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PERFORMANCE CHARACTERISTICS OF A GLOW DISCHARGE SHOCK TUBE

by

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ABSTRACT

Performance Characteristics of a Glow Discharge Shock Tube

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A glow discharge shock tube was designed and constructed in the present plasma facility in the Department of Mechanical and Aerospace Engineering and Materials Science, for the purpose of making a future experimental investigation of nonequilibrium corner expansion flows of dissociated oxygen. The theories of high frequency induction heating and chemiluminescent reaction are reviewed and simple shock tube theory is presented. Certain performance characteristics pertinent to the future application of the glow discharge shock tube (GDST) were examined. Among those presented are plasma initiation and stability, the character of the glow discharge, and shock speed and attenuation.
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1. **Introduction**

It was desired to design and construct a glow discharge shock tube facility for the specific future intention of carrying out an experimental investigation of nonequilibrium corner expansion flows of dissociated oxygen. The design and construction of the glow discharge shock tube (GDST) and the examination and determination of several pertinent performance and operating characteristics were of such merit as to warrant this thesis. It should also be taken into consideration that this author will fulfill the intent of the design and construction of the GDST, namely the experimental investigation of nonequilibrium corner expansion flow, and that the design and construction of the said GDST was carried out taking into account existing equipment in the plasma dynamics laboratory.

In essence, a GDST is a combination of a glow discharge tube and a simple shock tube. The glow discharge shock tube consists of a conventional shock tube modified in such a manner that a radio-frequency discharge is used to generate a partially dissociated gas in the driven section immediately prior to the passage of the shock. The reasons for this blend obviously vary as to application, but in this particular usage, the purpose was to artificially achieve some of the phenomenon associated with the hypersonic flow regime. GDST's have been used to study the catalytic efficiency of surfaces for atomic recombination and the excitation mechanisms leading to emission in active nitrogen.
The GDST used in this study is shown schematically in Figure I and pictorially in Figures II and III. The test gas, diatomic oxygen, flows continuously, at about 10-50 feet per second through "double-tough" Pyrex pipe, approximately 18-20 feet long and 4 inches in diameter, which is the driven section of the shock tube. Radio-frequency energy is applied at the upstream position by a 20 kilowatt, 4 megahertz Westinghouse generator. The RF energy inductively heats the oxygen, causing it to partially ionize and dissociate. The electrons and ions recombine rapidly, so that a few feet downstream of the discharge region only oxygen atoms and molecules remain. Since the wall recombination coefficient for atomic oxygen on Pyrex is very small, only a small percentage recombination will take place along the tube, and therefore, the driven section will contain a reasonably homogeneous, high concentration of atomic oxygen into which the shock wave is fired. When the discharged gas has convected to within a foot or so of the test section, the shock wave is fired by bursting the high pressure (1-3 atmosphere) driver section diaphragm with a solenoid operated plunger. As the shock wave passes through the partially dissociated oxygen, it compresses and heats it, and accelerates it to supersonic speed (of the order of $M \approx 1.3-1.9$). This slug of supersonically flowing partially dissociated gas then passes through the test section. The shock strength is such that density and temperature changes across it are not sufficient to cause appreciable additional dissociation; rather the shock wave is used primarily to accelerate the pre-dissociated gas
to supersonic speed before it passes the test section. Oxygen atom concentration as a function of time is followed by continuously adding a trace of NO just downstream of the RF discharge section. The NO reacts with the oxygen atoms to produce the chemiluminescent reaction:

\[
NO + O \rightarrow NO_2 + h\nu
\]

The oxygen atom concentration is established by monitoring the luminous intensity with a photomultiplier in a manner similar to that used by others. The intensity of radiation is proportional to the product of the NO and O concentrations; and since the NO concentration is essentially constant, the intensity is directly proportional to the O concentration. Shock speed is measured by the time difference between voltage rise at two ionization probe stations. A pair of stations allow attenuation to be determined.

The organization of this thesis is as follows: the various theories which relate to GDST operation will be briefly discussed. The experimental apparatus and the technique will be described in detail, and the final section will be a discussion of both qualitative and quantitative results.
2. Theory

2.1. RF Induction Heating

For about ten years, radio-frequency heating and its accompanying and resulting RF discharge have received the attention of gas dynamicists as a method of "artificially" producing some of the phenomenon associated with the hypersonic flow regime. By "artificially" produced, it is meant that the phenomenon, basically real gas effects, are generated by a different mechanism than in the natural occurrence in a high speed flow situation. In other words, real gas effects take place because of high frequency induction heating, rather than an encounter with a very strong shock. This leads naturally to the combination of glow discharge and shock tubes, to produce an economic but short duration hypersonic flow regime facility. A brief development of high frequency discharge follows: In the electrodeless RF discharge, the high frequency alternating field changes the polarity of the electric field so rapidly that there is no net migration of charged particles. Consequently, there is no space charge build up in any region of the gas, and the primary supplier of electrons is the gas itself. Initiation of the electrodeless high frequency discharge is simpler than in the case of the static arc discharge; since no secondary processes are required to replace primary electrons lost to the electrodes. Under the influence of the high frequency electric field, an electron concentration builds up in the gas and electrical breakdown subsequently
occurs; the discharge can be produced with the values of the electric field very much lower than are required with static discharges.

