METALLURGY

DEPARTMENT OF METALLURGY
Institute of Metals and Explosives Research

UNIVERSITY OF UTAH
SALT LAKE CITY, UTAH

ELECTRICAL AND PLASMA PHENOMENA ACCOMPANYING DETONATION

Final Report

Contract AF49(638)-1061

1 October 1961 - 30 September 1962

Project Director: M. A. Cook

Report prepared by: R. T. Keyes

ELECTRICAL AND PLASMA PHENOMENA ACCOMPANYING DETONATIONS

I. Introduction

The following constitutes the final report on contract AF-49(638)-1061 entitled "Electrical and Plasma Phenomena Accompanying Detonations". This contract extended through the period 1 October 1961 - 30 September 1962. The investigations carried out under the contract may be considered to fall under the following general classifications: 1) Ionization and electrical conductivity and its relationship to the deflagration to detonation transition in solid explosives, 2) Chemical reaction rates and the shock initiation of detonation of liquid explosives, 3) Mechanism of the "flash-across" phenomenon in the card-gap test for liquid explosives, and 4) Spectrographic studies of external detonation-generated plasmas. Technical notes have been prepared covering the essential results of the first two investigations. However, brief descriptions of these studies will be given below. The latter two investigations are currently in progress and have not as yet reached a logical stage for the preparation of a report.

During the contract period one graduate student received his Ph.D degree whose dissertation was based entirely upon research sponsored by the above contract and the earlier contract, AF-18(603)-100. In the case of another graduate student, who received the Ph.D degree during the year, about one half the research was AFOSR sponsored. At present three graduate students are working on the AFOSR contract at this laboratory in pursuance of the Ph.D degree.

II. Summary of Results

A. Ionization and electrical conductivity and its relationship to the deflagration to detonation transition in solid explosives: The essential results of this investigation were described in a technical note entitled "Ionization in the Shock Initiation of Detonation of Composition B". Some of the more important conclusions of this study will be described here briefly. Probe-conduction techniques using paralled probes (two long probes parallel and symmetrical with the axis of the receptor charge of the card-gap test, which gave an integrated value of the conduction within the receptor except at the barrier-receptor interface) and double sets of perpendicular

probes (perpendicular to the charge axis, diametrically opposed, with a small gap at the charge axis to measure essentially point conduction) were employed. Use of two sets of perpendicular probes served to determine in which direction the various disturbances propagated through the receptor charge, as well as determine the average velocity. In addition, an aquarium technique was applied to short receptor charges of differing lengths to measure the variation in pressure as a function of charge length occurring prior to the establishment of detonation by shock through the barrier.

Using perpendicular probes placed a distance from the barrier-receptor interface less than S_2, the point at which high order detonation occurred, three different ionization waves were detected. The first one was a broad wave of ionization appearing before the transition to high order detonation, which was produced by chemical reaction initiated by the initial shock wave. The second ionization wave was associated with the reverse detonation propagating back toward the barrier from the transition point, and the third was a much lower level ionization wave produced by a pressure pulse reflected from the barrier upon impact of the reverse detonation wave. The latter two ionization waves occurred, of course, only if a reverse detonation occurred. The reverse detonation was eliminated if the charge diameter was sufficiently small, particularly for barrier thicknesses near the sensitiveness limit. The perpendicular probes showed also that the reverse detonation propagated through the entire charge or it could be confined to a surface layer depending upon the conditions. For barrier thicknesses near the sensitiveness limit it tended to propagate only through the outer surface layer of the charge.

Probably the most interesting result was the relationship of the first ionization wave to the deflagration-to-detonation transition. This wave was a rather broad ionization wave which started coincident with the shock front but whose rise was apparently much more gradual than that of the pressure wave. However, as the initial shock propagated through the receptor the ionization wave became steeper and more intense, merging finally with the pressure front, the transition to high order detonation occurring when the "merging" took place. It is believed that this merging of the ionization front with the initial shock front, i.e., the formation of a plasma state permitting the conduction of heat to the shock front is a necessary condition for the transition to detonation

rather than being simply a by-product of the transition. Further studies to help establish or reject this hypothesis are planned for the coming year, one of these being controlling detonations with electric or magnetic fields.

If one interprets that the peak of the first ionization wave corresponds to the so called "flash-across" photographed in the shock initiation of liquid explosives, then its velocity characteristics were similar to those of the "flash across". That is, it was somewhat delayed at first with respect to the entrance of the shock wave into the receptor, but it propagated forward at high velocity overtaking the shock front, at which time high order detonation occurred. The above interpretation seems reasonable because the flash across appears very dim, being barely photographable. Thus, the peak of the ionization wave, which should correspond to maximum light emission, would be the part of the wave that was most likely to be seen on the photograph. Further, the variation of light intensity at the front of the flash across appears to be somewhat diffuse rather than sharp. These conclusions are also attractive in that they postulate the same mechanism of shock initiation for both solid and liquid explosives.

