March 26, 1968 C. S. GODFREY 3,374,668

HIGH EXPLOSIVE DRIVEN GAS INJECTOR AND FACILITY

Filed Oct. 19, 1964 4 Sheets-Sheet 1

Fig. 1.

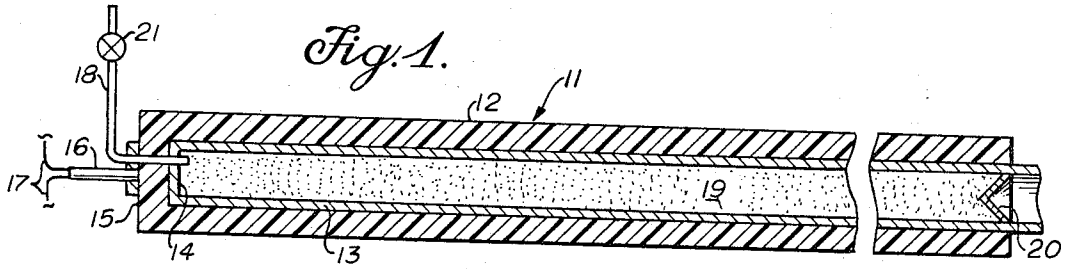


Fig. 2.

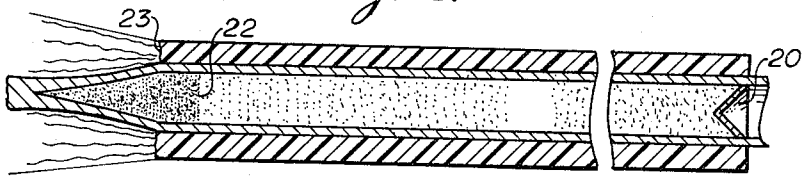


Fig. 3.

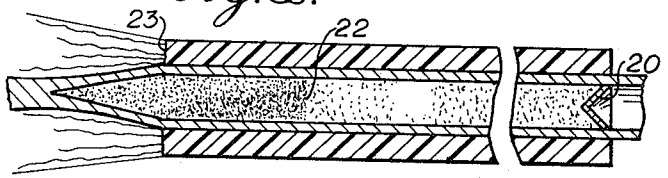
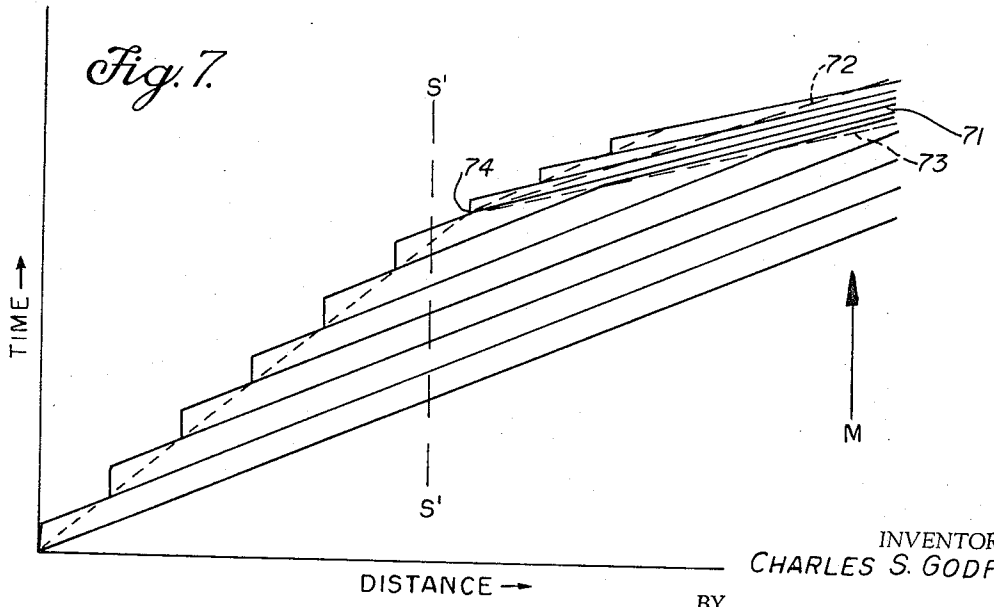


Fig. 7.



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HIGH EXPLOSIVE DRIVEN GAS INJECTOR AND FACILITY

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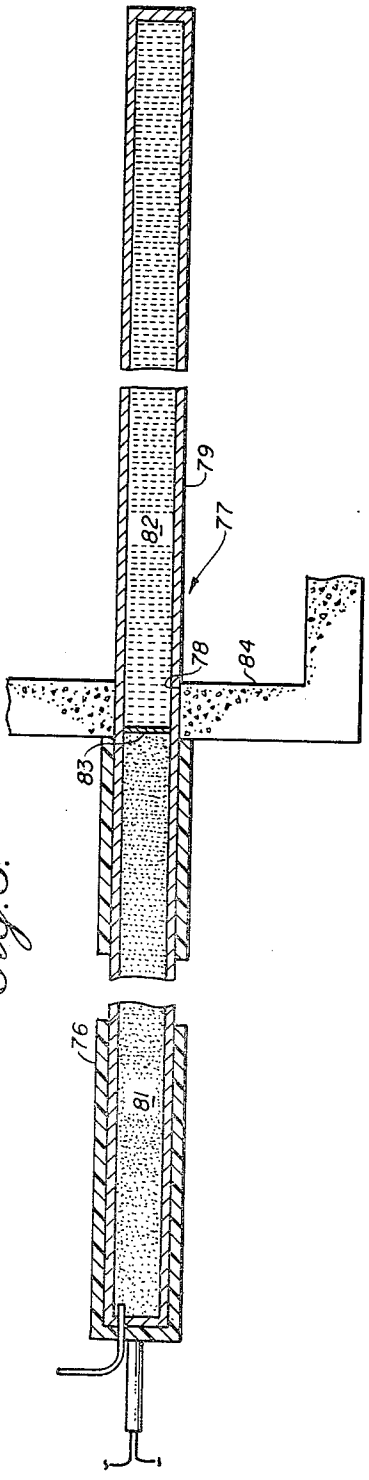


Fig. 8.

