great increase in entropy, so only the addition of thermodynamic "work" to a flowing stream remains of interest. Unfortunately, no way of adding large amounts of work to a moderately-dense, neutral gas flow seems known.

Common to all of the mechanical devices discussed, whether for the acceleration of a solid or a gas, is the need for a heated propellant, which in some instances may also serve as the test gas. When the required temperatures are greater than may be attained with chemical reactions, adiabatic compression and electric discharges provide possible means of heating the propellant gas. The electric discharges do introduce the need for insulators and electrodes and do concentrate the primary heating within filamentary channels. The necessary insulating materials generally do have poorer mechanical and thermal properties, but their effect presumably can be minimized through good design to reduce exposure and through adequate scale-up to improve surface-to-volume ratio. Contamination of the heated gas with electrode vapors also can be reduced through decrease in the current level at which power is delivered; that is, by increasing the overall voltage drop the electrode heating will become relatively less, since the sheath drop is constant. The channelized heating introduces the need for adequate mixing, without scouring of the chamber walls which would introduce impurities. However, the electric discharges will not be discussed at greater length in the present report. It is the technique of adiabatic compression, rather, and a novel mechanical device for the acceleration of gas which will be expounded in the subsequent sections.

SECTION II

ADIABATIC COMPRESSION

The overall effect of any departure from reversibility during an adiabatic compression process is readily deduced. Both the final pressure and the final temperature must be increased by irreversibility in compression through a given volume ratio from given initial conditions; but, as usual, irreversibility infers degradation of available energy, so these apparent gains surely do have an accompanying penalty. Moreover, since the same final state can also be attained with reversible adiabatic (isentropic) compression through suitable adjustment of initial conditions and compression ratio, a thermodynamically feasible alternative is known.

One example of an adiabatic compressor is the commonly-used shock tube. Because of the minimization of inertia within such a tube, the compression process is very rapid and highly irreversible, being accomplished entirely through a strong moving normal shock wave. This irreversibility is frequently regarded as an advantage, but does lead to increasingly difficult driver performance requirements. To reduce the irreversibility, the compression process may be slowed by increasing the inertia within the tube, through addition of a finite mass interface or "free piston", for instance. In the limit of infinite piston mass, the process would proceed infinitely slowly and it would undoubtedly be universally agreed that such compression would indeed approach the isentropic ideal. Thus, the family of free-piston compressors includes members capable of yielding any desired degree of irreversibility within the range from zero to that of the shock tube.

Since a free-piston compressor is merely a gas-filled gun with the muzzle boundary condition changed from open-end to closed-end, existing interior ballistics theory[2] is equally applicable to the compressor, outside of the range of influence of the downstream boundary condition. In such problems, natural length and time units are defined by the ratios a_o^2/α_i and a_o/α_i, respectively, where a_o is the sound speed of the undisturbed gas in the barrel and α_i is the initial acceleration of the piston. Alternatively, the natural unit for both distance and time may be regarded as the initial radius of curvature of the piston path in the x vs. $a_o t$ plane. In terms of the physical variables ratioed to these natural units, there is actually only a single ballistic solution corresponding to any specified piston path, outside the domain of influence of the downstream end. Since only the combination $\alpha_i x$ appears in such a solution, that solution may be considered as showing either the variation of conditions with distance and time in a single gun or compressor having a given piston mass; or alternatively, as showing the conditions at the same station in each member of a family of compressors or guns with various piston masses. Although the former is the usual interpretation of such a ballistic solution curve, the latter is the view which will generally prove more useful here.

The nature of the curve, though, is perhaps more apparent if it is first described in the former terms. So, considering an initially stationary piston which separates a stagnant high pressure driver gas from the stagnant lower pressure gas which is to be processed, the initial piston acceleration is readily calculated to equal the initial pressure difference divided by piston mass per unit cross-sectional area. The compression waves generated at the front face of the accelerating piston necessarily steepen and may form a shock wave, but as Friedrichs[3] showed, the shock cannot occur before the dimensionless distance and time $\frac{\alpha_i x}{a_o^2} = \frac{\alpha_i t}{a_o} = \frac{2}{\gamma+1}$, if the piston acceleration is constant or decaying. With a gaseous driver, the piston acceleration will always be decaying, approaching zero for large distances and times, so for a finite distance and time, shockless compression will be achieved. At its initial appearance, the shock must have zero strength, in these circumstances, and its growth in strength will not be instantaneous. Since the change in entropy and in the Riemann invariant of the other family across a weak shock may both be shown to be of third order in shock strength, the region behind a shock of less than third order strength remains "simple" and homentropic, permitting ready analysis. In particular, the path of the shock front and its growth in strength through second order may be quite easily deduced[4], since the integrated path of any particular curve of interest through a simple homentropic region is not difficult to determine. Remarkably, Pillow[5] has even extended such an analytic solution to third order, where the simple and homentropic assumptions must both be abandoned. For the still stronger shock, the numerical method of characteristics is probably a preferred approach, but the asymptotic behavior can be independently predicted if the piston acceleration eventually becomes zero, for a constant velocity piston does finally cause a constant velocity shock, and the situation then must be quite indistinguishable from the well-known shock-tube solution.

To summarize then, ahead of a piston with decaying acceleration, there is isentropic compression for a finite piston stroke, followed by compression through a weak shock (with negligible entropy rise) for an additional finite distance, then the Pillow (third order) situation, the large transient region of intermediate shock strength and, finally, the asymptotic (shock tube) steady solution. Re-interpreting this, five classes of free-piston compressors become recognized:

1) the isentropic compressors, with dimensionless strokes less than $\frac{2}{\nu+1}$;

2) the "quasi-isentropic" compressors, in which entropy rise remains practically negligible;

3) the "third order" compressors;

4) the "intermediate" compressors; and

5) the shock tube, a class which contains only a single (singular) member.

It is noteworthy that the ideal of isentropic compression, which is so frequently dismissed as unattainable, is so readily possible and that a very close approximation to that ideal is even more broadly feasible. It is merely necessary to keep the dimensionless stroke $\frac{a_i \ell}{a_o^2} \le \frac{2n}{\gamma+1}$, where ℓ is the stroke, n=1 for isentropic compression and $n \approx 1.5$ or 2 for the quasi-isentropic compression limit. Thus the minimum allowable piston mass is $m=\frac{\gamma+1}{2n}(\frac{\Delta pA\ell}{a_o^2})$, where Δp is the initial pressure difference across the piston and A is the cross-sectional area of the piston or barrel. For example, if $\Delta p=6000$ psi, $A=2$ in^2, $\ell=24$ ft. and $a_o=1000$ fps, then any piston mass greater than 11 pounds will insure isentropic compression and somewhat lighter pistons will only produce minor degradation.

The effect of the "closed muzzle" boundary condition is essentially to reflect the leading shock wave, which subsequently encounters the still-advancing piston and reflects from it in turn. After a sufficient number of such reflections, the piston must reverse its direction of motion and a net expansion of the processed gas must ensue. Since a reflected shock cannot be stronger than the incident, clearly in the quasi-isentropic compressors this sequence of reflections cannot generate any significant entropy rise. Thus, although such regions lack the "simple wave" character, analysis may be continued using the method of Riemann[6], which is quite analogous to the perhaps more familiar hodograph method.

As mentioned above, the compression process is ultimately terminated rather abruptly by the rebound of the piston. Neither steady nor uniform conditions are produced in the processed gas in this fashion, except for the asymptotic shock-tube case which can produce uniform conditions which are steady for a very brief period. In the case of the heavy-piston compressors, the pressure disturbances would rapidly equalize if the gas could somehow be held at peak conditions. It is conceivable that the piston might be clamped at the end of its stroke, but it has proven easier to trap the gas by installing simple check valves in the end wall of the compression tube. Rapid response is insured by use of multiple small valves, with consequent reduction in inertia. The compressed gas so trapped is thereafter sheltered from the expansion processes which occur in the tube and it will decay from the peak conditions only due to mass leakage and heat loss. For a given state in this reservoir of gas, the effect of heat loss will be determined by the surface-to-volume ratio of the container, so it can always in principle be reduced to an acceptable level by simple scale-up of the equipment, provided radiation losses (with their fourth-power dependence) remains unimportant. Mass leakage backwards through the valves need not be considered, unless some obvious malfunction occurs. Actually, cooling times measured in seconds have been observed for gas so trapped at quite high pressures and temperatures in a relatively small reservoir.

This combination of a heavy free piston and multiple check valves has been dubbed the "Longshot" type of compressor[7]. Two such installations were built in the Re-Entry Simulation Laboratory of the Republic Aviation Corporation. The largest was a 3-inch diameter tube, 76 feet long, which was used with a 5-pound piston to compress a large fraction of a pound of nitrogen routinely to 50,000 psi and 2500°K, as the supply for a conventional hypersonic wind tunnel. This facility, called "Longshot I", has recently been moved to the von Karman Institute for Fluid Mechanics in Brussels. The second installation has a 41 mm diameter tube, 24 feet long, in which a normal 5-pound piston has compressed nitrogen to nearly 200,000 psi, with correspondingly high temperatures[8]. It is believed that such combinations of gaseous pressures and temperatures have never been attained, using any other techniques, in the laboratory.

So, the feasibility of the heavy free piston compressor has been clearly demonstrated. Through reduction in the irreversibility of the compression process, it ameliorates the driver requirements, but requires increased stroke for the attainment of given final conditions. Since the pressure of the gas increases markedly only near the end of the stroke, the necessarily longer tubes need not be strong; hence the resultant costs can be less than those associated with the increasingly desperate driver techniques for the advanced shock tubes. Moreover, the duration of desired conditions may be increased by several orders-of-magnitude merely through addition of the "Longshot" type of check valves.

For many interesting types of studies, it appears desirable to maximize the unit Reynolds number at a given Mach number; that is, to maximize the product of density and sound speed divided by viscosity; but the sound speed and the viscosity may be found tabulated as a function of density and temperature, for thermodynamic equilibrium, so the calculation of this index is possible for any equilibrium test section state, except at extremely high densities for which the necessary tables undoubtedly do not exist. Since the viscosity must ultimately increase with density, it is to be expected that there will be a relative maximum in the index at some high density, but the effect of decreasing temperature should be more significant.