The intensity of the first ionization pulse was found to be very pressure sensitive. This was best illustrated by the fact that the level of ionization in short receptor charges was much less than in long receptor charges, other factors being equal. This result was attributed to elastic-plastic wave separation in the receptor with a release wave being reflected from the free end of the short receptor back into the ionization wave upon arrival of the elastic portion of the initial wave.

Parallel probes which gave an integrated value of the conduction, also yielded some interesting information regarding the buildup of ionization prior to the transition to detonation. For relatively thin barriers the ionization exhibited a smooth buildup until detonation occurred. For thicker barriers an inflection appeared, and in the case of glass and steel barriers with thicknesses near the sensitiveness limit a rise in ionization followed by a decrease and then another rise just prior to the transition occurred. Since this phenomenon was not exhibited in the case of lucite and water barriers, which do not exhibit elastic-plastic wave separation at the pressures involved as do steel and glass, it was concluded that the rise and fall in the ionization level was

due to a variation in the shape of the pressure pulse entering the receptor.

The variation in pressure of the initial shock wave was measured as a function of barrier thickness for various lengths of propagation into the receptor. Results showed that in general as the wave propagated into the receptor there was a "smooth" increase in pressure of this wave up to the detonation pressure. However, near the sensitiveness limit the pressure tended to remain nearly constant, and in some cases apparently even decayed a small amount, before a very rapid pressure increase occurred just prior to the transition. According to the shock pressure mechanism of initiation in the card-gap test of Ubbelohde,[1] Kistakowsky,[2] and Jacobs,[3] energy is fed into the initial shock wave through chemical reaction at a greater rate than it is lost by dissipative pressures. Hence, there is a smooth conversion from a shock wave to a detonation wave. On the basis of this theory one would not expect detonation to result when a drop in pressure occurred as was observed in some of the tests near the sensitiveness limit described above, because such an action signifies a failing wave.

If a plasma state is required for detonation, then the possibility existed that the presence of a metal (which might be considered a type of a plasma) at the barrier-receptor interface might possibly promote the formation of the detonation plasma and hence high order detonation. In order to test this possibility the entry surfaces of receptors were covered with a 0.005 cm thick layer of aluminum, silver, or copper foil, and then determinations were made to ascertain if 1) the sensitiveness limit, 2) the initial peak pressure in the receptor charge vs time to detonation, or 3) initial peak conductance vs time to detonation were influenced. No effect upon the sensitiveness limit was found within the 95% level of confidence based upon a series of 30 trials for each metal foil. However, there was a tendancy for the sensitiveness limit to be slightly longer when a metal foil was employed. For a given initial peak pressure in the receptor the time lag to initiation was found to be somewhat dependent upon the barrier material. Rather than this being due to a catalytic effect, however, the phenomenon was attributed more to the shape of the wave entering the receptor. For example, materials which exhibited elastic-plastic wave separation at the pressures involved, such as glass and steel, led to longer time lags for given peak pressures than did lucite and water where the

compression wave propagated as a pure shock. In these tests it should be mentioned that thin metal foils were not used, but that the barriers comprised a single material. Studies showed also that the initial peak conductance vs time to detonation was not altered significantly by the presence of aluminum, copper, or silver foil on the entry face of the receptor.

It was concluded, therefore, that any catalytic effect of metals upon the initiation of detonation by shock, if present, was small. In addition, to the fact that the sensitiveness limit tended to be increased slightly by metal foils on the receptor as mentioned above, another result indicated a possible though small effect. Namely, in the case of lucite and water barriers with metal foil on the receptor, a rise and fall of the ionization level prior to the final rise before detonation was detected with parallel probes for barrier thickness very near the sensitiveness limit. These traces were of a nature similar to those for glass and steel which were attributed to elastic-plastic wave separation of the compression wave entering the donor and without the metal foil were not obtained with water or lucite barriers. This apparently indicates some type of an effect from the metal foils.

Studies of initiation by plate impact were also carried out, the results of which showed that the mechanism was the same as shock initiation through a card gap.

B. Chemical Reaction Rates and the Shock Initiation of Detonation of Liquid Explosives.

The essential results of this investigation were described in a technical note entitled "Chemical Reaction Rates and the Shock Initiation of Detonation of Liquid Explosives." Detonation velocity-charge diameter curves were obtained for the liquid explosives, nitromethane (NM) dithekite 13 (D-13), NM/TNT (80/20), NM/Tetryl (80/20) and NM/2.8% ethylene diamine (EDA) in polyethylene tubes of 6 mil wall thickness. Wave shape and "edge effect" measurements were performed for NM, the "edge effect" observations being made in addition for D-13. The edge effect refers to a thin outer layer of explosive which reacts slowly and does not contribute to the support of the detonation wave. The so called effective diameter d' is thus the charge diameter minus the total "edge effect". For NM the wave fronts were found to be spherically shaped. At the critical diameter the ratio of the radius of curvature to the

effective diameter, R/d' was 1/2, meaning that the wave front was hemispherical. The R/d' ratio then increased rapidly with diameter and leveled off at a value of 3.3. The above results are all in good agreement with data for solid explosives. For NM the average total edge effect was 0.5cm in the diameter range 2.16 to 3.70 cm, and it was 0.4 cm for D-13 in the diameter range 0.83 to 1.23 cm. These values may be compared with an edge effect of 0.6 cm as determined for solids.