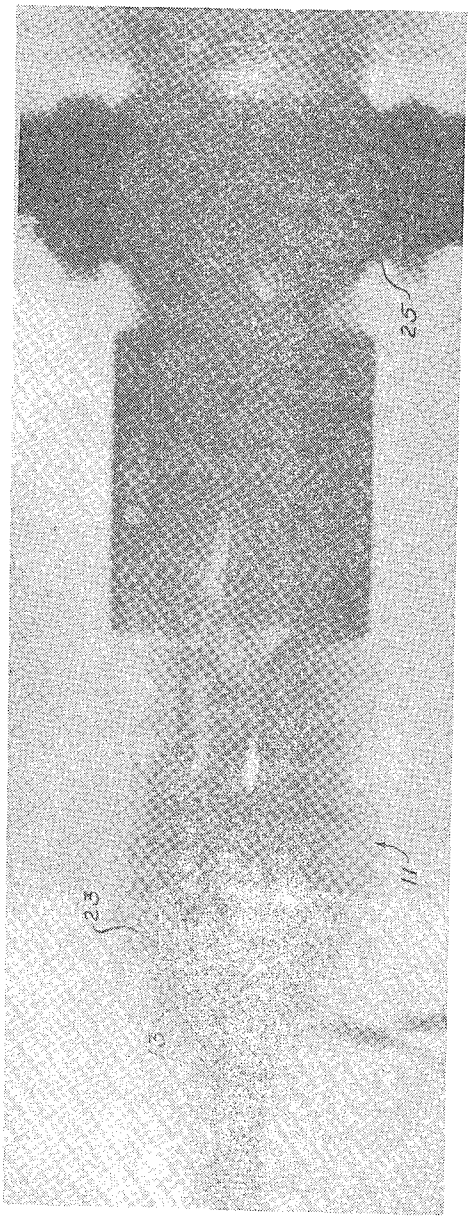


Fig. 4.

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HIGH EXPLOSIVE DRIVEN GAS INJECTOR AND FACILITY

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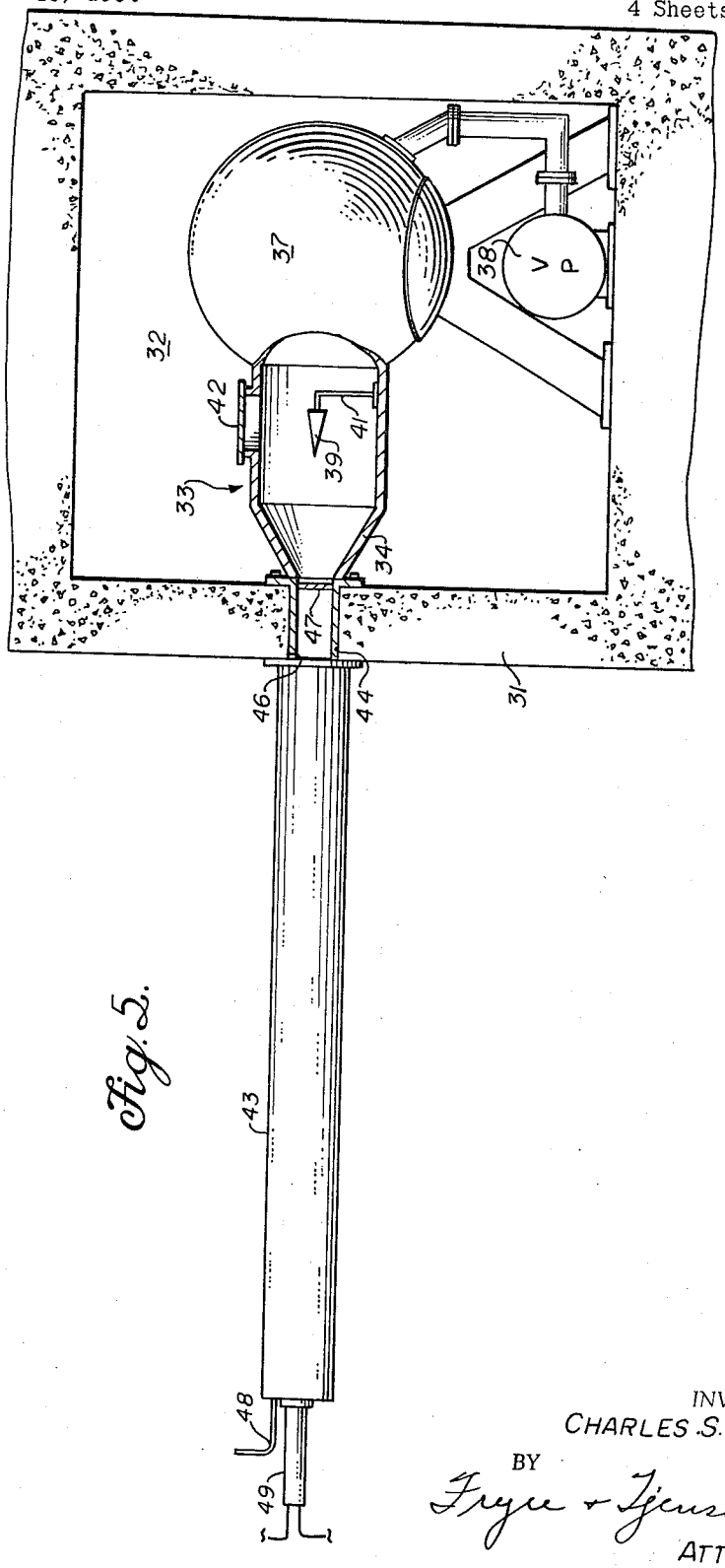


Fig. 5.

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HIGH EXPLOSIVE DRIVEN GAS INJECTOR AND FACILITY

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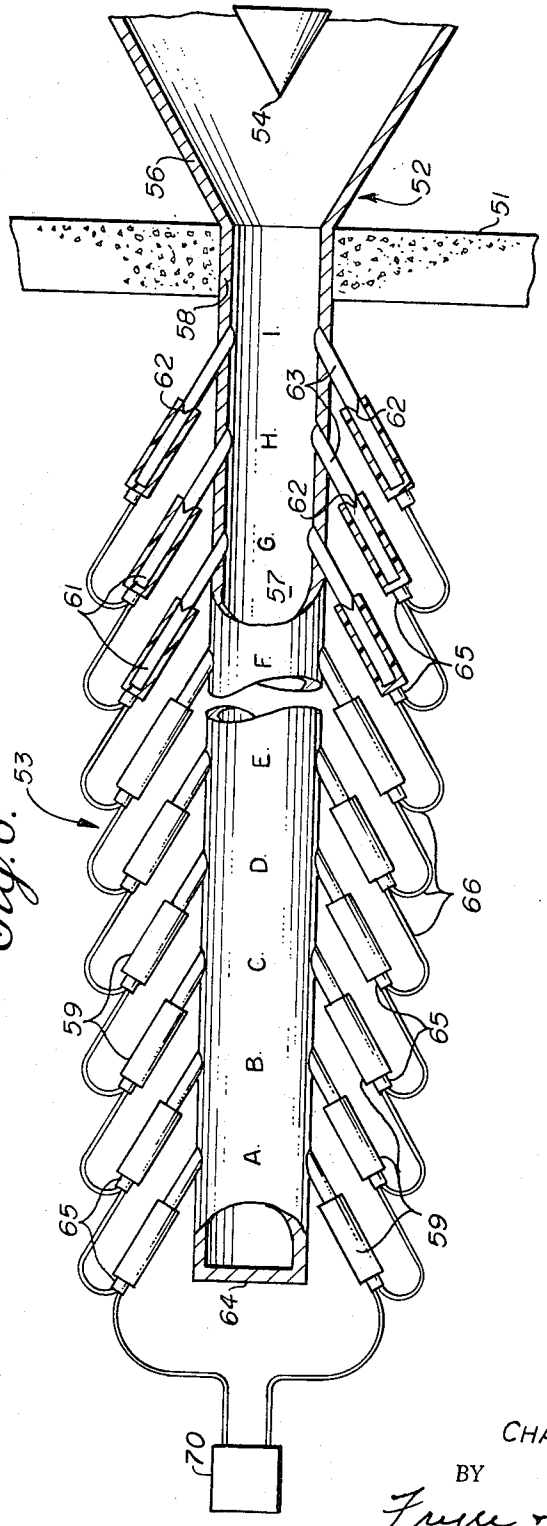


Fig. 6.

