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CHEMICAL ENERGY SYSTEM FOR A BOREHOLE SEISMIC SOURCE

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Abstract

We describe a detonation system that will be useful in the seismological examination of geological structures. The explosive component of this system is produced by the mixing of two liquids; these liquids are classified as non-explosive materials by the Department of Transportation. This detonation system could be employed in a borehole tool in which many explosions are made to occur at various points in the borehole. The explosive for each explosion would be mixed within the tool immediately prior to its being fired. Such an arrangement ensures that no humans are ever in proximity to explosives. Initiation of the explosive mixture is achieved with an electrical slapper detonator whose specific parameters are described; this electrical initiation system does not contain any explosive. The complete electrical/mechanical/explosive system is shown to be able to perform correctly at temperatures ≤ 120° C and at depths in a water-filled borehole of ≤ 4600 ft (i.e., at pressures of ≤2000 psig).

DISCLAIMER

I. Introduction

In this report, we discuss the development of a detonation system that will be useful for the seismological examination of geological structures below the earth's surface. The methodology to be discussed is based on the detonation of a liquid explosive. This liquid explosive has the unusual characteristic that it is produced by the mixing of two other liquids that are classed, for some purposes, as non-explosive; e.g., for shipping purposes within the United States.

Seismology is the science of characterizing the subterranean earth by interpreting the way in which known acoustic waves travel through the various strata and formations in the earth. Seismology is a major tool used by the oil industry to identify new reserves and to better characterize existing reserves. Since the inception of this technology there has been an ongoing search for acoustic sources, receiver/detector devices, and interpretive aids that will maximize the volume and resolution of the rock masses being imaged and minimize the cost and risk required in obtaining this information.

The exponential increase in available computing power in recent years and, particularly, the acquisition of super computers by the major oil companies has vastly increased the ability of seismologists to process and interpret seismic data. This processing ability has also greatly increased the search for improved data and techniques. One of the improved techniques is crosswell tomography, which introduces a seismic source in an existing borehole and places receivers in surrounding boreholes at various depths. If multiple source pulses are then introduced at varying known depths, it is possible to obtain a two-dimensional picture of the earth's structure between the "source" borehole and a "receiver" borehole; if multiple receiver boreholes are present an approximate three-dimensional picture can be obtained. As the amount of acoustic energy available at the source is increased, the boreholes can be more widely spaced and the volume of earth that can be evaluated increases rapidly with an accompanying reduction in the unit cost of the information.

Over the years, one of the important sources of acoustic energy for seismology has been explosives. While very effective sources of seismic energy, conventional explosives have a number of aspects that can cause concern. Some of these are:

(1) the administrative complexity of shipping and handling explosive materials, (2) the hazardous nature of accidental and untimely detonation due to careless handling, and (3) in the case of tomography, the difficulty of obtaining a large number of repetitive detonations at different known depths. Another salient problem with explosives is the perception that any explosive is generally dangerous and uncontrollable, no matter what the circumstances surrounding its application.

In order to deal with these considerations, the "Los Alamos Explosive Seismic Source" concept was conceived at Los Alamos National Laboratory. The realization of this concept would use the experience with high temperature, high pressure downhole tools obtained from the Los Alamos Hot Dry Rock Geothermal Energy Project coupled with the explosive technology and expertise that has been developed to support the nuclear weapons programs at Los Alamos. The basic concepts were that: (1) two or more non-explosive constituents would be stored in the downhole tool, (2) these constituents would be combined into an explosive mixture after being transported into a borehole, and (3) this explosive mixture would be detonated by the use of a non-explosive initiator; e.g., an electrical slapper detonator. Further, the constituents would be precisely mixed as a large number of small explosive charges which would each be detonated soon after being manufactured. This concept addressed all of the concerns arising from the use of conventional explosives, since explosives would only exist when the tool had been lowered into a borehole and operation was started.

It was hoped that the materials to be mixed could be liquids, since the packing factor for liquids would be very efficient and because the mixing of liquid constituents would be much easier than the combining of solids. A disadvantage of a liquid organic-chemical explosive is that its mass density is lower than the best solid explosives and, thus, so is its energy per unit volume.

In 1988, Los Alamos made a proposal to the joint DOE/Crosswell Seismic Forum for funding to start conceptual design on a downhole seismic source that would provide a thousand or more repetitive explosive pulses for each excursion into a wellbore and that would use a liquid explosive obtained by mixing other non-explosive liquid materials. The DOE Bartlesville Project Office (BPO) provided the initial funding to begin a feasibility study for the design. Since that time, there has

been funding provided by the DOE/BPO upon recommendations by the Crosswell Seismic Forum.

From the time of early discussions and proposal of this Explosive Seismic Source system, there has been a question of the possibility of damage caused by the explosions to existing, healthy wellbores, especially if they are producing wells. This was one of the first issues that was addressed during the early feasibility studies. Extensive computer analyses were performed which demonstrated that cemented casings in good condition would not be damaged by the detonation of charges of the size proposed for use in this seismic source.[1]

In this report, we describe work on the properties of a detonation system that fits the above description. As noted above, a primary a-priori constraint on the form of the explosive in this detonation system was that it should consist of a mixture of non-explosive liquids and that this mixture should itself be a liquid; here we define a non-explosive liquid as one that the Department of Transportation treats as such.

Earlier research at LANL and elsewhere[2-6] suggested that liquid nitromethane sensitized by an organic (amine) base was a possible candidate material. The bulk of this report is a discussion of work which demonstrates that it is feasible to use such a liquid mixture in borehole seismic applications.

There are several aspects to this demonstration. Among these are:

(1) can a two-liquid mixture be found that will propagate detonation in a size appropriate for use in a well-logging tool,

(2) given item (1)--can the explosive mixture be initiated by some method, adaptable for use in a tool in a borehole, which itself does not make use of explosives, and

(3) given items (1) and (2)--over what range of pressure and temperature characteristic of borehole environments will the liquid explosive mixture and its accompanying detonation system perform satisfactorily? Below, we present experimental results that answer these questions.

The remainder of this report is arranged as follows: Section II is a discussion of the two-component liquid explosive and its detonability at ambient temperature and pressure, Section III is a discussion of the initiability of the mixture at ambient temperature and pressure by an electrical slapper detonator system, in Section IV,

we discuss a method of maintaining the slapper initiation system's effectiveness at the high pressure characteristic of deep boreholes, in Section V, we present results concerning the initiablity and detonability of the mixture at the elevated temperature and pressure characteristic of deep boreholes, and in Section VI we discuss our results and draw conclusions.

II. The Two-Component Liquid Explosive Mixture and its Detonability

In earlier work[3,5] at LANL, detonation studies had been made of the liquid nitroalkane nitromethane (denoted as NM) mixed with the liquid organic (amine) base diethylenetriamine (denoted as DETA). The chemical formulae for NM and DETA are, respectively, CH_3NO_2 and $H_2N(CH_2)_2NH(CH_2)_2NH_2$. While the neat form of liquid NM can be detonated, it is an extremely insensitive explosive--so insensitive that the Department of Transportation defines it as a flammable liquid for the purposes of transporting it within the United States (see Code of Federal Regulations, Vol. 49, Sec. 172.101). The amine base, DETA, cannot be detonated in its neat form. Material Safety Data Sheets (MSDS) for NM and DETA are given in Appendix 1; these sheets list various chemical, physical, and safety characteristics of the two materials.

It is a remarkable fact that when even small amounts of DETA are added to NM, a significantly more sensitive explosive is produced.[3,4] As an example of this sensitization, consider the effect of DETA addition on the failure diameter of NM. Note that the failure diameter (D_f) of a long right circular cylinder of an explosive is the minimum cylinder diameter in which a steady self-sustaining detonation wave can be propagated.[7] For cylinder diameters smaller than D_f, any attempt to generate such a steady wave will fail; i.e., it will result in a shockwave that quickly decays to zero strength. The functional dependence of an NM/DETA-mixture's failure diameter on the amount of DETA present has been previously studied, under some conditions.[3] Figures 1 and 2 show this dependence for various concentrations of the DETA additive, when the explosives are contained in thick Pyrex cylinders. One sees from these two figures that with sufficient additive (ca. 2.5 wt%), the failure diameter can be reduced by over an order of magnitude.

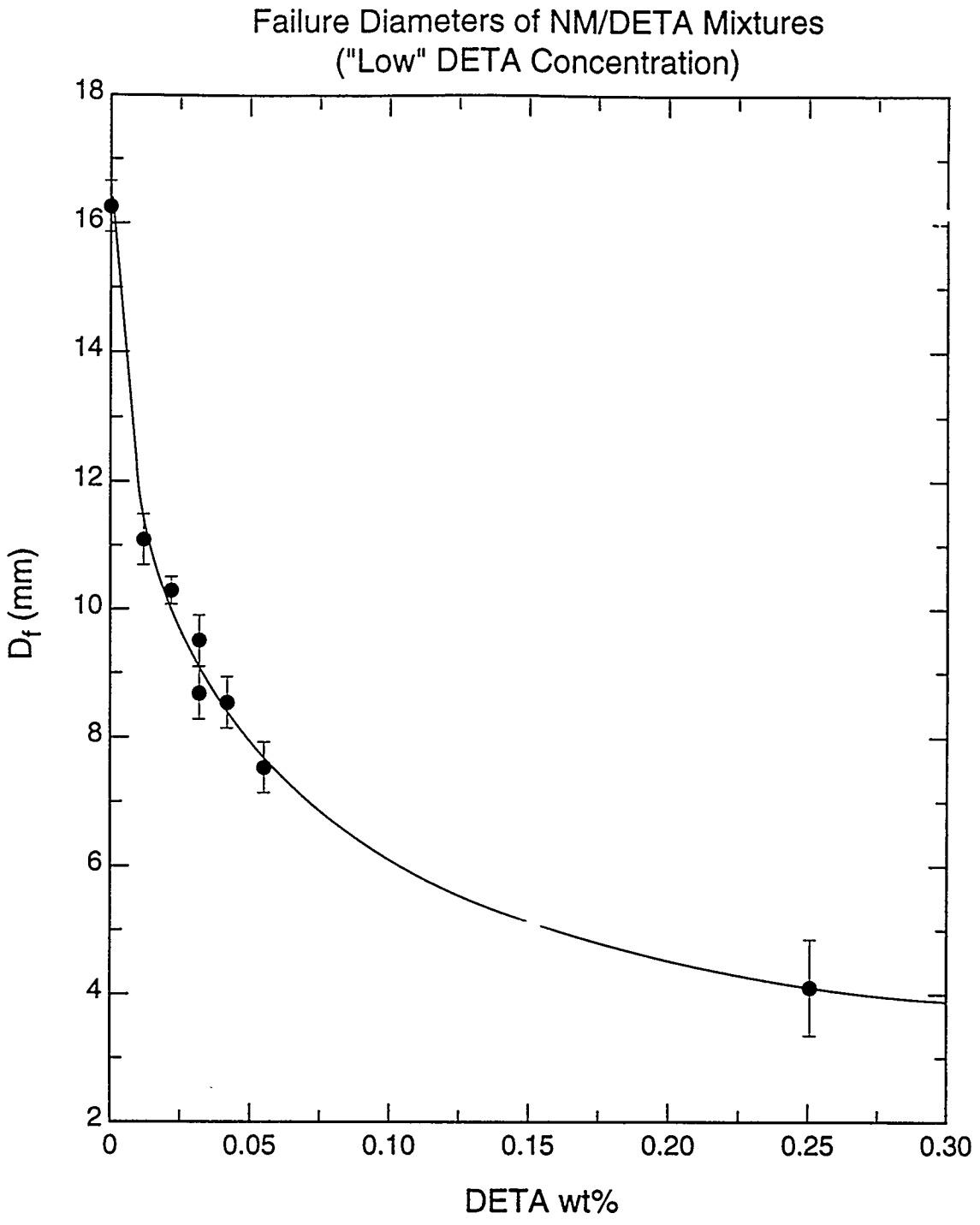


Figure 1. Failure diameters of NM/DETA mixtures fired in Pyrex tubes (confinment) at ambient temperature (ca. 23° C). This graph shows results when "small" amounts of DETA (≤0.25 wt%) are introduced into NM.

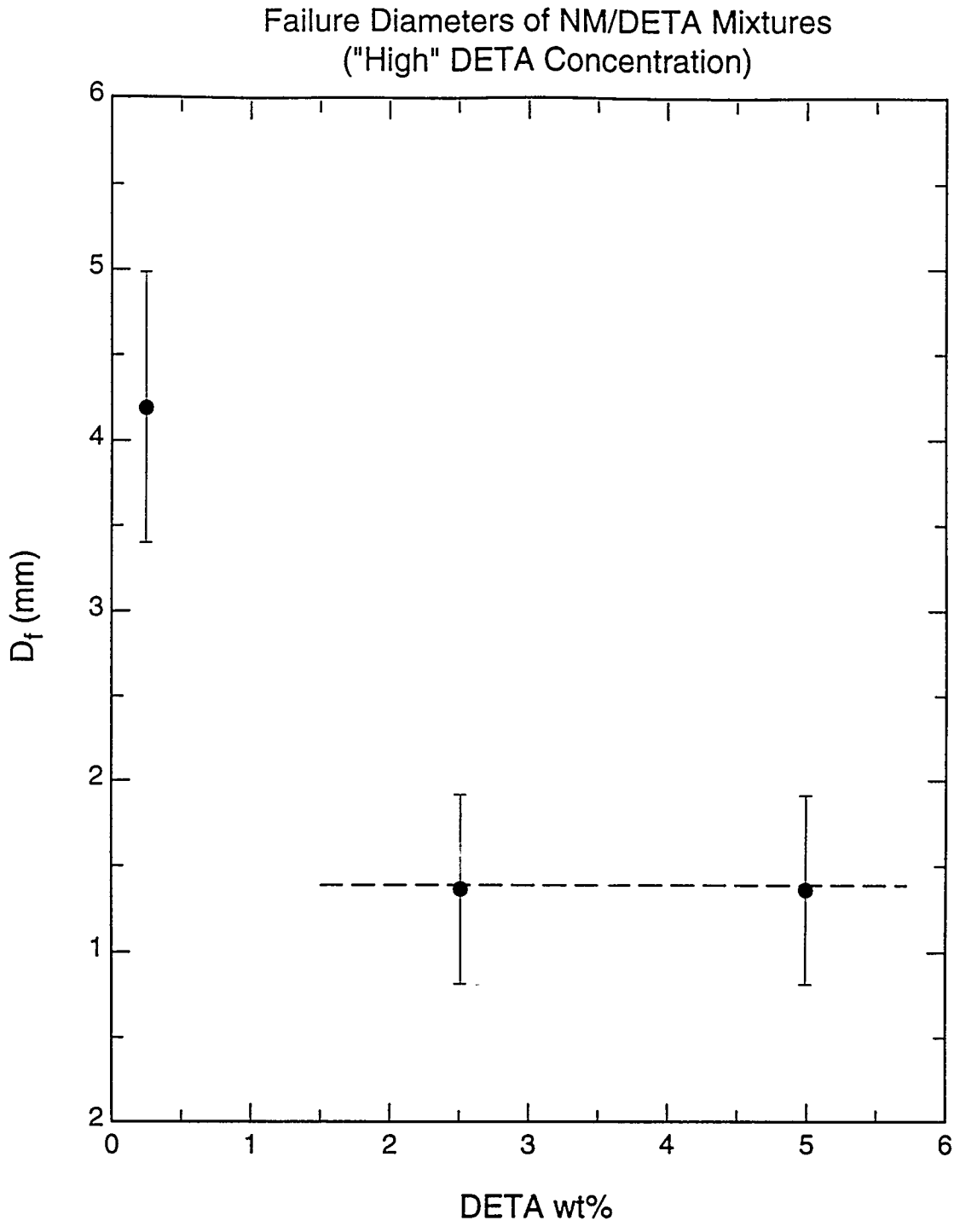


Figure 2. Failure diameters of NM/DETA mixtures fired in Pyrex tubes (confinement) at ambient temperature (ca. 23° C). This graph shows results when "large" amounts of DETA (0.25≤wt% DETA≤5.0) are introduced into NM. Note that, within the precision of the experiments, increasing the DETA concentration beyond 2.5 wt% does not decrease the failure diameter.

The first requirement in specifying the wellbore explosive system was to determine the shape and size of explosive charge required. It was initially proposed that the energy released per explosion in the wellbore should be ca. 0.5 kcal. The heat of detonation (ΔH_{det}) of NM is ca. 1.23 kcal/g and its mass density (ρ_o) is 1.13 g/cm^3 at ambient temperature.[8] Note that the heat of detonation of an explosive is the difference of the enthalpy of its undetonated form (i.e., CH_3NO_2 for NM) and that of the chemical reaction products generated by its detonation (i.e., N_2, H_2O, CO, CO_2, etc.). These values of ΔH_{det} and ρ_o suggest that our charge will need to have a volume of ca. 0.5 cm^3. The charge geometry should be a long right circular cylinder if the detonation wave is to reach steadiness and, thus, emit a highly reproducible acoustic signal. If the borehole tool is to be a valuable device it must be able to fire a large number of shots during one trajectory in the wellbore. The container materials for these shots must be stored in the small volume within the tool. A possible efficient method of storing the containers would be deflated; injection of the explosive mixture at shot time would then cause inflation. Inflatability of the containers suggests that they should be made of a strong pliable material, e.g., a plastic. A reasonable aspect ratio of such an inflated plastic cylinder would be one with length five times its diameter. This aspect ratio ensures detonation-wave steadiness for most of the detonation process. These considerations imply that the plastic-enclosed cylinder of explosive should be approximately 5-mm diameter X 25-mm long.

The failure diameter of an explosive is dependent on the character of the material it is contained in; this is called the effect of confinement. High mass-density/high sound-speed confining materials are best for producing a small failure diameter-- other things being equal. This is because such confinement reduces the amount of work the explosive does in directions lateral to the detonation shockwave direction. Plastics are inferior confiners; i.e., they give large D_f values when used as containers (see Table 1). Note, from Table 1, that neat NM confined in polyvinylchloride (PVC) plastic has a failure diameter of 22.3 ± 1.6 mm.[9] It is, therefore, impossible to propagate a steady detonation wave in NM contained in a PVC tube that has an i.d. of 5 mm. If we are to use plastic tubes of this diameter in

the acoustic source application, we must first determine whether an NM/DETA mixture exists with a D_f significantly smaller than 5 mm when fired in PVC.

The PVC D_f for NM of 22.3 mm suggests we need an NM/DETA mixture that reduces this value by about a factor of ten. The D_f results presented in Figs. 1 and 2 show that adding 2.5 to 5 wt% of DETA to NM produces an explosive with a D_f about ten times smaller than NM when fired in Pyrex. This suggests we examine the 95/5 wt% NM/DETA material for use in the borehole application; the 5 wt% sensitizer composition was chosen to err on the side of extra sensitizer.

We began this examination by determining the failure diameter of the 95/5 material when it is fired in PVC. The D_f experiments were conducted by drilling an array of six holes with diameters from 1 to 6 mm (in 1-mm increments) in a PVC block that was 37.5-mm thick by 152-mm square (see Fig. 3); the hole edges were, at least, 9 mm from the edge of the block. These holes were filled with the 95/5 mixture and then the mixture was strongly boosted by use of RP-1 detonators and 12.7-mm diam. X 12.7-mm long PBX-9407 high-density solid explosive pellets. Detonation or failure of the 95/5 mixture was detected by means of a single steel witness plate placed over the array of six holes. Detonation propagated in the holes with diameter greater than 2 mm. This experiment was performed twice and found to be reproducible. Therefore, the measured D_f of the 95/5 wt% NM DETA mixture is

$$D_f = 2.5 \pm 0.5 \text{ mm},$$

when fired at 24.5±0.5 °C in PVC plastic.[10] This result shows that insofar as failure diameter effects are concerned, it is possible to use the 95/5 wt% NM/DETA mixture in a 5-mm i.d. plastic tube for the borehole application.

III. System for Initiating the Two-Component Liquid Explosive

A.) A Method of Initiation

The work described in Sec. II shows that the 95/5 wt% NM/DETA mixture, contained in thick PVC plastic, is satisfactory insofar as its detonability is concerned. The next question to investigate is the material's initiablity by a means suitable for use in the borehole tool. For our purposes, an explosive's initiability is determined

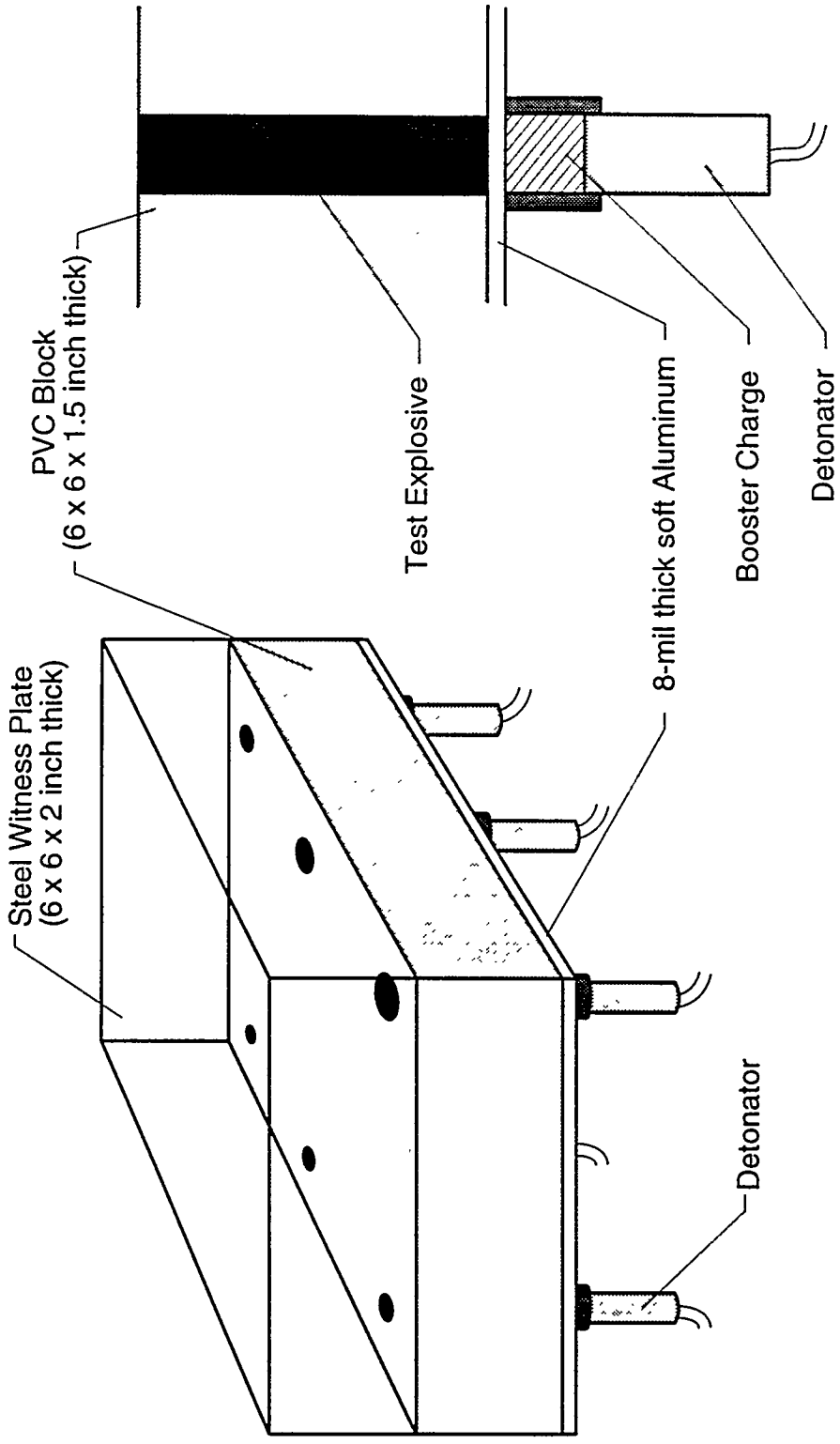


Figure 3. Schema of the experiment used to determine the failure diameter of the 95/5 wt% NM/DETA mixture confined in PVC plastic.

by the strength and duration of the shockwave necessary to produce "prompt" detonation--"prompt" will be defined more fully below.