The shapes of the detonation-velocity charge diameter waves were much different than those usually exhibited by solid explosives. The liquids exhibited non-ideal velocities over a range of diameters small compared to those of most solids, and the velocity fell steeply in this non-ideal range. The lowest value of detonation velocity recorded, which was the velocity at the critical diameter, was only 93 per cent of the ideal or "leveled-off" velocity. This corresponds to an extent of chemical reaction supporting the detonation wave of approximately 87 per cent, which contrasts to solid explosives where the velocity-diameter curves are less steep and the extent of chemical reaction required to maintain the wave may be as low as 50 per cent in pure compounds and lower still in mixtures.

The nature of the velocity-diameter curves for liquids provided information regarding the mechanism of reaction prevailing in detonation. Solid explosives in detonation react by the Eyring surface burning mechanism,[4] according to which the flame front is confined to the surfaces of grains making up the explosive. Thus, the rate at which energy supporting the wave is liberated, is greatest at the wave front because it is at this time when the greatest surface area is exposed to the flame front. The nature of the velocity-diameter curves for liquids indicated that most of the energy was released at the end of the reaction process. This would favor a scheme in which reaction starts at hot spots or reaction centers within the liquid and proceeds radially outward at nearly constant velocity. The energy release would thus be slowest at the start and most rapid near the end of the reaction zone where the surface area of the reaction centers exposed to the flame front was largest. This type of situation would lead to a condition where at a particular diameter the explosive may fail, whereas at a slightly larger diameter it may detonate almost at ideal velocity.

A theory based upon the "reaction center" scheme was developed and applied together with the detonation head model to the velocity-diameter curves for determinations of reaction zone length. This model was found to fit the velocity-diameter curves satisfactorily, and it yielded reaction zone lengths of 1.9 cm and 0.35 cm for NM and D-13 respectively. These values are in good agreement with determinations made from the initial length of the external detonation generated plasma and recent unpublished photographic observations of W. S. McEwan and H. D. Mallory of Naval Ordnance Test Station, China Lake, California.

Studies regarding the shock initiation of detonation were confined to NM using the card gap or SPHF (shock pass heat filter) plate test where shock from a donor charge, attenuated through a barrier, effects initiation in the receptor charge. The barrier material used was lucite. As mentioned earlier, photographic observations of the initiation of detonation in liquids by means of the above arrangement show a high velocity phenomenon (sometimes referred to by members of this group as the "flash-across") of somewhat lower luminosity than the normal high order detonation wave, which after some delay from the entrance of the initial shock into the receptor, starts at the barrier-receptor interface and overtakes the shock front. Normal high order detonation prevails after this occurs.

One explanation advanced was that the high velocity phenomenon represented the propagation of a dilute plasma condition which started at the barrier and flashed to the shock front, this "mergence" allowing high heat conduction to the wave front which was considered to be a necessary condition for high order detonation.[5] An alternate explanation was that the high velocity phenomenon was a detonation wave that started at the plate, the high velocity resulting from its propagating through the pre-compressed explosive.[6,7] The lower luminosity compared to that of the normal detonation wave was construed to be the result of a lower detonation temperature at the higher density. The latter explanation would require different mechanisms for liquids and solids, because in solids detonation starts at or very near to the shock front.

A crucial experiment that would serve to eliminate one of the above mechanisms is the measurement of the pressure of the high velocity phenomenon.

According to the first mechanism described, the phenomenon would not be governed by the hydrodynamic laws of wave propagation, and the pressure would not be expected to be high. Whereas in the second case the detonation pressure would have to be considerably greater than the normal detonation pressure of the liquid.

A technique involving the measurement of the initial velocity of the shock transmitted into a medium with a known equation of state was used to estimate the pressure of the high velocity phenomenon. The transmitting medium was chosen to be one that possessed shock characteristics as equal as possible to NM, and its entrance face was spaced a distance from the barrier-receptor interface that was supposed to be equal to or just slightly less than S_2, the distance from the barrier at which normal high order detonation formed. Providing the shock impedance of the transmitting material or pressure gauge material matched that of NM, then no reflected rarefactions or reflected shocks would be transmitted back into the explosive if the "flash-across" had not yet merged with the initial shock front before it reached the gauge material. Consequently, the events occurring in the NM leading to the establishment of normal high order detonation would be unaffected by the gauge material. Provided the "flash-across" phenomenon possessed a pressure appreciably higher than the initial shock, a "velocity overshoot" or pickup of velocity in the gauge material would be registered in cases where S_2 was slightly greater than the distance between the barrier-receptor interface and the gauge material. On the other hand, if the merging of the "flash-across" and the initial shock occurred just before the gauge material was reached, a pressure higher than the normal detonation pressure of NM should be recorded because if the "flash-across" were a detonation an "overpressure" would persist for some distance after the detonation wave overtook the shock front.