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Patented Mar. 26, 1968

3,374,668

HIGH EXPLOSIVE DRIVEN GAS INJECTOR AND FACILITY

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Filed Oct. 19, 1964, Ser. No. 404,837
18 Claims. (Cl. 73—147)

The present invention relates to gas injectors and more particularly to gas injectors driven by high explosives, and further to facilities wherein such devices are utilized.

The advent of the space age has brought into prominence the problems of designing vehicles which are capable of re-entering gaseous atmospheres from space without undue damage to the vehicle structure and especially without damage to the pay load, i.e., vehicle contents. The proper design of re-entry vehicles is of even greater importance where such vehicles are to be manned during flight. More specialized problems in this area are presented in the design of re-entry vehicles having the mission of delivering weapons systems. Such vehicles, in addition to encountering the normal re-entry environment, must also be designed to withstand high blast loadings from defensive countermeasures devices.

A great deal of data is needed to properly design such re-entry systems. Ideally, of course, the required data could best be acquired under actual re-entry conditions. However, the costs of conducting such experiments are extremely high, and in addition instrumentation problems are extremely great. Therefore, in order to acquire the requisite data, those active in the art have had to resort to facilities that simulate the conditions encountered in such a re-entry environment.

The ideal simulation facility would subject full scale re-entry vehicles to re-entry and blast conditions simulated exactly, or approximately, to the actual conditions and thereby assess the ability of those systems to withstand the re-entry requirements. Simulation tests in ground facilties inevitably provide less than the ideal requirement. Such facilities must simulate a re-entry environment in that air or an atmosphere must be provided at the proper density, temperature and relative velocity for the range of re-entry vehicle designs to be tested. In addition, where war head delivery systems are to be tested, the facility must provide blast loadings sufficient to provide data in the anticipated blast ranges. An ideal simulation facility should be able to reproduce blast loadings sufficient to test hardened vehicles under severe loading conditions. A reasonable facility which should be suitable for testing to the maximum envisioned requirement should be capable of reproducing atmosphere accelerations in the neighborhood of 1,000 G's.

Up to the present time many different types of facilities have been constructed for the purpose of reproducing re-entry conditions as noted above. Such facilities comprise so-called hypersonic wind tunnels, shock tubes, shock tunnels, free flight ballistic ranges, and rocket propelled sleds. However, each of the above noted types of facilities suffers from at least one defect which does not permit it to be used for the universal simulation of re-entry and blast conditions. Thus, for instance, while hypersonic wind tunnels have the advantage of stationary test models which can be easily and simple instrumented, it is extremely difficult to provide gaseous flow of sufficiently high velocity, mass and time duration to simulate the desired re-entry conditions. On the other hand, free flight ballistic ranges suffer from the defect of the more difficult instrumentation and gathering of data from the test model which must be flown in such a facility.

Furthermore modern re-entry vehicles are generally so complex structurally that their structural responses cannot be adequately reproduced in small scale models.

Many of the thermal or aerodynamic interactions between the vehicle and its environment cannot be scaled from small size to full size with any great degree of certainty. In general, the usefulness of a simulation facility increases as the model utilizable therein approaches full scale dimensions.

Now the present invention presents a re-entry simulation facility capable of reproducing a broad range of re-entry environments as well as blast conditions suitable for testing all types of space vehicles. A new driver technique is utilized wherein a plurality of explosively driven gas injectors deliver an initial flow of gas, most usually air, to simulate re-entry conditions. This flow of air is similar to a hypersonic wind tunnel and provides temperatures, pressures and velocities that correspond to the full range of re-entry conditions; however with the added advantage that essentially full scale models may be instrumented therein.

For testing blast effects a second set of injectors produce a shock wave that can be tailored to simulate a wide range of blast conditions wherein the time spacing between re-entry condition onset and the blast wave is precisely controlled. In addition the present facility using the unique driver technique delivers such a volume of air that the size of the model exposed to the re-entry and blast environments can approach full scale. The ability to use full scale models permits copious dynamic measurements of flow fields, loadings and structural responses of the model. In addition, since the model is stationary in the present facility, instrumentation and acquision of data from the model is quite easy and simple.

It is, therefore, an object of the present invention to provide a hypersonic wind tunnel wherein essentially full scale models may be utilized.

It is another object of the present invention to provide a hypersonic wind tunnel facility that will reproduce an extremely broad range of re-entry conditions.

It is another object of the invention to present a hypersonic wind tunnel facility that can superimpose a blast wave on the re-entry environment wherein the magnitude of such blast wave, as well as the timed spacing between onset of re-entry conditions and the blast wave, is precisely controlled.

Another object of the present invention is to provide a hypersonic wind tunnel that is driven by high explosive actuated gas injectors.

Still another object of the invention is to provide a gas injector for use in hypersonic wind tunnel, shock tubes and shock tunnels.

The features of the invention as well as a clear understanding of the present specification will be obtained from reference to the accompanying drawings in which:

FIG. 1 is a cross sectional schematic view of the explosive driven gas injector of the invention;

FIG. 2 is a schematic representation of the gas injector illustrated in FIG. 1 at a time several microseconds after initiation of the explosive;

FIG. 3 is a schematic representation of the gas injector illustrated in FIG. 1 at a period in time several microseconds later than that illustrated in FIG. 2;

FIG. 4 is a flash X-ray photograph of a gas injector of the invention actually imploding during a firing sequence;

FIG. 5 is a schematic illustration of a hypersonic wind tunnel facility of the present invention employing a single explosively driven gas injector;

FIG. 6 is a schematic illustration of one embodiment of a re-entry and blast simulator facility of the present invention wherein a plurality of explosively driven gas injectors are utilized;

FIG. 7 is a graph illustrating the flow of high velocity

air and a later arriving blast front in a re-entry and blast simulator facility as illustrated in FIG. 6; and

FIG. 8 is a schematic illustration of a shock tube facility utilizing the explosively driven gas injector of the invention.

The re-entry and blast hypersonic wind tunnel facility of the present invention is powered by explosively driven linear gas injectors **11** such as illustrated in FIG. 1 of the drawings. Such a gas injector is mechanically a very simple device and comprises an elongated tubular or "pipelike" outer body **12** fabricated from any suitable high explosive composition. High explosive outer body **12** surrounds a liner **13**. Liner **13** is most usually fabricated from a metal, and its wall thickness is very thin when compared to the thickness of the high explosive outer body **12**. The gas injector **11** is capped at one end with a wall liner **14** backed by a disc of high explosive **15**. A detonator **16** is inserted into the exterior end of high explosive disc **15**. Electrical connections **17** lead from detonator **16** to a source of electrical power (not shown). It should be understood that any suitable means may be employed to detonate detonator **16**. Thus permacord could be attached to detonator **16** in lieu of the direct electrical connection **17**.