Since a test section state within the vapor phase boundary is not considered acceptable, the permissible temperature decrease may be correspondingly limited. Fortunately, for the present purpose, though, nucleation is not instantaneous, so the onset of condensation in a dynamic expansion may be very significantly delayed, as shown in RARDE Memorandum 24/66, for example. Such experimental data is invariably presented on a plot of static pressure versus static temperature, although the latter is certainly not a measured quantity (and even measurement of the former is somewhat doubtful). If derived variables are to be used, then density and temperature would seem to be a more rational pair; but a Mollier diagram is even more revealing. If the available data is replotted in this form, then the curve marked "Empirical Condensation Line for Air" on Fig. 4. of the above reference will be seen to be asymptotic to some isentrope. For any higher entropies, condensation will therefore not be expected in equally-rapid expansions and the process may be extended down to any desired temperature. Consequently, the maximum of the unit Reynolds number at a given Mach number should be found at a test section state corresponding to the maximum entropy boundary of the contracted vapor dome and the lowest usable temperature. The corresponding reservoir conditions are readily calculated. As discussed earlier, these reservoir conditions may actually be produced in adiabatic compressors with differing amounts of entropy rise. Since an increase in the amount of entropy rise during compression reduces the compression ratio needed to reach a given final state from a fixed initial temperature, it seems beneficial at first glance. However, in the present case, the entropy in the compressed state is desired to be about equal to that at standard conditions, so density would be about standard. The more the desired entropy increase, the higher the required initial density, if the given final state is to be attained. Thus, the stronger, the desired shock, the denser the air into which it must be driven. With a fixed driver pressure, the diaphragm ratio decreases, so even with exotic driver techniques only relatively weak shocks can be created and the achievable entropy rise is bound to be relatively small, although perhaps not negligible.

It is interesting to note that if the reservior conditions calculated above can really be created, so that the same test section state can be reached for each Mach number, then the unit Reynolds number will actually increase with increasing Mach number.

SECTION III

THE "SLINGSHOT" DEVICE FOR NON-THERMAL ACCELERATION OF NEUTRAL GAS

Internal repulsive forces are certainly not the only forces which may be used to accelerate a relatively-dense neutral gas, despite the widespread use of the Laval nozzle for this purpose. Since the development of hypersonic wind tunnels has been limited by the disadvantages of the Laval nozzle as a gas accelerator, alternatives are of great current interest. The Laval nozzle suffers from severe throat heating, chemical non-equilibrium, and high reservoir pressure and temperature requirements in advanced applications. Since desirable test gases are seldom efficient propellants, the high pressure and temperature ratios are inherent, unless some carrier gas is introduced and species-sensitive instrumentation is available. Departures from chemical equilibrium are seemingly inevitable whenever an expansion from an excited condition continues below about standard atmospheric density, and are relatively independent of the particular reaction rates involved. So it would be very desirable to avoid all thermal processing of the test gas and to add only thermodynamic "work" to it. A slight step in this indicated direction has been taken recently with the addition of the "jxB" post-accelerators to Laval nozzles, but they apparently must deliver an excited gas at low density, so non-equilibrium remains a problem for them. Electromagnetic acceleration of a neutral gas through induction of dipole moments is being studied at the University of Chicago, but probably is limited to low beam densities.

Hence, the mechanical acceleration of a gas is of greatest interest here. Since rotary equipment has severely limited peripheral velocities, little energy can be added to a gas per stage, a handicap not shared by linear devices. An encapsulated gas can readily be accelerated in a gun or by a multi-stage rocket. Through encapsulation, except for the internal wave processes, the problem is converted from the acceleration of a gas, for which the technology is relatively stagnant, to the acceleration of a solid body, for which the technology is more vigorous. Another viewpoint, which leads to the same end, results from reconsideration of the use of an efficient auxiliary propellant when species-sensitive instrumentation is not available. Then physical separation of the test gas and propellant is an obvious solution, but a solid moving barier is not readily designed for an expanding channel. However, an unsteady supersonic expansion is more efficient than a steady supersonic expansion and may be accomplished in a tube of uniform cross-section, so an encapsulated test gas may readily be accelerated by the unsteady expansion of a propellant gas; but such a device is usually called a gun; hence, through quite different reasoning, the same method for the non-thermal acceleration of relatively-dense neutral gas may be deduced.

For a wind tunnel application, the gas-filled capsule so accelerated need merely admit axially a stationary instrumented aerodynamic model through an opening in the capsule's forward end, which is initially covered by a thin diaphragm (Fig. 1). Although the conception of this "Slingshot" type of wind tunnel did occur independently to the present author at the Polytechnic Institute of Brooklyn in September 1965,* it has subsequently been found very similar to a proposal for a novel dense molecular beam facility made to USAF Cambridge Laboratory in June 1963[9]. The two applications differ primarily in the much greater mass of gas which must be accelerated for a wind tunnel experiment and in the required complete "stripping" of the capsule for the proposed crossed molecular-beam experiments.

Since the capsule itself will represent a large fraction of the mass to be accelerated, it must be efficiently designed. Clearly, the buckling limit of this necessarily light-weight structure will establish one possible maximum tolerable acceleration level and a corresponding minimum distance for acceleration of the capsule to a desired final velocity. However, another possibly more stringent limit is imposed by the dynamics of the gas within the capsule. During acceleration, a compression wave will tend to be generated ahead of the rear face and an expansion wave will tend to arise behind the front face. In an infinitely short capsule, these effects will cancel at each instant and the condition of the

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*In the course of discussions with M.H. Bloom who was considering the performance of a staged device consisting of a gun-accelerated shock tube to move gas relative to a model.

gas will remain uniform. In longer capsules, because of the finite velocity of wave propagation, pressure gradients will appear during acceleration and for a transient period thereafter. The gradient in the compressive wave is known to steepen when the capsule is long enough that interaction with the expansion wave is sufficiently delayed. The process is then indistinguishable from the steepening of the wave ahead of a single accelerating piston, which was discussed in a previous section. Using those results, it can be deduced that a shock must form at a dimensionless distance and time equal to $\frac{2}{\gamma+1}$, in any capsule with a dimensionless length equal to or greater than $\frac{4}{\gamma+1}$. Once a shock forms in the test gas, undesirable striations and irreversibility result, so the length of the capsule should be less than would lead to shock formation anywhere in the capsule for the desired acceleration history. Of course, an additional factor approaching two in the tolerable length of the capsule for otherwise fixed conditions might be gained by accepting a quasi-isentropic shock, as in the previous discussion of adiabatic compressors.

To calculate the effects of the wave interaction upon the shock initiation, the method of Riemann, which was mentioned in the previous section, is applicable. In a subsequent section, the first stage of interaction will be so analyzed. For still more complex interactions, though, numerical methods appear more attractive. A computer program for this problem, based upon the Hartree fixed-grid variant of the numerical method of characteristics, has been tested[10]. Still another program, based upon direct numerical integration of the governing fluid mechanical conservation relations, is being tested at the Courant Institute. In the "simple wave" regions before interaction, both numerical methods have compared well with each other and with the well-known theory, when the numerical spatial resolution was no worse than 2% of the initial radius of curvature of the capsule path in the x vs. $a_o t$ plane and the temporal resolution was no worse than 1%. It is hoped to continue such comparisons into the first-interaction regime.

Capsule Sizing

In essence, a "Slingshot" test resembles a conventional wind tunnel test in which the entire test section is hurled past the model. Since relative velocity between the gas and the capsule wall is negligible, the usual allowance for nozzle boundary layer in sizing the minimum test section diameter for a given model size is unnecessary. The capsule inner diameter need only equal the usual "inviscid core" diameter.

The absolute duration of uniform flow is determined by the length of the capsule, the capsule velocity and any "starting" time loss. The effect of velocity upon the relative duration (i.e., the chord-lengths of useful flow) is limited merely to determining the relative starting loss. Since the starting wave moves into the undisturbed gas at sonic speed, it is only for markedly supersonic velocities and for capsules much longer than the models that wastage of gas can be tolerably low (Fig. 2). If, in addition to the unavoidable starting phenomena, it is also desired to prevent destruction of the model against the back wall of the capsule by suddenly creating a suitable opening in that wall, then another sonic "termination" wave must be created and additional test gas wasted. So we see here analogies to the "test slug" and the starting and stopping transients of more conventional wind tunnel practice.

Lengthening of the capsule to increase test duration has three potential disadvantages, namely, possible decreased rigidity of the necessarily longer model-supporting sting, possible buckling of the longer thin-walled cylindrical capsule during acceleration or "gap-jumping", and possible shock formation in the "sloshing" gas within the capsule during acceleration. Since shock formation would lead to entropy striations within the test gas resulting in deviations from the specified uniformity and state, acceleration levels must be suitably limited. This would simultaneously ameliorate also the buckling problem. Basically, all lengths (but not diameters) in such a system are expected to scale-up directly with increased capsule length, but driver pressure level will decrease. Thus, a hypervelocity gun designed to launch such a capsule must differ from conventional practice in two economically-compensating respects: the length must be very much increased, but pressure levels will be very much lower.

Other Capsule Design Considerations

Since the capsule represents an internally pressurized shell in the evacuated gun barrel, its structure may be very light and simple, except for the back face which is exposed to the driver pressure. The acceleration limits imposed by "sloshing" considerations are probably stricter than the structural limits. The resulting thin walls of the capsule are even expected to permit schlieren or other optical observation of the internal test flow.

Although the model may be permitted to open the capsule at low velocities directly by impact, at higher velocities some auxiliary opening mechanism will certainly be needed. The discharge of a capacitor through a metallized Mylar diaphragm via a pair of wall-mounted contacts a short distance upstream of the model should vaporize the film in an acceptably short time [11].

Provision of an opening of comparable size in the back face for safe passage of the model, however, is made very much more difficult by the necessarily greater thickness of that "pusher" plate. Any attempts to retard or deflect the capsule at hyper-velocities seem hopeless. Only methods involving small relative motion entirely within the moving frame of reference, such as the pyrotechnic-initiated swinging of a hinged door, appear feasible. Care is required to minimize the resulting wave in the trapped fluid. It would also be desirable to include in the capsule base a miniature pressure telemeter to transmit information about the wave amplitudes and the average pressure level in the test gas versus time, particularly if unusually high or low capsule loading pressure might cause leakage. The base must also include necessary external seals and attachment for the sheared disc from the primary driven diaphragm.