The high frequency discharge is a very uniform process as compared with the static field type and approaches a constant volume energy addition process. In a high frequency discharge, the electrode is not in contact with the gas; since an electromagnetic field can always be induced in the gas from an external oscillatory circuit so long as the wall separating the gas from the external circuit is made of a dielectric material.

Two types of high frequency discharges occur depending on the type of coupling between the oscillatory circuit and the gas:


2. "E" type discharge - capacitive coupling of power, axial current flow and azimuthal magnetic field.

The "H" type discharge will be explained as it is the type of interest in the specific application discussed in this thesis. The "H" type of high frequency discharge occurs due to excitation by an oscillating magnetic field. Eddy currents are induced in the plasma from a remote conductor carrying an oscillating current: This type of energy transfer is called inductive coupling. The induced currents meet resistance to their flow, and Joule heating of the plasma occurs. The usual conductor geometry for this type of discharge is a solenoid either longitudinally surrounding the discharge volume, or pancake shaped normal to the axis of the discharge volume. This type of conductor arrangement
induces an axial magnetic field and azimuthal closed current paths in the gas. Figure IV shows the conventional "H" type high frequency discharge configuration, the "E" type setup, and the specific discharge configuration in the device described in this thesis.

Two other aspects of RF discharges need to be mentioned to provide a general understanding of the process. These are discharge initiation, and development and maintenance of a stable discharge.

Since gases at ordinary temperatures and pressures are not electrically conducting, some auxiliary means of providing an initial source of ions in the discharge region must be provided. Several methods have been developed, but only one, low pressure discharge, will be discussed here, as it is the initiation method used in this application. It is achieved by pumping the gas down to approximately one mm (1000 microns) of mercury. In this pressure range, the mean free path of electrons is increased sufficiently that they acquire enough energy from the RF field between collisions, to cause ionization to cascade spontaneously. Once the discharge is established, the pressure may be gradually increased to the desired working level, while the power input is simultaneously increased.

The phenomenon of hydrodynamic instability (displacement and extinguishment of the plasma by the axial flow of cool gas entering the discharge region) has been described by several authors. The equilibrium position and shape of the plasma are sensitive functions of flow and power conditions. More of the stability problem will be discussed later in this thesis.
2.2. Chemiluminescent Reactions

Historically, since its discovery by Lord Rayleigh in 1910, the greenish-yellow air afterglow has been studied in great detail. Lord Rayleigh demonstrated that nitric oxide (NO) was necessary for the production of the glow and erroneously assumed ozone to be the other participant in the reaction. Later, Spealman and Rodebush (1935) showed that atomic oxygen was the second party in the now well-known reaction

\[
NO + O \rightarrow NO_2 + h\nu
\]

This is the reaction that is of particular interest in the application of the GDST facility. The beauty of the reaction and the reason that it is particularly handy as a diagnostic, is that the intensity of the greenish yellow chemiluminescence is proportional to the concentrations of atomic oxygen and nitric oxide, and independent of the nature or amount of added inert gases.

This development will present some of the kinetics of the glow, relate the intensity to the concentrations of O, NO, and added gases, and aid in the understanding of the glow to achieve a quantitative measure of the concentration of atomic oxygen. The general scheme is to flow oxygen through the Pyrex tube, apply RF energy to produce atomic oxygen and mix it with NO, and measure the intensity of the glow at room temperature along an observation tube by means of a spectrometer-multiplier set-up.
Kaufman experimentally showed that the intensity of the glow was proportional to the product of the partial pressures of atomic oxygen and nitric oxide. Similarly, Kaufman showed that the observed intensity was independent of the nature and amount of inert gases. Therefore, it has been verified experimentally that:

\[ I = k (O) (NO) \]

The intensity of the glow discharge is proportional to both the concentration of atomic oxygen and nitric oxide and is independent of inert gases present. The absolute value of the proportionality constant \( k \) is known and was determined by the following procedure. NO concentration was metered, O concentration was determined by NO\(_2\) titration, and the absolute intensity was measured after calibration by a lamp of known intensity. Kaufman found the intensity \( I (\lambda) \), to be approximately constant between 4800 and 6200 Å.