A gas fill pipe **18** penetrates high explosive end cap **15** and wall liner **14** and communicates into a central cylindrical chamber **19**. A metal diaphragm **20** caps the other end of gas injector **11**. End cap **20** is preferably of a conical shape wherein the apex of the cone projects into chamber **19**. However, a flat diaphragm may be substituted therefor under many circumstances. A valve **21** situated remote from gas injector **11** connects gas fill tube **18** to a remote source of gas (not shown).

In generating a pulse of gas at very high velocities, temperatures and pressures, injector **11** operates in the following manner. Valve **21** which is connected to a source of suitable gas, e.g., air, is opened to admit the gas under pressure into chamber **19**. The amount of gas admitted to chamber **19** and its attendant pressure is preselected in order that the gas will be accelerated to the desired temperatures and pressures as will be discussed hereinafter. After chamber **19** is filled with a suitable quantity of gas, valve **21** is closed whereby gas injector **11** is isolated from the gas source. Detonator **16** is then detonated by an electrical current passing through wires **17**.

The detonation of detonator **16** causes high explosive end cap **15** to explode and this explosion is communicated to high explosive outer body **12**. The explosion is propagated in outer body **12** from the left end, as illustrated in FIG. 1, progressively from left to right throughout the entire length of injector **11**. The progression of this explosion is illustrated in FIGS. 2 and 3 which schematically depict the explosion at successive periods in time. As shown in FIGS. 2 and 3, the explosion of outer body **12** implodes, or collapses, liner **13** successively along the length of the injector **11**.

Since the explosion proceeds from left to right as illustrated in FIGS. 1, 2 and 3, the liner is collapsed such that a cone of compressed liner **13** forms at the initiating end and proceeds progressively down the pipe to the other end. The collapsing liner **13** sweeps up the gas which is contained in chamber **19** and projects it axially down the chamber at a velocity equal to the detonation velocity of the high explosive. The relatively high density of the gas near the point of collapse suppresses the usual metallic jet normally expected to form in such an explosion configuration. As the gas is progressively swept up and projected down the chamber **19**, a shock front **22** forms at the interface between the moving gas and the undisturbed gas. This shock front moves with a constant velocity S given by

$$S=\frac{\eta D}{\eta-1}$$

where D is the velocity of the moving gas and is also equal to the detonation velocity of the explosive, η is the compression caused by this shock, i.e. the ratio of the shocked density of the gas to its original density. Since η is always greater than 1, it can be seen that S is always larger than D and hence the shock wave proceeds down the length of injector **11** ahead of the detonation and in fact becomes further and further ahead of it.

Shock front **22** eventually reaches diaphragm **20** causing its disintegration and the projection of the compressed pulse of gas within chamber **19** axially out the muzzle end of liner **13**. Such high pressure, high velocity pulse of gas is then utilized in a wind tunnel in a manner that will be subsequently shown.

The gas pressure generated behind shock from **22** may be calculated using the following equation where the indicated relation is true only for a perfect gas and therefore an approximation of actual gases:

$$P_1=\left(\frac{\gamma+1}{2}\right)\rho_0 D^2 \qquad (1)$$

The above equation also assumes the initial gas pressure is negligible compared to P_1, wherein P_1 equals the pressure generated behind shock front **22**, ρ_0 equals the initial density of the gas in chamber **18**, γ equals the ratio of specific heats of the particular gas accelerated in the injector, and D equals the detonation velocity of the high explosive used to implode the liner.

Thus it can be seen that the pressure generated behind shock front **22** depends upon the nature of the gas used to fill chamber **18**, its initial density therein, and the detonation rate of the high explosive used in fabricating outer body **12**. Thus for instance, if helium ($\gamma=5/3$) were placed in chamber **19** at an initial pressure of 170 atmospheres, or 0.030 gram per cubic centimeter, and if an explosive having a detonation velocity of 0.75 centimeters per microsecond (25,000 feet per second) were used to form outer body **12**, the pressure generated behind shock front **22** would be 23 kilobars, a very high pressure indeed. The corresponding temperature is 10,000° Kelvin.

As Equation 1 supra indicates, the shocked velocity of the gas pulse is dependent in part upon the high explosive used in the fabrication of outer body **12**. Suitable explosives may be TNT (tri-nitrotoluene), PETN (pentaerythritol tetranitrate), composition B (60% cyclonite, 40% TNT and 1% wax) or any other similar high explosive material. Such explosives are selected primarily from the standpoint of the desired detonation rate. Another explosive that has been found to be useful in the gas injector is the liquid high explosive known as NTN which comprises 51.7% nitromethane, 33.2% tetranitromethane and 15.1% 1-nitropropane. Such explosive has a detonation rate comparable to the aforementioned explosives, however, its use in the present gas injector requires an outer shell whereby the liquid explosive can be retained between such shell and liner **13**.

The ultimate velocity of the gas mass ejected from gas injector **11** can also be calculated mathematically. Thus, if the gas mass is expanded to zero enthalpy under steady flow conditions, the maximum velocity U_2 is calculated by means of the following equation (indicated for a perfect gas):

$$U_2=D\sqrt{\gamma+1} \qquad (2)$$

where all of the symbols are the same as those indicated in the quation above. Thus, if helium were charged into injector **11** under the same conditions as noted above, the gas could be expanded to a velocity of approximately 40,000 feet per second.

On the other hand, where the gas ejected from chamber **19** is expanded to zero enthalpy under non-steady flow conditions, the velocity U_2 is calculated from the following equation (assuming a perfect gas):

$$U_2=D\left(1+\sqrt{\frac{2\gamma}{\gamma-1}}\right) \qquad (3)$$

Once again utilizing helium at the figures first noted, it is found that the leading gas could be expanded to a velocity of approximately 80,000 feet per second. Helium acts essentially as a perfect gas in this region of pressure, temperature and volume. However, it should be understood that for air or other non-perfect gases, the velocities to which the gas mass will be accelerated are somewhat lower.

FIG. 4 is an actual flash X-ray photograph of the gas injector of the invention at a time when the liner has collapsed nearly to the end of its length. This illustrates pictorially the manner in which the liner collapses as previously described. The high explosive outer body cannot be seen in the figure since it is transparent to the X-rays. However the convergence of the liner **13** can clearly be seen to the left of the detonation front **23**. The muzzle end of the injector corresponds with the heavy diaphragm fitting **25** that appears as a dark vertical mass. Chamber **19** appears as the slightly lighter central portion running the length of the injector **11**. The heavy rectangular mass just to the left of the diaphragm fitting **25** is merely a heavy metal ring surrounding liner **13**. It is there for experimental purposes only and plays no part in the actual operation of the gas injector.