Usually in research on explosives as insensitive as NM and the NM/DETA mixtures, a more sensitive solid explosive is used to cause initiation. Such a means is not suitable in the borehole tool; i.e., we require a method of initiation that does not utilize other explosives.

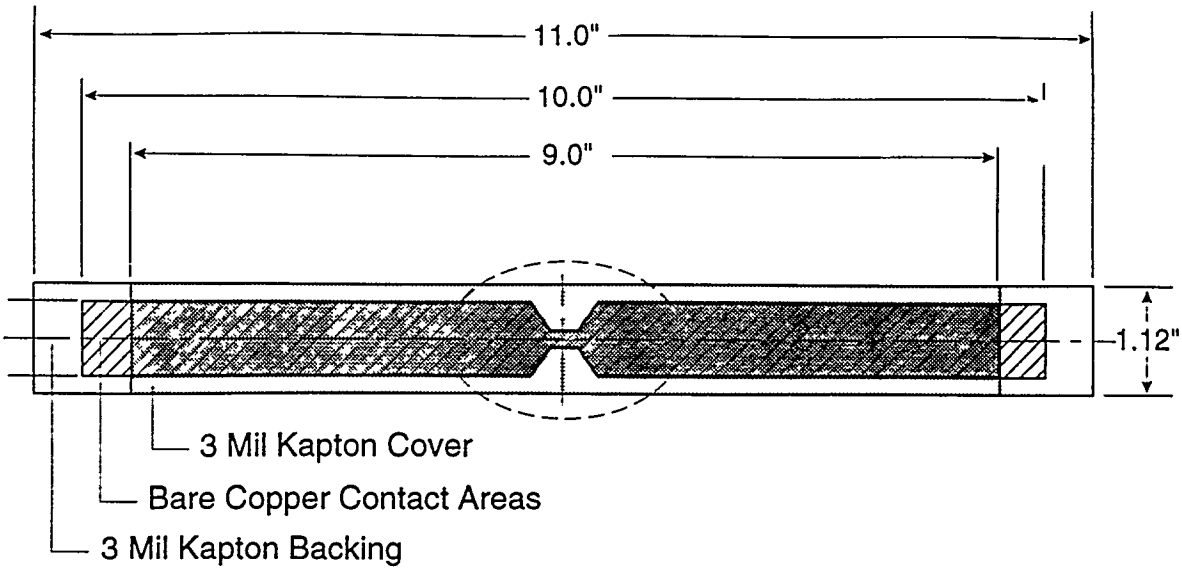
An explosive initiation technique that uses only electrical means is known[11,12] and there is a strong background in this technology at LANL. This methodology, called a slapper detonator system, uses thin plastic (Kapton) "flyers", traveling at high speed, to produce the initiation shock in the explosive to be initiated. The Kapton flyers are accelerated to speed by electrically bursting a thin copper "bridge" in contact with the flyer. The bridge is burst (i.e., turned into a plasma) by triggering a spark gap that very rapidly transfers the energy stored in a capacitor discharge unit (CDU) into the slapper circuit. Figure 4 is a drawing of such a slapper detonator. For the plasma to do work on the Kapton flyer, there must be a void space adjacent to the flyer. This region is termed a "barrel" in analogy to the barrel of a gun. In order for the plasma to do work preferentially on the flyer, a relatively massive "tamper" is placed on the opposite side of the bridge from the flyer.

While it was fairly certain that the failure diameter problem discussed in Sec. II could be dealt with successfully before starting the work, it was much less certain that the problem of initiating the 95/5 wt% NM/DETA mixture with a slapper system could be accomplished successfully.

B.) The Initial Slapper Experiments

First note that this subsection is a recapitulation of an earlier LANL Group M-9 quarterly report.[13]

The initial stage of the initiation study was purely experimental. The largest capacity CDU (12 μF), of reasonable geometrical volume, used for bursting slapper bridges was located at TD site of LANL group DX-10; note that in Appendix 2 we give further specifications of the electrical circuitry used for bursting the slapper bridges. The slapper units were chosen from the supply already in existence at DX-10; we used a number of guidelines in our choice of these slappers. A primary consideration was that we wished to "slap" as much of the cross-sectional area of



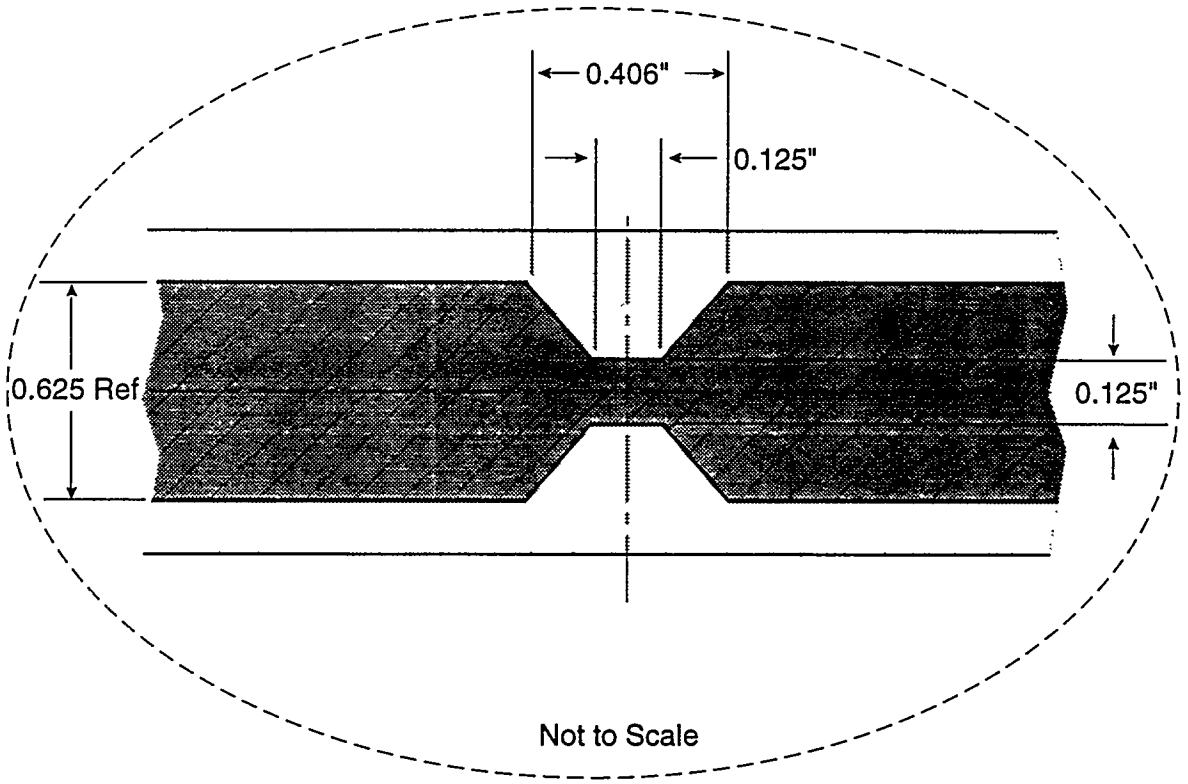


Figure 4. Detailed drawing of a typical slapper detonator used in the experiments.

the NM/DETA mixture as possible; this would minimize the volume of the explosive mixture not raised to high pressure by the impact with the flyer. Note that the cross-sectional area of the flyer thrown by the bridge burst is determined by the bridge cross-sectional area, larger area bridges throw larger area flyers and the flyer shape mirrors the bridge shape. Since our cylinders were to be ca. 5-mm i.d., this implies use of slappers with large bridges. Slappers fitting this description, and already available at TD-site, had square bridges with side lengths of 3.2 and 6.4 mm. The next consideration was the thickness of the Kapton flyer to be thrown by bridge burst. This thickness is related to how long high pressure is maintained in the explosive struck by the flyer; note that a quantitative discussion of this consideration will be given in Sec. IV. Clearly, maintaining the shock pressure longer is preferable; this implies that we need thick flyers. There is a tradeoff to be made here, however, since thicker flyers are not thrown at as high a speed as thin ones, other things being equal. Higher flyer speed produces higher pressure in the struck material. Fairly thick flyers with Kapton thickness of 1 and 2 mils were located at TD-site; these seemed be a good compromise between the production of high pressure in the explosive and the time duration this pressure would be maintained. Thus, slappers of these bridge widths and Kapton flyer thickness were chosen for the initial tests.

We knew from previous work[5] that it was going to be difficult to initiate the 95/5 wt% NM/DETA mixture with a slapper system. The earlier work had shown that to obtain planewave initiation it was necessary to single shock the material to ca. 70 kbar and then maintain this pressure for ca. 1 μs.

Because of the known difficulty of initiating the 95/5 material, what we wished to show in the initial experiments was that it is possible to slapper initiate the mixture in some configuration. Thus, rather than starting the experiments using plastic containers, we used 304 stainless steel (SS) as our first confining material. After success with SS confinement, we would move onto the more difficult case of PVC confinement. Our 304-SS tubes has i.d.'s of 3.0 mm; this value is much greater than the D_f of the 95/5 mixture in 304 SS and it is less than the bridge width of the 3.2-mm-bridge slapper. The latter fact assured that the entire cross-sectional area of the explosive would be "slapped". Furthermore, the flyers were allowed to collide

directly with the free-surface of the liquid-explosive mixture--i.e., there was no container material interposed between the flyer and the explosive. This was done as shown in Fig. 5. When a shot of this type was fired, it was setup so that the pine block was on the bottom of the stack of pieces. The 304-SS or PVC tube was filled with explosive with gravity being used to hold the explosive mixture in place. The Lucite jig-barrel-slapper-Lexan tamper assembly was then slipped over the cylinder containing the explosive. The relative sizes of the hole in the barrel and the o.d. of the explosive container insured that the barrel length (31 mils) was maintained. This assembly was placed in a "boom" box, the heavy brass weight put in place, and then the shot fired. Detonation or failure to initiate was determined by observation of the damage to the assembly. Detonation destroyed the entire assembly from the Lexan tamper to the cylinder containing the explosive. In addition, a circular plug of the aluminum shim stock was driven ca. 0.5 inch into the pine block (see Fig. 5). Failure to initiate produced only delamination of the glue joints of the assembly.

Table 2 is a list of the system parameters and the results of the eighteen experiments done with this type of assembly. The reader should note that the voltage the CDU was charged to was a vital parameter in each experiment; when it is not specifically referred to in the synopsis given below, its value can found in Table 2. Here, we summarize the conclusions that can be drawn from these experiments:

(1) Expts. 1 and 11 show that the 1-mil thick Kapton/3.2-mm wide copper bridge slapper is not suitable for use with the 12μF capacitor unit,

(2) Expts. 2 thru 4 show that it is possible to slapper initiate the 95/5 mixture in this very ideal 304 SS assembly; consequently, the next shots addressed the question of initiablity in PVC confinement,

(3) Expts. 5 and 6 show that it is possible to slapper initiate the 95/5 mixture in PVC confinement with the 2-mil-thick Kapton/6.4-mm wide bridge slapper, but that under the same conditions 100% NM does not initiate,

(4) Expt. 7 shows that 100% NM, confined in 304 SS, will not initiate under conditions where the 95/5 mixture will (compare to Expt. 3),

(5) Expt. 8 shows that in 304 SS, the 95/5 mixture can be initiated with the capacitor unit charged to 3 kV,

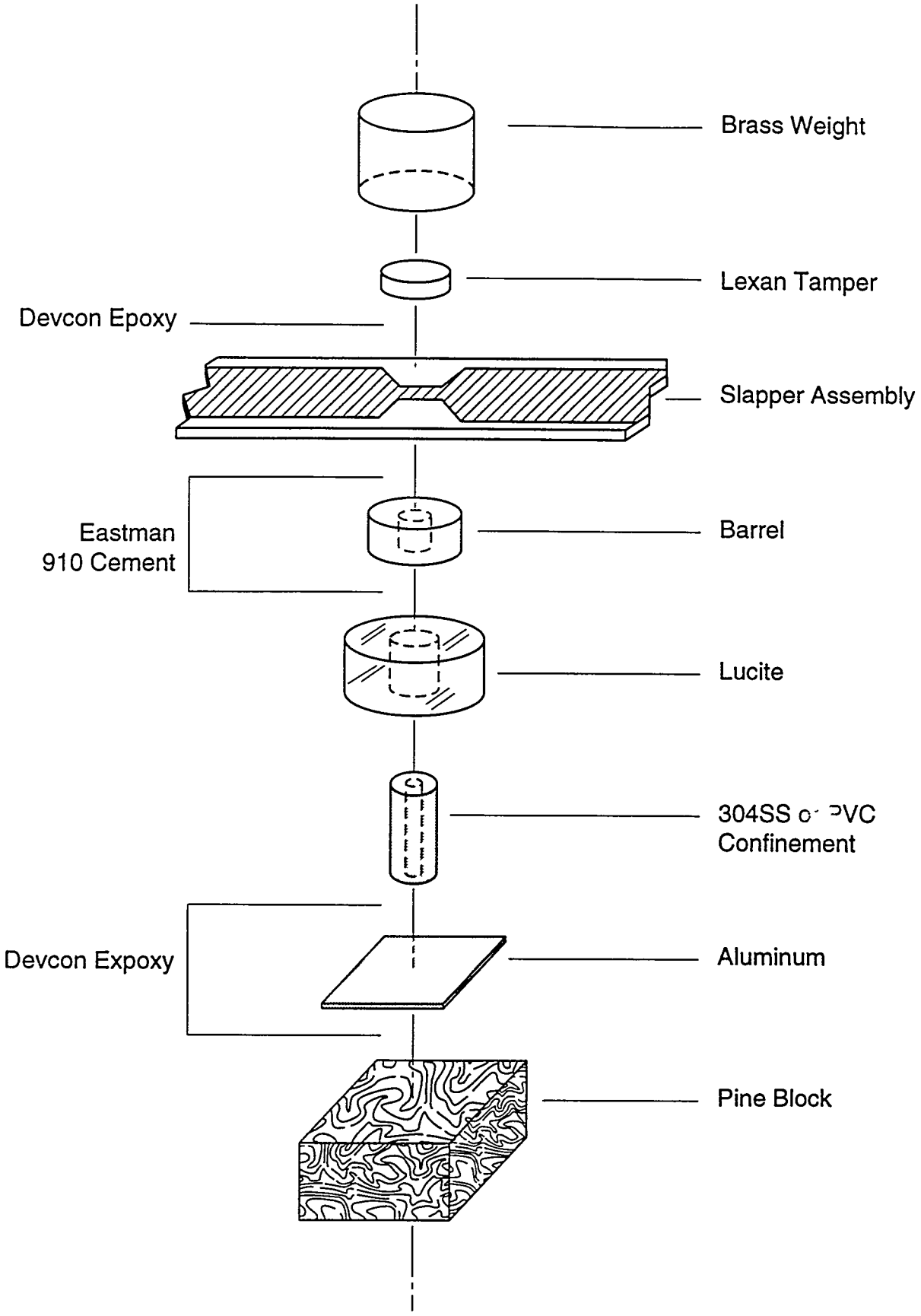


Figure 5. Schema of the assembly used in the first attempts to slapper initiate the 95/5 wt% NM/DETA mixture.

(6) Expts. 9 and 10 were lost due to difficulties of triggering the CDU properly when it was charged to 2 kV and below,

7) Expts. 12 and 13 show that, in 304 SS, the 95/5 mixture will initiate with the CDU charged as low as 3 kV, even when the barrel i.d. is reduced from 4.3 to 2.9 mm. Note that with this reduced barrel diameter, the edges of the explosive mixture and the confiner are not being slapped,

(8) Expts. 14 thru 16 show that the 95/5 mixture, confined in PVC, initiates or fails with the 2-mil-thick Kapton/6.4-mm-wide-bridge slapper when the CDU voltage is 5.45 or 4.40 kV, and

(9) Expts. 17 and 18 show that, with the various parameters as shown in Table 2, the threshold voltage for initiating the 95/5 wt% NM/DETA mixture confined in PVC is 5.25 ± 0.20 kV (the error bar is a range). This value is our most refined estimate of the lowest voltage that can be placed on the CDU and still initiate the 95/5 mixture in this type of assembly. Note also that in these shots the PVC confiner and the edges of the explosive mixture were not slapped due to the barrel i.d of 4.9 mm.

After this sequence of shots, it was concluded that probably the 95/5 wt% NM/DETA mixture could be satisfactorily initiated with a slapper system in the seismic source application. However, there was still a major unaddressed difficulty related to the initiation problem. This was that, in actual use, the explosive assembly will be exposed to the static pressure caused by the fluid in the wellbore. This means that a barrier must be placed between the liquid explosive and the barrel to maintain the free space in the barrel.

We knew this was going to be a thorny problem because the barrier material would have to be very strong to resist the highest wellbore pressures, but it would also have to very efficiently transport the mechanical energy delivered by the Kapton flyer into the liquid explosive. Such efficient energy transport would mean that the barrier material must have shock properties (e.g., a principal shock Hugoniot)[7,14] resembling an organic material (e.g., a plastic). In the next section, we address a solution to this problem in detail

IV. Hydrodynamic Effects and a System for Maintaining the Barrel Dimensions

A.) The Shock Pressure Produced in the Explosive

As explained at the end of Sec. III B., some type of substantial barrier is required to maintain the barrel volume (see Fig. 6) against the pressures experienced within wellbores. As noted above, this barrier needs to be very strong to resist the high static pressure that exists in the depths of wellbores and it must also be able to efficiently transfer the energy of motion of the Kapton flyer into the NM/DETA explosive. The last criterion implies that the shock impedance properties of the barrier material must be similar to those of Kapton and of the explosive mixture. For our purposes, the shock impedance of a material is defined by the material's principal shock Hugoniot. The principal shock Hugoniot of a material is defined to be the locus of all thermodynamic states reachable (from ambient conditions) by a single shock process.[7,14]

Given the principal shock Hugoniots of Kapton, the barrier material, and of nitromethane and the speed of the Kapton flyer, it is possible to calculate the pressure produced in the NM.[14] Here, we assume that the Hugoniot of the 95/5 wt% NM/DETA mixture is identical with that of NM; this is a good approximation because of the small amount of DETA present and because DETA is a liquid organic material. The Hugoniots of many materials have been measured and are available in the literature (see, e.g., Ref 15). Given the parameters of a slapper system, the speed at which a flyer is thrown can be approximately calculated by computer codes available at Group DX-10 of LANL.[16] Hence, given a barrier material, its Hugoniot, and the slapper system parameters, we can compute approximately the pressure delivered into the liquid explosive.

Discussions led to a possible candidate barrier material--i.e., some type of carbon composite. This candidate was chosen because carbon composites were known to be used in applications where high strength is required (e.g., aircraft structural members) and because it is an "organic-like" material. The latter characteristic suggests that it should be a reasonably good shock impedance match to other organic materials (e.g., NM and Kapton). It was found that the necessary

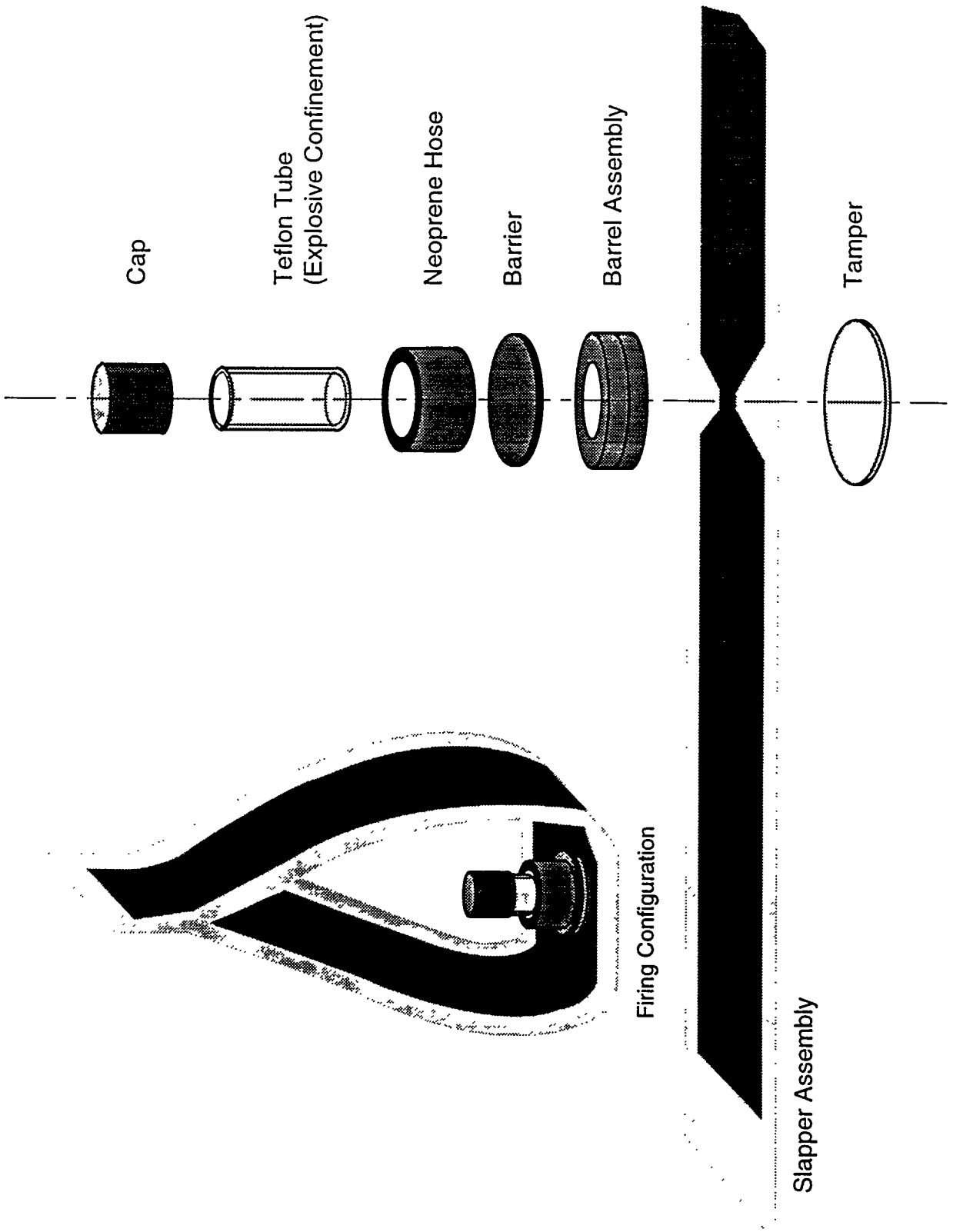


Figure 6. Explosive assembly with a barrier in place between the barrel and the explosive. This is the type of assembly used in the EMRTC experiments.

expertise and fabrication facilities for constructing such materials exist at Group ESA-WMA of LANL.