Test and Coast Sections

The test section need merely be rigidly mounted and isolated from the gun recoil. It may be provided with windows for optical instrumentation, as mentioned in the preceding section, since the capsule walls are expected to be thin enough to be transparent and gas densities will be unusually high. The model support must be a rigid cantilever of minimum frontal area and terminate in a conventional relatively slender sting, hollow for passage of instrumentation leads. The overall lengths should be sufficient to prevent contact before test termination. If the door in the capsule pusher plate is not provided, the entire model support will probably be demolished on each shot at hypervelocity, despite its massiveness. However, with such a door in the back wall, the model support need merely slit one side-wall of the capsule in order to survive. Presumably this might be feasible, even if replacement of the slitter blade might be frequently required. Thus, only the capsule itself, required to minimize the resulting wave in the trapped fluid. It would also be desirable to include in the capsule base a miniature pressure telemeter to transmit information about the wave amplitudes and the average pressure level in the test gas versus time, particularly if unusually high or low capsule loading pressure might cause leakage. The base must also include necessary external seals and attachment for the sheared disc from the primary driven diaphragm.

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A coast section, as mentioned before, should be provided between the accelerator and the test section to permit damping of the isentropic waves inevitably excited during acceleration. Actually it need only be an upstream extension of the test section tubing of sufficient length for its attenuation function and isolated from the gun muzzle by a relatively narrow gap across which the long capsules may be readily guided. Additional vents must be provided in the entrance region of the coast section to insure termination of the acceleration. The gap and vents must discharge into an evacuated region of adequate capacity to diffuse the muzzle blast and afterflow from the gun. The actual gap need only be sufficiently wide to isolate the gun recoil, but probably could be up to a quarter of the capsule length and still be rather readily negotiable if the capsule were slightly tapered back for perhaps an eighth of its length and the catcher lip were similarly tapered.

Launcher Considerations

Except for the lower acceleration level and consequently longer barrel, the launcher for this application need not differ from any other hypervelocity gun. Any successful driver technique, such as adiabatic compression of a light gas, electric discharge or combustion heating, may be utilized. However, the usual presentation of gun performance in terms of projectile velocity versus projectile mass, rather than in terms of the more-meaningful corresponding non-dimensional quantities does render the scaling task more difficult, since vital information such as the barrel length is frequently not readily available.

The attainment of sufficiently high velocities in a "Slingshot" to permit unique studies of boundary layer transition seems unquestionable. Unusual combinations of high Mach number and high Reynolds number will be available, while the usual noise from the turbulent nozzle wall boundary layer will be entirely absent. Achievement of the still higher velocities which are of interest for studies of significant real gas effects and non-equilibrium radiation will probably require much more sophisticated techniques and very long guns.

Initial Experimental Studies

To permit an early and very inexpensive demonstration of this "Slingshot" concept, the 41 mm pilot tube used for the early "Longshot" adiabatic compressor development was procured and modified (Fig. 3). It was merely fitted with a 1 mil Mylar secondary diaphragm at the downstream end and operated as an evacuated gun. The 24-foot barrel was evacuated to about 10 microns and the 12-foot driver was pressurized with helium to less-than-bottle pressures. The first capsule, shown before firing in Fig. 4 , apparently failed structurally during acceleration, but in six subsequent firings a simple cup-like Lexan design (Fig. 5) has proven successful. Such 1.5-inch ID by 8-inch long projectiles, weighing 160 to 180 grams, have been accelerated to nearly 2000 fps with this crude gun. Instrumentation has consisted of a pair of breakwires for capsule velocity measurement and a thin-film total temperature probe (Fig. 6), all installed (for reasons of expediency) in the last three feet of the barrel, where the capsule is still accelerating. At the present relatively low velocities, the probe has simply been allowed to pierce the 1 mil Mylar capsule diaphragm (Fig. 7). All capsules have been filled with air at ambient atmospheric conditions. Probe output has been successfully recorded with an oscilloscope-camera combination on the last two of the firings. Some evidence of the isentropic wave processes which are expected during acceleration seems to be present, but they could presumably be eliminated by the addition of a separate test section and intervening coast section.

SECTION IV

WAVES WITHIN AN ACCELERATING GAS-FILLED CAPSULE

The formation and growth of a shock wave ahead of an accelerating piston was originally discussed by Friedrichs[3], and then extended by Pillow[5],nearly two decades ago. Both assumed inviscid, adiabatic, continuum, one-dimensional flow of a perfect gas.

Now, the question has arisen as to the conditions under which a shock will form within an accelerating, rigid, gas-filled capsule of uniform cross-section. So we are led to consider the idealized wave processes within the gas confined between two pistons which are separated by an arbitrary distance and which both have the same acceleration history. It is then the effect of the interaction of the expansion wave generated by the foremost piston and the compression wave generated by the rear piston upon the formation and growth of the shock wave which is of interest here. Friedrichs dealt with the "simple-wave" degenerate case where all flow variables are constant along straight characteristics, whereas the present interaction problem is irreducibly two-dimensional. The related problem of the interaction of two centered expansion waves is discussed in Courant and Friedrichs[12].

The present task is deliberately restricted to the analysis of only the first "non-simple" interaction between the non-centered compression and expansion waves generated at two identical piston paths of arbitrary history and arbitrary separation (Fig. 8), although shock formation might conceivably occur in some subsequent interaction zone. Numerical methods have been chosen for the investigation of such later stages of the acceleration, because the complexity of the algebra in a continued analytical approach is expected to become quite unmanageable.

Since the initial acceleration of the pistons and the speed of sound in the initially quiescent confined gas may be so combined as to provide natural time and distance units, suitable nondimensionalization of all variables is indicated. Then the only free parameters are: the nondimensional distance between the pistons, which corresponds physically to the interior length of the rigid capsule; plus an arbitrary "shape" function which gives the dimensionless piston acceleration as a function of a single convenient parameter, such as the momentary piston velocity.

After nondimensionalization, the "heads" of the respective waves emanating from the pistons are merely straight lines at a 45° angle to the axes, so they intersect at the point $(\frac{\lambda}{2}, \frac{\lambda}{2})$, if λ is the capsule length. Both waves remain "simple" up to the corresponding cross-characteristic curve which passes through the above intersection point, that is, up to the penetrating head of the opposite wave. So, in Fig. 8, we distinguish an undisturbed region (I), two simple-wave regions (II and III), the first interaction region (IV) bounded by the curves ABCD, and the adjacent regions of more complex subsequent interaction (V, VI AND VII). The interaction to which our attention is here directed (region IV) can be recognized as a so-called "characteristic-value" problem. The variation of any physical variable along the bounding characteristics of the simple regions can be readily determined for any assigned piston motion, provided region II remains isentropic. Then, if our study of the growth of any shock is limited to only the early stages so region IV may also be assumed isentropic, the governing partial differential equations are homogeneous, and also linear when the Riemann invariants are taken as independent variables[12]. The solution of such a linear hyperbolic problem by the method of Riemann is presented in Courant and Hilbert[6].

Just as for the case of the two interacting expansion waves[12], the transformed differential equation (in the auxiliary plane with the Riemann invariants as independent variables) for the present problem will be:

$$t_{rs} + \frac{n}{r+s}(t_r + t_s) = 0 \qquad (1)$$

where here t, the nondimensional time, equals the physical time multiplied by the initial acceleration divided by the undisturbed sound speed;

$$r \equiv \left(\frac{2a}{\gamma-1} + u\right)/2a_o \quad \text{and}$$

$$s \equiv \left(\frac{2a}{\gamma-1} - u\right)/2a_o ;$$

and

$$n \equiv \frac{1}{2}\left(\frac{\gamma+1}{\gamma-1}\right) .$$

The domain of the solution in the transformed plane will also still be the rectangle bounded by the four characteristics: $r=r_o$, $r=r_1$, $s=s_o$ and $s=s_1$. The initial values of t will still be supplied along the intersecting characteristics $r=r_o$ and $s=s_o$. Since the gas is initially stagnant, $r_o=s_o=\frac{1}{\gamma-1}$. The limits of the validity of the solution, r_1 and s_1, will be determined in a subsequent section.

Riemann's representation of the solution of such a "characteristic-value" problem, in terms of the appropriate Riemann's function, $\mathcal{R}$, is[6]:

$$t(r,s) = t(r_o,s_o)\mathcal{R}(r,s;r_o,s_o) + \int_{r_o}^{r} \left(t_\rho + \frac{nt}{\rho+s_o}\right)\mathcal{R}(r,s;\rho,s_o)\,d\rho + \int_{s}^{s_o} \left(t_\sigma + \frac{nt}{r_o+\sigma}\right)\mathcal{R}(r,s;\, r_o,\sigma)\,d\sigma \qquad (2)$$

$$\text{for } r_o \leq r \leq r_1$$

$$\text{and } s_o \geq s \geq s_1 .$$

The Riemann's function may be regarded as an "influence" factor and is quite analogous to the Green's function associated with linear elliptic equations.

For the particular differential equation (1) considered here, the appropriate Riemann's function is known[6] to be:

$$\mathcal{R}(r,s;\ \rho,\sigma) = \left(\frac{r+s}{\rho+\sigma}\right)^n \Psi\left(1-n,n,1;-\frac{(r-\rho)(s-\sigma)}{(r+s)(\rho+\sigma)}\right), \qquad (3)$$

where Ψ represents the hypergeometric series. Both integrands in Eq. (2) will be shown later to vanish whenever a simple <u>centered</u> wave exists along each of the initial characteristics, as in the dual expansion interaction problem already referenced.