The results that \( I \propto k (O) (NO) \), independent of added gases, and that the reaction

\[ O + NO_2 \rightarrow NO + O_2 \]

is very fast, make the afterglow particularly well suited for the study of atomic oxygen. When (NO) is kept small, its contribution to the removal of \( O \) is also small and the glow becomes a direct measure of \( O \). Also, NO is quickly regenerated from the reaction between \( O \) and NO\(_2\) and therefore, NO is constant all the way down the tube.
Observation at points downstream along the tube will measure the decreasing O atom concentration directly,

\[ \frac{I_1}{I_2} = \frac{(0)_1}{(0)_2} \]

By knowing the velocity, rate constants are obtained for the first order disappearance of atomic oxygen

\[ k = \frac{2.3}{\Delta t} \log \left( \frac{I_1}{I_2} \right) \]

where \( I_2 \) is the afterglow intensity at position 2 and \( \Delta t \) is the time spent between 1 and 2. For this interpretation to be valid, several corrections need to be considered. These are i) viscous pressure drop, ii) effect of oxygen recombination and iii) wall combination. Of these, i) is large at low pressures and high flow rates. It can be measured by pressure transducers along the tube and will agree functionally with the Poiseuille flow expression

\[ p_2^2 - p_1^2 = f(n(V, \Delta h_2, R, T, \mu, d) \]

Intensity ratios can then be corrected by multiplying by the square of the pressure ratio. ii) Will be neglected as the percentage dissociation is not expected to be very high. iii) for Pyrex is extremely small and will be similarly neglected.

The trace reaction

\[ NO + O \rightarrow NO_2 + h_\nu \]
coupled with the fact that the intensity of the glow is directly proportional to the \( \text{O} \) concentration produces a significant diagnostic tool for the GDST facility. Metering the NO input, measuring the absolute intensity and knowing the rate constant \( k \), allow the \( \text{O} \) concentration to be determined as a function of distance down the tube for a given set of flow parameters. This leads to knowledge of the glow discharge flow regime which is essential to the operation of the GDST.

2. 3. **Performance Analysis of a Simple Shock Tube**

Basically, a shock tube is a device in which a plane shock wave is produced by the rupture of a diaphragm between two gases at different pressure. The simplest form of the tube is shown in Figure V where the low pressure section of driven section is on the right of the diaphragm, and the driver section is on the left. The driven section contains the experimental gas which is subjected to the shock wave. When the diaphragm is ruptured, a compression wave is formed in the low pressure gas. The compression wave steepens and forms a shock front. At the same time, an expansion wave moves back into the high pressure gas. The head of the expansion wave propagates with the speed of sound in the driver gas. But here the pressure change is smooth and continuous (unlike the shock front which has an associated pressure discontinuity.) This is known as an expansive fan. The driven and driver gas make contact at the contact surface, which moves rapidly along behind the
shock. The movements of the shock, the expansion wave, and the contact surface are shown in the standard x-t diagram in Figure VI. The variation of pressure and temperature along the tube at a certain time are similarly shown in Figures VII and VIII.

Adhereing to the usual notation of the subscript 1 denotes the initial undisturbed conditions in the driven section. Subscript 4 represents conditions in the high pressure driver prior to rupture. The region between the shock front and contact surface is denoted by the subscript 2 and 3 represents the regime between the contact surface and the expansive fan.

The value of the shock tube is that it can produce in-region 2, properties that are desirable in the study of high speed flow regimes. The only drawback is that the region of interest maintains constant properties only for a short length of time. This disadvantage is suitably overcome by the use of sophisticated diagnostic techniques, in particular, optical devices.

A sound wave is propagated through a gas in the form of a weak isentropic adiabatic compression. Only small amplitude longitudinal displacements of the molecules are involved in this process; there is no net movement of flow of gas in the direction of propagation of the wave; the changes in the physical state of the gas due to the wave are negligible, and the process is reversible by definition. The rate of propagation is known as the speed of sound and can be shown to be given by

\[ a = (\gamma RT)^{1/2} \]
for a perfect gas. The sound speed is related to \( \bar{c} \), the random molecular motion of gas molecules.

\[
\bar{c} = \left( \frac{\gamma}{\gamma - 1} RT \right)^{1/2}
\]

The sound wave is transmitted in the gas by collisions between gas molecules. Therefore, it is not at all surprising that a wave of a very different nature is set up in a gas, when a disturbance is forced through it with a speed greater than the characteristic sound speed at which the molecules communicate a weak compression. This is a shock wave. When a shock wave is generated, the pressure, temperature, and density must build up in the wave, since the gas molecules in its path can only move away from the front with the characteristic sound speed. Due to this effect the molecules will be carried along in the shock wave, and a flow in the direction of propagation results. This entrainment property and large changes in properties distinguish a shock wave from a sound wave. The initiation of a shock wave requires an agency capable of supersonic displacement of gas. The sudden release of a high pressure section into a lower one generates a shock wave.