Two different gauge materials were used, the first being lucite and the second a salt solution whose concentration was adjusted such that it was almost a perfect match to NM. The lucite, though a good match for NM, was inferior to the salt solution. However, it was more convenient and was used initially for this reason.

The first step was to define the detonability limits of NM at a chosen temperature in terms of the initial velocity of the shock wave in NM. At 30°C

the sensitiveness limit was found to be 4400 m/sec, i.e., an initial velocity lower than this did not effect a detonation. On the other hand a velocity greater than 5050 m/sec produced a detonation immediately upon entrance into the receptor. These two velocities corresponded to pressures in the NM of 74 and 100 kbars respectively. A number of pressure measurements of the flash across were carried out both with lucite and the adjusted salt solution pressure gauge. In no case was any evidence of an "over pressure" detected. In fact where S_2 was slightly longer than the distance between the barrier-receptor interface and the entrance face of the gauge material, the maximum pressure registered by the gauge was always lower than that of the initial shock when it entered the NM. However, according to data of Campbell, et.al.[6] the pressure of the high velocity pehnomenon should be about 4.5 times the normal detonation pressure of NM and about 7 times greater than the initiating shock wave pressure. It is felt, however, the point in question is so crucial with regard to the mechanism of initiation by shock and the mechanism of the propagation of-established detonations that further work should be carried out. For example, one must be certain that the method is sufficiently sensitive to detect a high pressure in the "flash-across" if it does exist. The method is certainly able to detect easily the magitude of pressure involved. However, problems could arise if the "high pressure" wave was very thin.

C. Ionization and the Mechanism of the Hypervelocity or Flash Across Phenomenon in the Shock Initiation of Liquid Explosives

This program was initiated by a new graduate student during the year. Plans are that he will, 1) perform additional experiments to measure the pressure of the "flash-across" phenomenon, 2) measure the buildup of ionization in the shock initiation of liquids similarly as was done with Composition B and 3) measure the velocity of "flash-across" phenomenon in liquids as a function of barrier thickness. The purpose of the above studies is to provide further information as to whether the mechanisms of shock initiation in solids and liquids are the same and to define better the "flash-across" phenomenon which would be an aid in understanding the deflagration to detonation transition and the mechanism of detonation.

The additional pressure measurements of the "flash-across" as mentioned earlier should be performed because the results are so crucial with regard

to the understanding of the whole detonation process. Ionization measurements have been performed in Composition B, and the results indicated that the peak of the initial ionization wave corresponded to the "flash-across" photographed in liquids. Photographic recording of the phenomenon in solids is impossible. Thus, the best check to determine if the intrepretations of the ionization results in Composition B were correct appears to be that of performing similar measurements in liquids, correlating the results with photographic observations, and comparing the ionization traces with those from Composition B. There are two obvious features of liquid explosives that are different from solids. Firstly, is the fact that in liquids chemical reaction starts at reaction centers from which the flame front expands radially outward until the explosive is consumed. Thus, energy is released most rapidly near the end of the reaction zone where the surface area exposed to the flame front is greatest. This behavior probably is the reason why liquids exhibit a rather narrow region of barrier thicknesses which will lead to an S_2. The second feature of liquids is that in shock initiation the initial wave is a stable shock wave; no elastic, plastic wave separation occurs as in the case of solids.

According to the interpretation that the peak of the first ionization wave in solids was the "flash-across" phenomenon, then the results indicate a "flash-across" velocity dependence upon barrier thickness. This is a point that needs checking in liquids where the "flash-across"velocity can be determined photographically.

Most of the efforts thus far have been devoted to developing methods for obtaining the desired data. Difficulty was encountered in the conduction-probe experiments in NM. Contrary to our experience in Composition B where the presence of the probes did not influence the transition to detonation, impact of the initial shock with the standard probes generally resulted in initiation at or slightly past the probes. Under such circumstances measurements of the build up of ionization prior to the establishment of high order detonationwere impossible. Tests subsequently have been carried out using various probe configurations and various size probes. It appears that finally a system has been achieved which does not cause premature initiation and will permit the desired measurements to be made. Experiments as yet are

in too premature a stage for conclusions to be given.

A number of methods have been tried to measure the "flash-across" velocity as a function of barrier thickness. One method entailed measurement of the delay between arrival of the initial shock and the "flash-across" at various distances from the barrier for a fixed barrier-donor system. Then by means of a measured relationship between the initial shock velocity vs the distance of propagation, the flash across velocity could be determined. The fact that the conductivity of the initial shock wave in NM is low permitted the time of arrival of the shock to be measured by a switch which closed upon impact of the shock. The arrival of the flash across could be recorded with conductivity probes. The fact that initiation of the NM resulted from the initial shock impacting the probes, however, eliminated this type of measurement.