Since n will be a positive integer greater than unity for the gases considered here, the hypergeometric series will reduce to the Legendre polynomial of order n-1, according to equation 15.4.4 of Ref. 13, which is true if either the first or second parameter of the hypergeometric series is negative. In this case, Eq. (3) becomes:

$$\mathcal{R}(r,s;\ \rho,\sigma) = \left(\frac{r+s}{\rho+\sigma}\right)^n P_{n-1}\left(1 + \frac{2(r-\rho)(s-\sigma)}{(r+s)(\rho+\sigma)}\right) \tag{4}$$

Substituting this into Eq. (2), we find the solution to have the form:

$$\begin{aligned} t(r,s) = {} & t(r_o,s_o)\left(\frac{r+s}{r_o+s_o}\right)^n P_{n-1}\left(1 + \frac{2(r-r_o)(s-s_o)}{(r+s)(r_o+s_o)}\right) \\ & + \int_{r_o}^{r}\left[t_\rho(\rho,s_o) + \frac{nt(\rho,s_o)}{\rho+s_o}\right]\left(\frac{r+s}{\rho+s_o}\right)^n P_{n-1}\left(1+ \frac{2(r-\rho)(s-s_o)}{(r+s)(\rho+s_o)}\right)d\rho \\ & + \int_{s}^{s_o}\left[t_\sigma(r_o,\sigma) + \frac{nt(r_o,\sigma)}{r_o+\sigma}\right]\left(\frac{r+s}{r_o+\sigma}\right)^n P_{n-1}\left(1+ \frac{2(r-r_o)(s-\sigma)}{(r+s)(r_o+\sigma)}\right)d\sigma \end{aligned} \tag{5}$$

Eq. (5) represents the desired solution in the domain of the auxiliary plane where $r_o \leq r \leq r_1$ and $s_1 \leq s \leq s_o$. When the initial values $t(r,s_o)$ for $r_o \leq r \leq r_1$ and $t(r_o,s)$ for $s_1 \leq s \leq s_o$ are supplied, then the production of an explicit solution for a particular problem is merely a matter of quadratures.

In each of the "simple" regions II and III, one family of characteristic curves will be straight lines along which all variables will be constant. The equations of such lines may be expressed as:

$$\frac{x(\delta)-x_p(\delta)}{t(\delta)-t_p(\delta)} = f(\delta) \tag{6}$$

where f is the slope of the straight characteristics and the arbitrary parameter δ is assumed known along some non-characteristic data curve $x_p(t_p)$, such as the piston paths in the present problem. This equation is fully equivalent to equation 13.1 of Ref. 2.

Differentiation with respect to δ then yields:

$$(t'-t_p')\left(\frac{dx}{dt}-f\right) - f'(t-t_p) + t_p'\left(\frac{dx}{dt} - \frac{dx_p}{dt_p}\right) = 0 \tag{7}$$

If $\frac{dx}{dt}$ and $\frac{dx_p}{dt_p}$ are known functions of δ, say $g(\delta)$ and $p(\delta)$, respectively, this is a linear ordinary differential equation for which the solution may immediately be given as:

$$t_g(\delta)-t_p(\delta) = e^{-F_g(\delta)}\left[c_g - \int \left(\frac{g(\delta)-p(\delta)}{g(\delta)-f(\delta)}\right) t_p'(\delta)e^{F_g(\delta)}d\delta\right]$$

where

$$F_g(\delta) = -\int \frac{f'(\delta)d\delta}{g(\delta)-f(\delta)} \tag{8}$$

and c_g is the appropriate constant of integration. Within a simple wave, the path of any curve for which $\frac{dx}{dt} = g(\delta)$ is thus related to the given variation of conditions along some non-characteristic data curve with slope $p(\delta)$ and location $t_p(\delta)$.

In the special case that we are herein concerned with, the data curve is the piston path and the desired solution is the path of the cross-characteristic, so a remarkable simplification results:

$$f(\delta) = u(\delta) \pm a(\delta) = \mp \frac{2}{\gamma-1} \pm 2na(\delta)$$

$$g_c - f = \mp 2a(\delta)$$

and $$\frac{g-p}{g-f} = \frac{1}{2} ,$$

where the upper sign pertains to region II and the lower sign pertains to region III. For this particular case, the integrating factor becomes:

$$F_c(\delta) = -\int \frac{\pm 2na'(\delta)d\delta}{\pm 2a(\delta)} = n\int d\ln a = \ln(a^n) .$$

The corresponding path is:

$$t_c(\delta)-t_p(\delta) = a^{-n}(\delta)\left[c_c - \frac{1}{2}\int t_p'(\delta)a^n(\delta)d\delta\right] \tag{9}$$

Clearly then, the simplest choice for the so-far arbitrary parameter δ is the sound speed, a, itself, so

$$t_c(a)-t_p(a) = a^{-n}\left[c_c - \frac{1}{2}\int t_p'(a)a^n da\right] \tag{10a}$$

but $t_c(1)-t_p(1) = \frac{\lambda}{2}$, so

$$t_c(a)-t_p(a) = \frac{a^{-n}}{2}\left[\lambda - \int_1^a t_p'(a)a^n da\right] \tag{10b}$$

The limits of region IV will be determined by the intersections of the cross-characteristics and the corresponding piston paths, that is, by the roots of

$$\int_1^a t_p'(a)a^n da = \lambda \tag{11}$$

In region II, the speed of sound will be greater than one and $t_p'(a)$ will be positive; that is, a will increase along the piston path. In region III, the speed of sound will be less than one, $t_p'(a)$ will be negative and a will decrease along the piston path. In either case, the integral as shown will be positive, as it should be.

However, before assuming a specific shape of the piston path in order to solve (11), let us first examine the general behavior of the combination, $t_c'(a) + \frac{nt_c}{a}$, which appears in the solution (5). From Eq. (10),

$$2t_c'(a)=t_p'(a) - na^{-(n+1)}\left[\lambda - \int_1^a t_p'(a)a^n da\right] \tag{12}$$

so we find the rather surprisingly simple relation,

$$t_c'(a) + \frac{nt_c}{a} = \frac{1}{2}\, t_p'(a) + \frac{nt_p}{a} \; . \qquad (13)$$

For a centered simple wave, the right-hand terms will vanish if the center is taken as t=0; hence the two integrals along the characteristic boundaries will vanish in the solution (5), leaving only the leading term, as mentioned earlier.

The simplest piston history which appears of practical interest corresponds to acceleration of a capsule by an ideal gas propellant in an evacuated gun, in which any effect of the internal processes upon the acceleration may be neglected. For this case[2],

$$t_p(u) = \frac{2R}{G+1}\left[\left(1-\frac{G-1}{2R}\,u\right)^{-\left(\frac{G+1}{G-1}\right)} - 1\right]$$

and

$$t_p'(u) = \left(1-\frac{G-1}{2R}\,u\right)^{-\frac{2G}{G-1}} \qquad (14)$$

where G ≡ specific heat ratio of the propellant

and R ≡ ratio of sound speed in propellant to sound speed in capsule.

Now, combining (5), (13) and (14), we obtain:

$$t(r,s) = \frac{\lambda}{2}\left(\frac{r+s}{r_o+s_o}\right)^n P_{n-1}\left(1+ \frac{2(r-r_o)(s-s_o)}{(r+s)(r_o+s_o)}\right)$$

$$+ \int_{r_o}^{r} \left\{\frac{1}{2}\left[1- \frac{G-1}{2R}(\rho-s_o)\right]^{-\frac{2G}{G-1}} + \frac{2n\ R}{(G+1)(\rho+s_o)}\left[\left(1-\left(\frac{G-1}{2R}\right)(\rho-s_o)\right)^{-\frac{G+1}{G-1}}-1\right]\right\}$$

$$\left(\frac{r+s}{\rho+s_o}\right)^n P_{n-1}\left(1+ \frac{2(r-\rho)(s-s_o)}{(r+s)(\rho+s_o)}\right)d\rho$$

$$+ \int_{s}^{s_o} \left\{- \frac{1}{2}\left[1- \frac{G-1}{2R}(r_o-\sigma)\right]^{-\frac{2G}{G-1}} + \frac{2n\ R}{(G+1)(r_o+\sigma)}\right.$$

$$\left.\left[\left(1-\left(\frac{G-1}{2R}\right)(r_o-\sigma)\right)^{-\left(\frac{G+1}{G-1}\right)}-1\right]\right\}$$

$$\left(\frac{r+s}{r_o+\sigma}\right)^n P_{n-1}\left(1+ \frac{2(r-r_o)(s-\sigma)}{(r+s)(r_o+\sigma)}\right)d\sigma \qquad (15)$$

The domain of validity of the solution (15), is then found from Eq. (11):

$$\int_{r_o}^{r_1} \left[1- \frac{G-1}{2R}(\rho-s_o)\right]^{-\frac{2G}{G-1}} \left(\frac{\gamma-1}{2}\right)^n (\rho+s_o)^n d\rho = \lambda$$

and

$$\int_{s_1}^{s_o} \left[1- \frac{G-1}{2R}(r_o-\sigma)\right]^{-\frac{2G}{G-1}} \left(\frac{\gamma-1}{2}\right)^n (r_o+\sigma)^n d\sigma = \lambda \qquad (16)$$

If $n < \frac{G+1}{G-1}$, as it is expected to be for interesting combinations of gases, then these integrals become:

$$\left(-\frac{G-1}{2R}\right)^{-(n+1)}\left\{\sum_{i=0}^{n}\frac{(-1)^{i}n!\left[1-\frac{G-1}{2R}(\rho-s_o)\right]^{n-\frac{G+1}{G-1}-i}\left(1+\frac{G-1}{R}s_o\right)^{i}}{(n-i)!\,i!\,\left(n-\frac{G+1}{G-1}-i\right)}\right\}_{r_o}^{r_1}=\left(\frac{2}{\gamma-1}\right)^{n}\lambda$$

and

$$\left(\frac{G-1}{2R}\right)^{-(n+1)}\left\{\sum_{i=0}^{n}\frac{(-1)^{i}n!\left(1-\frac{G-1}{R}r_o\right)^{i}\left[1-\frac{G-1}{2R}(r_o-\sigma)\right]^{n-\frac{G+1}{G-1}-i}}{(n-i)!\,i!\,\left(n-\frac{G+1}{G-1}-i\right)}\right\}_{s_1}^{s_o}=\left(\frac{2}{\gamma-1}\right)^{n}\lambda$$

(17)

For bimolecular gases, such as hydrogen for the propellant and air for the encapsulated fluid, $n=3$ and $\frac{G+1}{G-1}=6$, so the above restriction is satisfied and Eqs. (17) apply.

