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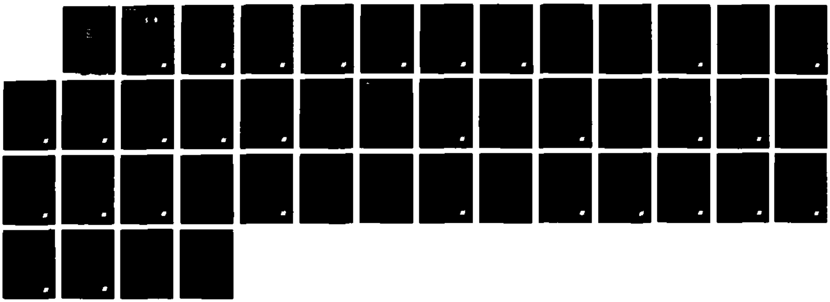

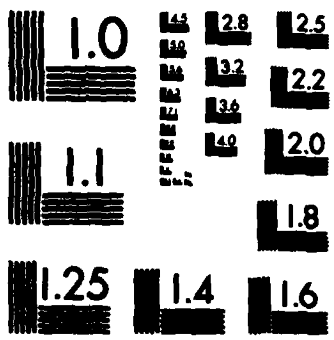

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GC-TR-84-402

SOFT IGNITION SYSTEM

SELF-CONTAINED MUNITIONS

PREPARED FOR

U.S. DEPARTMENT OF THE ARMY

ARMAMENT RESEARCH & DEVELOPMENT CENTER

U.S. ARMY ARMAMENT, MUNITIONS & CHEMICAL COMMAND

DOVER, NEW JERSEY 07801

CONTRACT NO. DAAK10-84-C-0032

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TECHNICAL ABSTRACT

Phase I of the research and development of a soft ignition system for self-contained and sensitive munitions has been completed. The principles of the proposed ignition system have been defined and studied and are based on a laser/fiber optic (LFO) sub-system to achieve simultaneous multiple point ignition at several axial and radial positions within the propelling charge. Effective designs for laser sensitive primers have been developed and demonstrated. Ignition delay and the resultant jitter have been measured as a function of such variables as igniter mass and case material, etc. The resultant ignition delay of these designs has been determined to be largely a function of confinement and case material specifications. The minimum ignition delay measured was 120 μS and ignition jitter can be reduced to two percent (2%) by judicious application of the information derived from the present effort. The effort to date has demonstrated that the degree of simultaneity will be ultimately limited by the uniformity of the manufacturing process and the materials employed. The designs developed and demonstrated in this work define the basic primer performance and the intrinsic delay.

EXECUTIVE SUMMARY

New munitions development of the Department of Defense depends heavily on a variety of sophisticated target acquisition and projectile guidance systems to deliver the warhead to its target. To provide as smooth an acceleration up the gun tube as possible so that the effectiveness of the projectile is not compromised, it has become increasingly necessary to minimize undesirable loads on the projectile during launch.

Pressure waves formed during the ignition sequence of a granular propellant bed have been shown to be partially responsible for variable projectile velocity and damage to certain types of sensitive projectiles. For conventional center-core primer tubes with single end ignition, the formation of these undesirable pressure waves has been shown to result directly from the high pressure region behind the ignition front as it propagates down the primer tube. Despite numerous investigations, it appears that achievement of uniform radial flamespread with rapid axial propagation is difficult to achieve with conventional pyrotechnics and designs.

An alternative approach requires ignition of the propellant bed at several points simultaneously. Although some limited experimentation and preliminary design has been completed using conventional electrically initiated pyrotechnics, it is doubtful that acceptable jitter and, hence, degree of simultaneity can be achieved with a reasonable safety margin. The use of laser energy coupled to the igniter through a network of fiber optics offers a new approach of accomplishing simultaneous multiple point ignition safely.

Phase I of the preliminary research and development of a soft ignition system for self-contained and sensitive munitions has been completed. The basic principles of the proposed ignition system have been defined and studied. The proposed ignition approach, based on a laser/fiber optic (LFO) system to achieve simultaneous multiple point ignition at several axial and radial positions within the propelling charge, has been demonstrated within the limits of the Phase I effort.

A pyrotechnic ignition train comprised of three stages is employed to accomplish propellant ignition. A laser-sensitive material is enclosed and confined as Stage 1. An intermediate igniter material is enclosed in a second case and forms the Stage 2 ignition event. Figure 1 schematically illustrates both Stages 1 and 2 of the LFO concept. The interface between this stage and the propellant bed forms Stage 3 which is shown in Figure 2 in two possible configurations. Figure 2(a) shows the center-core LFO configuration and Figure 2(b) shows the alternative to the center-core primer approach.