The gas injector illustrated in operation in FIG. 4 had a steel liner with an inside diameter of 5/8", and a wall thickness of 35 mils. The high explosive outer body was Du Pont EL 506 A, a PETN explosive. The outside diameter of the high explosive was 2 inches. The detonation front (at a position adjacent the beginning of the liner convergence) is approximately 23 inches from the initiating end of the liner.

The gas in liner **13** was nitrogen and it had an initial pressure of 9.2 atmospheres. The explosive had a detonation velocity of 25,300 feet per second. The observed velocity of shock in the nitrogen was 30,000 feet per second. Such a nitrogen pulse would have a pressure in excess of 7.0 kilobars and a temperature in excess of 14,000° Kelvin.

In order for a hypersonic wind tunnel to yield a desirable amount of data, it should deliver a large mass of gas (so that the expansion chamber may have the largest diameter possible) and it should further deliver this mass of gas for as long a period of time as possible, in order that the phenomena desired to be observed can reach equilibrium and measurements can be made. It should be noted, however, that the linear gas injector as illustrated in FIG. 1 of the drawings has either a limited pressure or a limited injection time.

As noted above, a helium gas charge at an initial pressure of 2500 p.s.i. generates a pressure within the injector of about 23 kilobars. Such a sustained shock pressure may be sufficient in itself to detonate the high explosive in outer section **12**. Thus, as shock front **22** proceeds down the length of injector **11**, the pressure generated in the gas immediately behind the front may be sufficient to pre-ignite the explosive whereby liner **13** is improperly imploded and the mass of gas within chamber **19** is not properly gathered up and accelerated down the length of the injector **11**. This pre-ignition of the high explosive puts an upper limit on the shock pressure which can be built up in the pipe. The upper limit can be extended by employing an insensitive explosive to form outer body **12**.

On the other hand the shock pressure can be reduced by reducing the initial density of the gas injected into chamber **19**. If, however, the shock pressure exceeds the strength of the liner **13**, the latter will expand under the influence of the advancing pressure behind shock front **22** until the detonation front **23** reaches that position. If the expansion has been too large (either because the magnitude or the time duration of the pressure was excessive) pipe liner **13** will probably have failed before it can be imploded by the high explosive. Metal liners can rarely be expanded to twice their diameter without failing. Thus there exists a limit to the length of the gas pulse that can be built up in the pipe. All of the above noted limitations indicate that the linear gas injector as illustrated in FIG. 1 has a maximum gas injection time of about 30 microseconds at the high pressures discussed.

Even such a pulse, however, delivers an impressive amount of air. And this amount of air is extremely useful for hypersonic wind tunnel purposes. As an illustration, a gas injector, having the geometry as illustrated in FIG. 1 of the drawings, wherein the liner **13** has a diameter of 1½ inches, a length of 5 feet, and wherein chamber **19** was initially filled with air at 20 atmospheres' pressure, and using a high explosive having a detonation velocity of approximately 20,000 feet per second, delivered 50 grams of air in a time period of 30 microseconds. In addition such mass of air had a pressure of 11 kilobars at a temperature of 11,400° Kelvin. It should be further noted that the above pressure and temperature are not the customary stagnation values, since the air mass has a large kinetic energy in addition to its potential energy. As the air is expanded to the desired working density it reaches a considerably higher velocity.

Of course longer pulse times may be achieved by reducing the pressures within the gas injector and/or increasing the wall thickness of liner **13** as well as using steels of high yield strength. If the generated pressure does not stress the liner beyond its ultimate strength, the injector pulse time can be made indefinitely long. Using a single gas injector, if it is desired to secure longer pulse times, the pressures generated and the mass of gas delivered must be correspondingly reduced. As an illustration, by initially reducing the pressure of gas in chamber **19** the overall length of the gas injector may be greatly increased. Thus if the 1½ inch diameter liner as previously illustrated is increased to 120 feet long and is initially filled with air at a pressure of ¼ atmosphere and is enclosed with an outer body of the same explosive, it will deliver 14 grams of air over a period of one millisecond at a pressure of 160 atmospheres and a velocity of approximately 20,000 feet per second before expansion. Liner **13** would need a wall thickness of 40 to 70 mils, depending upon the yield strength of the steel used.

Although bound by the limitations discussed supra, the explosively driven gas injector of the present invention can produce relatively massive pulses of gas at experimentally useful pressures and velocities. One such use is schematically illustrated in FIG. 5 of the drawings. FIG. 5 illustrates a hypersonic wind tunnel utilizing a single gas injector of the invention. As illustrated therein, a massive bunker **31** defines an experimental equipment chamber **32**. Housed within chamber **32** is the wind tunnel **33** including an expansion nozzle section **34** at one end thereof, a test portion **36** comprising the model, and a vacuum tank **37** at the end opposite expansion nozzle **34**. Vacuum tank **37** is connected to a vacuum pump **38** by suitable means whereby the atmosphere within wind tunnel **33** may be regulated to any desired pressure level. A model or test specimen **39** is supported axially within test section **36** of the wind tunnel. A suitable stand **41** serves to support model **39** as well as to furnish a conduit for test leads (not shown) from model **39**. Access to the interior of wind tunnel **33** is afforded through hermetically sealed cover **42** in the wind tunnel test section.

An explosively driven gas injector **43** is supported by suitable means (not shown) outside of bunker **31**, however, with the muzzle end **44** thereof passing through a port **46** in the bunker wall and connected to nozzle **34** of wind tunnel **33**. Gas injector **43** is placed in axial alignment with wind tunnel **33**; however, it is sealed from direct communication therewith by a diaphragm **47** interposed between muzzle end **44** and nozzle **34**.

Gas injector **43** is in all respects identical with gas injector **11** as illustrated in FIG. 1 of the drawings. Thus, a gas fill tube **48** and detonator **49** are fixed into the end of gas injector **43** remote from bunker **31**.

In operation a suitable gas such as air is loaded into

the interior of gas injector **43** at the desired pressure. Detonator **49** is then fired and the explosion proceeds down the length of gas injector **43** in the manner as previously described. The gas in the interior of the gas injector is gathered up by collapse of the liner and accelerated down the length of the gas injector. As the shock front reaches diaphragm **47** the diaphragm disintegrates permitting the mass of high pressure high velocity gas to be expanded through nozzle section **34** of the wind tunnel. The expanded gas moving at great velocity rushes past model **39** in the test section of the wind tunnel. The interaction of the model with the gas flow is then observed by suitable instruments.