Photographic techniques similar to those of Campbell, Davis, and Travis[6] currently are being used. In this method the receptor charge of NM, by means of an inclined front surface mirror, is viewed from the top along a direction perpendicular to the barrier-receptor interface. The start of the flash-across from the barrier plate is evidenced by a faint luminosity barely recordable with the streak camera at this laboratory, although some improvements over initial recordings of this type have been achieved through the use of special film processing and applying a reflecting metal coating on the receptor surface of the barrier plate. Brighter luminosity results a short time later when the "flash-across" overtakes the initial shock front, i.e., when normal high order detonation is established. The time the normal high order detonation reaches the surface of the NM is shown by the highly luminous external detonation-generated plasma. The average "flash-across" velocity then may be determined from such records if the time of entrance of the initial shock wave and its velocity-distance characteristics are known.

The above method may not be as accurate as desired for the thinner barriers in which case the S_2 distance is short. Consequently the use of a photomultiplier set-up, feeding into an oscilloscope which records light intensity vs time was being investigated at the end of the year. It is hoped that this system will provide a more accurate determination of the events occurring during the transition to detonation in the shock initiation of NM.

Spectrographic Studies of External-Detonation Generated Plasmas

This program was also initiated during the present contract period. One of the main purposes of the study is to identify the origin of the intensly luminious plasma that results when a detonation wave reaches the free surface of a charge. According to one explanation the expanding detonation products act as a high velocity piston, driving a shock wave through the medium surrounding the charge, and the luminosity is radiated from this shock wave. An alternate explanation does not deny a contribution from the above means in some gases. However, the major share of the luminosity is asserted to be the result of the decay of ionized and excited products propelled from the detonation reaction zone. Although the latter explanation has not been widely accepted in general, there are a number of results that indicate it is correct. The spectroscopic study should establish definitely whether or not this is so.

The two phases of this investigation include (1) the spectral analysis of detonation-generated plasmas and (2) the time resolution of detonation-generated plasmas. Spectrograms, for purposes of spectral analysis, have been obtained using the arrangement shown in Fig. 1. The charge, generally about 25 g, being used thus far, was detonated inside a small concrete bunker -- located adjacent to the Institute of Metals and Explosives Research's laboratory building on the upper part of the University of Utah campus. The plasma is viewed from the front along the direction of the charge axis, the luminosity from the plasma being reflected by an aluminum-coated front surface mirror to a 1.5 meter Bausch and Lomb spectrograph. The mirror and the spectrograph are located in the laboratory building adjacent to the firing bunker. By means of a series of steel and wooden baffles shown in Fig. 1, it was possible to attenuate the blast sufficiently that no safety glass was required to protect the instruments. This eliminated undersirable absorption of the ultra violet region of the spectrum.. The effective spectral range of the 1.5 meter Bausch and Lomb spectrograph is from 4500 Å to 7000 Å first order and 2250 Å to 3500 Å second order with a dispersion of 10 Å 1/mm in the first order and 5 Å 1/mm in the second order.

Although most of the effort to date has been devoted to the second phase entailing time resolution of the plasma luminosity, a number of spectrograms have been obtained. The spectra consisted of a continuous black body spectrum

superimposed upon which were molecular and atomic spectra. In particular there have been recorded CN bands near the 3300 Å region, a great number of molecular bands that as yet have not been identified, and carbon lines. Also, the 5890 Å and the 5895 Å sodium lines invariably occur as a result of sodium contamination.

It has also been determined that in general when metal nitrates were added to the explosive the metals were excited sufficiently to emit visible radiation which shows up in the plasma spectrum. This has been done using RDX mixed with approximately 10% Na, Ba, Ag, Sr, Cu, In, and Pb nitrates, the mixtures being hand pressed into compact charges in cardboard tubes. This fact is being used in the time resolution studies which will be described below.

Another characteristic feature of the detonation spectra is broadening of the lines. This broadening is probably the result of temperature and collision broadening. In addition to identification as well as is possible of the species making up the atomic and molecular spectra it is intended that a quantitative analysis of the line broadening will be performed. Also possibly

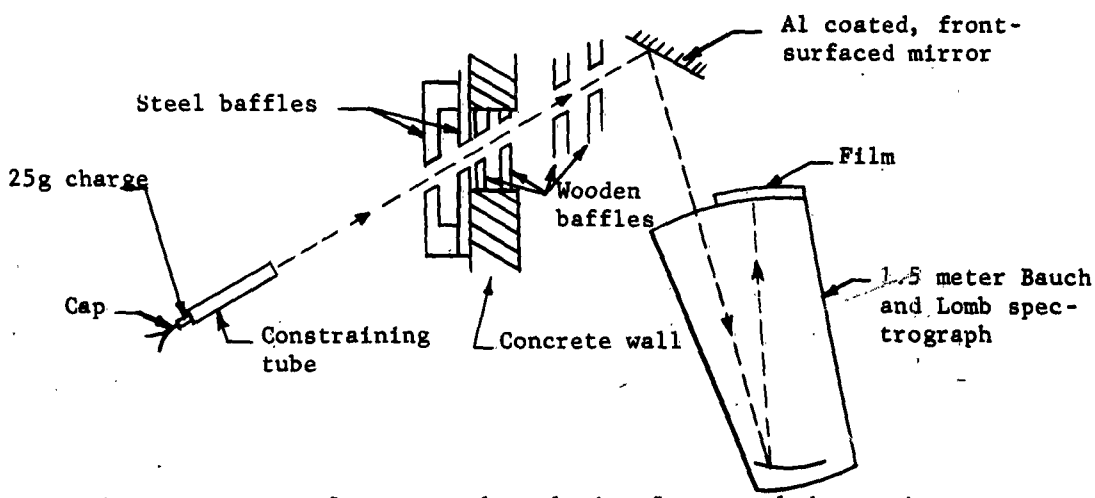

Figure 1: Arrangement for spectral analysis of external detonation-generated plasmas.

the black body spectrum may be analyzed to determine the temperature.