Before discussing, in detail, the types of carbon composites we eventually employed as barriers, we will illustrate their superiority in being able to effectively transform the kinetic energy of a Kapton flyer into pressure in the liquid explosive.

We use three barrier materials to make this illustration--i.e. a stainless steel, 2024 aluminum, and a carbon fiber material. The Hugoniots of these materials can be found in Ref. 15 and they are collected in Appendix 3. We assume a variety of Kapton flyer speeds centered around 4 mm/μs. This choice was made because R. Yaktor's calculations[16] indicated that this value is typical of the flyer speeds obtained with the slappers and capacitor unit/voltages being used; also see Appendix 4 where direct experimental measurements of flyer speed are discussed.

The impedance match calculations,[14] done to obtain the pressure in the explosive mixture, neglected the rarefaction wave(s) that arise at the Kapton free surface after the collision. These are considered in Sec. IV. B. Figure 7 shows the results of the calculations; i.e., the pressure generated in the NM-based explosive: (1) as a function of the Kapton flyer speed before the collision with the barrier and (2) as a function of the barrier material. As a specific example of the superiority of the carbon composite material as a barrier, consider the pressure in the explosive generated by a flyer moving at 4.0 mm/μs at the instant of impact. In this case, the pressures generated in the liquid explosive are ca. 132, 107, and 60 kbar for the carbon composite, aluminum, and stainless steel barriers, respectively (see Fig. 7). Clearly, the stainless steel barrier is not a candidate; it yields less than one-half the pressure transferred by the carbon-composite material. Under the same conditions, the aluminum barrier gives a pressure in the explosive down by ca. 25 kbar relative to the carbon-composite barrier. Even this pressure difference is very significant because the initiation of the explosive must take place very rapidly in our system, if it is to occur at all.

These results indicated that a carbon-composite material is a good choice for a barrier material insofar as the shock pressure produced in the explosive was concerned.

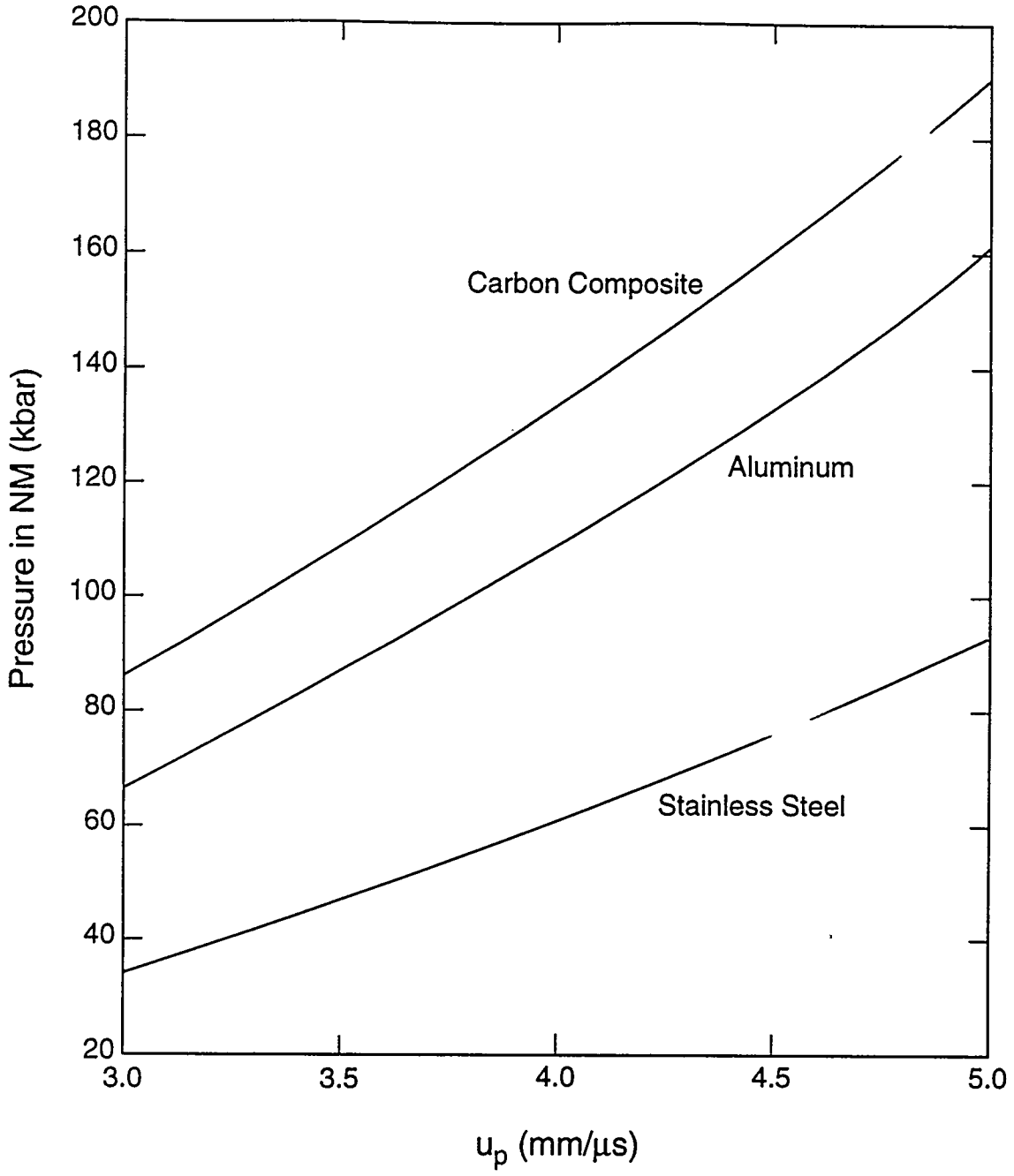


Figure 7. Pressures generated in nitromethane through various barrier materials by a Kapton flyer moving at particle speed u_p. The shocks are assumed to be planar; i.e., edge effects and other imperfections are neglected. The three barrier materials considered are carbon composite, aluminum and stainless steel. The material Hugoniots used to obtain these results are from Ref. 15. These results illustrate the advantage of using a carbon-fiber material relative to metals as the barrier material, insofar as pressure generation in the NM-based explosive is concerned.

B.) Estimate of the Time Available for Initiation of the Explosive

The requirement of very rapid initiation is illustrated by the information on Fig. 8. This figure is a time-space diagram that shows the most important shock and rarefaction waves generated by the collision of the Kapton flyer with the barrier. As shown, the collision first produces two shockwaves at the Kapton flyer/barrier interface. One of these travels backward into the Kapton and the other travels forward into the barrier material and, eventually, into the explosive. The physical conditions resulting from the shock traveling into the explosive is what causes initiation, if it occurs.

When the shock traveling back into the Kapton reaches the free surface of the Kapton, it decelerated this surface. This results in a rarefaction (i.e., a pressure-reducing) wave moving through the Kapton toward the barrier and the explosive. Before initiation, the shockwave in the explosive travels more slowly than this rarefaction wave and so the rarefaction can catch the shock. If overtake occurs (see point t_2 on Fig. 8), the rarefaction wave degrades the shock, i.e., decreases its speed and pressure. Why is this important in the design of our system? Since the flyers we are using are quite thin (e.g., 2 to 3 mils thick), the events just outlined occur very rapidly. Numerical fluid mechanical calculations show that for a 3-mil thick Kapton flyer, it takes approximately 20 ns after the collision for the rarefaction to reach the Kapton/explosive interface, under conditions similar to our system. After the rarefaction reaches the interface, it must still catch the shock in order to degrade it. The time this takes is more difficult to estimate, because the rarefaction is running into a chemically-reacting fluid whose sonic characteristics are not accurately known. A study of the rarefaction-wave-overtake process has been made for an organic inert (anthracene) for another purpose.[17] This study casts some light on the present problem; it showed that after reaching the Kapton/inert interface, it took ca. 60 ns more for the rarefaction to reach and, significantly, degrade the shock pressure. We, therefore, make the very rough estimate that initiation must occur in our system within ca. 100 ns. Experimental data in Ref. 5 (see Fig. 6 of that reference) show that it takes a sustained pressure pulse of ca. 100 kbar to initiate the 95/5 wt% NM/DETA mixture within 100 ns.

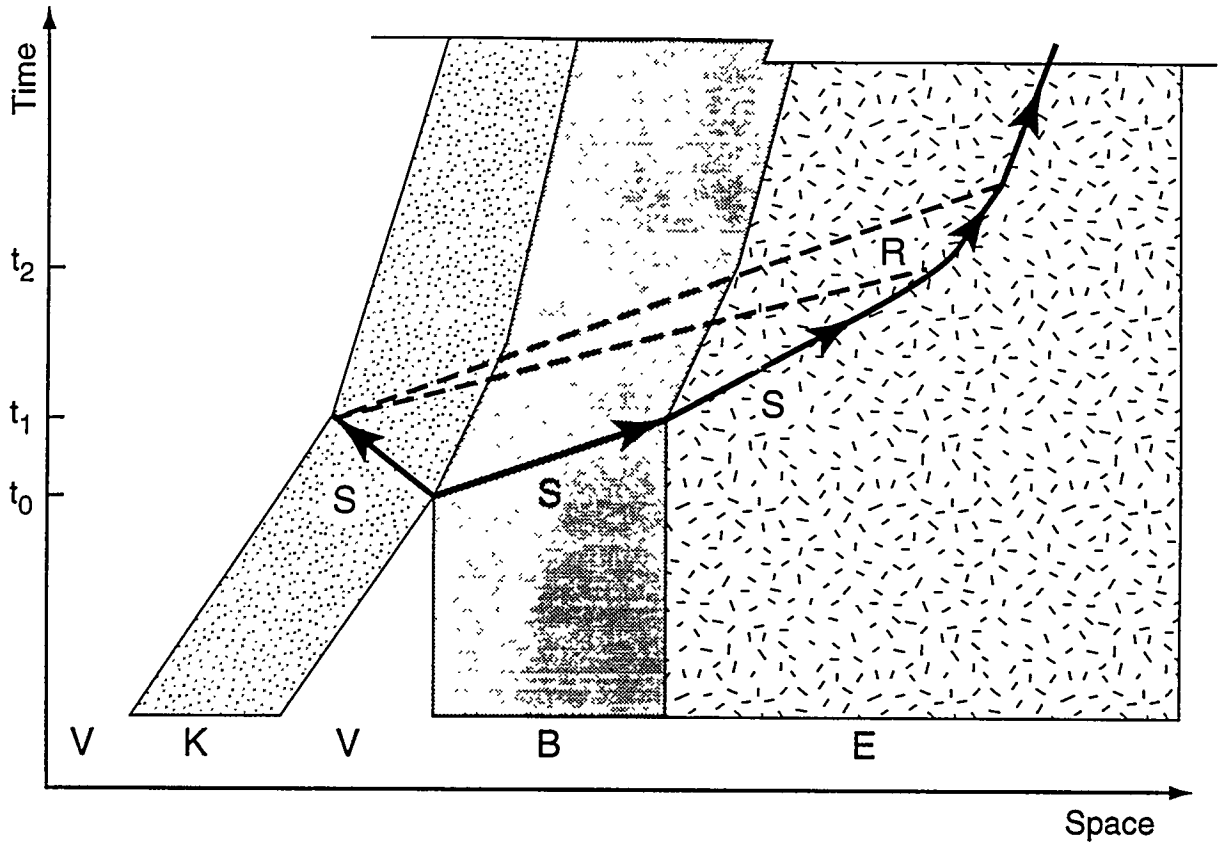


Figure 8. Highly simplified schema of the waves present in a Flyer/Barrier/Liquid Explosive system due the impact of the flyer with the barrier. The system is considered planar; i.e., edge effects and other imperfections are neglected. Only the first wave processes are shown. The following symbols are used: K = slapper flyer, V = void (barrel) space, B = barrier material, E = liquid explosive, S = shockwave, and R = rarefaction wave. The times t_0, t_1 and t_2 correspond, respectively, to the collision of the slapper flyer with the barrier material, the production of the rarefaction wave in the flyer by the reflected-shock interaction with the flyer free surface, and the rarefaction wave overtaking the shock in the explosive. The rarefaction wave overtake of the shockwave reduces its strength (pressure) and, therefore, its ability to initiate the explosive promptly.

These factors and those noted in Sec. IV.A indicate that of the three barrier materials considered in our example only the carbon-composite barrier would be acceptable insofar as initiation of the 95/5 explosive mixture by a 3-mil Kapton flyer is concerned.

C.) The Carbon-Composite-Barrier Material

Various configurations of carbon composite were tested to establish the best trade-off of properties. Thin membranes of composite were constructed with layers of carbon fibers at various angles to each other and bonded together with cured resin. The greater the number of layers of fibers, the stronger and thicker the barrier membrane is. Also, when there are a greater number of layers at smaller angles to each other, the resulting membrane is flatter; a thin two-layer membrane has considerable natural "curl". In the subject application, the membrane needed to be as thin as possible while providing strength to withstand the hydrostatic pressure and also providing surface integrity to physically contain the liquid explosive.

Various carbon-composite samples were fabricated at ESA-WMA. Since it was desired that the barrier material maintain the barrel air gap without collapsing at well depths up to ca. 15,000 feet (6500 psig hydrostatic pressure), an experimental program for measuring the burst pressure of these samples was instigated. Testing was conducted on various materials and various configurations of carbon composites as shown in Table 6. This testing was done using the test fixture shown in Fig. 9. Carbon composites are significantly stronger in tension or compression than in shear[18] and, unfortunately, this application loads the CC barrier in shear. The apertures in the test fixture were 180 and 240 mils. The CC samples were clamped on the low pressure interface against a 90 durometer fluorocarbon rubber (Viton) gasket that was 32-mils thick, to reduce the effect of premature bursting due to shear Of the alternate constructions of CC tested, two were chosen to be used for detonation testing. We note parenthetically that the industry standard test for specifying the "hardness" of rubber is the Type A durometer, manufactured by Shore Instrument Company. A durometer has a calibrated spring that forces an indentor point into the test specimen against the resistance of the rubber. A reading of Shore A100 represents no penetration and lower numbers indicate softer materials. The Viton sheet used to fabricate our barrels had a hardness of Shore A90.

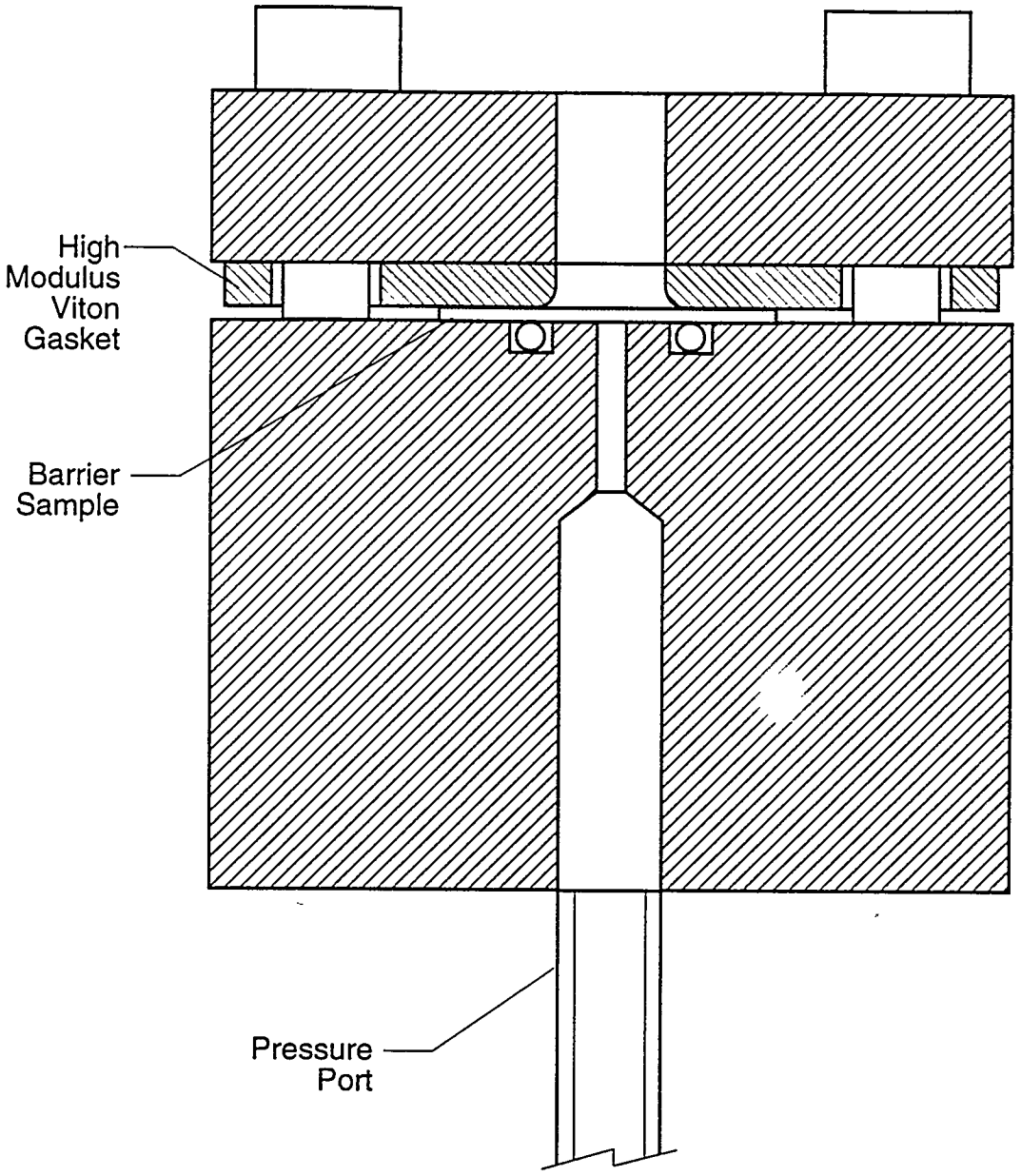


Figure 9. Burst test fixture used in the study of the ability of the carbon-composite materials to withstand a pressure differential.

The first sample to be discussed (which we designate as "A") consisted of four carbon-composite (CC) plies woven and bonded together with a 0, 90, +45, -45° fiber orientation. A 1-mil thick Mylar layer was bonded to this laminate; the resultant compressed material was ca. 12-mils thick. The following materials were utilized in the construction: (1) 3-mil thick Thornel T-300 carbon fibers, (2) DOW-332 room curable epoxy, and (3) Jefferson Chemical T-403 epoxy curing agent.

The second sample studied in detail (which we designate as "B") had a two ply 0, 90° fiber orientation and was manufactured from PEEK unidirectional tape, 5 mils in thickness; the resultant material was ca. 11.5-mils thick. The primary material used in its fabrication was carbon reinforced thermoplastic, APC-2, made by ICI Composites, Inc.; it is a IM-6 carbon fiber/polyetheretherketone (PEEK) unidirectional tape. The two-ply material was molded at 390° C for two hours, held under compression and cooled to room temperature. Note that no Mylar was used in material "B".

The type "A" material was constructed with the Mylar layer, because it was found that gaps between fibers in the carbon composite not filled with resin would result in liquid leaking through the barrier. However, it was determined that care in fabrication and inspection on a light table would yield material without gaps. Type "A" material was found to have a burst pressure of ca. 3750 psig maximum, while type "B" was burst tested to ca. 7200 and 8600 psig.

Samples of type "A" and "B" were chosen for detonation testing. The barriers used in testing were 0.50-inch outside diameter and were laser cut to prevent delamination of layers that can occur when the material is cut with a shearing or sawing type tool.

D.) Barrel /Barrier Assembly Design

Because it is necessary to use the barrier material in a configuration that results in shear loading, the successful performance of the barrier is highly dependent on the barrel material and design. Testing was performed using a simulated barrel that is better described as a rubber gasket. This is true because the rubber was generally about 32-mils thick, had an inside diameter of 0.180 or 0.240 inches and an outside diameter of 2.00 or more inches. Also this gasket was fully supported by being clamped between two metal flanges. When this combination of materials was transposed into a functional

explosive assembly, the barrel was required to be at least 0.062 inch long, while the outside diameter was arbitrarily limited to 0.50 inch. This problem was further magnified when it was discovered through VISAR testing (see Appendix 4) that longer barrels would improve performance of the detonation system. Functional testing of barrel/barrier deflections at pressure were attempted with mixed results (see Table 10).

A majority of firing tests were conducted with barrels of 0.062 to 0.070 inch length and 0.200 inch inside diameter. Late in the program, during testing at the Energetic Materials Research and Test Center of the New Mexico Institute of Technology (EMRTC), barrels of 0.120 to 0.159 inch length and approximately 0.250 inch inside diameter were successfully used. These longer barrel units were constructed by using either multiple layers of fluorocarbon rubber or combined layers of metal and fluorocarbon rubber. In all cases the carbon composite barrier was bonded to the rubber layer of the barrel. This construction technique allowed greater variation in barrel lengths, but required additional adhesive joints that could fail and allow the entry of fluid into the barrel volume.

E.) First Initiation Experiments with a Barrier

The material in this section is a recapitulation of M7-QR-93-1, pp.7-[illegible][19] This material is written in a manner parallel to Sec. III B. Sets of shots are discussed in groups in which specific questions were asked and answered. The generic assembly used in the tests to be described is shown in Fig. 10; i.e., it consisted of a tamper, slapper, carbon-composite barrier, barrel and the 95/5 w% NM/DETA explosive emplaced in some type of confiner. These experiments were done in a similar manner to those discussed in Sec. III B.; i.e., they were fired in a "boom" box and the same 12 μF CDU was used.