A development of the governing equations concerning shock waves in ideal gases can be found in any gas dynamics text and for the sake of brevity, only a few characteristic parameters will be discussed in detail here. The strength of a shock wave initiated in a gas by the bursting diaphragm method depends on the pressure ratio across the diaphragm and the physical properties of the two gases.
For an ideal gas

\[ \frac{p_2}{p_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1} \leq 1 - \frac{\gamma - 1}{\gamma + 1} \frac{\gamma}{\gamma - 1} \left( \frac{M_1}{M_1 - \frac{1}{\gamma - 1}} \right)^{\frac{\gamma - 1}{\gamma + 1}} \]

In the limit, the strongest possible shock is obtained when

\[ \frac{p_2}{p_1} \to \infty \Rightarrow \frac{M_1}{M_1 - \frac{1}{\gamma - 1}} \to \frac{\gamma}{\gamma - 1} \]

The strongest shocks are therefore obtained by using a driver gas having a high speed of sound and low specific heat ratio. For these reasons, a low density gas such as hydrogen or helium is usually used in the driver section.

Since region 2 is the region of interest in the GDST application to the study of non-equilibrium corner expansion flow, it is relevant to express property ratios across the shock in terms of the shock, Mach number. The desired relations are as follows:

\[ \frac{p_2}{p_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1} \]

\[ \frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)M_1^2}{(\gamma - 1)M_1^2 + 2} \]

\[ \frac{T_2}{T_1} = \frac{(\gamma M_1^2 - \frac{\gamma + 1}{2} + \frac{\gamma - 1}{2} M_1^2 + 1)}{(\gamma + 1)^2 M_1^2} \]
From these relations the pressure, density, and temperature behind a shock wave through an ideal gas may be obtained if the shock speed and initial conditions are known.
3. **Experimental Apparatus and Technique**

3.1. **Plasma Source**

The experimental investigations are carried out using an RF induction heated plasma as a source of radiant energy. The plasma is generated within the 4" nominal diameter Pyrex pipe; the pipe being centered in a work coil of the RF heater. The energy to the plasma is supplied by a Westinghouse, 20kw, 4 mh industrial RF generator. Work Coils of various configurations and inductances were tried and because of plasma stability requirements and load matching considerations certain sizes of coil proved unacceptable. Because the generator is merely a large tuned circuit, it proved necessary to design a coil within certain inductance limits. Frequency is determined by the inductance of the work coil, all other coils remaining fixed. Therefore, for the generator to operate within its recommended frequency range, it was necessary to design the coil accordingly. This is called load matching. Another coil design criterion was the hydrodynamic stability of the plasma itself, within the confines of the coil. It was discovered that even though a particular coil would oscillate satisfactorily, it didn't necessarily follow that a stable plasma could be maintained, under varying flow and power conditions. When an axial flow was introduced in some plasma coil configurations, it was observed that the plasma "migrated" to the downstream turns of the coil. This was due in part to the cooling or extinguishment of the plasma by the influx of unheated gas.
Adhering to the heretofore stated design criterion, a coil compatible to load matching and stability requirements was made and used extensively. The final and current coil consists of 1/4" copper tubing in the following configuration: Two turns, approximately 2" in length, and of mean radius 2 5/8". Accordingly, the inductance of cylindrical coils is given by the following empirical relation:

\[
L = \frac{n^2 r^2}{9r + 10} \quad \text{in } \mu\text{H}
\]

Therefore, the inductance of the work coil is .633\muH + 5%. Plasma initiation results from low pressure breakdown, and it was determined experimentally that a pressure in the order of 2000 L was sufficient to facilitate initiation.

3.2. Spectrometer

A. Jarrell-Ash .5 meter Ebert Scanning Spectrometer with photomultiplier readout is intended to be used in the GDST intensity measurements. The instrument has a ruled grating of 1180 grooves per millimeter, with the option of either fully motorized or high speed manual drive. The motor and the reduction gear system provide a smooth scanning motion in eight speeds, ranging from 2\AA\ per minute to 500 \AA\ per minute, with a counter reading directly in Angstrom units. The wave length coverage is from 2000 \AA\ to 8000 \AA\ in the first order, with a reciprocal linear dispersion at the exit slit of 16 \AA\ per millimeter. The resolution is at least 0.2\AA\ in the first order. The spectrometer was mounted on a
sturdy table and positioned near the observation portion of the GDST to facilitate data taking.

3.3. **Optical System**

The optical system consists of two adjustable mirrors mounted on a track paralleling the glow discharge portion of the tube, and a combination of mirrors and lenses mounted on tracks on the spectrometer table, prior to the entrance slit. At any station along the glow where an observation is desired, the image of a thin longitudinal slice of the chemiluminescence can be focused on the entrance slit through a suitable combination of mirrors and lenses. The centerline of the glow discharge tube, the midpoints of all mirrors and lenses, and the center of the entrance slit, all lie in the same horizontal plane, thereby facilitating the slice image transfer from the source to the spectrometer slit.