Such a wind tunnel facility, as illustrated in FIG. 5 of the drawings, is capable of producing a flow of air having an initial velocity at the entrance of the wind tunnel nozzle section of from 20,000 to 30,000 feet per second at pressures in excess of 10 to 20 kilobars. Such an output is quite useful in gathering much of the data desired from re-entry vehicle models. However, as pointed out above, a single gas injector of the present invention is limited either in the time of injection of the gas pulse or in the pressure of the gas pulse. Furthermore, it is most desirable to extend the time duration of the high pressure, high velocity gas flow to as long a period as possible. Also, a single gas injector as illustrated in FIG. 1 of the drawings, cannot produce a blast wave that moves dynamically with the gas flow ejected from the gas injector device. As pointed out supra, the development of blast fronts in the high velocity gas flow is necessary when it is desired to test the effect of countermeasures upon weapon systems delivery vehicles. Thus a second type of wind tunnel facility is provided by the present invention, which facility delivers a flow of high pressure, high velocity gas over a long period of time and which further provides a blast front in said gas flow that is tailored to the requirements of the experimenter.

One embodiment of a wind tunnel facility that produces a sustained flow of high pressure, high velocity gas is illustrated schematically in FIG. 6 of the drawings. Only that portion of the wind tunnel upstream of the model is illustrated. All portions of the wind tunnel downstream of the model are identical with that facility illustrated in FIG. 5 of the drawings.

Specifically, a thick bunker wall **51** separates the wind tunnel test section **52** from the gas injector section **53**. A test model **54** is supported axially within test section **52** in the downstream portion of a diverging nozzle section **56**.

Axially upstream from test section **52** and forming the central portion of the gas injector section **53** is a central injector pipe **57**. The mouth or muzzle end of central injector pipe **57** passes through a port **58** in bunker wall **51**, and connects to the upstream end of divergent nozzle **56**.

Arranged at regular intervals along the length of central injector pipe **57** are a plurality of gas injectors **59**. These gas injectors **59** are identical with the gas injector of the invention previously described. All of the gas injectors are held in fixed position and their muzzle ends project into the interior space of central injector pipe **57**. Also, gas injectors **59** are inclined at an acute angle to the axis of central injector pipe **57**. The gas chambers **61** of each of the gas injectors **59** are sealed from the interior of central injector pipe **57** by means of a diaphragm **62**. The muzzle end of each gas injector is sealed into a port **63** that opens into the interior of central injector pipe **57**.

It should be also noted that the gas injectors **59** are arranged in even multiples along the length of central injector pipe **57** at a series of stations, which for convenience shall be designated as stations A, B, C, D, etc. Also the gas injectors at each station are arranged to be diametrically opposite to at least one other injector at that station. Thus, it will be noted with reference to station A, that the two injectors depicted are arranged across a diameter passing through the axis of central injector pipe **57**. A similar situation holds true with all of the injectors arranged along the central pipe **57**. Although FIG. 6 illustrates the gas injectors at each station, it should be understood that four, six, eight, etc., gas injectors could be arranged about central injector pipe **57** at each station. The reason for such arrangement will become apparent hereinafter upon description of the operation of the wind tunnel facility.

The end of central injector pipe **57** beyond station A is closed by an end wall **64** which, together with the diaphragms **62** in each of the gas injectors **59**, serves to seal central injector pipe **57** from the external atmosphere, as well as from the gas charges within gas injectors **59**. Each gas injector **59** is furnished with a detonator **65** and a primacord connector **66** to its neighboring injectors **59**. Such length of each primacord connector is arranged to fire the gas injectors at each station in a sequential manner and at any preselected interval of time. The gas injectors **59** at station A are connected to a primacord igniter **70** by identical lengths of primacord. Igniter **70** is, in turn, actuated by a suitable source of power (not shown).

The wind tunnel facility as illustrated in FIG. 6 operates as follows: Initially model **54** is placed within wind tunnel section **52** and suitable instrumentation is prepared therefor. Any desired vacuum is then drawn upon test section **52** and this vacuum will of course be communicated into central injector pipe **57**. The desired quantity of injector gas is charged into each of gas injectors **59** by means previously described. The wind tunnel is then ready for firing. The power source is then actuated to detonate the first primacord connectors **66** which, in turn, simultaneously detonate detonators **65** of the gas injectors **59** at station A. Simultaneous high pressure, high velocity gas pulses are ejected through the diaphragms **62** of the station A injectors through ports **63** into evacuated central injector pipe **57**.

The gas pulses from the fired injectors at station A meet at the central axis of injector pipe **57** and, since they are being injected at an angle to said axis, merge and proceed down injector pipe **57** in the direction of wind tunnel section **52**.

The merged pulse from station A proceeds down central injector pipe **57** past the injectors at station B. At such instant of time, the gas injectors **59** at station B are fired by primacord connectors **66**. They in turn generate gas pulses as previously described and inject these pulses into central injector pipe **57** immediately behind the merged pulse from station A which is just passed thereby. The merged pulse from the injectors at station A and the merged pulse from the injectors at station B following immediately therebehind proceed down central injector pipe **57** to a position adjacent station C at which time the gas injectors at station C are fired by primacord. The gas injectors at station C in turn fire pulses into central injector pipe **57** which pulses merge and form a pulse at station C following immediately behind the pulses A and B.

Such sequence of firing continues down the line along the length of central injector pipe **57** with each station adding its pulse, in sequence, at the rear of the train of pulses traveling down the length of the central injector pipe. Thus it can be seen that as the pulses travel down the central injector pipe, the train length increases by an increment equal to the length of the pulses generated by the gas injectors at each station. Eventually, of course, the train of pulses, ever increasing in length, travels down central injector pipe **57** to emerge into expansion nozzle **56** in the wind tunnel section **52**.

Although the resultant gas pulse or pulse train initially has a non-uniform axial density distribution, i.e., due to individual pulses from each station being added in sequence, the prolonged pulse as it emerges into divergent nozzle section **56** of the wind tunnel has very little density differences along its length. This "smoothed-out" density

results from equalization and diffusion as the pulse train travels down the length of central injector pipe **57**. Thus the gas flow appears to model **54** as one continuous pulse of high pressure, high temperature gas.

Since the high explosive outer bodies of gas injectors **59** are close to the wall of central injector pipe **57**, it is destroyed progressively as the injectors at each station are detonated. This destruction of the wall of the central injector pipe has no effect upon the gas pulse train being injected into the wind tunnel, since it has such a high velocity that it will have already traveled down the injector pipe by the time the wall is destroyed.

Besides permitting the injection of multiple pulses of gas into the central injector pipe, the angled alignment of the gas injectors **59** furnishes another advantage. Specifically as the gas charge within each gas injector **59** is gathered and accelerated down the length thereof, it is compressed to high pressures as previously described. As this pressure front hits diaphragm **62** the diaphragm is destroyed and, due to its conical shape, forms a penetrating jet of metal that is projected out the muzzle end of the gas injectors **59**. Since the diaphragm particles are being injected into the central injector pipe at an angle, they will be projected across the width thereof and penetrate the far wall of the injector pipe shortly before its destruction as previously described. By such means any possible contamination of the gas pulse by the diaphragm particles is eliminated.

It can be readily seen that by using the construction as illustrated in FIG. 6, the mass of gas injected into wind tunnel section **52** of the facility and the time duration of such gas pulse is limited only by the number of gas injectors **59** and the length of central injector pipe **57**.