The experimental arrangement for time resolution studies of detonation-generated plasmas is shown in Fig. 2. The charge is initiated by a blasting cap. When the detonation front reaches the end of the charge, the luminous plasma propagates down the constraining tube making contact with the trigger and the ionization probes, radiating light by means of the front surface mirror to the slit of the spectrograph as it passes the slit in the constraining tube. The constraining tube used has been carboard in which case a narrow slit was cut in the tube, or it has been glass which was covered with an opaque material except for the desired slit. In this manner radiation from the front of the plasma and succeeding rearward sections were sampled progressively by the spectrograph as the plasma propagated past the slit of the constraining tube. The light after being dispersed into its spectral components passed through an optical slit located on the film track of the spectroscope and thence into a DuMont 6291 photomultiplier (P.M.) tube. The signal from the P.M. tube was amplified and fed into a Tektronix oscilloscope. For time resolution of the detonation generated plasmas the ionization probes were assembled on the same plane as the light slit, and the signal from them was fed into a second oscilloscope triggered simultaneously with the first. Hence the intensity-time trace of any spectral region on which the film track slit was placed could be correlated with the ionization which is known to coincide with the leading luminosity of the plasma.

The fact that metal nitrates, when mixed with an explosive, react to produce the atomic spectrum of the metal provides convenient, known lines for observation in the time resolution experiments. Indium nitrate is a particularly attractive additive because it has a strong line at 4511 Å which is considerably isolated from other lines of the plasma spectrum, and this wave length lies in the sensitive wavelength region of the photomultiplier tube in use. Another important factor is the absence of any inherent indium contamination in the explosive and in the atmosphere. Thus, when the 4511 Å line is observed, one is certain that it resulted from the addition of indium in the explosive, and the excited material was projected from the detonation reaction zone. Although some observations have been made on the sodium