The first six of these experiments (i.e., Expts. 19 to 24 of Table 3) were fired to attempt to determine whether we could initiate the 95/5 mixture under very favorable conditions with a barrier in place. Therefore, the shots were fired with quite high voltage on the CDU and, in some cases, the explosive was confined in 304 SS--a material we did not envision being used in an actual seismic tool. Two-mil thick flyers were used in every case. Furthermore, the slapper bridges and barrels had dimensions such that the area of the flyer that impacted the barrier was equal to or larger than the facial area of the explosive. The "A" type carbon-composite barrier

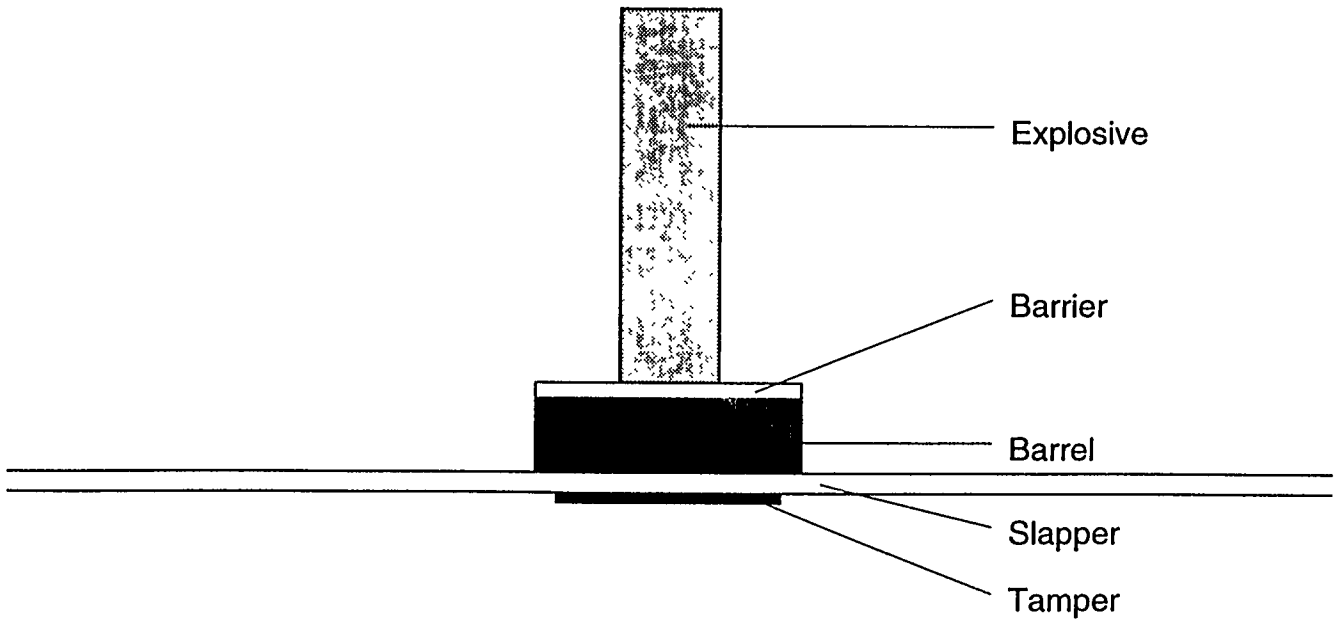


Figure 10. The type of shot assembly used in the first experiments in which initiation across a barrier was attempted.

was used in Expts. 19 to 23. Detonation was not produced in any of these experiments. It did appear from the damage to the recovered assembly that we were close to achieving detonation in Expt. 22. The detailed parameters used in the experiments are given in Table 3. To regain contact with the previous work, Expt. 24 was fired; it reproduced Expt. 4 exactly in terms of the assembly and approximately insofar as the CDU voltage was concerned (i.e., 5.5 kV in Expt. 24 vs 5.0 kV in Expt. 4). Since Expts. 4 and 24 reproduce each other, we felt confident that nothing was out of control in Expts. 19 to 23.

These results show that inclusion of the carbon-composite (CC) barrier significantly increases the problem of initiating the NM/DETA mixture. After contemplating these results, it was decided that the parameter to alter to improve the system was the Kapton flyer thickness. As discussed above, increasing the flyer thickness will increase the length of time high pressure is maintained in the explosive (see Fig. 8). Since the thicker flyer is more massive, it will, however, be moving at a lower speed when it collides with the barrier.

Due to this line of thinking, we built the assemblies used in Expts. 25 to 28 (see Table 3). These assemblies are the same as those used in Expts. 19 to 23, except that the slapper flyer thickness has been increased by 50% (i.e., from 2 to 3 mils). Note that the confinement in these experiments is 304 SS. Both the "A" and "B" type CC barriers were in these assemblies. Detonation occurred in all four experiments, including one with the CDU voltage set as low as 5.5 kV. These results caused us to abandon use of slappers with flyers thinner than 3 mils.

Finally, note that when the CC barrier is replaced by a thin Kapton barrier (as in Expt. 29), it is possible to detonate the NM/DETA mixture even with a 2-mil thick flyer. These results led to our next set of experiments.

Since a significant improvement in performance was obtained with the thicker 3-mil flyers, we had a set of slappers constructed with 5-mil thick flyers in the hope this would give further improvement. These slappers had 6.0-mm wide X 1.4-mil thick copper bridges. Their burstablity was tested by viewing the current/voltage profiles produced when they were fired with the 12 μF CDU charged to 8kV. Experiments 30 and 31 of Table 4 showed that these slapper detonators do not perform properly with this CDU; a larger capacitance unit is needed to burst them properly. Therefore, we

discontinued their use and returned to use of the 3-mil-thick-flyer slappers used successfully in Expts. 25 to 28.

Our next effort was directed at initiating the NM/DETA mixture with a CC barrier present, but confined in PVC plastic. We wished to do this because PVC mimics the confiner that would actually be used in the seismic tool.

Experiments 32 and 35 showed that the 6-mm-bridge slapper would not initiate the explosive, confined in PVC, across the "A" CC barrier even when the CDU was charged to 8.3 kV, when a 31-mil long barrel was used. However, damage observed on the recovered assemblies showed that we were near a configuration in which detonation could be achieved in PVC. In Expt. 33, the barrel length was increased to 62 mils and detonation was achieved in PVC confinement with the "A" type barrier in place. Comparison of Expts. 32 and 33 shows that the longer barrel qualitatively changes the observed result. In Expt. 34, we fired an assembly identical to that used in Expt. 33, but with the CDU charged to only 7.0 kV; detonation was not achieved. Therefore, with assemblies of this type, the critical voltage for initiating the explosive is in the range 7.5 ±0.5 kV. In Expts. 36 and 37, we changed back to the 3-mm-wide bridge/3-mil-thick Kapton-flyer slapper. In these experiments, with 31-mil long barrels and "A" barriers, detonation was obtained with the CDU voltage as low as 7.5kV.

At this point, we switched exclusively to the use of the "B" type barrier because of its measured burst strength (see Table 6) and the simplicity of its construction. Also the higher flyer speed achieved with the 3-mm wide bridge slapper was useful--so this type slapper was chosen for the remaining work.

The purpose of Expts. 38 to 41 was to determine the critical voltage for producing initiation in PVC with the "B" type barrier in place and to examine the effect of barrel length on the critical voltage. Experiments 38 and 39 showed that with the 31-mil long barrel, the threshold voltage was < 6 kV. Experiments 40 and 41 showed that with a 62-mil long barrel, the threshold voltage is in the range 4.25±0.75 kV; i.e., detonation occurs at 5.0 kV and failure occurs at 3.5 kV. Detailed parameters for these shots are given in Table 5.

Detonation could be reliably produced in this assembly with the "B" type barrier in place and with the explosive confined in PVC plastic.

The PVC confinement used in the experiments described hitherto has a ca. 5-mm thick wall. Use of this material is not possible if the explosive containers are to be inflatable. A candidate material for use in the tool is thin-walled Teflon. Teflon FEP film has an acoustic impedance greater than PVC. Thus, if a given slapper-barrier system will initiate the NM/DETA mixture in PVC, it should be able to do so in Teflon also. Since a Teflon film was to be used, the foregoing statement assumes that the wall thickness is irrelevant for the PVC and Teflon materials being used. This had to be verified by experiment. FEP-Teflon tubes (baggies) with ca. 2.5-mil thick walls thermoformed by Welsh Fluorocarbons, Inc. were obtained. Such tubes could be stored in a "crushed" form in the tool and then inflated by filling them with the liquid explosive immediately before use. This design mitigates the storage problems associated with the tool's small internal volume. The purpose of the next set of experiments was to determine a threshold voltage for this type assembly. Experiment 42 (see Table 5) showed that detonation with this type assembly occurs when the 12 μF CDU is charged to 7.5 kV. In Expts. 43 to 45, we sequentially lowered the CDU voltage until in Expt. 45 failure occurred with the CDU charged to 4.5 kV. In Expt. 46, we reproduced Expt. 44 to firmly establish that detonation occurs when the CDU is charged to 5.0 kV. The last assembly (Expt. 47) was used to refine the threshold voltage. It was fired at 4.75 kV and detonation occurred. Used with the result of Expt. 45, we obtain a threshold voltage of 4.63±0.13 kV for this type of assembly.

We did Expts. 48 and 49 (see Table 7) to determine whether the slapper detonator would be subject to electrical arcing problems when it is fired submerged in water. Two assemblies of the type used in Expts. 42 to 47 were built--but the Teflon baggy was replaced by a 10-mil thick aluminum witness plate. The two assemblies were then fired submerged in water. The witness plates indicated that the flyers were properly thrown and no arcing was evident on the recovered flat cables. Consequently, we were ready to test this part of the explosive system under conditions similar to ones found in boreholes.

V. Detonation of the Explosive at High Pressure and Temperature

A.) Pressure and Temperature Conditions within a Borehole

In the design of a downhole tool, such as the proposed seismic source that will be used in a wellbore of any significant depth, there are a number of critical environmental factors that must be considered. The most important of these are: (1) the increasing temperature with depth in the wellbore, (2) the increasing hydrostatic pressure with depth due to the presence of the wellbore fluid, and (3) the fact that fluids, and even gases, encountered in a wellbore will probably be corrosive.

In light of the above factors, it was necessary to do representative tests that would indicate if the chosen detonation system would perform satisfactorily at other than ambient laboratory conditions. There were many aspects of the conceptual system that could be unfavorably influenced by the expected environment in a deep wellbore. Basic questions to be addressed were the effects of the wellbore environment on the chemical stability of the explosive mixture, as well as effects on the specific electrical/mechanical configuration of the detonation assembly that would influence the ability to reliably initiate the explosive charge.

As discussed above, numerous ambient laboratory tests were completed that resulted in the definition of a baseline system of explosive composition, mechanical configuration, and initiation energy of the slapper. At the completion of these ambient tests, a series of tests were defined that would attempt to characterize the ability of the baseline system to operate at the various extremes expected in a borehole. A contract was established between LANL and EMRTC to perform these tests.

Prior to beginning the tests at EMRTC considerable preparation and preliminary testing were completed at LANL. The tasks required to pursue a testing program were: (1) the acquisition of an appropriate pressure vessel, (2) design and fabrication of an electrical feedthru that would withstand test pressures up to 6400 psig while being able to handle the large electrical current pulse required for bursting the slapper bridge, and (3) demonstration that the required large currents could be delivered to a slapper that was suspended in a pressure vessel filled with water.

B.) The Pressure Vessel and the Electrical Feedthrus

The pressure vessel was located at LANL as a surplus item from a previous project. It was a vessel of ideal size which was designed for a working pressure of 5000 psig at 350° C and was proof tested to 7500 psig at 22° C. The vessel was fabricated from 316 stainless steel. It was originally designed for long term, high temperature, high pressure tests. Modifications were required to: (1) accommodate the electrical feedthru, (2) provide the pressure plumbing ports required for the scheduled tests, (3) seal some unused ports, and (4) facilitate the frequent opening and closing which would be required during multiple tests. Figure 11 is a sketch of the pressure vessel.

A principal feedthru was constructed (that would easily withstand the static pressures required) by use of three single-conductor electrical feedthrus procured from Kemlon of Houston, Texas.[20] These basic feedthrus are rated to 20,000 psig, but were not designed to accommodate the high electrical current pulses required for this test series. It was known from previous work at Los Alamos that the very wide, thin electrical conductors that carry current to and away from the slapper bridge should run in close proximity to each other to reduce the cable self inductance and that this is the preferred way to conduct current pulses of the required magnitude over any reasonable distance. By incorporating a system of wide, flat copper conductors on each side of the actual high-pressure feedthrus it was possible to reduce the system inductance to a level that would allow repeatable, successful slapper operation and therefore initiation of the explosive charge. This principal feedthru was installed into the test chamber filled with water. It was found that with this configuration it was possible to achieve successful operation of the slapper and initiation of the explosive charge when it was submerged in water at ambient temperature and pressure.

However, in the initial design, the shock wave from the detonating explosive was transmitted through the principal feedthru in such a way that the electrical insulators inside the individual high pressure feedthrus were cracked. Cracking of the individual insulators caused high voltage failure during the next test after the first occurrence of this phenomenon. Subsequent failure of individual feedthrus was detected by the use of a hi pot test after each firing. Two redesigns of the principal feedthru assembly were made.

into the chamber. The test chamber was then closed and the pressure quickly increased. We then circulated preheated fluid that raised the temperature of the test assembly to 120° C. The schematic of the test set-up is shown in Fig. 12. When modification of the plumbing was completed, tests indicated that the temperature of the fluid inside the chamber, and therefore of the test specimen, could be raised from 90° C to 120° C within about two minutes, if the reservoir of hot fluid was maintained at 150° C. This was considered to be an acceptable time and was subsequently found to be so in testing. The working fluid chosen for these high temperature tests was ethylene glycol. This fluid was chosen because it is cheap and readily available, it has a boiling point in excess of 150° C, and it will not flash to steam (as water would) in case of a misstep at 120° C. At the start of the high temperature testing, pure laboratory grade ethylene glycol was used. As problems were encountered and the starting supply of ethylene glygol was expended, commercial automotive anti-freeze was substituted with no apparent degradation of performance.

One interesting and significant result of using ethylene glycol was that after being immersed for a period of time, the feedthru would not withstand a hi pot test above approximately 2000 volts. However, it was still possible to successfully detonate the explosive liquid with no apparent degradation of slapper performance. Early experience with water had indicated that a feedthru that would not withstand 5000 volts in a hi pot test, would not provide the pulse required to operate a slapper successfully. This aspect of feedthru operation needs further investigation to determine design requirements for a system that will work in a variety of fluids as could be encountered in a borehole.

D.) Final Explosive Assembly Configuration for Pressure/Temperature Tests

Pressure/temperature testing that was to be done at EMRTC required that the mechanical and electrical parameters be as consistent as possible. Therefore in all experiments after Expt. 63, the explosive assembly was defined as shown in Fig. 6. (In Expts. 50 to 62, thin Teflon "baggies" were used as confinement). The basic substrate for the assembly is the slapper, which was defined during earlier tests. This configuration was 0.7-mil thick copper, 0.625-inches wide and 10-inches long with a 0.125-inch-square bridge at the center. This copper was laminated between a

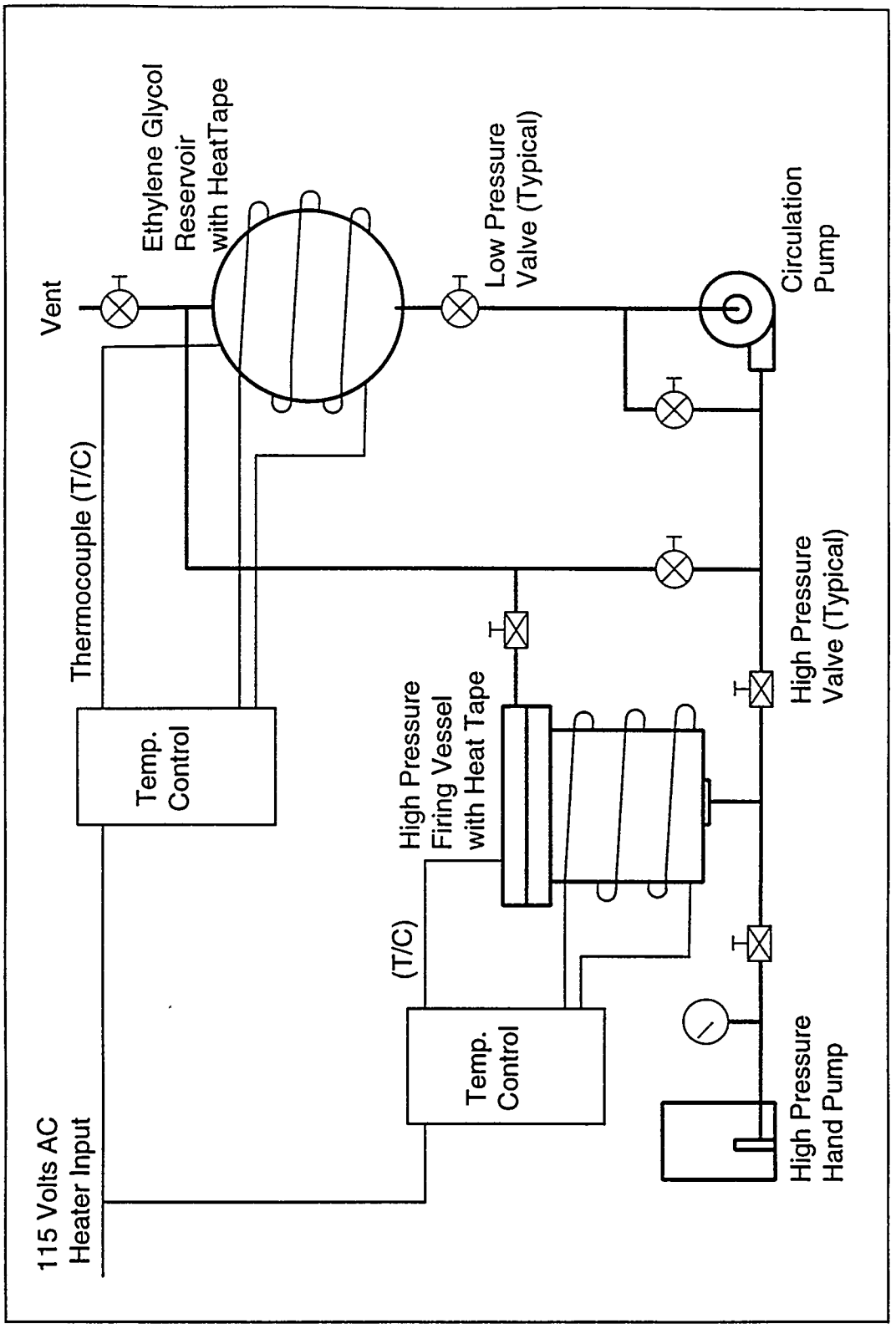


Figure 12. The temperature test setup used for the high-temperature tests of the detonation system at EMRTC.

layer of 3-mil Kapton on each side so that a 0.500- X 0.625-inch electrical contact area was left exposed at each end. The copper was insulated by at least 0.25 inch of laminated Kapton at all edges (see Fig. 4). On one side of the slapper a 0.500-inch diameter by 0.010-inch thick stainless-steel tamper is centered over the bridge area and bonded to the Kapton with Hysol 9340 epoxy. Hysol 9340 epoxy was used for all bonds in this assembly and was chosen because it will maintain bond strength to a temperature of 150° C. On the opposite side of the slapper, a barrel is centered over the bridge area and bonded. The barrels used were approximately 0.500-inch outside diameter and 0.250-inch inside diameter. Barrel length was initially fixed at 0.064 to 0.070 inch depending on Viton material thickness. Late in the test program barrel lengths up to 0.159 inch were tested. These longer barrels were constructed by building up layers of Viton or of metal and Viton. In all cases, the top layer (the layer bonded to the barrier) of the barrel was Viton. These multiple layers were bonded together with the Hysol 9340 epoxy. Next, the barrier, a 0.500-inch diameter by 0.012-inch thick 2-layer carbon composite disk (type "B" defined above), was bonded to the barrel. The tube that confines the NM/DETA mixture was Teflon tubing of 0.250-inch inside diameter, 0.032-inch wall thickness, and 0.550-inch length. This piece of tubing was supported by a washer of neoprene tubing that was 0.312-inch inside diameter, 0.500-inch outside diameter, and 0.19-inch length. This assembly was cured in an oven at the minimum recommended temperature of 60 °C for at least two hours. In addition, assemblies were not used for tests for many days after fabrication, so that complete cure of the adhesive was assured (see Fig. 6).

For functional testing, the Teflon tube was filled completely with the NM/DETA mixture. Particular attention was required to ensure that no air bubbles were trapped in the NM/DETA. If there were a bubble in the liquid and the orientation of the explosive assembly allowed that bubble to rise against the barrier, the explosive liquid would not initiate because the full energy of the flyer would not be transferred effectively to the liquid surface. A polyethylene cap was placed over the open end and sealed with Devcon 1-minute epoxy. It was discovered in early tests that the polyethylene cap was deforming at 120° C. For all remaining tests at 120° C, aluminum covers were fabricated and used. Just before the test assemblies were placed in the test chamber, a small aluminum strip with an identifying code stamped

into it was taped to the side of the NM/DETA tube. This strip served as a "witness plate"; when detonation of the explosive liquid occurs there is a distinct damage pattern observed on the aluminum plate.

E.) EMRTC Test Series Details

i.) Small Scale Safety Tests

The tests reported below were conducted by EMRTC in December 1992.

Gas Evolution Test - This is a standard test used in the explosives industry to predict the safety and stability of an explosive material. Small quantities of explosive (20 milligrams) are sealed into glass capillary tubes (capsules) of 2-mm inside diameter, 0.2-mm wall thickness and 15- to 20-mm in length. These capsules are then heated slowly to a specified temperature and held at that temperature for a relatively long time; they are then fully cooled to room temperature to ensure that any gases that remain within the capsules are the product of chemical reaction and/or decomposition and not just vapor from heating. When fully cooled, each capsule is placed in a sealed chamber and broken. This chamber is instrumented with a sensitive transducer that measures the pressure increase caused by the released gases within the chamber. Since the volumes of the chamber and the capsule are known, the amount of gas released from the capsule can be calculated from the pressure rise recorded. The normalized amount of gas is calculated as cubic centimeters of evolved gas per gram (cm^3/g) of original material. The normalized amount of gaseous reaction products is a good indication of the stability of the explosive. Stability in this case means not only that the material will not self explode over the test temperature range, but also that it will not be degrade and, thus, can be detonated when intended. A generally accepted limit of 1.0 cm^3/g or less indicates a stable explosive material.

Both pure NM and a 95/5 wt% NM/DETA mixture were tested. The results indicated that, as expected, the pure NM is more stable than the mixture (see Figure 13). Up to 130° C the evolved gas is less than 0.6 cm^3/g for both liquids; this indicates that the chosen explosive is very stable up to maximum temperature encountered in most boreholes. At temperatures of 140° C and above, the 95/5 mixture begins to show a significant increase in the amount of gas evolved. This result is not of concern in the case of a seismic source, since the mixed explosive would be detonated very soon after mixing. It should be noted that the pure NM produces much less than 1 cm^3/g at 140° C.