The optical system shown in Figures IX and X consists of several components: two plane rectangular mirrors adjacent to the tube, a spherical condensing lens, and the capability of using filters and shutters and additional mirrors and lenses. The two mirrors on the track parallel to the tube, are plane, rectangular front surfaced, and measure about 2" by 9". Each turns the image through 45°, while keeping the image in a vertical plane. Both mirrors have several modes of adjustment to allow for accurate allignment of the image on the entrance slit. Because of the rather large distance (about 4 to 8 feet) between the source and
the spectrometer, it is necessary to use a spherical quartz lens of
1.5 diopter focal length and $\frac{1}{4}$-inch diameter to focus the image of the
radiant slice on the spectrometer entrance slit. The option exists to
include either an additional spherical condensing lens or a bi-convex
cylindrical lens of 1.5 inch focal length in the optical path. The latter
of the two optional lenses can be used to increase the illumination on
the spectrometer slit, and is worthwhile because it amplifies the
photomultiplier output. Filters, shutters, and time step devices can
easily be incorporated in the optical system if desired.

3.4. **Standard Light Source**

The radiation standard to be used for absolute intensity calibration
of the glow discharge, is a tungsten ribbon filament lamp. The lamp is
a General Electric type 30A/T24/17 bulb calibrated by Eppley Laboratories
to National Bureau of Standards specifications for spectral radiance from
2500 Å to 26,000 Å when run at 35.0 amperes AC. Current flowing through
the standard is monitored within 0.1 percent using an Electro-Instruments
precision AC-DC differential voltmeter. A schematic of the standard lamp
circuit is shown in Figure XI. The standard is viewed by the spectro-
meter using an alternate, but identical, optical path that used in
observing the glow discharge.

3.5. **Shock Tube**

3.5.1. **Driver Section**

The driver section of the GDST is made of the same basic material
as the remainder of the tube — "double-tough" Pyrex brand conical pipe.
A two foot length of 4" pipe was chosen for the driver portion. The maximum recommended working pressure for the 4" pipe size is 35 psig or approximately 50 psia. Therefore, with a pressure capability in the driver ranging up to 50 psia and a vacuum capability in the driven section of about 10 microns, it is possible to achieve pressure ratios (\(\frac{P_1}{P_2}\) across the diaphragm prior to rupture) from slightly greater than one to 258,000.

The blind end of the driver consists of a 1/4" aluminum plate through bolted to the standard aluminum flange with a Teflon gasket in between. The aluminum plate is tapped to take a multipurpose delivery line and two electrical feed through connections. The driver system is both evacuated and charged with Helium by means of the one delivery line, and a valved manifold. Lines for instrumentation and delivery of various gases in the driver section are all Imperial "polyflo" 3/8" and 1/4" tubing and connectors. The Helium delivery system is gauged so that any desired pressure up to 50 psia can be achieved in the driver. The driver section is shown in Figure XII.

At the other end of the driver all that separates it from the driven section is a mylar diaphragm. The particular thickness chosen for this application was .001" or one mil. Through a series of destructive over pressure rupture tests, in which approximately ten samples of one mil mylar were attached to the driver which was subsequently pressured up until diaphragm failure resulted, it was found that the one mil mylar ruptured at a differential pressure of 26 psid.
$1 \text{ psid. Multiple thickness of } 1 \text{ mil mylar can be used to produce higher required differential bursting pressures.}

Since diaphragm rupture by over pressure did not prove to yield consistent results pertaining to bursting pressure differential, it followed that the rupture needed to be initiated or triggered. For this specific purpose, a solenoid driven plunger was designed. The plunger is made of 3/16" diameter stainless steel approximately 2' in length. One end of the plunger is pinned through a reversing linkage arm to the core of the solenoid attached to the plate end of the driver. The plunger is "cocked" when a diaphragm is inserted, and when the solenoid is activated by flipping a switch, the plunger moves about one inch. The solenoid plunger device was designed with a 1" throw because in the process of pressuring up the driver it was observed that the mylar stretched or bulged nearly 3/4" prior to the time when rupture could be initiated. Therefore, it was desirous to have a 1" throw on the plunger to assure rupture triggering.

The mylar diaphragms are held in place by being clamped between a Teflon gasket and the primary oxygen inlet manifold.

3. 5. 2. Driven Section

The driven section of the GDST consists of four lengths of 4" Pyrex pipe, that are respectively 3, 2, 10 and 3 feet in length. The first of these sections, the three foot piece next to the driver, is the station where the RF energy is applied. Following are the NO inlet
section, the flow monitoring section, and the test section. Each of these sections will be dealt with in detail, because although they are physically similar, there are distinct functional differences. A schematic of the entire GDST facility is shown in Figure I.

RF energy is applied at the 3' section of the driven portion of the tube, immediately downstream of the driver. Between the business end of the driver and the RF section lies the primary oxygen inlet manifold. The manifold was designed to feed in oxygen uniformly about the interior circumference of the tube. Donut shaped with a thickness of 5/8", and an ID of 4" and an OD of 7 1/2", the aluminum manifold allows oxygen to flow radially inward at six points. The work coil is located in the middle of the three foot RF section. The coil, with and without plasma are shown in Figures XIII and XIV. Care was taken to insure adequate standoff distance between the interior of the coil and the exterior of the Pyrex. An early coil configuration which almost touched the glass, caused an implosion at the RF coil when the Pyrex failed. It seemed reasonable that the failure resulted from thermal fatigue and repeated thermal shock focused on the helical locus where the axial plane of the coil perpendicularly intersected the Pyrex.