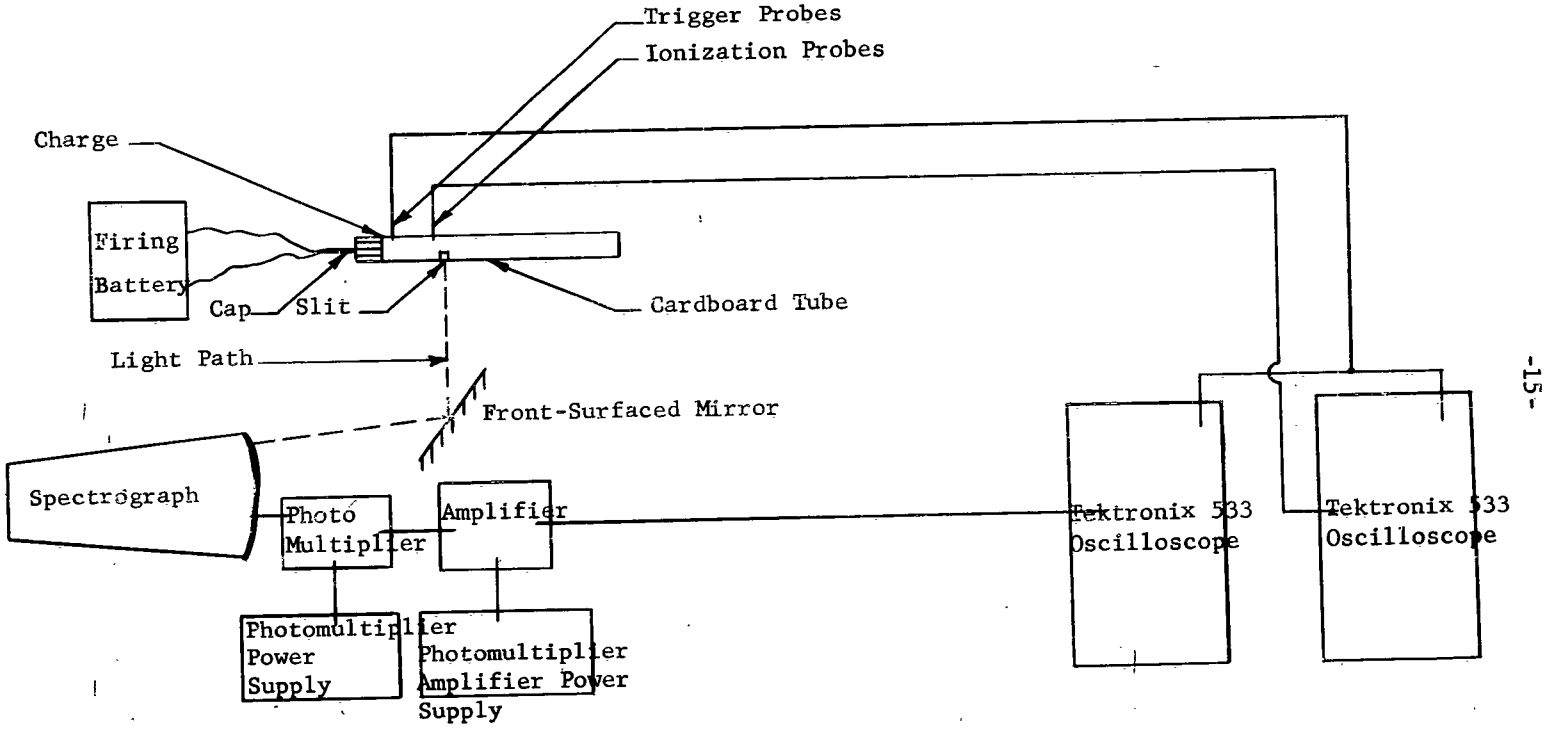

Figure 2: Schematic and block diagram of system for time resolution of detonation-generated plasmas.

line, the results may be open to question because sodium is such a common contaminent that one cannot, therefore, be certain as to the origin of the line. It might be argued, for example, that the atmosphere or the constraining tube contained sufficient sodium that the sodium spectrum was produced as a result of excitation of the contaminent by a shock wave propagating down the constraining tube.

In the time resolution studies carried out thus far involving indium nitrate additive the usual procedure has been to coat the emergent end of a 1" x 1" (diameter - length) cast pentolite charge with a thin layer of indium nitrate. In this manner a high density charge is achieved, and much less indium nitrate is required than if it is mixed with the charge. The results appear to be about the same as with mixtures although they are less reproducable. When the techniques have been completely worked out, they will be applied to mixtures also.

Though the results at the present state of the program can only be considered tentative they show that excited indium atoms exist at the front of the luminious zone or plasma generated upon emergence of the detonation wave. A corollary to this then is that some of the plasma luminosity results from excited and ionized material projected from the detonation reaction zone.

Plasmas have been projected down cardboard tubes possessing a diameter equal to the charge diameter. The plasma was viewed by the spectroscope through an approximately 1 mm slit cut through the wall of the cardboard tube which was located varying distances from the terminal end of the charge. The charges were detonated with and without indium nitrate on the terminal end, and the radiation of the 4511 Å line was measured with the photomultiplier equipment in each case. Shooting in the cardboard tubing resulted in an intensity trace with a double peak when indium was used and a single peak without indium, the amplitude also being lower in the latter case. These results are illustrated in Fig. 3. The increased intensity with indium nitrate on the face of the charge was a result of radiation at 4511 Å from indium in the plasma. The double peak must be related to the manner in which the plasma "squirted" out from the slit in the cardboard tubing because such an effect was not noted when glass tubing, opaqued except for a narrow viewing slit, was used. With glass tubing the intensity at 4511 Å was still increased

(a) (b)

Figure 3: Photomultiplier output from the 4511 Å indium line for plasmas projected down a cardboard tube from a 50/50 pentolite charge. The plasmas were viewed through an approximately 1 mm slit in the wall of the tube 3 cm from the terminal end of the charge a) indium nitrate placed on the end of the charge b) bare charge, the light emission being black body radiation.

markedly by the addition of indium nitrate but the double peak was no longer evident. Preliminary results showing the relative intensity at 4511 Å as a function of distance from the terminal and of the charge with and without indium nitrate are given in Fig. 4.

A number of modifications are now in process to improve the validity of the experiment, firstly, the assembling of instrumentation to measure total radiation from the plasma simultaneously with the intensity at 4511 Å. This should provide a determination of the manner in which the black body radiation in the vicinity of the 4511 Å line is affected, while measurements at 4511 Å are being taken under varying circumstances. We want to be certain whether the increased intensity at 4511 Å resulting from the addition of indium nitrate is due to increased black body radiation or whether it stems largely from excitation of the indium line. A conclusion regarding this man be inferred from consecutive measurements at and near 4511 Å, and such observations have been performed. However, one cannot be certain of