As an illustration of the output of such a construction, a 500 microsecond gas flow out the end of central injector pipe **57** would require seventeen pairs of gas injectors having the capacity of a 50 gram-30 microsecond gas output as heretofore described. The total gas flow in such an output would be 1,700 grams of air. Expanding this air pulse in nozzle section **56** to a working density equivalent to 100,000 foot altitude, and with an air velocity of approximately 25,000 feet per second, the diameter of test section **52** would be 17 feet, certainly large enough to accommodate full scale re-entry vehicles. 400 pounds of an explosive such as NTN would be necessary to power the 17 pairs of injectors.

As stated supra, the gas pulse injector construction illustrated in FIG. 6 of the drawings, is easily adapted to not only produce a prolonged pulse of gas at simulated high altitude pressures and velocities, but to superimpose on such gas pulse a blast wave. Such blast waves simulate a wide range of blast conditions wherein the time spacing between the onset of the gas pulse and the blast wave is precisely controlled.

More particularly, to superimpose a blast wave on the gas pulse entering test section **52** of the wind tunnel facility, it is only necessary to substitute gas injectors of a more powerful nature (that is having an initial higher gas pressure or a more powerful explosive outer body **12**) for the last injector stations along central injector pipe **57**. Thus, for instance, the more powerful gas injectors are positioned at injector stations F, G, H and I along central injector pipe **57** as illustrated in FIG. 6.

Upon detonation of the injector sequentially along the length of central injector pipe **57**, the injectors at stations A, B, C, D and E produce a pulse train as heretofore described. As the end of such pulse train arrives at station F, the more powerful injectors thereat are fired to produce a stronger, i.e., higher temperature, pressure and velocity gas pulse at the end of said pulse train. Similarly as the end of the pulse train passes stations G, H and I, further such augmented pulses are added to the end thereof.

Subsequently, as the pulse enters test section **52** of the wind tunnel, model **54** would first be subjected to a gas flow generated by the earlier stations in the injector. At a point determined by the firing position of stations F, G, H and I, model **54** would experience a blast wave whereby the effect of such a blast simulation would be apparent from a study of the model.

FIG. 7 of the drawings illustrates graphically the gas flow of such a gas injector sequence wherein a blast front is superimposed upon the gas flow. In FIG. 7 each bar indicates the gas pulse generated by each successive injector station. The bars having their origin to the left of the vertical line indicated as S'—S' depict the gas pulses generated by the early gas injectors. The bars having their origin to the right of the vertical line indicated as S'—S' depict the blast pulses generated by the blast injectors. A contact discontinuity **71** is indicated as occurring along the front where the gas pulse injector flow and blast injector flow meet. The dotted lines **72** and **73** having their origin at point **74** denote the blast shocks that are generated within the gas flow entering test section **52** of the wind tunnel facility. Thus it can be seen that the model positioned at a distance indicated by the vertical arrow M experiences blast shocks at a time subsequent to the initial gas flow.

The properties of the blast wave, i.e., peak pressure and decay characteristics, are controlled by the designed spacing and/or timing of the more powerful type of gas injectors. For instance, if it is desired to produce a 1000 G shock for a period of 100 microseconds on a re-entry vehicle after it has experienced a 40,000 foot altitude re-entry environment for 500 microseconds, there are required approximately 24 injectors of the 50 gram-30 microsecond type previously discussed. This is assuming that a 5-foot diameter wind tunnel test section is desired. A 1000 G blast wave at 40,000 feet requires a pressure ratio of 100, a density ratio of 7.4 and a material velocity of Mach 8 across the shock. The mass of air necessary to produce such a shock is defined as:

$$\text{Mass} = (\text{area}) \times (\text{density}) \times (\text{velocity}) \times (\text{time}) \quad (4)$$

Thus the mass of air necessary to produce such a shock would be 2700 grams.

The blast injectors needed to produce the blast front are the same as those previously described except they would employ an explosive having a higher detonation velocity than the explosive used in the initial gas flow injectors. For the particular conditions necessary in this example, the air velocity in the blast should be approximately 30,000 feet per second in order to give the desired shock characteristics. Thus, approximately 55 injectors of the blast type would be needed to produce the desired blast front.

The example given above illustrates the number of gas injectors needed to achieve the 1000 G blast wave at 40,000 feet. Blast simulations at higher altitude conditions would require much less air and hence many fewer gas injectors.

It will be understood that the gas injectors utilized in a facility such as illustrated in FIG. 6 may be varied in any desired manner along the length of central injector **57** in order to achieve any gas flow characteristics within test section **52**. It will be further apparent that such a facility has the capability of producing an extremely broad range of re-entry gas flow conditions as well as blast conditions if desired.

FIG. 8 illustrates schematically another facility wherein the gas injector of the invention can provide a useful high pressure, high temperature gas pulse. In this embodiment the gas injector **76**, which is in all respects identical to that shown in FIGS. 1–5 is used to drive a shock tube facility **77**. Such shock tube facilities are well known in the art and are useful for developing much desired data.

In this instance the gas injector **76** has its muzzle end **78** connected directly to a closed shock tube **79**. Central chamber **81** of the injector **76** is compartmented from

a test chamber **82** of the shock test section by a diaphragm **83**. The shock tube test chamber **82** is protected from the exploding gas injector **76** by a bunker wall **84**.

In operation helium or hydrogen gas is charged into chamber **81** of the gas injector while air is charged into the shock tube test chamber **82**. The gas injector is then exploded, as previously described, whereby the air in the test chamber is shocked by the helium or hydrogen gas pulse.

I claim:

1. A method for creating a high pressure shock front in a gas comprising the steps of confining a mass of gas within a long cylindrical volume defined by a liner material, explosively imploding said liner material radially inward progressively along the length of said volume from one extreme end thereof to the other whereby said gas is progressively gathered and driven at high velocity along the axis of said volume and thereby forms a shock front at the interface between the driven high velocity gas and the as yet unshocked gas mass and wherein said shock front travels along the length of said cylindrical volume.

2. A method for creating a high pressure shock front in a gas comprising the steps of confining a gas charge within a long cylindrical volume defined by a solid material liner, enclosing the cylindrical volume and one end surface of said solid material with a high explosive body, closing the other end of said cylindrical volume with a frangible diaphragm, detonating said high explosive body at the end remote from said diaphragm and having the detonation proceed progressively from said one end along the length of said cylindrical volume, coincidentally having the detonating high explosive body compress and implode said liner radially and progressively along the axis of said cylindrical volume to gather and drive said gas charge down the length of said cylindrical volume to said other end, disintegrating said frangible diaphragm by the arrival of the high pressure shock front whereby said gas charge is ejected axially from said cylindrical volume.

3. An apparatus for compressing and driving gases to extremely high pressures and velocities comprising a liner defining a cylindrical chamber, a wall portion of said liner closing one end of said cylindrical chamber, a frangible diaphragm closing the other end of the chamber, a high explosive outer body enclosing said liner and end wall, a detonator affixed to the end wall portion of said high explosive body, detonation means secured to said detonator, and gas fill means passing through said high explosive body and said liner into said cylindrical chamber.