The NO inlet manifold is sandwiched between the RF section and the NO inlet section. This manifold is similar in dimensional configuration to the O₂ inlet manifold and also has six radial influx points. A photograph of the NO inlet manifold in operation clearly shows the six, relatively equal, jet plumes in Figure XV. It was observed experimentally that by letting in too much NO, the glow discharge could be
made to "back up" toward the RF coil. The capability exists to add a trace of either NO or CO, and meter and regulate either addition. Due to intensity considerations, the NO trace proved to be better suited to this particular diagnostic application.

The flow-monitoring section is a ten foot length of Pyrex with, at present, four monitoring stations. These data points are located one and two feet from both ends and all lie on the same ray in the cylindrical pipe. Four $5/16''$ holes were drilled in the Pyrex at the heretofore mentioned locations, with a diamond core bit. Extreme caution was exercised in the actual drilling operation to insure that a smooth hole was produced. The technique and procedure were developed on several practice runs on another piece of Pyrex pipe. Imperial poly-flow fittings were epoxied to the Pyrex with a Teflon saddle insert between the outer surface of the glass and the fitting. Currently, the fittings have a dual capability, accommodating either ionization probes or pressure transducer taps. Later the present pattern can be extended to provide more data stations. The pressure transducer taps can be used in both steady state and transient or shock applications. The ionization probes are used strictly as transient devices. Both of these diagnostics will be discussed in detail under monitoring devices.

Following the flow monitoring section comes the test section, where the actual study of the non-equilibrium corner expansion flow will occur. Currently, the test section is simply a three foot section prior to the dump tank. Between the test section and the dump tank is an exhaust or
outlet manifold. This manifold leads, through a series of valves and pressure gauges, to the vacuum system. Back pressure is controlled by throttling the flow to the vacuum pumps. Therefore, with variable back pressure control, it is possible to achieve a wide latitude of flow parameters within the tube prior to firing the shock. Back pressure control is necessary to achieve the proper glow discharge diffusion front.

3. 5. 3. Dump Tank & Vacuum Pumps

The dump tank is on the far right end in the schematic in Figure I. The tank is a converted water tank, which was adapted to the present usage by welding a flange on one end to accommodate a connection to the Pyrex pipe. The tank is mounted on a metal frame, which can be adjusted vertically to insure proper alignment with the tube. The purpose of the dump tank is to lessen the strength of any would be reflected shock wave. Overall approximate dimensions of the cylindrical tank are 2 feet in diameter and 5 feet long. A 2" vacuum line runs into the side of the tank, and this is used as the primary exhaust line for the GDST facility. The 2" line leads directly to Consolidated Vacuum Corporation (CVC) mechanical type vacuum pump DK-180. This is a CVC rotary plunger, oil-sealed, two-stage, mechanical vacuum pump with a capacity of 180 cfm. A smaller vacuum pump is also used in the vacuum system. Its purpose is for the driver evacuation and reference pressure for the differential pressure transducers.
3.5.4. Monitoring Devices

The monitoring devices consist of standard static pressure gauges, flow meters, pressure transducers, and ionization probes. Only the transducers and ionization probes will be discussed since a general knowledge of flow meters and gauges is assumed. The differential pressure transducers and associated electronics are a product of Pace Engineering Company and work on the variable reluctance principle. In this particular transducer, a magnetic stainless steel diaphragm separating the two pressure cavities moves between the two coils contained in the Stainless Steel case. The coils are part of an A.C. bridge circuit. The voltage increase resulting from a pressure imbalance is converted to a low level signal in the demodulation circuitry. An extensive attempt was made to use these Pace differential transducers to monitor the arrival of the shock front, and thereby obtain the shock speed and attenuation data. However, it was observed using an oscilloscope camera, that the transducer output was characteristically cyclic, and non responsive to anything that happened between cycles. This rendered the transducers useful to only steady state type readings.

The ionization probes consist of two short thin metal pins or wires, about .1" apart and projecting about .1" into the tube, which are insulated from each other. A potential difference, insufficient to produce a discharge, is applied between them so that, when a shock passes the probe, the increase in conductivity of the gas, together with the formation of ionized species in stronger shocks, cause electrical breakdown and the
subsequent discharge produces a suitable signal. The circuitry employed with the four probes in the GDST facility is shown in Figure XVI. Note that high circuit impedance is required since the resistances between the electrodes is still very large, about $10^4 \Omega$ minimum, even after discharge. The diodes prevent shorting of the signals from the other detectors. In evaluating the data some caution is necessary, because the details of what happens when a shock passes over electrical probes are by no means completely understood. There are reports of unexpected signals associated with nearby, but apparently unconnected probes. This has been observed in several photographs of output traces by this author. The advantages of these detectors, are their generally fast response, their ruggedness, and freedom from the effects of vibration, and their simple and inexpensive construction.
4. GDST Procedure

The procedure and technique of operation of the GDST facility naturally divides itself into two distinct procedures. First, the development and monitoring of the glow discharge; and second, the firing of the shock tube and the shock's subsequent detection. For the establishment of the glow discharge, the following procedure should be adhered to.