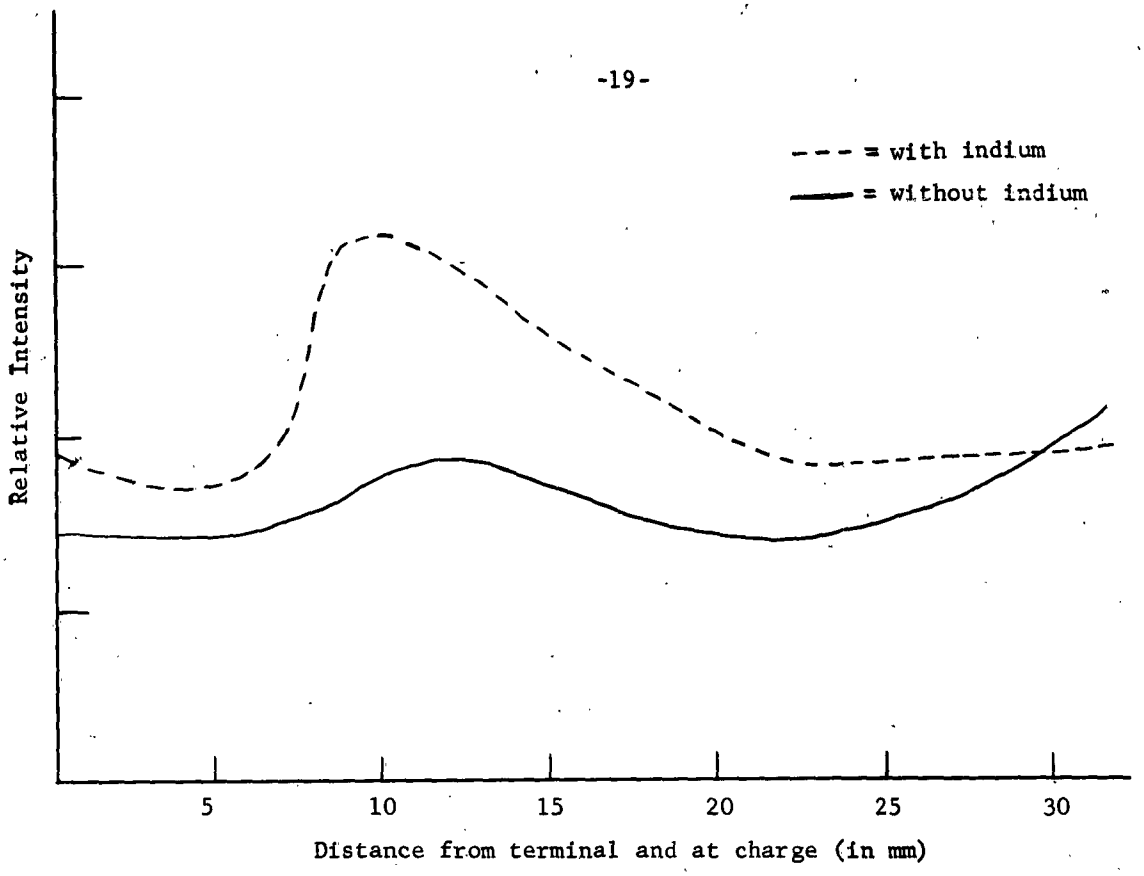

Figure 4: Relative intensity at 4511 Å (with and without indium on the end of the charge) vs distance of the viewing slit from the terminal end of the charge for plasmas projected into glass tubing.

reproducibility from shot to shot which renders the results questionable until the reproducibility is checked. Some of the factors which affect the results and are currently being investigated are: 1) the effect of trigger probes near the end of the charge, 2) the amount of indium on the end of the charge; we may need to mix the indium nitrate with the charge to control this factor, 3) the density of the charge, 4) the smoothness of the end of the charge, and 5) the exact dimensions of slit width.

It appears at this initial stage of the investigation that a great deal of useful, new information should be gained from this experiment.

REFERENCES

1. Ubbelohde, A. K., Third Symposium on Combustion, Flame and Explosion Phenomenon, Williams and Wilkins, Baltimore, Maryland, 1949.

2. Kistiakowsky, G. B., ibid, p 560.

3. Jacobs, S. J., Conference on Wave Shaping, J. P. L. Pasadena, California, July 1956.

4. Eyring, H., Powell, R. E., Duffey, G. H., and Parlin, R. B., Chem. Rev., 45, 69 (1949).

5. Cook, M. A., Pack, D. H., and Gey W. A., Seventh Symposium (International) on Combustion, September 1958, p 210-236, Butterworth Scientific Publications.

6. Campbell, A. W., Davis, W. C., and Travis, The Physics of Fluids, 4, 498, (1961).

7. Chaiken, R. F., Third ONR Symposium on Detonation, Princeton University, September 1960.

REFERENCES

1. Ubbelohde, A. K., Third Symposium on Combustion, Flame and Explosion Phenomenon, Williams and Wilkins, Baltimore, Maryland, 1949.

2. Kistiakowsky, G. B., ibid, p 560.

3. Jacobs, S. J., Conference on Wave Shaping, J. P. L. Pasadena, California, July 1956.

4. Eyring, H., Powell, R. E., Duffey, G. H., and Parlin, R. B., Chem. Rev., 45, 69 (1949).

5. Cook, M. A., Pack, D. H., and Gey W. A., Seventh Symposium (International) on Combustion, September 1958, p 210-236, Butterworth Scientific Publications.

6. Campbell, A. W., Davis, W. C., and Travis, The Physics of Fluids, 4, 498, (1961).

7. Chaiken, R. F., Third ONR Symposium on Detonation, Princeton University, September 1960.