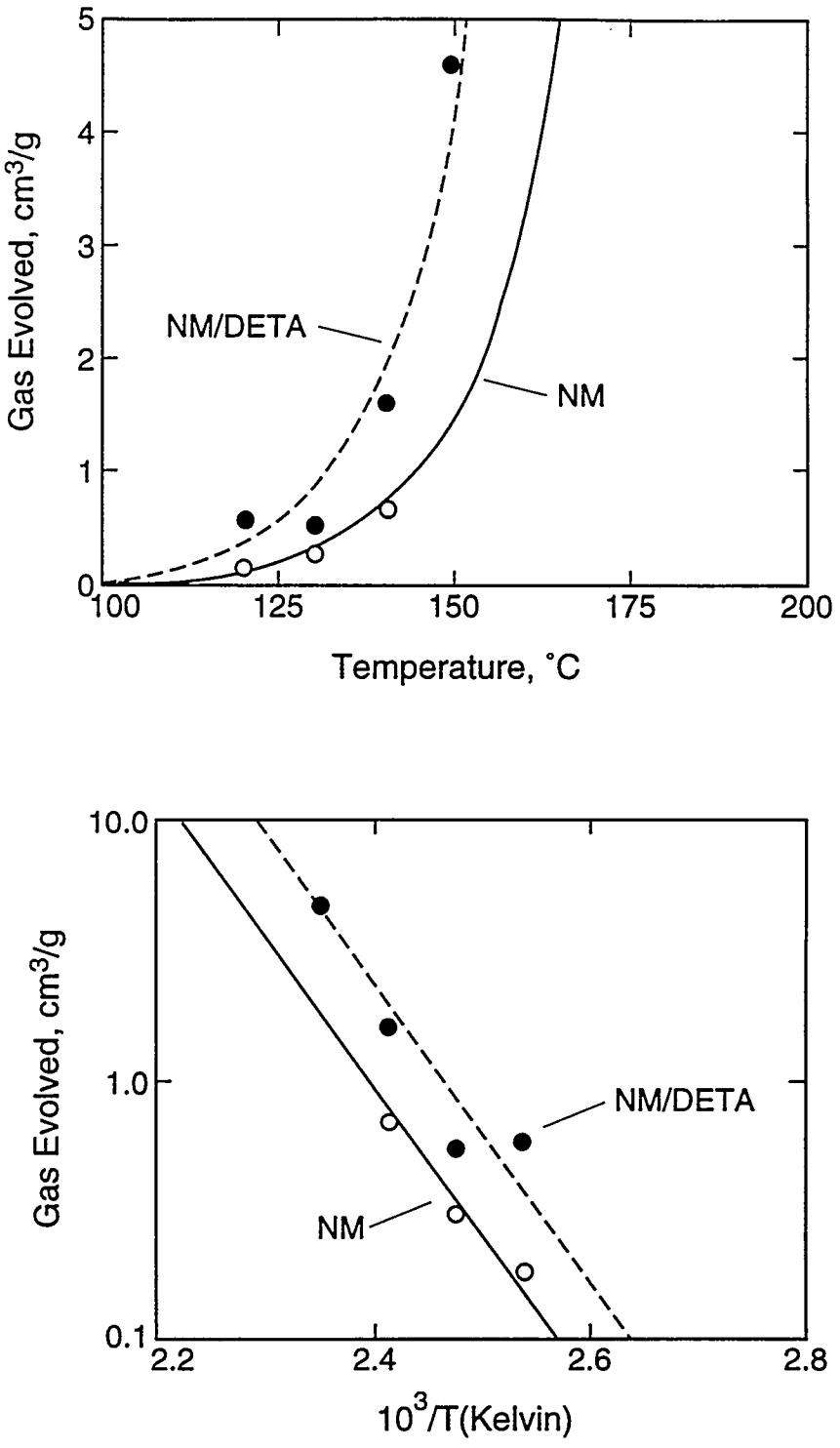


Figure 13. Results of the gas evolution tests performed at EMRTC. The top and bottom panels are the data plotted in a linear-linear plane and an Arrhenius plane (i.e., log of gas evolved vs 1/T), respectively.

Examination of the test capsules after breakage showed that the neat NM capsules were clean inside, while the NM/DETA capsules were coated with a black residue.

ii.) Pressure Deflection Test Results

A number of attempts were made to measure the deflection of the barrel/barrier system under pressure. None of the methods used was completely successful; however, some information that could be useful in future designs was obtained. Tabulated results are given in Table 10.

The first test was a single unit that incorporated electrical contacts inside the barrel. An assembly of a slapper, tamper, Viton barrel, and a carbon-composite barrier was made with a measured gap between conductors inside the barrel. A hard contact point of conductive epoxy and copper was attached to the slapper with a very fine copper wire passing thru the barrel/slapper glue line. A small circle of metallized Mylar was bonded to the inside of the barrier with a flexible adhesive. These two contact points were attached to the test chamber electrical feedthru and resistance was monitored as the pressure was increased. The unit was assembled with an approximately 0.065-inch long barrel, a 0.012-inch thick barrier, and a 0.010-inch thick stainless steel tamper. The gap between the contacts was 0.010 inch. When pressurized, the resistance measurements were inconclusive as to when contact occurred. However, after the pressure was increased to 4000 psig and released, disassembly revealed that the fixed contact had indented the barrier.

A second set of tests was attempted with assemblies that were similar to the first test unit. These four test assemblies were all assembled with approximately 0.065-inch long barrels, 0.012-inch thick barriers, and 0.010-inch thick stainless-steel tampers. The four assemblies had internal gaps of 0.004, 0.020, 0.026 and 0.027 inch between contacts. Deflection increased with pressure as expected, but the deflection was relatively less as the pressure increased. The largest gap unit showed "switch closure" at about 1800 psig, which indicates that 40% of gap distance is lost at 28% of target maximum pressure. The two largest gap units were pressurized to 6000 and 6500 psig, respectively, and returned to ambient pressure. Both returned to "zero", were not damaged, and when disassembled there was no indication of water inside the barrel. The 0.020-inch-gap unit showed switch closure at 900 psig, but after being pressurized to 3000 psig the resistance did not return to

"high" and the barrel was found to be filled with water. The 0.004-inch-gap unit showed "switch closure" at 400 psig and the barrier was punctured by the fixed contact at 2700 psig

A third set of deflection tests was done in which the measuring technique was totally passive. A total of six test specimens were fabricated, all with 130-mil long barrels. Three of these specimens were constructed with barrels that were made of two layers of 65-mil thick Viton and the remaining three units were constructed with a 65-mil thick metal layer and a 65-mil thick Viton layer. These six barrels were bonded to slappers and 10-mil thick stainless-steel tampers were bonded to the reverse side of the slappers. These barrels were then partially filled with modeling clay. One of each barrel construction was filled so that when the carbon-composite barrier was attached, the void space remaining was 20, 35, or 50 mils high. The six assemblies were then placed in the pressure chamber and subjected to 6500 psig. After returning to ambient pressure, the assemblies were carefully opened and inspected for the presence of water and changes of shape of the clay surface.

Of the three units with all-rubber barrels, all three had changes in the clay surface and two of the three units contained water droplets. The 20-mil void unit had a slight convex shape to the clay which may indicate complete compression of the assembly ; this assembly also contained water droplets. The 35-mil void unit had a large indent in the clay, but contained no water droplets. The 50-mil void unit had a small indent and water was present.

Of the three units with metal/rubber barrels, only the unit with the 20-mil gap had an indent in the clay and only the unit with the 35-mil gap contained water. The results are tabulated in Table 10.

An additional set of passive tests was done in which three standard complete test assemblies were used. These test assemblies were as described above with one- layer 0.065-inch long barrels. For these tests, blue-colored water (ink) was substituted for the explosive liquid. Two units were pressurized to 3000 psig and removed for inspection. Both were found to be leaking the colored water thru a partial (approximately 60° included angle) delamination of the tube support ring from the barrier. The two units were repressurized to 4000 psig and again removed for inspection. The tube support ring and tube were separated from the rest of the

assembly. The barrier/barrel/slapper assembly appeared to be intact, but the barrier showed a slight dimple of approximately 5 to 10 mils into the inside diameter of the barrel. Also, the tamper appeared to have a very slight dimple. A third complete inert assembly was added and all three were again repressurized to 5000 psig and removed for inspection. The tube support ring and tube were broken from the third unit also, but the rest of the assembly remained intact for all three. There were similar dimples in all three assemblies.

As a follow up to these tests, two new standard assemblies with 0.125-inch long barrels (2-layer Viton) were assembled with special care. These two units were filled with blue water and pressurized to 3000 psig and removed for inspection. There was no indication of leakage of the blue water or other damage to either unit. These units were rinsed, dried and refilled with the NM/DETA mixture. One detonated at 1000 psig and the second detonated at 2000 psig. Two additional units which had laminated metal/Viton barrels, one having a 0.120-inch long barrel and the second a 0.156-inch long barrel were tested in a similar but more severe way. The units were pressurized to 6500 psig and removed for inspection. There was no sign of leakage or damage to either. They were refilled with the NM/DETA mixture and both failed to detonate at 3200 psig.

iii.) EMRTC Test Series Details

Tests were started based on a test matrix, that would continuously increase the temperature and then the pressure toward a maximum of 6400 psig at 120°C (see Table 11). The plan was to complete five tests at each step of the matrix. Prior to beginning the tests as defined by the matrix, numerous tests were performed to check out and validate the test set-up. Tests were first conducted to confirm that the pressure system would attain the maximum required pressure and hold that pressure for a reasonable time. The capacitor discharge unit (CDU) was set up near the pressure chamber. The high-voltage power supply for charging the CDU, the firing control console, and necessary instrumentation were set up in an adjacent room to ensure personnel safety during the actual firing in the pressure chamber. Bare slappers and then complete explosive assemblies were fired in air through the principal feedthru to establish the baseline firing voltage to be used. This voltage was established at 5750 volts. This voltage was established to be as low as

practical, but high enough to be confident that slapper operation would be correct. A hi pot tester was set up adjacent to the pressure chamber so the feedthru could be tested after each firing, if necessary. In order to be able to fire test assemblies as quickly as possible after immersion in the hot liquid, a counterbalance was rigged to the chamber cover to facilitate handling and an impact wrench was used for tightening the cover bolts.

It was expected that the explosive mixture would function properly at the high temperatures that were specified in the test matrix, but because the effect of high pressure on t · explosive/mechanical system performance was less well understood, many tests were done out of the sequence. Some ambient temperature, high pressure firings were attempted early on in the test series. Table 9 is a complete collection of the firing-test results obtained at EMRTC.

Testing at EMRTC was divided into two groups. The division of the tests was required because of the boiling point of the explosive liquid, which is less than 100° C at the test altitude. The first and largest group was all tests that could be completed at or below 90° C. The second group was those tests that were completed at 120° C and which required the more elaborate test set-up using a circulation pump and secondary reservoir of 150° C ethylene glycol. This test set-up is shown schematically in Figure 12. The deflection test were distributed throughout these two groups of tests.

a.) First Group

The results of the first group of tests are tabulated as S1 thru S46 in Table 9. There are missing test numbers in this table. The missing tests were deflection tests and are tabulated in Table 10. Note also that some of the tabulated tests did not contain explosive. These non-explosive tests were slapper/barrel/barrier-only assemblies in which slapper performance was estimated by examination of debris or they were standard assemblies that were filled with colored water, taken to a specified pressure, and then inspected for leaks due to deflection induced cracking of adhesive joints. Tests S1 thru S6 were shakedown tests to familiarize the EMRTC personnel with the test set-up and to sort out problems. Tests S7 thru S26R were an attempt to establish a possible upper operating pressure limit that could help direct the test effort away from unnecessary tests. The maximum pressure at which detonation was obtained was 2000 psig (tests S25R and S26R). These two test specimens were assembled with particular

care and were pre-pressure tested to establish that they would not be damaged by deflections during pressurization.

Tests S27 thru S31 were tests at ambient pressure at approximately 60° C and 90° C. These tests indicated that higher temperatures were not a problem as long as the explosive mixture was not exposed to the higher temperatures for long periods of time.

Tests S35 thru S46 were further tests to establish upper pressure limits.

In addition to the tests reported in Table 9, EMRTC completed five tests in each of the first six steps of the test matrix. These were the tests at ambient pressure in air and water with the temperature at ambient, 60° C, and 90° C.

This group of tests indicates that the chosen explosive and the confinement/initiation system will readily function up to 90° C and, if special care is taken in assembly, will also function at static pressures up to 2000 psig.

b.) Second Group

The second group of tests is tabulated as S47 thru S60 in Table 9. All of these tests were done by first raising the system pressure to a range between 200 and 500 psig and then circulating the 150° C ethylene glycol from the reservoir into the test chamber to obtain a firing temperature of 120° C.

Tests S47 thru S50 were again shakedown tests for the modified test set-up. Also, it was learned from these tests that the polyethylene cap being used to close the explosive assembly was changing shape as the temperature exceeded 100° C and the explosive mix was being diluted with water, resulting in failure.

Tests S51 thru S60 were performed using an aluminum cap to close the explosive assembly. This resulted in three detonations at or above 120° C and one at 112° C. However, there were six tests in this group that were failures: five of which were due primarily to non-explosive system failures. These failures serve to emphasize the fact that obtaining reliable, multiple detonations in a wellbore environment will be difficult.

c.) Deflection Tests

While not a specific group, there were eleven deflection tests performed as tabulated in Table 10 and discussed in detail in Sec. V. E. ii. These tests did not provide quantitative results, but they yield a very strong indication that deflection and deformation of the slapper/barrel/barrier assembly, as currently designed, becomes a serious problem as hydrostatic pressure increases.

VI. Discussion of Results and Conclusions

A detonation system is described that is fabricated by mixing two non-explosive materials; here "non-explosive" means a material that DOT regulations define as such. The two materials are the liquid organic compounds nitromethane (NM) and the organic base diethylenetriamine (DETA). The composition used here is 95/5 wt% NM/DETA.

It has been demonstrated that this explosive can be initiated by an electrical slapper detonator system which utilizes no chemical explosives.

Thus, with a mixing system and the appropriate ancillary equipment, a borehole seismic tool could be constructed which never exposes humans to explosives.

The energy content per seismic event can range from ca. 0.5 kcal to an arbitrarily large amount.

The major technical difficulty to overcome in producing this explosive system is to achieve initiation of the explosive across the container (barrier) in which the explosive is enclosed--with a slapper detonator. A container (barrier) is required to maintain the slapper barrel geometry against the hydrostatic head experienced within wellbores. Metals are not strong candidates as barrier materials because of their large shock impedance mismatch with organic compounds. Because of this, we used a carbon-fiber material to construct our barriers.

The EMRTC testing demonstrated that the explosive system, as now configured, could function properly under pressures as high as those found in wellbores $\leq$ 4,600 ft deep.

The restriction on wellbore depth results from deflection, distortion, and loss of integrity of the barrier/barrel assembly. These factors cause shortening of the barrel, non-planarity of the surface the slapper flyer impacts, and even admission of wellbore fluid into the barrel volume. If the explosive system needs to be used at depths $\geq$ 4,600 ft, a reconfigured barrier/barrel assembly is the central problem to be addressed. We did not address it further not because of lack of available technical approaches, but because of loss of personnel associated with the project and its subsequent termination.

The EMRTC tests also showed that the explosive mixture is capable of performing satisfactorily at well bore temperatures as high as 120° C. This is in spite

of known evidence that the 95/5 wt% NM/DETA mixture degrades over time and that this degradation accelerates as temperature increases. The EMRTC testing showed that detonation can be achieved after three minutes at 120° C. Since the actual seismic source would mix and initiate the explosive within times significantly less than one minute, temperatures of ≤ 120° C do not cause difficulties.

Acknowledgments

This report was written by the two listed authors, however many other workers contributed to obtaining the results described herein. We now give a list of these workers and of their contributions to this work. Jim Albright (EES-4) first noted that a seismic source that employed a mixture of non-explosive materials would be of value in downhole seismic work and he obtained the initial funding used to pursue such a possibility. Alan Kammerman (formerly of EES-4) made the initial searches and analysis of candidate materials; he was deeply involved in the project up to the barrier burst tests. Ismael Garcia (DX-10) very ably assisted in performing Experiments 1 to 91, the results of which are listed in Tables 2 to 8. Billy Powell (DX-10) answered our questions concerning slapper behavior and fabrication and supplied all the slappers used in the experiments. Richard Yactor (DX-10) provided us with the predictions of slapper speed vs. barrel length that allowed the early estimates of the pressures produced in the explosive mixture under various conditions. Willard Hemsing's (DX-13) work to increase the Visar sensitivity made the direct measurement of the slapper speed histories possible; these measurements allowed us to accurately estimate the pressure produced in the explosive. Warren Pierce of DDP provided machine shop services for fabrication and modification of the pressure/temperature test chamber hardware. Douglas Hemphill and Renita Cook of ESA-WMA assisted with the design and fabrication of the carbon composite materials for the barrier. Thomas Harlow of ESA-MT performed the pressure burst tests for the barrier.

At EMRTC, Douglas Olson was the project engineer and Andrew Block-Bolton performed the small scale safety tests. John Reed and Roy Baca were responsible for the setup and performance of all the testing.

We also thank Ruth Bigio (EES-4) for constructing the finished figures and tables.

We note that the following proprietary names are trademarks--Pyrex, Kapton, Mylar, Viton, Teflon, Devcon, and Hysol; these names have been used in the text without trademarks indicated.

Appendix 1

MSDS's for Nitromethane and Diethylenetriamine

Product #: 230731 Name: NITROMETHANE, 99+%
Material Safety Data Sheet Valid 5/95- 7/95
Printed: 05/12/1995 15:03:02

Sigma Chemical Co.
P.O. Box 14508
St. Louis, MO 63178
Phone: 314-771-5765

Aldrich Chemical Co., Inc.
1001 West St. Paul
Milwaukee, WI 53233
Phone: 414-273-3850

Fluka Chemical Corp.
980 South Second St.
Ronkonkoma, NY 11779
Phone: 516-467-0980
Emergency Phone: 516-467-3535

SECTION 1. - - - - - - - - - - CHEMICAL IDENTIFICATION- - - - - - - - - -
PRODUCT #: 23073-1
NAME: NITROMETHANE, 99+%
SECTION 2. - - - - - COMPOSITION/INFORMATION ON INGREDIENTS - - - - - -
CAS #:75-52-5
MF: CH3NO2
SYNONYMS
NITROCARBOL * NITROMETAN (POLISH) * NITROMETHANE (ACGIH,DOT,OSHA) *
UN1261 (DOT) *
SECTION 3. - - - - - - - - - - HAZARDS IDENTIFICATION - - - - - - - - -
LABEL PRECAUTIONARY STATEMENTS
FLAMMABLE
HARMFUL
HARMFUL BY INHALATION, IN CONTACT WITH SKIN AND IF SWALLOWED.
IRRITATING TO EYES, RESPIRATORY SYSTEM AND SKIN.
HEATING MAY CAUSE AN EXPLOSION.
TARGET ORGAN(S):
LIVER
KIDNEYS
KEEP AWAY FROM SOURCES OF IGNITION. NO SMOKING.
IN CASE OF CONTACT WITH EYES, RINSE IMMEDIATELY WITH PLENTY OF
WATER AND SEEK MEDICAL ADVICE.
WEAR SUITABLE PROTECTIVE CLOTHING.
SECTION 4. - - - - - - - - - - FIRST-AID MEASURES- - - - - - - - - - -
IN CASE OF CONTACT, IMMEDIATELY FLUSH EYES OR SKIN WITH COPIOUS
AMOUNTS OF WATER FOR AT LEAST 15 MINUTES WHILE REMOVING CONTAMINATED
CLOTHING AND SHOES.
IF INHALED, REMOVE TO FRESH AIR. IF NOT BREATHING GIVE ARTIFICIAL
RESPIRATION. IF BREATHING IS DIFFICULT, GIVE OXYGEN.
IF SWALLOWED, WASH OUT MOUTH WITH WATER PROVIDED PERSON IS CONSCIOUS.
CALL A PHYSICIAN.
WASH CONTAMINATED CLOTHING BEFORE REUSE.
SECTION 5. - - - - - - - - - - FIRE FIGHTING MEASURES - - - - - - - - - -
EXTINGUISHING MEDIA
WATER SPRAY.
CARBON DIOXIDE.
APPROPRIATE FOAM.
DO NOT USE DRY CHEMICAL POWDER EXTINGUISHER ON THIS MATERIAL.
SPECIAL FIREFIGHTING PROCEDURES
WEAR SELF-CONTAINED BREATHING APPARATUS AND PROTECTIVE CLOTHING TO
PREVENT CONTACT WITH SKIN AND EYES.

USE WATER SPRAY TO COOL FIRE-EXPOSED CONTAINERS.

UNUSUAL FIRE AND EXPLOSIONS HAZARDS

FLAMMABLE.
MAY EXPLODE WHEN HEATED.
VAPOR MAY TRAVEL CONSIDERABLE DISTANCE TO SOURCE OF IGNITION AND FLASH BACK.
CONTAINER EXPLOSION MAY OCCUR UNDER FIRE CONDITIONS.
FORMS EXPLOSIVE MIXTURES IN AIR.
EMITS TOXIC FUMES UNDER FIRE CONDITIONS.

SECTION 6. - - - - - - - - - ACCIDENTAL RELEASE MEASURES- - - - - - - - -

EVACUATE AREA.
SHUT OFF ALL SOURCES OF IGNITION.
WEAR SELF-CONTAINED BREATHING APPARATUS, RUBBER BOOTS AND HEAVY RUBBER GLOVES.
ABSORB ON SAND OR VERMICULITE AND PLACE IN CLOSED CONTAINERS FOR DISPOSAL.
USE NONSPARKING TOOLS.
VENTILATE AREA AND WASH SPILL SITE AFTER MATERIAL PICKUP IS COMPLETE.

SECTION 7. - - - - - - - - - - HANDLING AND STORAGE- - - - - - - - - - -

REFER TO SECTION 8.

ADDITIONAL INFORMATION

NITROMETHANE CAN DETONATE IF SENSITIZED BY AMINES, ALKALIES, STRONG ACIDS, AND HIGH TEMPERATURES. IT CAN BE DETONATED BY ADIABATIC COMPRESSION. THE DRY ALKALI OR AMINE SALTS OF NITROMETHANE ARE SHOCK-SENSITIVE AND THE SODIUM SALT BURSTS INTO FLAME UPON CONTACT WITH WATER.

SECTION 8. - - - - - - EXPOSURE CONTROLS/PERSONAL PROTECTION- - - - - -

CHEMICAL SAFETY GOGGLES.
RUBBER GLOVES.
NIOSH/MSHA-APPROVED RESPIRATOR.
SAFETY SHOWER AND EYE BATH.
MECHANICAL EXHAUST REQUIRED.
DO NOT BREATHE VAPOR.
DO NOT GET IN EYES, ON SKIN, ON CLOTHING.
AVOID PROLONGED OR REPEATED EXPOSURE.
WASH THOROUGHLY AFTER HANDLING.
HARMFUL LIQUID AND FUMES.
IRRITANT.
KEEP TIGHTLY CLOSED.
KEEP AWAY FROM COMBUSTIBLE MATERIALS, HEAT, SPARKS, AND OPEN FLAME.
STORE IN A COOL DRY PLACE.

SECTION 9. - - - - - - - PHYSICAL AND CHEMICAL PROPERTIES - - - - - - -

APPEARANCE AND ODOR

COLORLESS LIQUID
BOILING POINT: 101.2 C
MELTING POINT: -29 C
FLASHPOINT 95 F
34C
AUTOIGNITION TEMPERATURE: 784 F 417C

LOWER EXPLOSION LEVEL: 7.3% 33 C
VAPOR PRESSURE: 27.3MM 20 C
VAPOR DENSITY: 2.1
SPECIFIC GRAVITY: 1.127

SECTION 10. - - - - - - - - -STABILITY AND REACTIVITY - - - - - - - - -

CONDITIONS TO AVOID

KEEP AWAY FROM HEAT, SPARKS, AND OPEN FLAME.