Also,

$$5R^{4}\left\{\sum_{i=0}^{3}\frac{(-1)^{i+1}6\left(\frac{R+1}{R}\right)^{i}\left[1-\frac{\rho-s_o}{5R}\right]^{-3-i}}{(3-i)!\,i!\,(3+i)}\right\}_{r_o}^{r_1}=\lambda$$

and

$$5R^{4}\left\{\sum_{i=0}^{3}\frac{(-1)^{i+1}6\left(\frac{R-1}{R}\right)^{i}\left[1-\frac{r_o-\sigma}{5R}\right]^{-3-i}}{(3-i)!\,i!\,(3+i)}\right\}_{s_1}^{s_o}=\lambda\ , \qquad (18)$$

which may be expanded to:

$$\frac{\lambda}{5R^{4}}=-\frac{1}{3}\left(1-\frac{r_1-s_o}{5R}\right)^{-3}+\frac{3}{4}\left(\frac{R+1}{R}\right)\left(1-\frac{r_1-s_o}{5R}\right)^{-4}-\frac{3}{5}\left(\frac{R+1}{R}\right)^{2}\left(1-\frac{r_1-s_o}{5R}\right)^{-5}$$
$$+\frac{1}{6}\left(\frac{R+1}{R}\right)^{3}\left(1-\frac{r_1-s_o}{5R}\right)^{-6}+\frac{1}{3}-\frac{3}{4}\left(\frac{R+1}{R}\right)+\frac{3}{5}\left(\frac{R+1}{R}\right)^{2}-\frac{1}{6}\left(\frac{R+1}{R}\right)^{3}$$

and

$$\frac{\lambda}{5R^{4}}=\frac{1}{3}\left(1-\frac{s_o-s_1}{5R}\right)^{-3}-\frac{3}{4}\left(\frac{R-1}{R}\right)\left(1-\frac{s_o-s_1}{5R}\right)^{-4}+\frac{3}{5}\left(\frac{R-1}{R}\right)^{2}\left(1-\frac{s_o-s_1}{5R}\right)^{-5}$$
$$+\frac{1}{6}\left(\frac{R-1}{R}\right)^{3}\left(1-\frac{s_o-s_1}{5R}\right)^{-6}-\frac{1}{3}+\frac{3}{4}\left(\frac{R-1}{R}\right)-\frac{3}{5}\left(\frac{R-1}{R}\right)^{2}+\frac{1}{6}\left(\frac{R-1}{R}\right)^{3}$$

(19)

Note that when R=1, a remarkable simplification of the latter equation occurs. This is a reflection of the identity then of the simple expansion waves in the driver gas and within the capsule. Since the simple wave within the driver of an evacuated gun is known to have a virtual center, the expansion waves within the capsule will also have a virtual center before interaction occurs, when the sound speeds and specific heat ratios of both gases are equal. For this case,

$$s_1 = 5\left(1+\frac{3}{5}\lambda\right)^{-\frac{1}{3}} - \frac{5}{2}$$

but $0 \le s_1 \le \frac{5}{2}$, so $0 \le \lambda \le \frac{35}{3}$

Eqs. (19) have been solved numerically for the special cases of R=1 and $\sqrt{14.5}$, with the resulting r_1 and s_1 plotted versus λ in Fig. 9.

With the same limitation to bimolecular gases, Eq. (15) reduces to:

$$t(r,s) = \frac{\lambda}{2}\left\{6\,\frac{(r+s)(r-r_o)^2(s-s_o)^2}{(r_o+s_o)^5} + 6\,\frac{(r+s)^2(r-r_o)(s-s_o)}{(r_o+s_o)^4} + \left(\frac{r+s}{r_o+s_o}\right)^3\right\}$$
$$+\int_{r_o}^{r}\left\{\frac{1}{2}\left[1-\frac{\rho-r_o}{5R}\right]^{-7} + \frac{5\,R}{2(\rho+s_o)}\left[1-\frac{\rho-r_o}{5R}\right]^{-6} - \frac{5\,R}{2(\rho+s_o)}\right\}$$
$$\left\{6\,\frac{(r+s)(r-\rho)^2(s-s_o)^2}{(\rho+s_o)^5} + 6\,\frac{(r+s)^2(r-\rho)(s-s_o)}{(\rho+s_o)^4} + \left(\frac{r+s}{\rho+s_o}\right)^3\right\}d\rho$$
$$+\int_{s}^{s_o}\left\{-\frac{1}{2}\left[1-\frac{s_o-\sigma}{5R}\right]^{-7} + \frac{5\,R}{2(r_o+\sigma)}\left[1-\frac{s_o-\sigma}{5R}\right]^{-6} - \frac{5\,R}{2(r_o+\sigma)}\right\}$$
$$\left\{6\,\frac{(r+s)(r-r_o)^2(s-\sigma)^2}{(r_o+\sigma)^5} + 6\,\frac{(r+s)^2(r-r\ )(s-\sigma)}{(r_o+\sigma)^4} + \left(\frac{r+s}{r_o+\sigma}\right)^3\right\}d\sigma \qquad (20)$$

This solution, however, may not be single-valued. If not, it is expected that a "fold" will occur in the back-mapping to the physical plane. Along the edges of such a fold, the second derivative t_{rr} should be expected to vanish, since it is only the r characteristics which can converge within the first interaction region. Such a fold is expected to originate in a cusp, at which point the first derivative t_r must also vanish. Identifying the point of shock initiation with the location of such a cusp, then the formation of a shock will be signalled by the simultaneous vanishing of t_r and t_{rr}, but

$$
\begin{aligned}
t_r(r,s) = \frac{\lambda}{2}\Big\{ & \frac{6(s-s_o)^2}{(r_o+s_o)^5}\Big[(r-r_o)^2+2(r+s)(r-r_o)\Big] + \frac{6(s-s_o)}{(r_o+s_o)^4}\Big[(r+s)^2+2(r+s)(r-r_o)\Big] \\
& + \frac{3(r+s)^2}{(r_o+s_o)^3}\Big\} + \frac{(r+s)^3}{(r+s_o)^4}\left(\frac{5R}{2}\right)\left\{\left(1-\frac{r-r_o}{5R}\right)^{-7}\left(\frac{R+1}{R}\right)-1\right\} \\
& + \int_{r_o}^{r}\frac{5R}{2(\rho+s_o)}\left\{\left(1-\frac{\rho-r_o}{5R}\right)^{-7}\left(\frac{R+1}{R}\right)-1\right\} \\
& \Big\{\frac{6(s-s_o)^2}{(\rho+s_o)^5}\Big[(r-\rho)^2+2(r+s)(r-\rho)\Big] + \frac{6(s-s_o)}{(\rho+s_o)^4}\Big[(r+s)^2+2(r+s)(r-\rho)\Big] \\
& \quad + \frac{3(r+s)^2}{(\rho+s_o)^3}\Big\}\, d\rho \\
& + \int_{s}^{s_o}\frac{5R}{2(r_o+\sigma)}\left\{\left(1-\frac{s_o-\sigma}{5R}\right)^{-7}\left(\frac{R-1}{R}\right)-1\right\} \\
& \Big\{\frac{6(s-\sigma)^2}{(r_o+\sigma)^5}\Big[(r-r_o)^2+2(r-r_o)(r+s)\Big] + \frac{6(s-\sigma)}{(r_o+\sigma)^4}\Big[(r+s)^2+2(r+s)(r-r_o)\Big] \\
& \quad + \frac{3(r+s)^2}{(r\ +\sigma)^3}\Big\}\, d\sigma
\end{aligned}
\qquad (21)
$$

and

$$
\begin{aligned}
t_{rr}(r,s) = {} & \lambda\left\{\frac{6(s-s_o)^2}{(r_o+s_o)^5}\Big[2(r-r_o)+(r+s)\Big] + \frac{6(s-s_o)}{(r_o+s_o)^4}\Big[2(r+s)+(r-r_o)\Big]\right. \\
& \left. + \frac{3(r+s)}{(r_o+s_o)^3}\right\} + \frac{7}{2}\left(\frac{R+1}{R}\right)\frac{(r+s)^3}{(r+s_o)^4}\left(1-\frac{r-r_o}{5R}\right)^{-8} \\
& + \frac{5R}{2}\left[\left(1-\frac{r-r_o}{5R}\right)^{-7}\left(\frac{R+1}{R}\right)-1\right]\frac{2(r+s)^3}{(r+s_o)^5} \\
& + \int_{r_o}^{r}\frac{5R}{2(\rho+s_o)}\left\{\left(1-\frac{\rho-r_o}{5R}\right)^{-7}\left(\frac{R+1}{R}\right)-1\right\} \\
& \left\{\frac{12(s-s_o)^2}{(\rho+s_o)^5}\Big[2(r-\rho)+(r+s)\Big] + \frac{12(s-s_o)}{(\rho+s_o)^4}\Big[2(r+s)+(r-\rho)\Big] + \frac{6(r+s)}{(\rho+s_o)^3}\right\}d\rho \\
& + \int_{s}^{s_o}\frac{5R}{2(r_o+\sigma)}\left\{\left(1-\frac{s_o-\sigma}{5R}\right)^{-7}\left(\frac{R-1}{R}\right)-1\right\} \\
& \left\{\frac{12(s-\sigma)^2}{(r_o+\sigma)^5}\Big[2(r-r_o)+(r+s)\Big] + \frac{12(s-\sigma)}{(r_o+\sigma)^4}\Big[2(r+s)+(r-r_o)\Big] + \frac{6(r+s)}{(r_o+\sigma)^3}\right\}d\sigma
\end{aligned}
\tag{22}
$$

The requirement of the vanishing of the right-hand sides of Eqs. (21) and (22) simultaneously does impose two restrictions upon the two variables r and s, so such a cusp point may or may not be found for a particular pair of values of the parameters λ and R. If a solution of these simultaneous polynomial equations is somehow determined, then the corresponding pair r_c, s_c can be inserted in Eq. (20) to calculate the dimensionless time of shock initiation, $t(r_c, s_c)$.