4.1. GD Procedure

A. Turn on all valves connecting cooling water to the generator heat exchanger system. This provides internal cooling of the generator components and the work coil.

B. Turn the control power for the generator on, and allow for a ten minute warmup period.

C. Turn both the small vacuum pump and the large CVC 180 cfm unit on, and continuously evacuate the driven section of the shock tube.

D. When the driven section has been sufficiently evacuated, (ie: Absolute pressure in the order of 1000 \( \mu \) of mercury or 1 mm Mercury absolute) activate the HF button on the generator.

E. Slowly, bring the power up until a violent dazzling plasma is generated (ie: Power on about 20\% in an efficiently load matched circuit.)
F. Immediately introduce a low oxygen flow into
the plasma by gradually turning the $O_2$ valve.
It is observed that the plasma visibly undergoes
a dramatic change in the transition from a static
air discharge, to an oxygen plasma with axial
flow. The plasma undergoes both dimensional
and color changes.

G. By a combination of $O_2$ inlet metering and back
pressure control and variable power input,
achieve the desired flow rate and pressure in
the tube. It is necessary to bring the power up
when the flow rate is increased in order to assure
plasma stability and avoid extinction due to cool
gas influx.

H. Now, inject a continuous trace of NO at the NO
inlet manifold and observe the characteristic
glow discharge. At this point, if the desired
glow discharge character is not achieved, it might
be necessary to adjust either the power input, the
$O_2$ rate, or the back pressure. After repeated runs,
2
a feel for the four coupled parameters a.) power;
b.) $O_2$ rate; c.) NO rate and d.) back pressure is
achieved and the desired glow discharge character can
usually be generated.
I. Monitor the intensity of the glow discharge with spectrometer-photomultiplier set up. 

This concludes the glow discharge procedure and leads to the shock tube procedure.

4. 2. ST Procedure

A. Before GD procedure, make sure diaphragm plunger is cocked and that a new mylar diaphragm is securely in place.

B. After GD procedure, evacuate driver section and reference side of all differential pressure transducers. Care must be taken to avoid premature rupture of the diaphragm by causing it to bulge back onto the plunger. Always make sure that the pressure in the driver section is greater than the pressure in the driven section.

C. When most of the air has been removed from the driver, repressurize it with helium. The pressure in the driver can range from 0 to $\sim 50$ psia depending on the desired pressure ratio across the diaphragm.

D. Activate the monitoring circuits, (ie: Transducers and/or ionization probes.)

E. Fire a shock through the glow discharge region by rupturing the diaphragm with a solenoid operated plunger. In conjunction with rupture initiation,
down the RF generator.

F. Glen desired data at test section and observe shock-speed and attenuation from transducer and ionization probe output traces.

G. Repeat entire procedure for additional runs. In the case of a terminal run:

1) Cut off generator, vacuum pumps, and cooling water.
2) Purge entire system with air.
3) Cut off monitoring systems.
4) Turn off all gas regulators and cylinders bleed gases out of lines.

This concludes the shock tube procedure.

4. 3. Miscellaneous Comments

4. 3. 1. Mylar Diaphragms

It was occasionally observed that upon rupture, the diaphragm would tear irregularly and send a piece of mylar down the tube. In the future application where the test section will contain a model, this ballistic mylar is undesirable. Two things can be done to prevent this irregular rupture: 1) the mylar can be scribed to cause the diaphragm to petal uniformly; 2) the plunger tip can be machined to initiate a uniform rupture pattern in the mylar.

4. 3. 2. Cleaning the Interior of GDST

Two methods were tried and both proved valuable in different situations.
One was a ballistic plug method, and the other consisted of swabbing out the interior with a wad on a 16 foot aluminum rod. Both have their advantages and disadvantages. The ballistic plug could be used in tight quarters, but was a lot of trouble as far as preparing the pig for insertion of the tube. The swab was awkward to use because of its size, but did a better cleaning job with less passes. In both cases distilled water is used as the cleansing fluid. The interior is wiped dry with Kim-Wipes. A clean tube interior is necessary to lessen atomic oxygen wall combination.

4. 3. 3. Torque Required for Teflon Gaskets

It was learned by experience that special attention need to be paid to applying adequate torque to flanged connections where there are one or more Teflon gaskets. Teflon "creeps" under compressive stress and therefore, it is necessary to check the torque on various bolted connections quite regularly. Torque in the order of 150 in-lbs. is necessary to maintain a good vacuum seal.
5. Discussion of Operating Characteristics

5.1. Plasma Initiation and Stability

Plasma initiation is a function of the gas pressure, the gas itself, coil configuration, discharge chamber size, and power input. For a given tube, a given gas, and a given coil configuration, the only remaining variables are pressure and power input. Data presented in Tables I and II show how the actual plasma initiation and appearance depend on pressure and certain generator output properties. Plasma stability is more of a qualitative determination and plots of relative flow rate versus power for both an O₂ plasma and an air plasma are given in Table III.