4. The apparatus of claim **3** wherein said high explosive outer body is a high explosive composition selected from the group consisting of TNT, PETN, composition B, and NTN.

5. The apparatus of claim **3** wherein said frangible diaphragm is in the shape of a cone with the apex thereof facing into said cylindrical chamber.

6. A hypervelocity wind tunel facility comprising a wind tunnel test section, a vacuum chamber connected to one end of said test section, vacuum pump means for pumping gases from said vacuum chamber, an explosively driven gas injector connected to the other end of said test section and in axial alignment therewith and wherein said gas injector comprises a cylindrical gas chamber defined by a solid liner material and a high explosive outer body enclosing said liner on the lateral surface and one end surface remote from said test section, a frangible diaphragm disposed between said gas chamber and said test section, and detonator means attached to the end of said gas injector remote from said test section.

7. A method for injecting a prolonged pulse of extremely high pressure and velocity gas into a hypersonic wind tunnel test section comprising generating in succession a plurality of relatively short time duration high pressure and velocity gas pulses, and injecting such short time duration pulses into said test section in rapid sequence, timing said sequence so that the front portion of each pulse except the first pulse meets and merges with the after portion of each preceding pulse whereby a continuous prolonged gas pulse is injected into said test section.

8. A method for injecting a prolonged pulse of extremely high pressure and high velocity gas into a hypersonic wind tunnel test section comprising the steps of disposing a long central injector pipe having a central chamber in communication with the test section and axially aligned therewith; placing a plurality of high energy gas injectors at predetermined intervals along the length of the central injector pipe, said injectors being in communication with the central chamber; firing, in succession, said gas injectors along the length of said central injector pipe, with the injector remote from the wind tunnel test section being fired first; injecting a high pressure, high velocity gas pulse from each injector into said central chamber in a predetermined sequence whereby each injector fires and injects its gas pulse immediately upon the passage of the pulse from the next preceding injector past the firing injector's position along said central injector pipe, to form a prolonged pulse train in said central injector pipe; and injecting said pulse train into said hypersonic wind tunnel test section.

9. The method of claim **8** wherein the gas pulse from each gas injector is injected into said central chamber in the direction of said wind tunnel test section and at an acute angle to the longitudinal axis of said central injector pipe.

10. The method of claim **8** wherein at least a partial vacuum is maintained in said wind tunnel test section and said central injector pipe prior to the firing of the gas injectors.

11. The method of claim **8** wherein said gas injectors are placed in multiples of two at each interval along the length of the central injector pipe and where one of each duo of gas injectors is placed at opposite ends of diameter passing transverse to the longitudinal axis of said central injector pipe and further where each duo of gas injectors at any one position along the length of said central injector pipe is fired simultaneously.

12. An apparatus for producing a prolonged pulse of extremely high pressure and high velocity gas comprising an elongated central injector pipe including a first and second end thereof and wherein said pipe defines a central injector chamber; a plurality of gas injectors disposed at spaced intervals along the length of said pipe on the outer surface thereof; muzzle ends forming a part of each such injector and wherein said muzzle end opens through a port in the pipe into the interior of said central chamber; said gas injectors being of a linear configuration and wherein each such gas injector is inclined towards the second end of said pipe at an acute angle to the longitudinal axis of said pipe; firing means attached to each gas injector and adapted to fire each of said gas injectors in progressive succession from the first end of said central injector pipe to the second end thereof; and vacuum means attached into said central injector chamber.

13. The apparatus of claim **12** wherein said gas injectors are explosively driven gas injectors.

14. The apparatus of claim **12** wherein said gas injectors are disposed in multiple of two at each position along said central pipe and wherein each injector pair has one injector disposed diametrically across said central pipe from the other gas injector.

15. A hypervelocity wind tunnel facility comprising a model test section; a vacuum chamber connected to one end of said test section; vacuum pump means for pumping gases from vacuum chamber; a gas pulse injector connected to the other end of said model test section, said gas pulse injector comprising an elongated central injector pipe having a closure at the end thereof remote from said test section; and a plurality of gas injectors spaced at intervals along the exterior length of the central pipe, each

of said gas injectors having a muzzle end opening into the interior of said central pipe and wherein each of said gas injectors is inclined at an acute angle to the axis of said central pipe and has said muzzle end directed toward said model test section; and gas injector firing means attached to said gas injectors and adapted to fire the gas injectors in a predetermined sequence.

16. A method for superimposing a blast front on a pulse of high velocity gases for injection into a hypervelocity wind tunnel test section comprising the steps of generating in succession a first plurality of relatively short time duration high pressure and velocity gas pulses; injecting such short time duration gas pulses into said test section in rapid sequence; timing said sequence so that said first plurality of pulses form a first pulse train wherein the first pulse generated leads said pulse train and each successive pulse follows in close order; generating a second plurality of gas pulses of higher pressure and velocity than said first plurality, wherein said second plurality of pulses are generated as individual short time duration pulses in rapid sequence to form a second pulse train; injecting the first of said second plurality of higher pressure and velocity pulses into said test section immediately behind said first pulse train whereby the head of said second pulse train contacts the tail of said first pulse train to form a blast front discontinuity between said first and second pulse trains.

17. A method for superimposing a blast front on a prolonged pulse of extremely high pressure and high velocity gas that is injected into a hypervelocity wind tunnel test section comprising the steps of disposing a long central injector pipe having a central chamber in communication with the test section and axially aligned therewith; placing a first plurality of high energy gas injectors at predetermined intervals along the length of said pipe but terminating at a distance from said test section; placing a second plurality of gas injectors of higher energy than said first plurality at predetermined intervals along the length of said central pipe between said first plurality of gas injectors and said test section; all of said first plurality and second plurality of gas injectors being in communication with said central chamber; firing, in succession, said

gas injectors along the length of said pipe with the gas injector most remote from the wind tunnel test section being fired first and successively along said length to said test section; injecting a gas pulse from each of said first plurality of gas injectors into said central chamber and towards said test section in a sequence to form a pulse train; injecting a gas pulse from each of said second plurality of gas injectors into said central chamber; each said pulse having higher pressure and velocity than the pulses of the first plurality of gas injectors, in a sequence to form a second pulse train wherein the head of the second pulse train contacts the tail of said first pulse train to form a blast front discontinuity; and injecting said prolonged gas pulse and subsequent blast front into said wind tunnel test section.

18. A shock tube facility comprising an elongated shock tube test section having one end thereof closed by a wall portion and the other end closed by a frangible diaphragm, means for filling a test gas into said shock tube section, an explosively driven gas injector connected to said shock tube test section at the end having the frangible diaphragm and wherein said gas injector is in alignment with said test section, and said diaphragm partitions said gas injector from said test section, said gas injector comprising a cylindrical gas chamber defined by a solid liner material and a high explosive outer body enclosing said liner on the lateral surface and one end surface remote from said shock tube test section, and detonator means attached to the end of the gas injector remote from said test section.

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