To find the corresponding location of the shock initiation, we may integrate either the differential relation $x_s=(u+a)t_s$ along an r characteristic, or the relation $x_r=(u-a)t_r$ along an s characteristic. Choosing the latter gives $x_r=(0.8r-1.2s_c)t_r$, along the s characteristic through the cusp, for a bimolecular gas. Hence,

$$x(r_c,s_c) - x(r_o,s_c)= \int_{r_o}^{r_c} (0.8\rho-1.2s_c)t_\rho(\rho,s_c)d\rho \tag{23}$$

where

$$x(r_o,s_c) - x(r_o,s_o)=- \int_{s_c}^{s_o} (1.2r_o-0.8\sigma)t_\sigma(r_o,\sigma)d\sigma$$

and $x(r_o,s_o)= \frac{\lambda}{2}$; so,

$$x(r_c,s_c)= \frac{\lambda}{2} +\int_{r_o}^{r_c} (0.8\rho+1.2s_c)t_\rho(\rho,s_c)d\rho-\int_{s_c}^{s_o} (1.2r_o-0.8\sigma)t_\sigma(r_o,\sigma)d\sigma \tag{24a}$$

or, integrating by parts,

$$x(r_c,s_c)=(0.8r_c+1.2s_c)t(r_c,s_c)+(0.4r_o-2s_c)t(r_o,s_c)-.8\int_{r_o}^{r_c} t(\rho,s_c)d\rho \\ -.8\int_{s_c}^{s_o} t(r_o,\sigma)d\sigma \tag{24b}$$

For shock initiation in the simple region, Friedrichs showed that when the piston acceleration was non-increasing, the cusp appeared along the leading compressive characteristic, which also formed the upper edge of the fold, with the entire overlap region lying ahead of that initial characteristic. Although in that degenerate "simple-wave" case the mapping is nowhere one-to-one, it still might seem reasonable to expect generally similar behavior in the interaction region; however, numerical experiments indicate an entirely different behavior. These results indicate that steepening of the compression wave-front is immediately halted by the interaction with the expansion, so shock formation apparently can never result if it has not already occurred before interaction. The only effect of still further decrease in capsule length below the critical value of $\frac{4}{\gamma+1}$ seemingly is to cause the freezing of the gradient at decreasing levels, since the compression will not have steepened so much and the expansion will not have flattened so much before interaction. If these indications, which contradict the conclusions of Genovese[10], are indeed true, then Eqs. (21) and (22) cannot have a common root within the indicated domain.

Presumably, similar phenomena are to be expected in the steady, planar, irrotational, supersonic, initially uniform flow through a channel with identically curved walls which are both parallel to the undisturbed velocity at entrance and which have decreasing radius of curvature along the channel.

SECION V

CONCLUSIONS

In a hypervelocity aerodynamic test facility the basic objective is to provide a test gas of specified composition and thermodynamic state, which simultaneously has a specified velocity relative to a test body. Usually the test speed need not equal actual flight speed. Because of the many advantages of a stationary model and the relative densities of gas and model it is generally preferable to accelerate only the gas, if this can be accomplished without significant degradation of the final state of the gas.

The most common method of accelerating the gas for such "wind tunnels" has been the adiabatic expansion of previously heated and compressed gas. The compression of the test gas has sometimes been accomplished by electric discharge at constant volume, but more usually through the mechanism of a strong moving normal shock wave. Of all adiabatic compression processes, such shock compression requires the shortest stroke for the attainment of desired final conditions; but is so irreversible that driver requirements become a severe limitation. Hence, slower adiabatic compressions approximating closely the ideal isentropic process are deservedly of increasing interest, despite the required longer strokes.

For test gases of usual interest, though, the pressure and temperature ratios required for acceleration to hypervelocities, using adiabatic expansion, are extremely high. That is to say, the desirable gases for an aerodynamic test facility are very unlikely to be efficient propellants; so specified test conditions frequently correspond to prohibitive reservior conditions. Therefore, non-adiabatic expansions have attracted increasing attention; but because significant changes in thermodynamic state still occur during such acceleration, finite-rate chemistry must still be expected to lead to unwanted deviations of the final state.

Only if the specified test section density and temperature are unusually high or the state of the gas is not required to change at all during acceleration do non-equilibrium effects, which usually are undesirable, seem avoidable. External mechanical acceleration of encapsulated gas does satisfy the latter requirement and thus offers the possibility of markedly surpassing performance limitations of known types of hypervelocity wind tunnels. Apparently shock formation within the confined test gas during acceleration will not inpose intolerable limits upon such a technique. Propulsion of such a capsule may be by the unsteady expansion of a hot compressed driver gas, by direct electromagnetic acceleration, kinematically-staged rockets, or by any other ballistic method or combination which does not exceed the acceptable acceleration level; but the less the decay in acceleration, the shorter the distance required to attain a desired velocity.

SECTION VI

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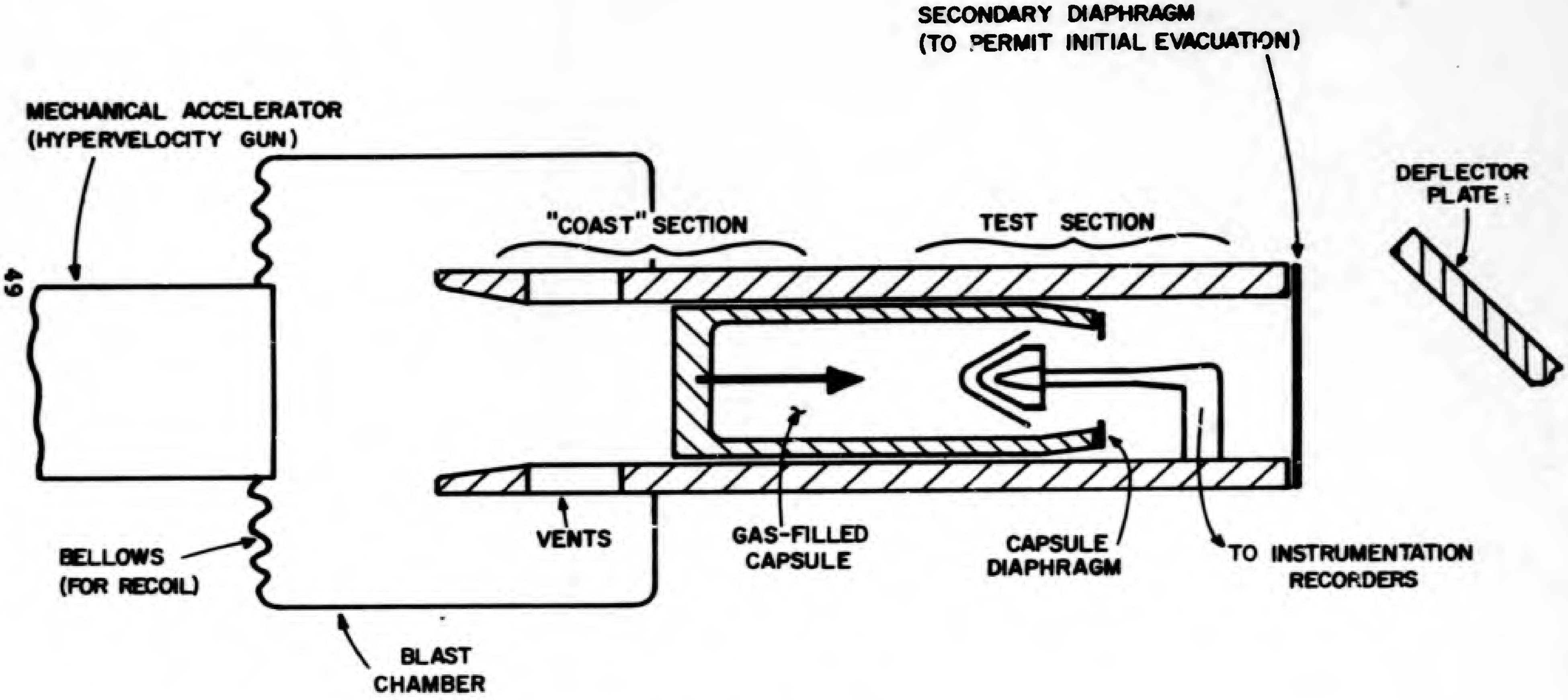


FIG (I) THE "SLINGSHOT" CONCEPT

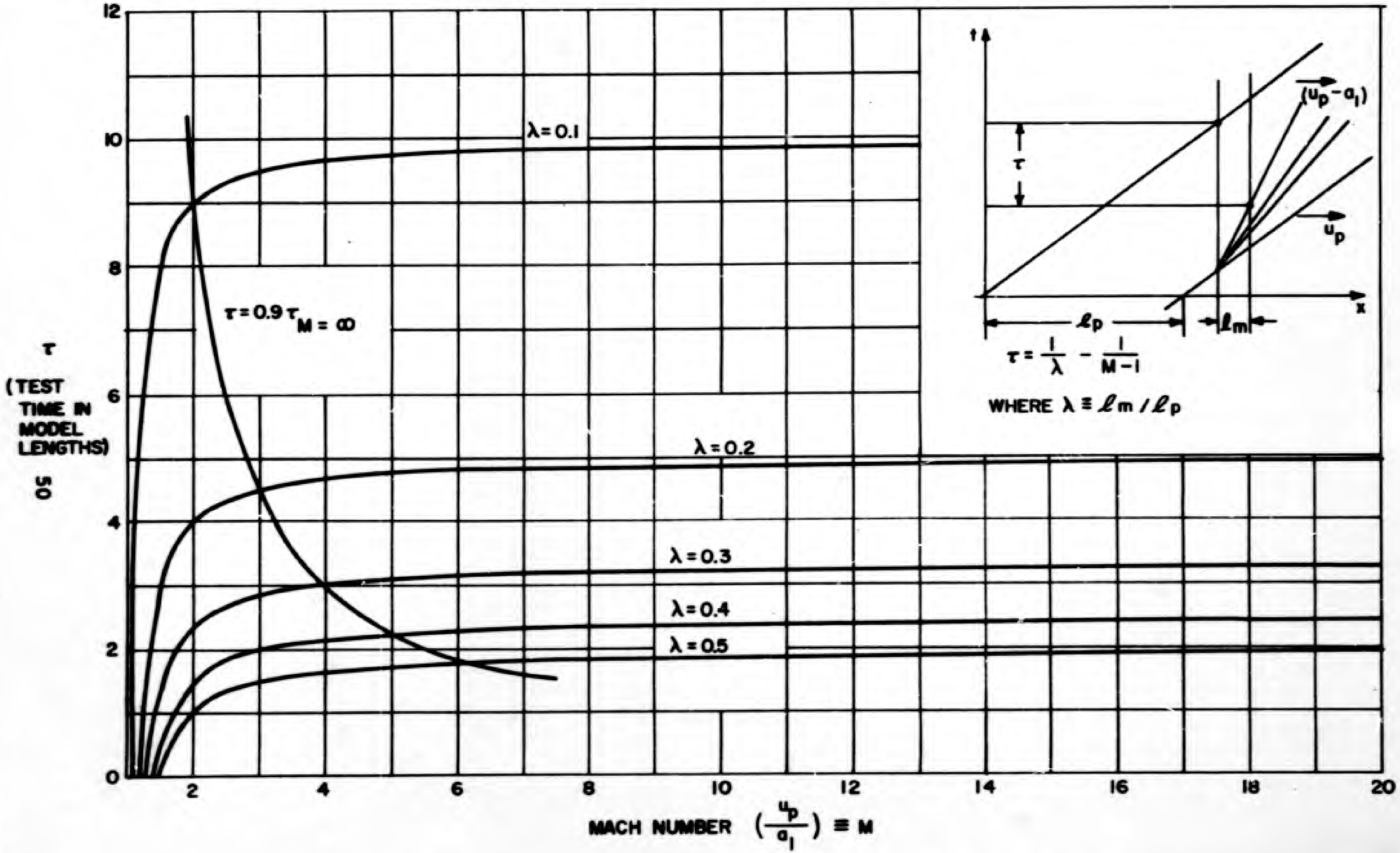
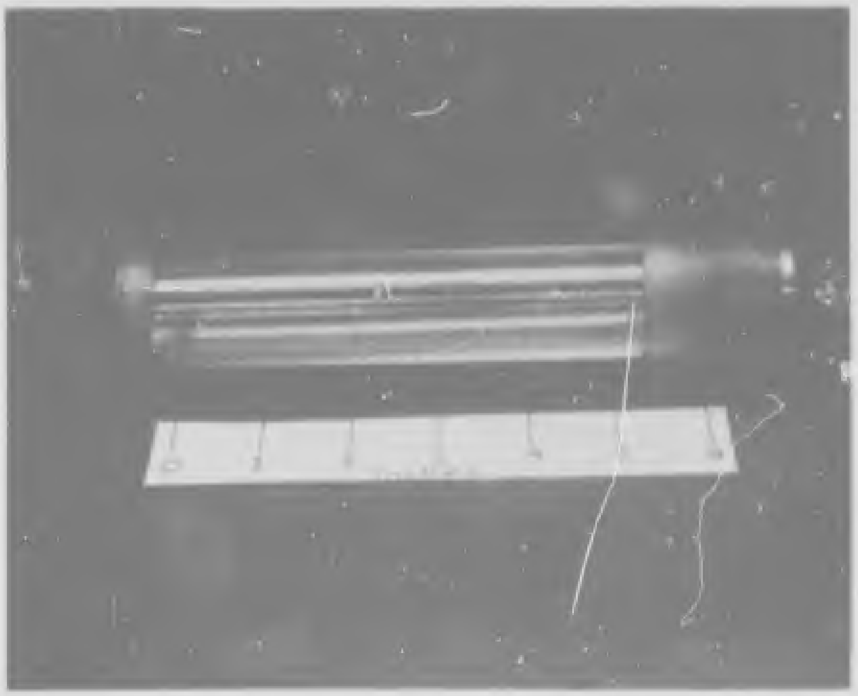