5.2. Character of the Glow Discharge

As pointed out in the discussion of the theory of chemiluminescent reactions (in particular the \(0 + NO\rightarrow NO_2 + h\nu\) reaction) the intensity of the radiant glow is proportional to the product of the NO concentration and the O concentration. Since the NO concentration is maintained essentially constant by the shuffle reaction, the intensity varies as the oxygen concentration alone. Therefore, the intensity of the glow depends inversely on processes other than the trace reaction, that take out atomic oxygen. These processes can be 1) wall combination, 2) oxygen recombination, and 3) other reactions that have atomic oxygen as a reactant. One and two have already been discounted in earlier statements. That leaves three as the sole contributor to premature glow extinction.
"Other reactions" can generally be described as needing a catalyst to take place. The catalyst is traditionally referred to as "M". The amount of "M" and the reactants mix are the determining factors in the early extinction. Therefore, by lessening the amount of non-participant "M" in the glow discharge area, and by avoiding gross turbulent mixing, the intensity of the discharge can be heightened.

An interesting qualitative observation can be made by comparing an "air torch" with the standard NO glow discharge. For a given flow velocity the air flame gives an afterglow at least twice as long as the $0 + NO \rightarrow NO_2 + h\nu$ discharge. This indicates that additional $O_2$ in the discharge system lessens the intensity. This is due to ozone production. Remedies for early glow extinction, include increased power input at the RF (not so much to increase $O_2$ concentration, but to decrease $O_2$), and back pressure control to generally slow the flow and cut down on gross turbulent mixing. The GDST facility is shown in operation in Figures XVII and XVIII.

5.3. Shock Speed and Attenuation

Shock speed is monitored by ionization probes coupled with an oscilloscope camera. After approximately 70 firings of the shock tube, reasonable shock speed data has been finally observed. For an air to air shock with a pressure ratio the order of magnitude of 1000, and resultant predicted shock velocity the order of $M=3$, data has been
obtained which concurs with prediction within about 10%. A photograph of a representative oscilloscope trace is shown in Figure XIX.

At present, only gross shock speed readings have been taken and additional diagnostic technique refinement is required to obtain relevant attenuation data. According to most theory in the current literature, for a shock tube of the dimensional configuration similar to the GDST, in question, attenuation should tend to be negligible. (ie: Less than 5%) Refinements of the ionization probe circuitry, more uniform probe make-up, and practice and experience with the oscilloscope camera, will produce more accurate quantitative results.
Figure I Glow Discharge Shock Tube Schematic
Figure IX Optical System and Spectrometer Table

Figure X Schematic of Optical System
Figure XI Standard Lamp Circuit Schematic Diagram, Reference: (Journal of Research, National Bureau of Standards, Vol. 64A, no. 4, 1960 pp. 291-296)
Figure XII  Driver Section and RF Section

Figure XIII  RF Coil without Plasma
Figure XVI Ionization Probe Circuitry

-400V

22kΩ  0.001µF  Diode  Probe 1
22kΩ  0.001µF  Diode  Probe 2
22kΩ  0.001µF  Diode  Probe 3
22kΩ  0.001µF  Diode  Probe 4

30kΩ
Figure XVII  GDST Facility in Operation

Figure XVIII  GDST Facility in Operation
Figure XIX
### Table I Generator Data and Plasma Initiation

**Wolfer set on 8**

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Generator would not oscillate

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22 Plasma out

**Wolfer set on 10**

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33* Plasma out

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19 Plasma out

**Wolfer set on 12**

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19 Plasma out

**Wolfer set on 13**

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21 Plasma out
Explanation of Symbols used in Table I

* Denotes onset of plasma

E Excitation current in amperes

PI Plate input current in amperes

HF High frequency current in amperes

KV DC voltage in kilovolts

ACV AC voltage

Pressure Initial pressure in microns of mercury
Upper Curve -- Plasma Initiation
Lower Curve -- Extinction

Supply Pressure (mm of mercury)

Table II
Power ($)$

$20\%$  $40\%$  $60\%$  $80\%$  $100\%$  Flow Rate

Hydrodynamic Stability ($O_2$ Plasma)

Curves Represent Plasma Extinction Due to Cool Gas Influx

Power ($\%$)

$20\%$  $40\%$  $60\%$  $80\%$  $100\%$  Flow Rate

Hydrodynamic Stability (Air Plasma)

Curves Represent Plasma Extinction Due to Cool Gas Influx
REFERENCES


I. I. Glass, W. Martin, and G. N. Patterson; A Theoretical and Experimental Study of the Shock Tube; UTIA Report #2; Toronto, 1953.