INCOMPATIBILITIES

AMINES
STRONG ACIDS
STRONG BASES
STRONG OXIDIZING AGENTS
STRONG REDUCING AGENTS
COPPER, COPPER ALLOYS
LEAD
AND ITS ALLOYS.

HAZARDOUS COMBUSTION OR DECOMPOSITION PRODUCTS

THERMAL DECOMPOSITION MAY PRODUCE CARBON MONOXIDE, CARBON DIOXIDE, AND NITROGEN OXIDES.

SECTION 11. - - - - - - - - - TOXICOLOGICAL INFORMATION - - - - - - - -

ACUTE EFFECTS

HARMFUL IF SWALLOWED, INHALED, OR ABSORBED THROUGH SKIN.
CAUSES EYE AND SKIN IRRITATION.
VAPOR OR MIST IS IRRITATING TO THE EYES, MUCOUS MEMBRANES AND UPPER RESPIRATORY TRACT.
ABSORPTION INTO THE BODY LEADS TO THE FORMATION OF METHEMOGLOBIN WHICH IN SUFFICIENT CONCENTRATION CAUSES CYANOSIS. ONSET MAY BE DELAYED 2 TO 4 HOURS OR LONGER.
TARGET ORGAN(S):
LIVER
KIDNEYS
CENTRAL NERVOUS SYSTEM

RTECS NO: PA9800000
METHANE, NITRO-

TOXICITY DATA

ORL-RAT LD50:940 MG/KG	GISAAA 32(9),9,67
ORL-MUS LD50:950 MG/KG	GISAAA 32(9),9,67
IPR-MUS LD50:110 MG/KG	KHFZAN 10(6),53,76

TARGET ORGAN DATA

BEHAVIORAL (SOMNOLENCE)
BEHAVIORAL (ATAXIA)
LUNGS, THORAX OR RESPIRATION (RESPIRATORY DEPRESSION)
LUNGS, THORAX OR RESPIRATION (RESPIRATORY STIMULATION)
LIVER (HEPATITIS: HEPATOCELLULAR NECROSIS, ZONAL)
KIDNEY, URETER, BLADDER (CHANGES IN BOTH TUBULES AND GLOMERULI)
ONLY SELECTED REGISTRY OF TOXIC EFFECTS OF CHEMICAL SUBSTANCES (RTECS) DATA IS PRESENTED HERE. SEE ACTUAL ENTRY IN RTECS FOR COMPLETE INFORMATION.

SECTION 12. - - - - - - - - - ECOLOGICAL INFORMATION - - - - - - - - -

Product #: D93856 Name: DIETHYLENETRIAMINE, 99%
Material Safety Data Sheet Valid 5/95- 7/95
Printed: 05/12/1995 15:02:49

Sigma Chemical Co.
P.O. Box 14508
St. Louis, MO 63178
Phone: 314-771-5765

Aldrich Chemical Co., Inc.
1001 West St. Paul
Milwaukee, WI 53233
Phone: 414-273-3850

Fluka Chemical Corp.
980 South Second St.
Ronkonkoma, NY 11779
Phone: 516-467-0980
Emergency Phone: 516-467-3535

SECTION 1. - - - - - - - - - - CHEMICAL IDENTIFICATION- - - - - - - - - -
PRODUCT #: D9385-6
NAME: DIETHYLENETRIAMINE, 99%
SECTION 2. - - - - - COMPOSITION/INFORMATION ON INGREDIENTS - - - - - -
CAS #:111-40-0
MF: C4H13N3
SYNONYMS
AMINOETHYLETHANDIAMINE * 3-AZAPENTANE-1,5-DIAMINE * BIS(2-AMINOETHYL) AMINE * BIS(BETA-AMINOETHYL)AMINE * D.E.H. 20 * DETA * 2,2'-DIAMINODIETHYLAMINE * DIETHYLAMINE, 2,2'-DIAMINO- * ETHYLAMINE, 2,2'-IMINOBIS- * ETHYLENEDIAMINE, N-(2-AMINOETHYL)- * UN2079 (DOT) *
SECTION 3. - - - - - - - - - - HAZARDS IDENTIFICATION - - - - - - - - -
LABEL PRECAUTIONARY STATEMENTS
HIGHLY TOXIC (USA DEFINITION)
TOXIC (EUROPEAN DEFINITION)
TOXIC BY INHALATION, IN CONTACT WITH SKIN AND IF SWALLOWED.
MAY CAUSE SENSITIZATION BY INHALATION AND SKIN CONTACT.
CAUSES BURNS.
READILY ABSORBED THROUGH SKIN.
TARGET ORGAN(S):
LIVER
KIDNEYS
IN CASE OF ACCIDENT OR IF YOU FEEL UNWELL, SEEK MEDICAL ADVICE IMMEDIATELY (SHOW THE LABEL WHERE POSSIBLE).
IN CASE OF CONTACT WITH EYES, RINSE IMMEDIATELY WITH PLENTY OF WATER AND SEEK MEDICAL ADVICE.
TAKE OFF IMMEDIATELY ALL CONTAMINATED CLOTHING.
WEAR SUITABLE PROTECTIVE CLOTHING, GLOVES AND EYE/FACE PROTECTION.
STORE UNDER NITROGEN.
SECTION 4. - - - - - - - - - - FIRST-AID MEASURES- - - - - - - - - - -
IN CASE OF CONTACT, IMMEDIATELY FLUSH EYES OR SKIN WITH COPIOUS AMOUNTS OF WATER FOR AT LEAST 15 MINUTES WHILE REMOVING CONTAMINATED CLOTHING AND SHOES.
ASSURE ADEQUATE FLUSHING OF THE EYES BY SEPARATING THE EYELIDS WITH FINGERS.
IF INHALED, REMOVE TO FRESH AIR. IF NOT BREATHING GIVE ARTIFICIAL RESPIRATION. IF BREATHING IS DIFFICULT, GIVE OXYGEN.
IF SWALLOWED, WASH OUT MOUTH WITH WATER PROVIDED PERSON IS CONSCIOUS.
CALL A PHYSICIAN IMMEDIATELY.
WASH CONTAMINATED CLOTHING BEFORE REUSE.

DISCARD CONTAMINATED SHOES.

SECTION 5. - - - - - - - - - - FIRE FIGHTING MEASURES - - - - - - - - - -

EXTINGUISHING MEDIA

CARBON DIOXIDE, DRY CHEMICAL POWDER OR APPROPRIATE FOAM.
WATER SPRAY.

SPECIAL FIREFIGHTING PROCEDURES

WEAR SELF-CONTAINED BREATHING APPARATUS AND PROTECTIVE CLOTHING TO PREVENT CONTACT WITH SKIN AND EYES.

UNUSUAL FIRE AND EXPLOSIONS HAZARDS

EMITS TOXIC FUMES UNDER FIRE CONDITIONS.

SECTION 6. - - - - - - - - - ACCIDENTAL RELEASE MEASURES- - - - - - - - -

EVACUATE AREA.
WEAR SELF-CONTAINED BREATHING APPARATUS, RUBBER BOOTS AND HEAVY RUBBER GLOVES.
ABSORB ON SAND OR VERMICULITE AND PLACE IN CLOSED CONTAINERS FOR DISPOSAL.
VENTILATE AREA AND WASH SPILL SITE AFTER MATERIAL PICKUP IS COMPLETE.

SECTION 7. - - - - - - - - - - - HANDLING AND STORAGE- - - - - - - - - - -

REFER TO SECTION 8.

ADDITIONAL INFORMATION

DIETHYLENETRIAMINE (DETA) HAS BEEN REPORTED TO FORM COMPLEXES WITH SILVER, COBALT OR CHROMIUM WHICH CAN BE EXPLOSIVE. IT HAS BEEN REPORTED TO CAUSE SPONTANEOUS IGNITION OF CELLULOSE NITRATE.

SECTION 8. - - - - - - EXPOSURE CONTROLS/PERSONAL PROTECTION- - - - - -

WEAR APPROPRIATE NIOSH/MSHA-APPROVED RESPIRATOR, CHEMICAL-RESISTANT GLOVES, SAFETY GOGGLES, OTHER PROTECTIVE CLOTHING.
SAFETY SHOWER AND EYE BATH.
USE ONLY IN A CHEMICAL FUME HOOD.
FACESHIELD (8-INCH MINIMUM).
DO NOT BREATHE VAPOR.
DO NOT GET IN EYES, ON SKIN, ON CLOTHING.
AVOID PROLONGED OR REPEATED EXPOSURE.
READILY ABSORBED THROUGH SKIN.
WASH THOROUGHLY AFTER HANDLING.
HIGHLY TOXIC.
CORROSIVE.
SENSITIZER.
KEEP TIGHTLY CLOSED.
STORE IN A COOL DRY PLACE.

SECTION 9. - - - - - - - PHYSICAL AND CHEMICAL PROPERTIES - - - - - - -

APPEARANCE AND ODOR

COLORLESS LIQUID
BOILING POINT: 199 C TO 209 C
MELTING POINT: -35 C
FLASHPOINT 202 F
94C
AUTOIGNITION TEMPERATURE: 676 F 357C
UPPER EXPLOSION LEVEL: 6.7%
LOWER EXPLOSION LEVEL: 2%

VAPOR PRESSURE: 0.08MM 20 C
VAPOR DENSITY: 3.6
SPECIFIC GRAVITY: 0.955

SECTION 10. - - - - - - - - -STABILITY AND REACTIVITY - - - - - - - - -

INCOMPATIBILITIES

STRONG OXIDIZING AGENTS
STRONG ACIDS
COPPER, COPPER ALLOYS
ABSORBS CO2 FROM AIR.

HAZARDOUS COMBUSTION OR DECOMPOSITION PRODUCTS

TOXIC FUMES OF:
CARBON MONOXIDE, CARBON DIOXIDE
NITROGEN OXIDES

SECTION 11. - - - - - - - - - TOXICOLOGICAL INFORMATION - - - - - - - -

ACUTE EFFECTS

MAY BE FATAL IF INHALED, SWALLOWED, OR ABSORBED THROUGH SKIN.
MATERIAL IS EXTREMELY DESTRUCTIVE TO TISSUE OF THE MUCOUS MEMBRANES AND UPPER RESPIRATORY TRACT, EYES AND SKIN.
INHALATION MAY BE FATAL AS A RESULT OF SPASM, INFLAMMATION AND EDEMA OF THE LARYNX AND BRONCHI, CHEMICAL PNEUMONITIS AND PULMONARY EDEMA.
SYMPTOMS OF EXPOSURE MAY INCLUDE BURNING SENSATION, COUGHING, WHEEZING, LARYNGITIS, SHORTNESS OF BREATH, HEADACHE, NAUSEA AND VOMITING.
MAY CAUSE ALLERGIC RESPIRATORY AND SKIN REACTIONS.

CHRONIC EFFECTS

TARGET ORGAN(S):
LIVER
KIDNEYS
TO THE BEST OF OUR KNOWLEDGE, THE CHEMICAL, PHYSICAL, AND TOXICOLOGICAL PROPERTIES HAVE NOT BEEN THOROUGHLY INVESTIGATED.

RTECS NO: IE1225000

DIETHYLENETRIAMINE (ACGIH,DOT,OSHA)

IRRITATION DATA

SKN-RBT 10 MG/24H OPEN SEV	JIHTAB 31,60,49
SKN-RBT 500 MG OPEN MOD	UCDS** 12/30/71
SKN-RBT 500 MG	IYKEDH 6,170,75
EYE-RBT 750 UG OPEN SEV	JIHTAB 31,60,49

TOXICITY DATA

ORL-RAT LD50:1080 MG/KG	AMIHAB 17,129,58
IPR-RAT LD50:74 MG/KG	AMIHAB 17,129,58
UNR-RAT LD50:970 MG/KG	GISAAA 37(7),103,72
IPR-MUS LD50:71 MG/KG	AMIHAB 17,129,58
UNR-MUS LD50:970 MG/KG	GISAAA 37(7),103,72
SKN-RBT LD50:1090 MG/KG	JIHTAB 31,60,49
UNR-RBT LD50:970 MG/KG	GISAAA 37(7),103,72
SKN-GPG LD50:170 UL/KG	JIHTAB 26,269,44
UNR-GPG LD50:600 MG/KG	GISAAA 37(7),103,72

TARGET ORGAN DATA

BEHAVIORAL (CONVULSIONS OR EFFECT ON SEIZURE THRESHOLD)

Appendix 2

The Electrical Circuitry Used to Burst the Slapper Bridges and Two Discharge Current Histories

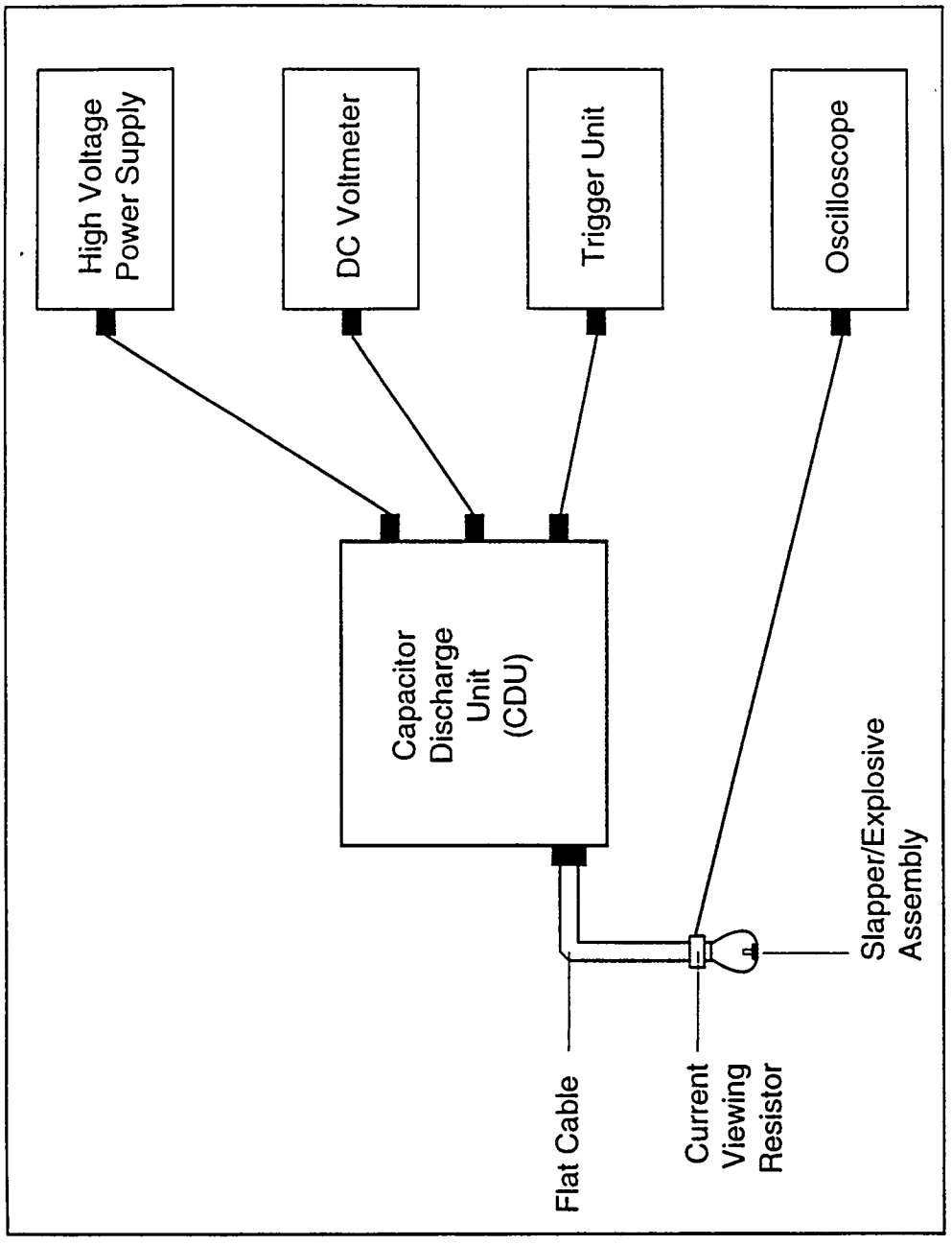
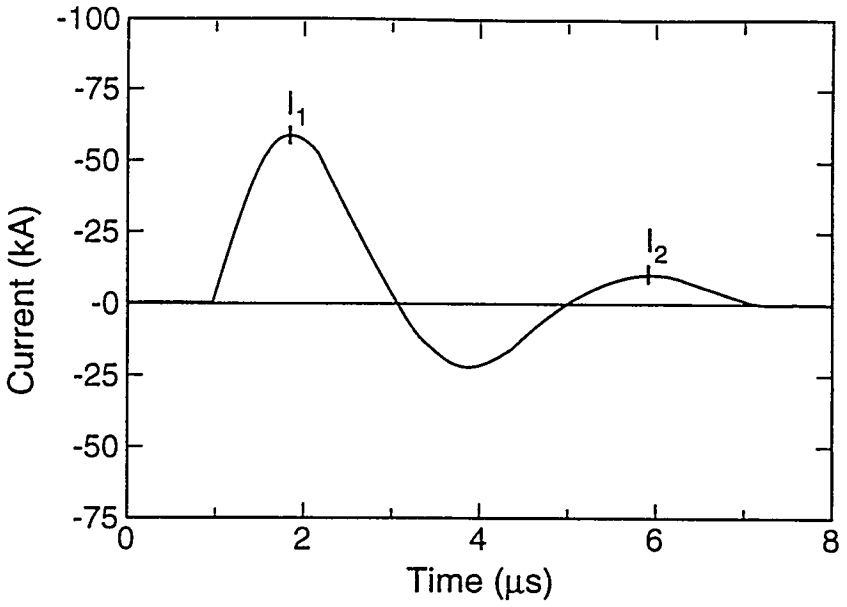


Figure A2-1. Rudimentary block digram of the electrical circuitry used to burst the slapper detonator bridges. The CDU is triggered by the breakdown of a spark gap.



Circuit Parameters

I_1	First current peak – 62.7 (kA)
I_2	Second current peak – 9.1 (kA)
	Time between I_1 and I_2 – 4.03 (μs)
	Voltage on CDU – 5.0 (kV)
	CDU capacitance – 12 (μF)
	Circuit inductance – 31.3 (nH)
	Circuit DC resistance – 30 (mΩ)

Figure A2-2. Ringdown history of the CDU circuitry with the CDU charged to 5.0 kV and then discharged through a shorted load. The quantities in the box are measured and derived values. The circuit inductance and DC resistance are obtained from a lumped circuit analysis of the ringdown.

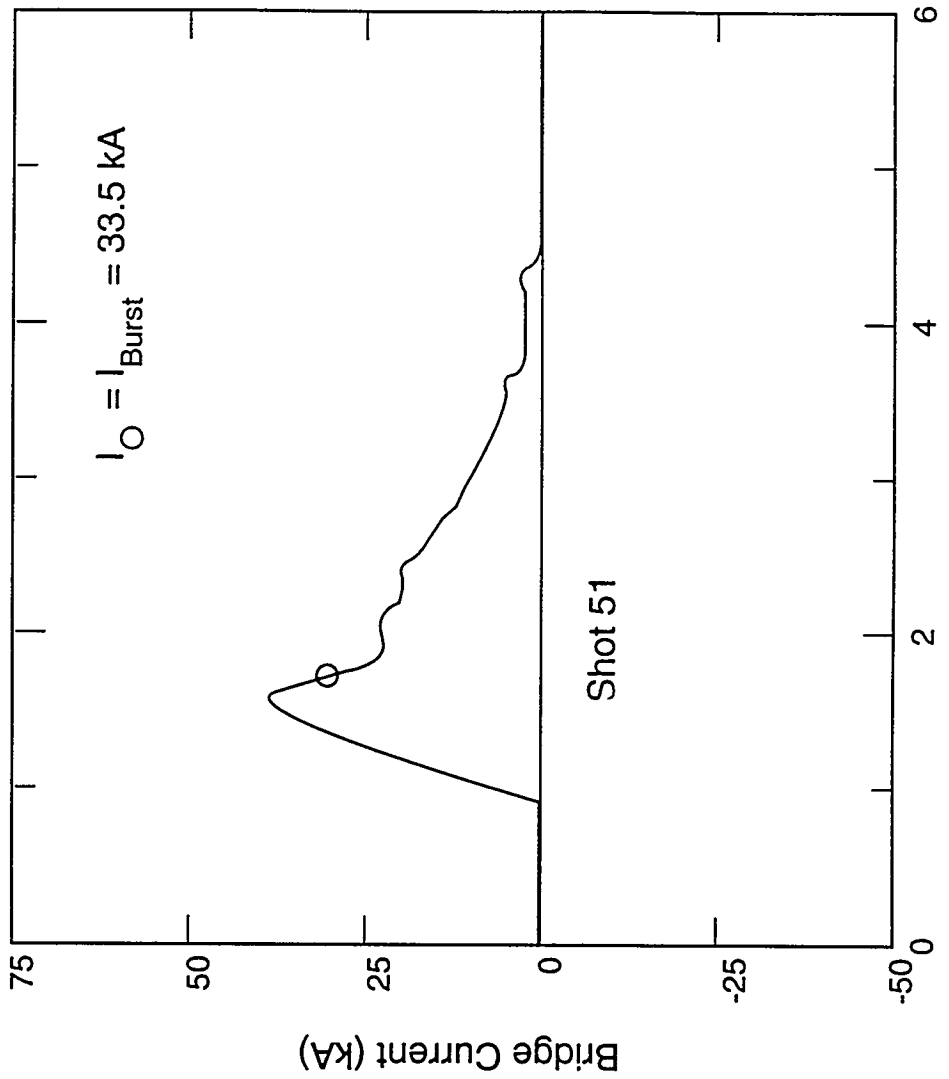


Figure A2-3. Current history obtained from bridge burst of the assembly type used in the EMRTC experiments; this record is from experiment 51 of Table 7. Note that the current flowing through the plasma at burst is ca. 33.5 kA, in this case.

Appendix 3

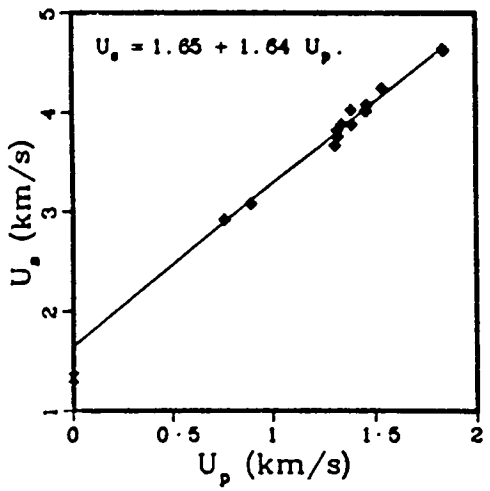
Various Shock Hugoniots

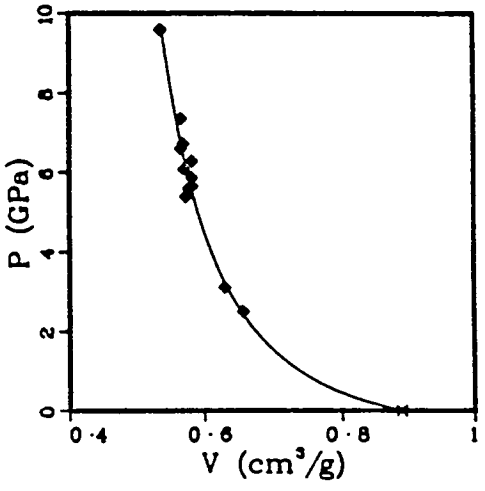
NITROMETHANE

Average ρ_0 = 1.125 g/cm³.