FIG. (2) RELATIVE TEST TIME VERSUS MACH NUMBER

(a) DRIVER END

(b) TEST SECTION

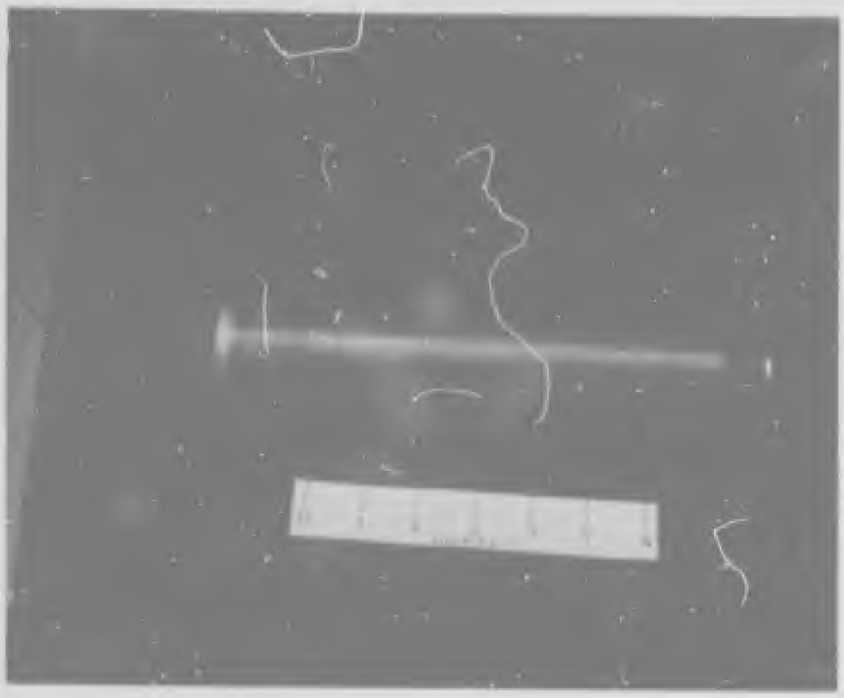
FIG. (3) SLINGSHOT PILOT TUBE (MOUNTED ABOVE LARGE SHOCK TUBE)