Experimental determination of ignition delay and jitter of the Stage 1 design was conducted with the experimental variables shown in Table 1 in a closed bomb.

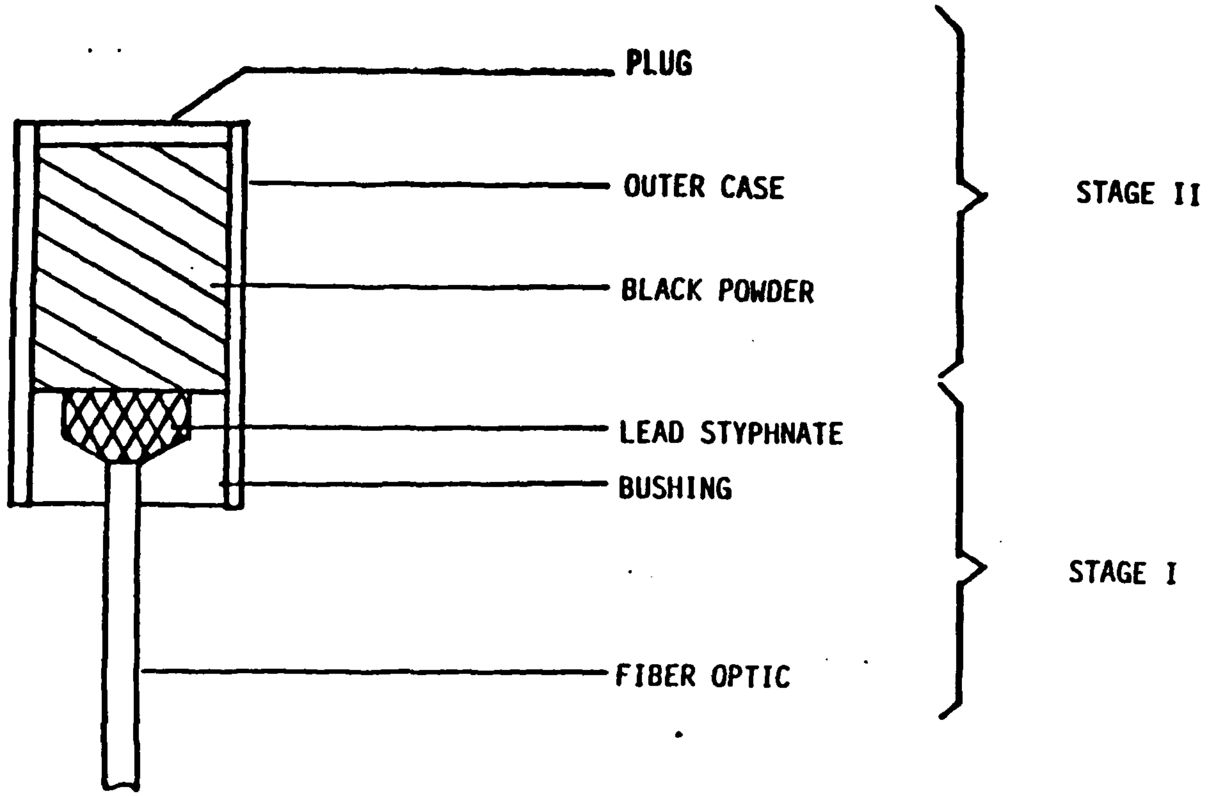


Figure 1. Ignition Stages I and II of LFO Concept.