Sound velocities longitudinal 1.34 km/s.
shear 0.00 km/s.

ρ_0 (g/cm³)	U_s (km/s)	U_p (km/s)	P (GPa)	V (cm³/g)	ρ (g/cm³)	V/Vo	Exp
1.125	1.335	0 000	0.000	.8889	1.125	1.000	ssp ×
1.125	2.918	62	2.501	.6568	1.523	.739	wdg ◆
1.125	3.080	96	3.105	.6303	1.587	.709	wdg ◆
1.125	3.670	1.304	5.384	.5731	1.745	.645	wdg ◆
1.125	3.819	1.315	5.650	.5828	1.716	.656	wdg ◆
1.125	3.761	1.319	5.581	.5772	1.733	.649	wdg ◆
1.125	3.885	1.340	5.857	.5823	1.717	.655	wdg ◆
1.125	4.025	1.387	6.281	.5828	1.716	.655	wdg ◆
1.125	3.882	1.390	6.070	.5706	1.753	.642	wdg ◆
1.125	4.016	1.460	6.596	.5657	1.768	.636	wdg ◆
1.125	4.077	1.465	6.719	.5695	1.756	.641	wdg ◆
1.125	4.243	1.540	7.351	.5663	1.766	.637	wdg ◆
1.125	4.639	1.839	9.598	.5365	1.864	.604	wdg ◆
1.125	4.629	1.841	9.587	.5354	1.868	.602	wdg ◆





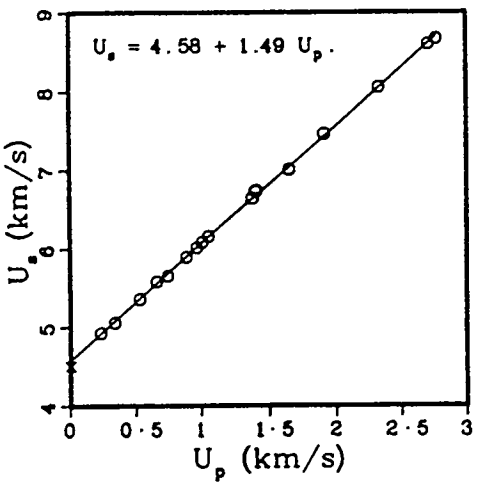
STEEL, 304

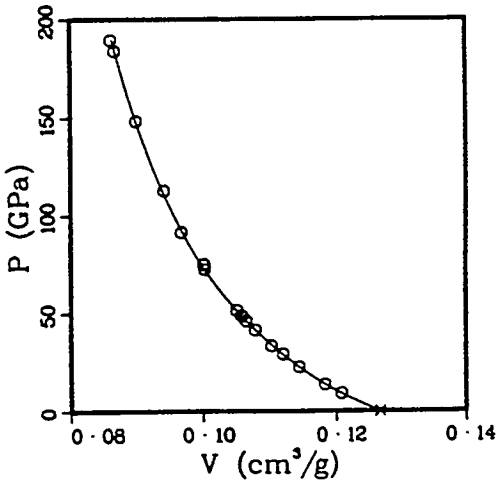
Average ρ_0 = 7 890 g/cm^3.

Sound velocities longitudinal 5.77 km/s.
shear 3.12 km/s

Reference 13

ρ_0 (g/cm^3)	U_s (km/s)	U_p (km/s)	P (GPa)	V (cm^3/g)	ρ (g/cm^3)	V/Vo	Exp
7.890	4.507	0.000	0 000	.1267	7.890	1.000	ssp ×
7 890	4.925	.232	9.015	.1208	8.280	.953	iml o
7.890	5.056	.339	13.523	.1182	8.457	.933	iml o
7.890	5.355	.529	22.351	.1142	8.755	.901	iml o
7 890	5.577	.659	28.998	.1118	8.947	.882	iml o
7.890	5.651	.745	33.217	.1100	9.088	.868	iml o
7.890	5.891	.889	41.321	.1076	9.292	.849	iml o
7.890	6.011	.969	45.957	.1063	9.406	.839	iml o
7.890	6.080	1.010	48.451	.1057	9.462	.834	iml o
7.890	6.152	1.057	51.306	.1050	9.527	.828	iml o
7.890	6.639	1.383	72.444	.1003	9.966	.792	iml o
7.890	6.732	1.409	74.840	.1002	9.978	.791	iml o
7.890	6 734	1.409	74.862	.1002	9.978	.791	iml o
7.890	7.007	1.653	91.386	.0968	10.326	.764	iml o
7.890	7.460	1.915	112.716	.0942	10.615	.743	iml o
7.890	8.054	2.334	148.317	.0900	11.109	.710	iml o
7.890	8.600	2.711	183.952	.0868	11.522	.685	iml o
7.890	8.667	2.772	189.557	.0862	11.600	.680	iml o





ALUMINUM . 2024

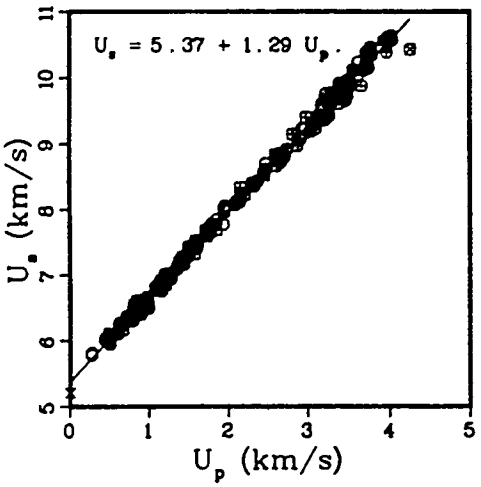
Average ρ_0 = 2.784 g/cm^3.

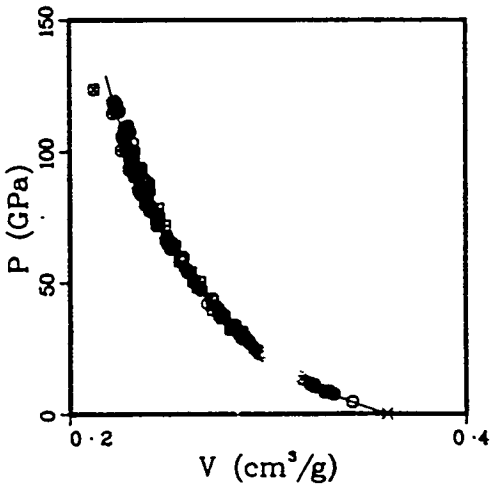
Sound velocities longitudinal 6.36 km/s.
shear 3.16 km/s.

References 2, 6, 11, 12, 13, 17, 18

ρ_0 (g/cm^3)	U_s (km/s)	U_p (km/s)	P (GPa)	V (cm^3/g)	ρ (g/cm^3)	V/Vo	Exp	
2 785	5.209	0.000	0.000	.3591	2.785	1.000	ssp	×
2.784	5 811	.278	4.497	.3420	2.924	.952	iml	o
2 784	5.782	.279	4.491	.3419	2.925	.952	iml	o
2.784	6.021	.440	7.375	.3329	3.003	.927	iml	o
2.782	6.054	.472	7.950	.3314	3.017	.922	iml	o
2.785	6.025	.497	8.339	.3294	3.035	.918	spl	⊞
2.785	6 098	.502	8.525	.3295	3.035	.918	spl	⊞
2.784	5.996	.503	8.397	.3291	3.039	.916	iml	o
2.785	6.055	.507	8.550	.3290	3.040	.916	spl	⊞
2.783	5.947	.509	8.424	.3286	3.043	.914	iml	o
2.784	5.953	.509	8.436	.3285	3.044	.914	iml	o
2.785	6.125	.608	10.371	.3234	3.092	.901	iml	o
2.785	6.103	.609	10.351	.3232	3.094	.900	iml	o
2.782	6.262	.626	10.905	.3235	3.091	.900	iml	o
2 782	6.228	.627	10.864	.3233	3.093	.899	iml	o
2.784	6.226	.650	11.267	.3217	3.109	.896	iml	o
2.782	6.164	.671	11.506	.3203	3.122	.891	spl	⊞
2.782	6.277	.677	11.822	.3207	3.118	.892	iml	o
2.785	6.367	.722	12.803	.3183	3.141	.887	iml	o

(Continued)

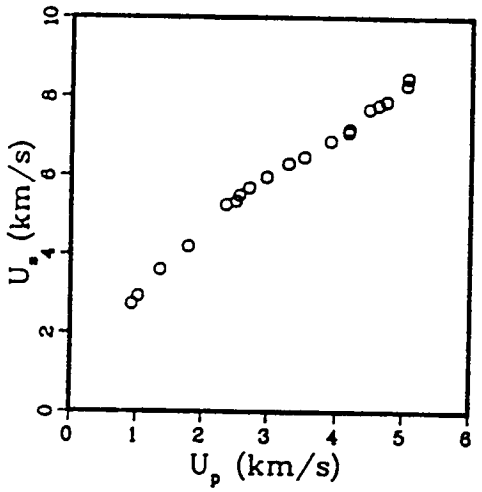


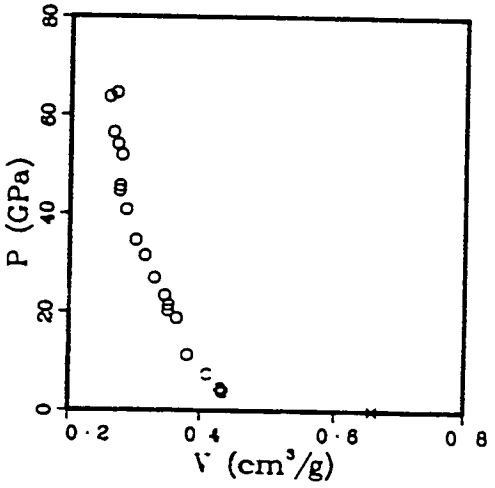


CARBON, fibers woven three-dimensionally

Average ρ_0 = 1.519 g/cm³.

ρ_0 (g/cm³)	U_s (km/s)	U_p (km/s)	P (GPa)	V (cm³/g)	ρ (g cm⁻³)	V/Vo	Exp
1.518	2.733	.924	3.833	.4360	2.293	.662	iml o
1.510	2.933	1.018	4.509	.4324	2.313	.653	iml o
1.520	3.608	1.353	7.420	.4112	2.432	.625	iml o
1.515	4.198	1.781	11.327	.3800	2.631	.576	iml o
1.518	5.264	2.361	18.866	.3633	2.753	.551	iml o
1.515	5.357	2.516	20.419	.3501	2.857	.530	iml o
1.524	5.505	2.563	21.503	.3507	2.852	.534	iml o
1.520	5.693	2.707	23.425	.3451	2.898	.525	iml o
1.527	5.965	2.968	27.034	.3290	3.039	.502	iml o
1.527	6.307	3.282	31.608	.3141	3.184	.480	iml o
1.528	6.472	3.509	34.701	.2996	3.338	.458	iml o
1.525	6.885	3.893	40.875	.2850	3.509	.435	iml o
1.512	7.110	4.159	44.711	.2745	3.643	.415	iml o
1.527	7.181	4.166	45.682	.2750	3.637	.420	iml o
1.511	7.695	4.467	51.938	.2776	3.602	.419	iml o
1.509	7.793	4.602	54.118	.2714	3.685	.409	iml o
1.518	7.887	4.720	56.510	.2645	3.780	.402	iml o
1.527	8.305	5.029	63.776	.2583	3.871	.394	iml o
1.509	8.486	5.041	64.552	.2690	3.717	.406	iml o





Appendix 4

Visar Measurement of the Kapton Flyer Speed

Late in this program, direct measurement of the Kapton flyer speed was made as a function of barrel length. These measurements were made with a "Visar" system that was already setup for use in other programs. These direct flyer-speed measurements superseded the earlier theoretical values.[16]

First, to orient the reader, we give a cursory description of what a Visar (Velocity Interferometer System for Any Reflector) apparatus is.[21] Roughly speaking a Visar is a Michelson interferometer than can determine the speed of an object by the Doppler shift of a laser beam reflected from the object's surface. This measurement is done by mixing the beam reflected from the moving surface with a reference beam reflected from the same surface a short time earlier. Figure A4-1 is the measured speed of a slapper flyer obtained from a Visar experiment; one curve on Fig. A4-1 is the measured speed and the second curve is the time-integrated speed, i.e., the flyer trajectory. The abscissa of Fig. A4-1 is the flyer's time of flight referred to an arbitrary time origin. The reader should note that to obtain the flyer's speed at a given barrel length, one draws a vertical line on the figure connecting that distance (as shown on the right ordinate) to the speed curve; then one can read the speed value from the left ordinate scale.

The results on Fig. A4-1 are for an assembly similar to that used at EMRTC in the high pressure/high temperature tests. Specifically, the Kapton flyer was 3-mil thick, the copper bridge was 3-mm square and 0.7-mil thick, the barrel was 120-mil long and 3-mm i.d., and the tamper was 10-mil thick stainless steel. The CDU was charged to 5.75 kV when the shot was fired.

Note the Visar record on the figure tracks the flyer trajectory for ca. 90 mils (2.25 mm). A second, nominally identical experiment, followed the flyer trajectory to greater than 3 mm (120 mils) and showed that for a barrel this long, speeds greater than 4.5 mm/μs were attained. This second experiment accurately reproduced the first one over their common data range (i.e., for less than ca. 2.25 mm of flight).

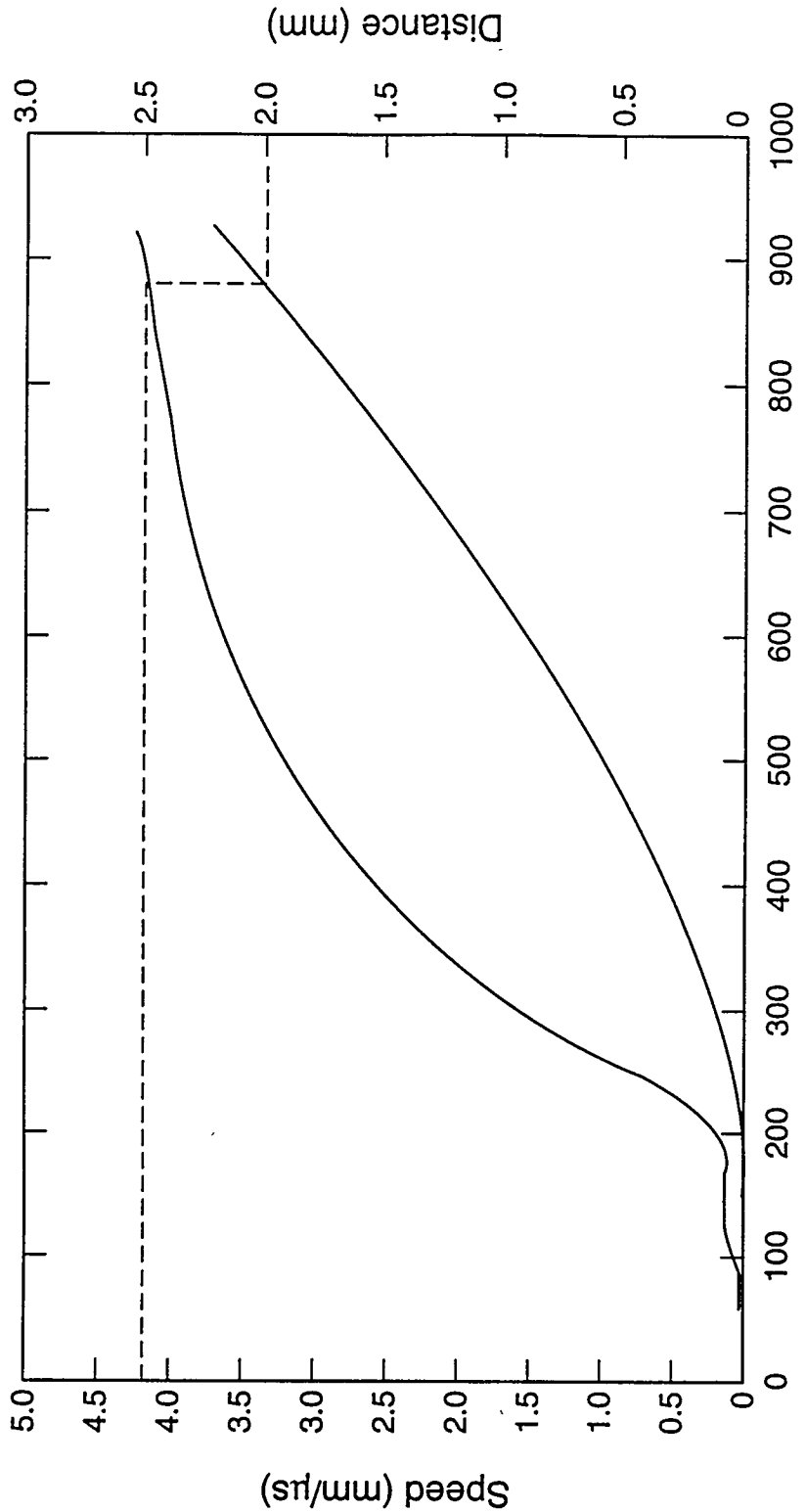


Figure A4-1. Experimental (Visar) record of the speed and position of a flyer as a function of time. The flight history displayed is for a slapper of the type used in the EMRTC experiments; the 12 μF CDU was charged to 5.75 kV in this shot.

These experiments showed three significant things: (1) the speed regime used in the impedance-match calculations of Sec. IV was correct (i.e., ca. 4 mm/μs), (2) the flyer speed history is highly reproducible and so, therefore, is the pressure input into the explosive mixture, and (3) higher flyer speed (and consequently, higher pressure in the explosive) can be achieved by using barrels longer than 60 mils.

References

1. (a) M. Malzhan (EES-4) and E. Fugelso (MEE-13), LANL, Private communication (1988), (b) G. A. Winbow, Geophysics, **56**, 1055 (1991).

2. E. H. Eyster, L. C. Smith, and S. R. Walton, U. S. Naval Ordnance Lab. Report. No. NOLM 10336, (1949).

3. R. Engelke, Phys. Fluids **23**, 875, (1980) and references therein.

4. B. N. Kondrikov, G. D. Kozak, V. M Raikova, and A. V. Starshinov, Dok. Akad. Nauk. SSSR **223**, 402 (1977) [Sov. Phys. Dokl. **223**, 315 (1977)].

5. S. A. Sheffield, R. Engelke, and R. R. Alcon, Proc. Ninth Symp. (Intl.) on Detonation, Office of Naval Research OCNR/#113291-7 Washington: US GPO, pp. 39-49 (1989).

6. F. E. Walker, Astronaut, Acta **6**, 807 (1979).

7. R. Engelke and S. A. Sheffield, *Ency. of Applied Phys.,* **6** p. 345, VCH Publishers, Inc. N.Y., (1993).

8. B. Dobratz and P. C. Crawford, *LLNL Explosives Handbook,* UCRL-52997, Livermore, CA: Lawrence Livermore National Laboratory, (1985).

9. R. Engelke, M7-QR-91-July, August, Sept, 1991, p. 19.

10. R. Engelke, M9-QR-89-4, pp. 26-27.

11. R. C. Weingart, R. S. Lee, R. K. Jackson, and N. L. Parker, Proc. Sixth Symp. (Intl.) on Detonation, ONR Symp. Report ACR-221 Washington: US GPO, pp. 653-663 (1976).

12. A. C. Schwarz, Sandia Laboratory Report SAND 75-0314, Dec. 1975.

13. R. Engelke, I. Garcia, and A. Kammerman, M9-QR-89-4, pp. 27-37.

14. M. B. Boslough and J. R. Asay, *High-Pressure Shock Compression of Solids*, pp. 7-42, Springer-Verlag, N.Y., (1993).

15. S. P. Marsh (ed.), *LASL Shock Hugoniot Data,* U. of CA. Press, Berkeley, CA., (1980).

16. Richard Yaktor, Group DX-10, LANL, Private communication, Oct., 1989.

17. R. Engelke and N. C. Blais, J. Chem. Phys. **101**, 10,901 (1994).

18. B. D. Tapley and T. R. Poston (eds.), *Eshbach's Handbook of Engineering Fundamentals,* J. Wiley and Sons, N.Y., (1990), pp. 16.138-16.139, Tables 16.77 and 16.78.

19. R. Engelke, I. Garcia, and A. Kammerman, M7-QR-93-1, pp. 7-17.

20. Kemlon Products and Development Co., Electrical Feedthru Division, Houston TX, 77021.

21. (a) L. M. Barker and R. E. Hollenbach, J. Appl. Phys. **43**, 4669 (1972); (b) W. F. Hemsing, Rev. Sci. Instrum. **50**, 73 (1979).

Table 1
Failure Diameter of NM vs Confinement[a,b]

Confinement Material	Failure Diameter (mm)	Acoustic Impedance[c]
Stainless Steel (304)	1.9±0.5	36.1
Brass (330)	2.3±0.8	31.5
Pyrex	16.2±0.4	8.7
Polyvinylchloride	22.3±1.6	2.7

[a]Unpublished LANL data obtained by R. Engelke.

[b]Firing temperatures in all cases were in the range 24±2° C.

[c]Acoustic impedance is the product of the mass density of a material and its sound speed ($\rho_o c$); units here are $(g/cm^3)(mm/\mu s)$.

Table 2

First Sensitized Nitromethane Slapper Initiation Experiments[a]

Expt. No.	Assembly No.	Firing Voltage (kV)	Composition[b] (wt%)	Flyer Thickness (mils)	Bridge[c] Width (mm)	Barrel Diam. (mm)	Confiner Material	Confiner I.D. (mm)	Confiner O.D. (mm)	Result
1[d]	1	9.00	95/5	1	3.2[e]	4.3	304SS	3.0	4.6	Failed
2	4	9.00	95/5	2	3.2	4.3	304SS	3.0	4.6	Detonated
3	5	7.00	95/5	2	3.2	4.3	304SS	3.0	4.6	Detonated
4	6	5.00	95/5	2	3.2	4.3	304SS	3.0	4.6	Detonated
5	7	8.10	95/5	2	6.4	8.7	PVC	5.1	10.4	Detonated
6	8	8.10	100	2	6.4	8.7	PVC	5.1	10.4	Failed
7	9	7.00	100	2	3.2	4.3	304SS	3.0	4.6	Failed
8	10	3.00	95/5	2	3.2	4.3	304SS	3.0	4.6	Detonated
9[d]	11	1.30	95/5	2	3.2	4.3	304SS	3.0	4.6	Failed
10[d]	12	2.00	95/5	2	3.2	4.3	304SS	3.0	4.6	Failed
11[d]	2	3.00	95/5	1	3.2[e]	4.3	304SS	3.0	4.6	Failed
12	13	4.00	95/5	2	3.2	2.9	304SS	3.0	4.6	Detonated
13	14	3.00	95/5	2	3.2	2.9	304SS	3.0	4.6	Failed
14	15	4.40	95/5	2	6.4	8.7	PVC	5.1	10.4	Failed
15	16	6.50	95/5	2	6.4	8.7	PVC	5.1	10.4	Detonated
16	17	5.45	95/5	2	6.4	8.7	PVC	5.1	10.4	Detonated
17	18	5.45	95/5	2	6.4	4.9	PVC	5.1	10.4	Detonated
18	19	5.05	95/5	2	6.4	4.9	PVC	5.1	10.4	Failed

[a]All experiments were fired with 31 mil long barrels and at 22±2° C.