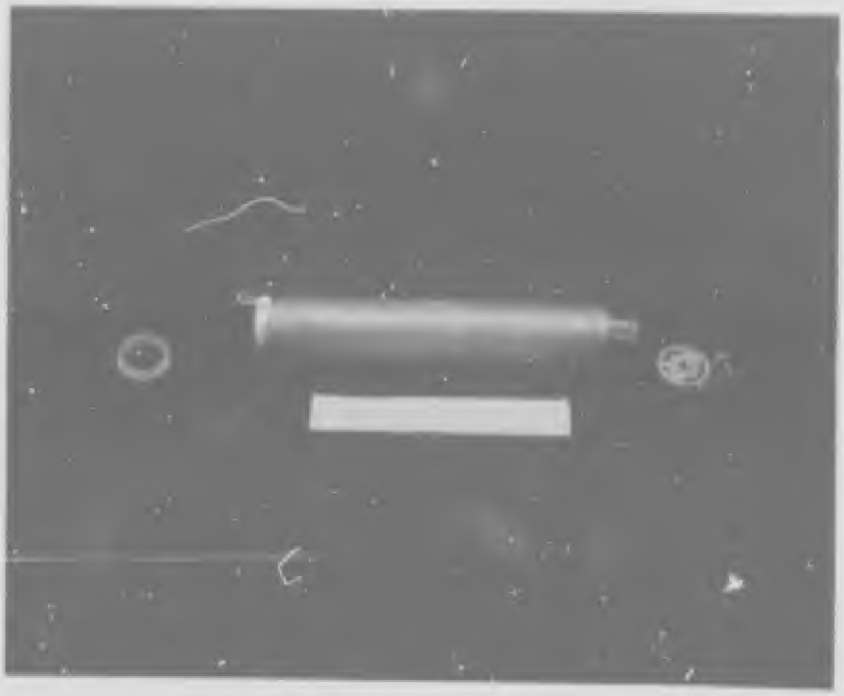
(a) ASSEMBLY

(b) FASTENED TO PRIMARY DIAPHRAGM, CUTTER DISK, AND SUPPORT PLATE

FIG. (4) INITIAL CAPSULE

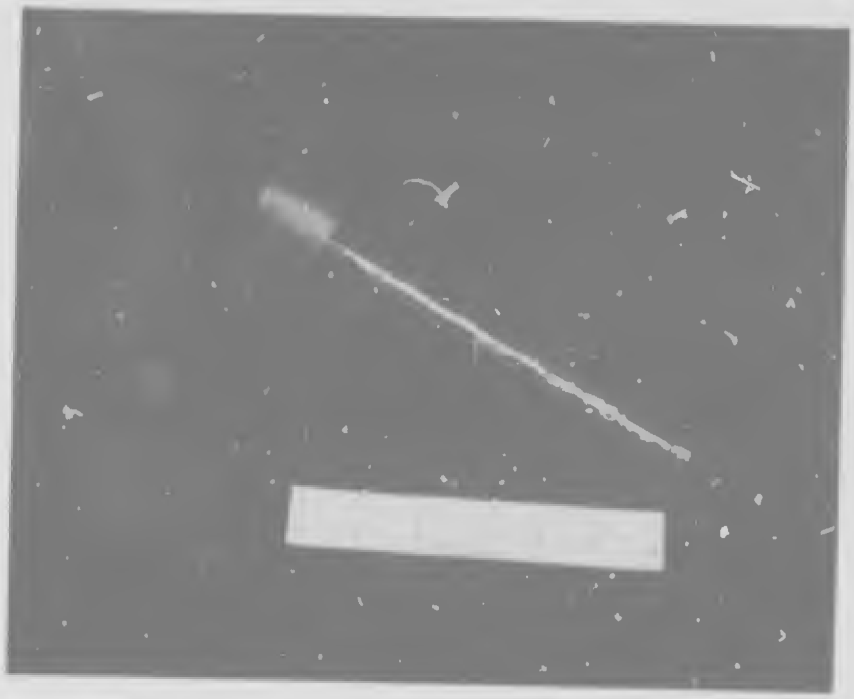


(a) ASSEMBLY



(b) DIAPHRAGM CLAMP RING, CAPSULE, AND CUTTER DISK

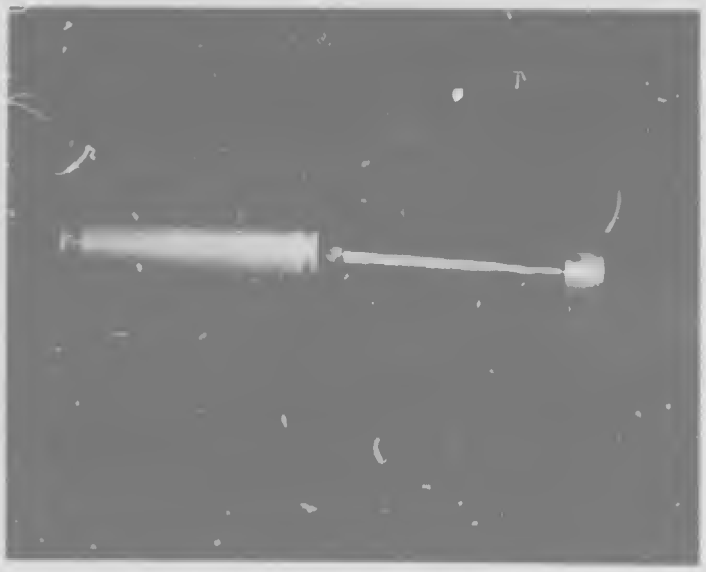
FIG. (5) INTEGRAL LEXAN CAPSULE



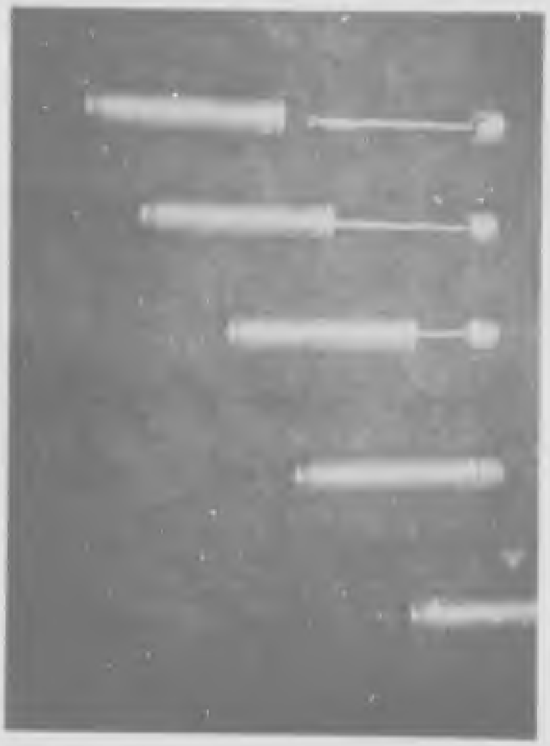
(a) PROBE ON SUPPORT

(b) DIAPHRAGM CUTTER

FIG. (6) TOTAL TEMPERATURE PROBE



(a) RELATIVE POSITION BEFORE TEST



(b) SIMULATED TEST SEQUENCE

FIG.(7) CAPSULE AND INSTRUMENTATION PROBE

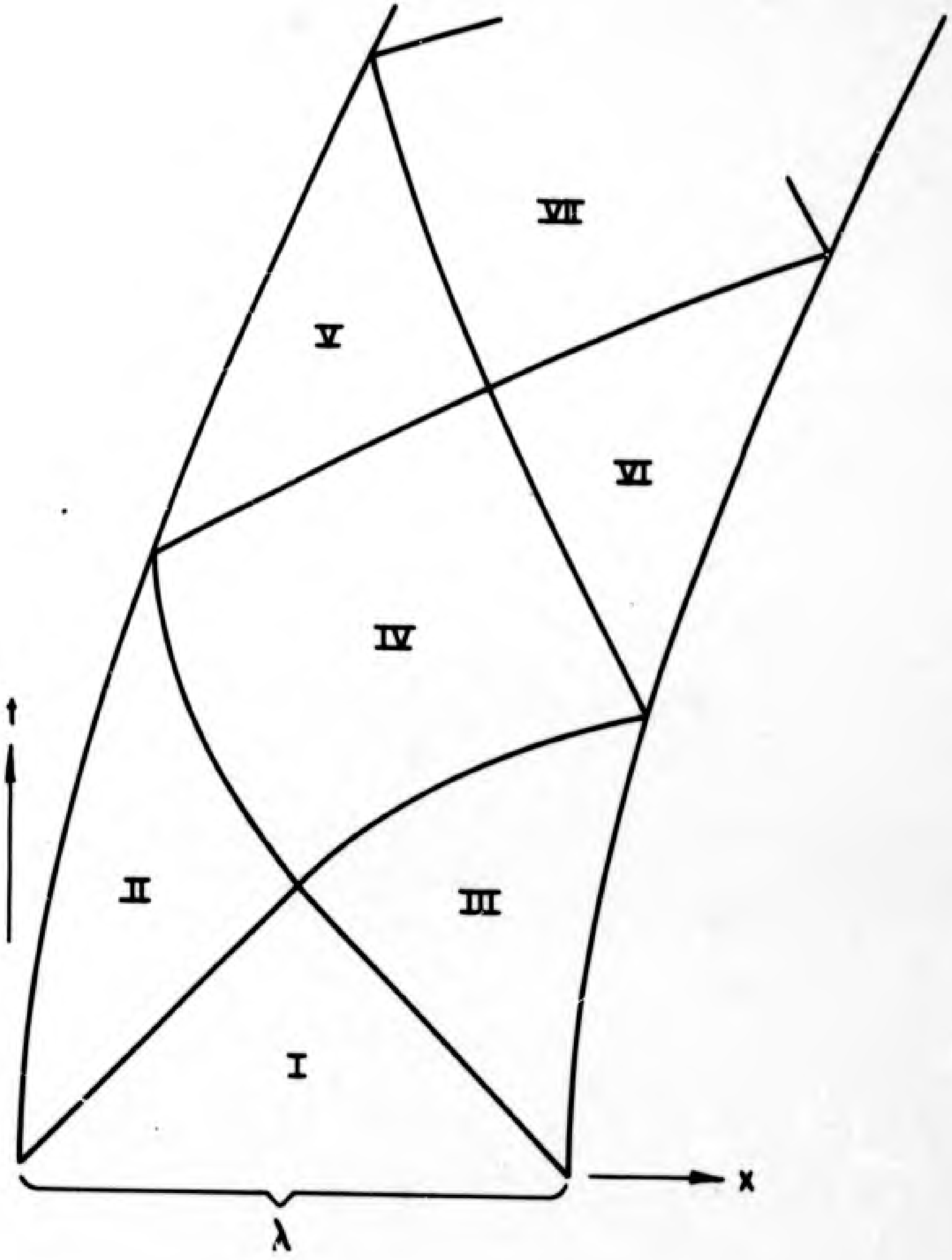


FIG. (8) WAVES WITHIN AN ACCELERATING GAS FILLED CAPSULE

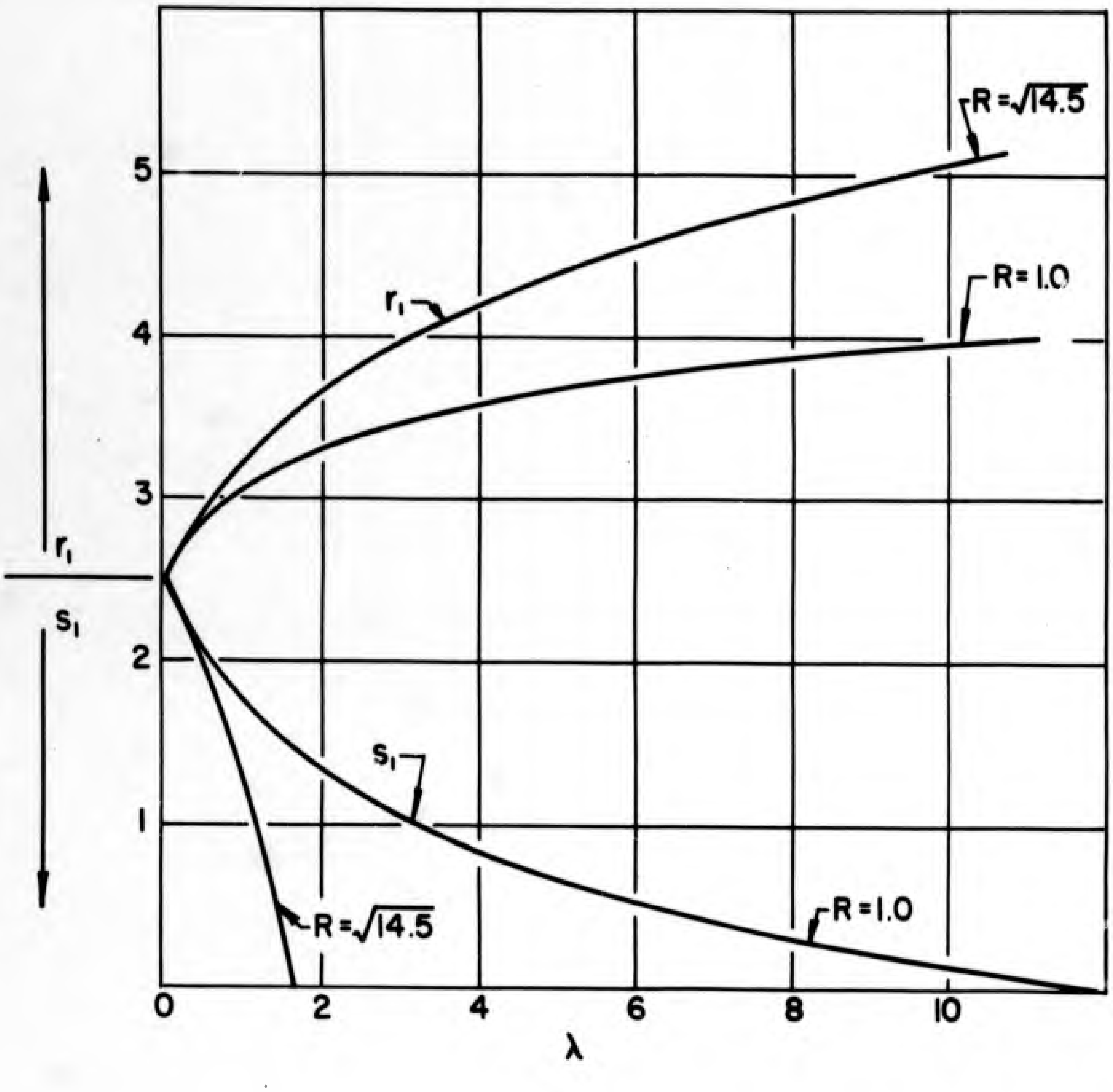


FIG. (9) LIMITING CHARACTERISTICS OF FIRST INTERACTION REGION (FOR $\gamma = G = 1.4$)

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13. ABSTRACT

Mechanical acceleration of an encapsulated relatively dense, neutral gas is suggested for the gas supply of a non-conventional wind tunnel. Design considerations for such a novel aerodynamic test facility, christened "Slingshot", are discussed. Particular attention is concentrated upon the possibility of shock formation within the confined gas during acceleration.

The relationship of the widely-used "shock compressor" within the general class of adiabatic compressors and its limitation for the production of increased temperatures of dense gases are also explained. The potential advantage of "kinematic staging" for advanced aerodynamic test facilities is stressed.

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