[b]Composition indicates the relative weight of nitromethane and DETA.

[c]The copper bridge thickness was 0.7 mil, except where noted.

[d]The slapper assembly in this experiment did not burst properly.

[e]The copper bridge thickness was 0.2 mil.

Table 3
First Nitromethane Slapper Inititation Experiments with a Barrier in Place[a]

Expt. No.	Firing Voltage (kV)	Peak Current (kA)	Confinement Material/ID[b] (mm)	Flyer Thickness[c] (mils)	Barrel Diam./Length (mm/mils)	Bridge Width[d] (mm)	Barrier Type[e]	Result[f] (D/F)	Comments
19	ca. 4.7	–	304SS/3.0	2	4.3/31	3.0	A	F	CDU fired prematurely
20	7.7	–	304SS/3.0	2	4.3/31	3.0	A	F	
21	8.1	–	304SS/3.0	2	4.3/31	3.0	A	F	
22	8.0	–	PVC/5.1	2	8.7/31	6.0	A	F	Initiation incipient
-	ca. 8.5	–	PVC/5.1	2	8.7/31	6.0	A	F	Cable arced
24	5.5	–	304SS/3.0	2	4.3/31	3.0	none	D	~ reproduces expt. No. 4
25	7.5	55.4	304SS/3.0	3	4.3/31	3.0	B	D	
26	7.5	55.4	304SS/3.0	3	4.3/31	3.0	A	D	Compare with Expt. No. 20
27	6.5	52	304SS/3.0	3	4.3/31	3.0	A	D	
28	5.5	48.5	304SS/3.0	3	4.3/31	3.0	B	D	
29	7.5	69.4	PVC/5.1	2	8.7/31	6.0	Kapton	D	2.5-mil thick Kapton barrier

[a] Chemical composition in all the experiments was 95.0/5.0 wt% NM/DETA within 0.1 wt%.
[b] Confinement material (i.e., the explosive container) and its internal diameter.
[c] All flyers were Kapton.
[d] Copper bridge thickness was 0.7 mil in all cases.
[e] Here we define the type of carbon composite (CC) material used in the barrier between the barrel and the liquid explosive.
A=4 ply at angles ±45° and ±90°. The bonded CC was ca. 11 mils thick and had a 1 mil Mylar layer glued to it. The Mylar side was next to the liquid explosive.
B=2 ply at angles 0° and 90°. The bonded CC was ca. 11.5 mils thick and there was no Mylar present.
[f] D=detonated and F=failed.

Table 4
Further Slapper Initiation Experiments[a]

Expt. No.	Firing Voltage (kV)	Peak Current (kA)	Confinement Material/ID[b] (mm)	Flyer Thickness[c] (mils)	Barrel Diam./Length (mm/mils)	Bridge Width[d] (mm)	Barrier Type[e]	Result[f] (D/F)	Comments
30	8.0	93.1	–	5	8.7/31	6.0[g]	–	F	Slapper burst test
31	8.0	93.1	–	5	8.7/31	6.0[g]	–	F	Same as expt. No. 30
32	ca. 8.0	77.4	PVC/5.2	3	6.3/31	6.0	A	F	Initiation incipient
33	8.0	77.4	PVC/5.2	3	6.3/62	6.0	A	D	Assembly destroyed
34	7.0	71.1	PVC/5.2	3	6.3/62	6.0	A	F	Initiation incipient
35	8.3	71.1	PVC/5.2	3	6.3/31	6.0	A	F	Initiation incipient
36	8.0	58.3	PVC/5.2	3	6.3/31	3.0	A	D	Assembly destroyed
37	7.5	56.9	PVC/5.2	3	6.3/31	3.0	A	D	Assembly destroyed

[a] The chemical composition of the explosive was 95.0/5.0 wt% NM/DETA within 0.1 wt%.
[b] Confinement material (i.e., the explosive container) and its internal diameter.
[c] All flyers were Kapton.
[d] Copper bridge thickness was 0.7 mil, except where noted.
[e] Here we define the type of carbon composite (CC) material used for the barrier between the barrel and the liquid explosive. A=4 ply at angles ±45° and ±90°. The bonded CC was ca. 11 mils thick and had 1 mil of Mylar glued to it. The Mylar side was placed next to the liquid explosive.
[f] D=detonated and F=failed.
[g] Burst tests of a slapper system with a 5 mil flyer and a 1.4-mil thick copper bridge.

Table 5
Further Slapper Initiation Experiments[a]

Expt. No.	Firing Voltage (kV)	Peak Current (kA)	Confinement Material/ID[b] (mm)	Flyer Thickness[c] (mils)	Barrel Diam./Length (mm/mils)	Bridge Width[d] (mm)	Barrier Type[e]	Result[f] (D/F)	Comments
38	7.5	55.4	PVC/5.2	3	4.5/31	3.2	B	D	Assembly destroyed
39	6.0	46.0	PVC5.2	3	4.5/31	3.2	B	D	Assembly destroyed
40	5.0	42.1	PVC/5.2	3	4.5/62	3.2	B	D	Assembly destroyed
41	3.5	36.8	PVC/5.2	3	4.5/62	3.2	B	F	Glue joints broken
42	7.5	54.2	Teflon/5.3	3	4.5/64	3.2	B	D	2.5-mil thick Teflon
43	5.5	49.3	Teflon/5.3	3	4.5/64	3.2	B	D	Assembly destroyed
44	5.0	42.8	Teflon/5.3	3	4.5/64	3.2	B	D	Assembly destroyed
45	4.5	41.3	Teflon/5.3	3	4.5/64	3.2	B	F	Glue joints broken
46	5.0	44.8	Teflon/5.3	3	4.5/64	3.2	B	D	Reproduces Expt. No. 44
47	4.75	44.0	Teflon/5.3	3	4.5/64	3.2	B	D	Assembly destroyed

[a] The chemical composition of the explosive was 95.0/5.0 wt% for these experiments.
[b] Confinement material (i.e., the explosive container) and its internal diameter.
[c] All flyers were Kapton.
[d] Copper bridge thickness was 0.7 mil in all cases.
[e] Here we define the type of carbon composite (CC) material used for the barrier between the barrel and the liquid explosive. B=2 ply at angles 0° and 90°. The bonded CC was ca. 11.5 mils thick and no Mylar was present.
[f] D=detonated and F=failed.

Table 6
Barrier Burst Pressure Test Summary

Test	Material	Thickness (inches)	Aperture Diameter (inches)	Burst (psig)
1	Stainless Steel	0.010	0.180	7160
2	Aluminum	0.010	0.180	2146
3	Aluminum	0.010	0.180	2110
4	P1 = 4-Ply Woven Carbon Composite 0°, 90°, +45°, -45° with 1 mil Mylar	0.011	0.180	650
5		0.011	0.180	N/R
6		0.011	0.180	2422
7		0.011	0.180	1253
8		0.011	0.180	2236
9		0.011	0.180	3759
10		0.011	0.180	3753
11	2 Layers P1	0.024	0.180	4230
12	2 Layers P1	0.024	0.180	7878
13	3 Layers P1	0.040	0.180	11250
17	P3 = 3-Ply Carbon Composite 0°, 120°, 240°	0.0175	0.180	11458
18		0.017	0.180	12406
19		0.0172	0.240	9344
20	P1	0.011	0.180	N/R
21	P1	0.011	0.180	4279
22	P1	0.011	0.240	2914
23	Stainless Steel	0.010	0.180	23065
24	Stainless Steel	0.010	0.180	N/R
25	P1	0.011	0.240	3013
26	P1	0.011	0.240	2293
27	P4 = 2-Ply Carbon Composite 0°, 90°	0.0113	0.240	7220
28		0.0113	0.240	8601
29	P5 = 2-Ply Woven, 1/4" Strips	0.010	0.240	7274

Table 7

Preliminary Tests at LANL in Preparation for High Temperature/High Pressure Tests

Expt. No.	Comp.	Firing Voltage (kV)	Result	Comments
48	None	5.5	Good	These tests each used a slapper/barrel/aluminum plate assembly. Both were fired under water to evaluate mechanical and electrical slapper performance.
49	None	8.0	Good	
50	Mix	5.0	Detonate	Slapper/explosive assembly submerged in water.
51	Mix	4.75	Fail	Same as No. 50, lower voltage.
52	None	5.0	–	This was standard system evaluation test (ring down) in which the CDU is fired into a dead short and current measured. This test was done to establish a base-line current for evaluating feed thru performance. Current ≅ 63kA.
53	None	5.0	Poor	Thru shorted feedthru - insufficient current ≅ 31kA.
54	None	5.0	Poor	Thru shorted feedthru - improved but low current ≅ 38kA.
55	None	5.0	–	Repeat No. 54 by firing slapper - debris indicated normal operation - current ≅ 33kA.
56	Mix	5.0	Fail	Repeat No. 55 with complete explosive assembly. Slapper did not initiate NM - current unknown.
57	None	5.0	Good	Modified/improved feedthru fired into short - current ≅ 52kA.
58	None	5.0	–	Fired folded slapper thru feedthru - current ≅ 31kA.
59	None	5.0	–	Fired unfolded slapper thru feedthru - current ≅ 33kA.
60	None	5.0	–	Repeat No. 58 - current ≅ 35kA.
61	None	5.0	–	Repeat No. 60 - current ≅ 36kA.
62	Mix	7.5	Detonate	Thru feedthru in air - folded slapper - current ≅ 50 kA.
63	Mix	6.5	Detonate	Thru feedthru in air - folded slapper - NM in Teflon tubing - current ≅ 44kA.
64	Mix	6.5	Detonate	Repeat No. 63 except slapper looped - current ≅ 41 kA.

Note: The above experiments No. 48 thru No. 64 used the following hardware as appropriate:
Slapper – 3 mils thick Kapton, 0.7 mils thick copper, 125 mils square bridge; barrel – 62 mils long x 200 to 250 mils inside diameter; barrier – two layer CC, 0°-90°, 11 mils thick; mix confinement through No. 62 – Teflon "baggie" 210 mils ID, 1.5 mils wall thickness, silicone rubber septa; mix confinement No. 63 and No. 64 – Teflon tube 250 mils ID, 32 mils wall, covered with polyethylene cap. Mix refers in all cases to a 95/5 wt% NM/DETA mixture. Mass of NM/DETA for each experiment is approximately 0.5 grams.

Table 8
LANL Tests in Temperature/Pressure Chamber

Expt. No.	Comp.	Firing Voltage (kV)	Result	Comments
65	Mix	6.5	Detonate	First test in pressure chamber - filled with distilled water.
66	Mix	6.0	Detonate	Same as No. 65, reduced voltage.
67	Mix	5.5	Detonate	Same as No. 66, reduced voltage.
68	Water	6.0	–	Control experiment to ensure previous tests detonated – used "dirty" water in chamber from previous test.
69	Mix	5.5	Detonate	Same as No. 67.
70	Mix	5.0	Fail	Establishing lower voltage limit for reliable initiation in chamber.
71	Mix	5.25	Detonate	Voltage increment between No. 69 and No. 70.
72	Mix	5.0	Fail	Attempt to reproduce No. 70 - failure due to feedthru assembly high voltage breakdown. Internal, individual feedthrus cracked by shock after five detonations.
73	Mix	5.5	Detonate	Feedthru rebuilt and hardened - slapper loop reversed to start shock wave away from feedthru.
74	Mix	5.5	Fail	Feedthru damaged in test No. 73. Hi pot testing after each firing started.
75	Mix	5.5	Detonate	3 rubber mounted steel baffle plates added between feedthru and explosive assembly. Feedthru damaged. (As a result of adding the baffle plates, all tests from No. 75 on used a flat conductor "extension cord" between feedthru and slapper.)
76	Mix	5.5	Detonate	Modified feedthru - explosive assembly "aimed" toward side of chamber. Feedthru damaged.
77	Mix	5.5	Detonate	Feedthru assembly redesigned and rebuilt to "soften" area around individual feedthrus. Feedthru assembly survived.
78	Mix	5.5	Detonate	Repeat No. 77, feedthru assembly survived.
79	Mix	5.5	Fail	High voltage cable breakdown, external to chamber.
80	Mix	5.5	Detonate	Repeat tests No. 77 and 78 to evaluate feedthru. Feedthru survived these four detonations, but was damaged due to application of excessive voltage during hi pot testing after test #83.
81	Mix	5.5	Detonate	
82	Mix	5.5	Detonate	
83	Mix	5.5	Detonate	

Table 8 (continued)
LANL Tests in Temperature/Pressure Chamber

Expt. No.	Comp.	Firing Voltage (kV)	Result	Comments
84	Mix	5.5	Detonate	Feedthru identical to tests No. 80 thru 83 with new individual feedthrus installed.
85	Mix	5.5	Detonate	Repeats test No. 84 to evaluate feedthru assembly – no damage detected.
86	Mix	5.5	Detonate	
87	Mix	5.5	Detonate	
88	Mix	5.5	Detonate	
89	Mix	5.5	Detonate	
90	Mix	5.5	Fail	Inspection of debris and current pulse indicated proper operation of slapper. Mix was apparently diluted by a water leak.
91	Mix	5.5	Detonate	Feedthru in "as new" condition following seven detonations.

Note: The above experiments No. 65 thru No. 91 used the following hardware as appropriate:
Slapper – 3 mils thick Kapton, 0.7 mils thick copper, 125 mils square bridge; barrel – 62 mils long x 200 to 250 mils inside diameter, barrier – two layer CC, 0°-90°, 11 mils thick; mix confinement – Teflon tube 250 mils ID, 32 mils wall, covered with polyethylene cap. Mix refers in all cases to a 95/5 wt% NM/DETA mixture. Mass of NM/DETA for each experiment is approximately 0.5 grams.

Table 9
EMRTC Temperature/Pressure Test Summary

Expt. No.	Comp	Firing Voltage (kV)	Pressure/ Media	Temp (°C)	Barrel Length/Material (see Note1)	Result	Comments
S1	Mix	5.75	Amb. Air	Amb.	70	Fail	Slapper/ext. cord joint failed, allowing HV breakdown.
S2	Mix	5.75	Amb. Air	Amb.	70	Detonate	Repeats No. S1.
S3	Mix	5.75	Amb. H_2O	Amb.	70	Fail	Slapper/ext. cord joint failed, allowing HV breakdown.
S4	Mix	5.75	Amb. H_2O	Amb.	70	Detonate	Repeats No. S3.
S5	Mix	5.50	Amb. H_2O	Amb.	70	Fail	Lower voltage apparently resulted in failure. Debris inspection indicated good slapper operation.
S6	Mix	5.75	Amb. H_2O	Amb.	70	Detonate	Repeat No. S5 at 5.75 kV.
S7	Mix	5.75	4000 H_2O	Amb.	70	Fail	Slapper operation appears to be substandard.
S8	None	5.75	4000 H_2O	Amb.	70	Poor	Slapper/barrel/barrier assembly only. Debris inspection shows marginal operation.
S9	None	5.75	Amb. H_2O	Amb.	70	OK	Repeats No. S8 at Amb. pressure - operation appears normal.
S10	Mix	5.75	1000 H_2O	Amb.	70	Fail	Barrier damage marginal.
S11	Mix	5.75	Amb. H_2O	Amb.	70	Detonate	Repeats No. S4 - reality check.
S12	Mix	5.75	500 H_2O	Amb.	70	Detonate	
S13	Mix	5.75	1000 H_2O	Amb.	70	Fail	Extension cord failed - HV breakdown.
S14	Mix	5.75	1000 H_2O	Amb.	70	Detonate	
S15	Mix	5.75	2000 H_2O	Amb.	70	Fail	NM/DETA was cloudy prior to test.
S16	Mix	5.75	2000 H_2O	Amb.	70	Fail	Repeats No. S15
S18	Ink	–	3000 H_2O	Amb.	70	Fail	Ink leaking at barrier/explosive interface.
S19	Ink	–	4000 H_2O	Amb.	70	Fail	Explosive tube separated from barrier. Barrier dimpled.
S20	Ink	–	5000 H_2O	Amb.	70	Fail	Explosive tube separated from barrier. Barrier dimpled.

Table 9 (continued)
EMRTC Temperature/Pressure Test Summary

Expt. No.	Comp.	Firing Voltage (kV)	Pressure/ Media	Temp (°C)	Barrel Length/Material (see Note1)	Result	Comments
S25	Ink	–	3000 H_2O	Amb.	120R	Good	No leaks of ink charge after pressure.
S26	Ink	–	3000 H_2O	Amb.	120R	Good	No leaks of ink charge after pressure.
S25R	Mix	5.75	1000 H_2O	Amb.	120R	Detonate	Units from No. S25 and S26 were cleaned, dried and refilled with explosive after being pressurized to 3000 psi.
S26R	Mix	5.75	2000 H_2O	Amb.	120R	Detonate	
S27	Mix	5.75	Amb. H_2O	54	70	Detonate	
S28	Mix	5.75	Amb. H_2O	56	70	Detonate	
S29	Mix	5.75	Amb. H_2O	82	105M/R	Fail	Charge at 85°C for 15 minutes before firing.
S30	Mix	5.75	Amb. H_2O	88	109M/R	Detonate	3 minutes at 90°C.
S31	Mix	5.75	Amb. H_2O	89	114M/R	Detonate	
S35	Mix	5.75	3200 H_2O	Amb.	120M/R	Fail	Pre-pressurized with ink charge to 6500 psi - no leakage
S36	Mix	5.75	3200 H_2O	Amb.	156M/R	Fail	Pre-pressurized with ink charge to 6500 psi - no leakage
S37	Mix	5.75	3200 H_2O	Amb.	120M/R	Fail	No pre-pressure.
S38	Mix	5.75	2000 H_2O	Amb.	122M/R	Fail	Cable breakdown failure. Dissass. .oly found water in barrel.
S39	Mix	5.75	2000 H_2O	Amb.	122M/R	Fail	
S40	Mix	5.75	Amb. H_2O	Amb.	122M/R	Detonate	Reality check.
S44	Mix	5.75	500 H_2O	Amb.	120M/R	Fail	
S45	Mix	5.75	500 H_2O	Amb.	130R	Fail	
S46	Mix	5.75	Amb. H_2O	Amb.	130R	Detonate	
S47	Mix	5.75	200 EG	99	150M/R	Fail	Attempted 120°C shot. 9 minutes install to shot. Red poly cap in small ball.

Table 9 (continued)
EMRTC Temperature/Pressure Test Summary

Expt. No.	Comp.	Firing Voltage (kV)	Pressure/ Media	Temp (°C)	Barrel Length/Material (see Note 1)	Result	Comments
S48	Mix	5.75	200 EG	70	154M/R	Detonate	Attempted 120°C shot. Circulation system failed.
S49	Mix	5.75	200 EG	111	157M/R	Fail	Debris indicated proper slapper operation.
S50	Mix	5.75	200 EG	106	120R	Fail	Polyethylene cap again found in ball.
S51	Mix	5.75	200 EG	112	119R	Detonate	Aluminum cap used on tests No. S51 thru No. S60.
S52	Mix	5.75	200 EG	120	121R	Fail	Pressure may have dropped low enough for NM to boil.
S53	Mix	5.75	200 EG	121	153M/R	Detonate	
S54	Mix	5.75	200 EG	114	154M/R	Fail	Extension cord breakdown.
S55	Mix	5.75	200 EG	116	156M/R	Fail	
S56	Mix	5.75	200 EG	120	156M/R	Fail	Feedthru found to be degraded. Also affected test S55.
S57	Mix	5.75	200 EG	117	156M/R	Fail	Extension cord failure.
S58	Mix	5.75	200 EG	118	157M/R	Detonate	
S59	Mix	5.75	200 EG	119	159M/R	Fail	Extension cord failure.
S60	Mix	5.75	200 EG	123	157M/R	Detonate	

1. All 70-mil barrels are single-layer Viton. Numbers followed by "R" indicate 2-layer Viton; M/R indicates 1-layer metal, 1-layer Viton.
2. Media used were tap water (H_2O) or ethylene glycol (EG).
3. The above experiments used the following hardware: Slapper – 3 mils thick Kapton, 0.7 mils thick copper, 125 mils square bridge; barrel – 62 mils long x 200 to 250 mils insidediameter; barrier – two layer CC, 0°-90°, 11 mils thick; mix confinement – Teflon tube 250 mils ID, 32 mils wall thickness, covered with polyethylene cap, except experiment No. S51 thru S60 covered with aluminum caps. Mix refers in all cases to a 95/5 wt% NM/DETA mixture. Mass of NM/DETA for each experiment is approximately 0.5 grams.
4. Ambient temperature was in the range of 20° C to 38° C depending on the time of day and season.

Table 10
EMRTC Deflection Test Results

Expt. No.	Barrel Length and Materials	Deflection to Indication (mils)	Comments
S17	70 Viton	10	Indication not readable. Barrier deformed on conductive cone.
S21	70 Viton	4	Switch closure at 400 psig, barrier punctured by cone at 2700 psig.
S22	70 Viton	20	Switch closure at 900 psig - at 3000 psig assembly leaked.
S23	70 Viton	26	Switch closure at 1500 psig - pressurized to 6500 psgi with no damage or water inside.
S24	70 Viton	27	Switch closure at 1800 psig - no damage or leakage to 6500 psig.
S32	130 M/V	20	Indent in clay - no water inside.
S33	130 M/V	35	No indent in clay - water inside.
S34	130 M/V	50	No indent in clay - no water inside.
S41	130 V/V	20	No indent in clay, slight convex shape to clay indicating total compression, water inside.
S42	130 V/V	35	Large indent in clay, no water inside.
S43	130 V/V	50	Small indent in clay, water inside.

Note: 1. Tests S32 - S34 and S41 - S43 pressurized to 6500 psig and inspected.
2. 130 mils barrels were made of two layers, 65 mils thick metal and 65 mils thick Viton (M/V) or two each 65 mils thick Viton (V/V).

Table 11
EMRTC Temperature/Pressure Test Matrix

	Temperature			
Pressure	Ambient	60° C	90° C	120° C
Ambient Air	1	2	3	x
Ambient Water	4	5	6	x
200 psig	7	8	9	10
1600 psig	11	15	19	23
3200 psig	12	16	20	24
4800 psig	13	17	21	25
6400 psig	14	18	22	26

Numbers indicate test sequence.