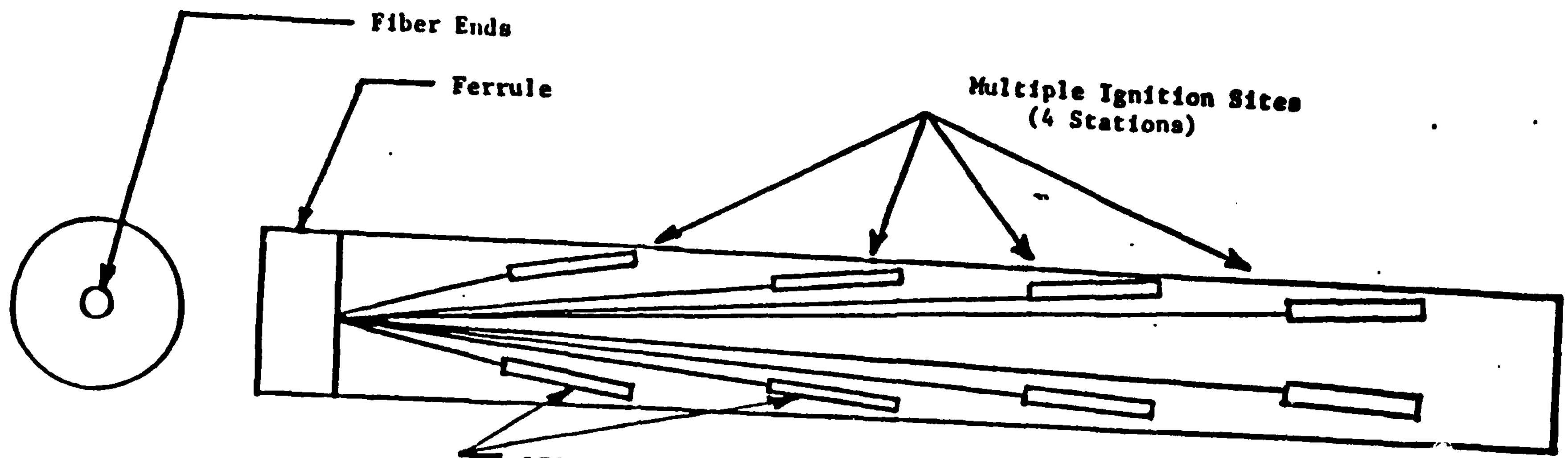


Figure 2(a). Revised LFO Concept for Center-Core Igniter Tube.

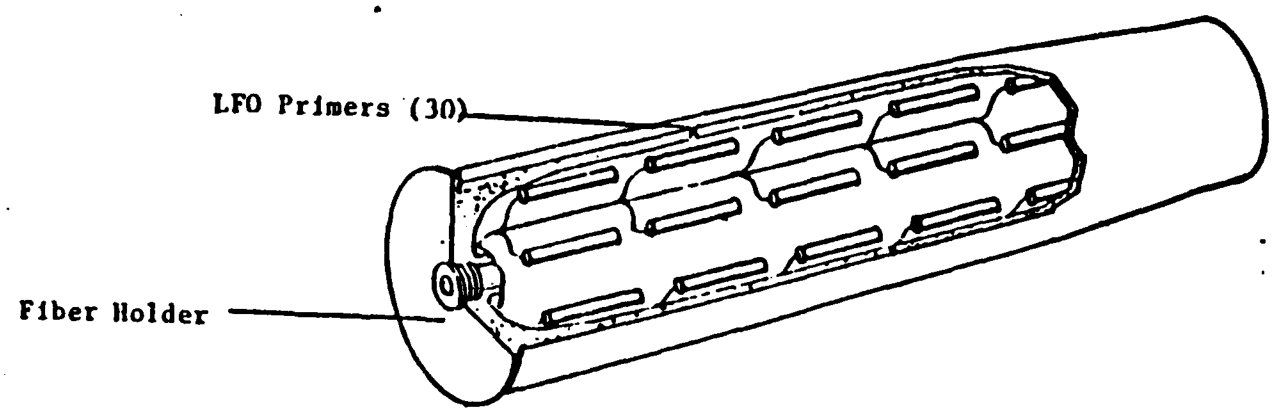


Figure 2(b). LFO Concept for 105 mm Cartridge.

TABLE 1 - LFO STAGE 1 AND GEOMETRIC VARIABLES

Design Number	Hole Diameter (inches)	Volume (cc)	Lead Styphnate Mass(mg)
1	0.050	0.0022	6.0
2	0.060	0.0028	8.4
3	0.077	0.0050	15.1
4	0.088	0.0067	20.1
5	0.109	0.0100	30.0

Figure 3 shows the results of these tests. These refined Stage 1 designs perform much better than earlier designs as the ignition delay and the subsequent jitter are reduced more than an order of magnitude. Based on these and other supporting data, configuration 4 (mass = 20 mg, bushing volume = 0.0067 cc) has been selected for further experimentation and development. As is shown in Figure 3, the casing of the primers were constructed with either polypropylene, copper, polycarbonate, or cloth-filled phenolic tubing and tests have been completed to evaluate these variables. The resultant ignition delay of these designs has been determined to be largely a function of Stage 2 confinement and, hence, case material specifications.

Although full-scale prototype demonstration testing is planned for the Phase II effort, the proof-of-principle testing has been completed during this phase as planned. The research and development of this effort have unequivocally demonstrated that the degree of simultaneity will be ultimately limited by

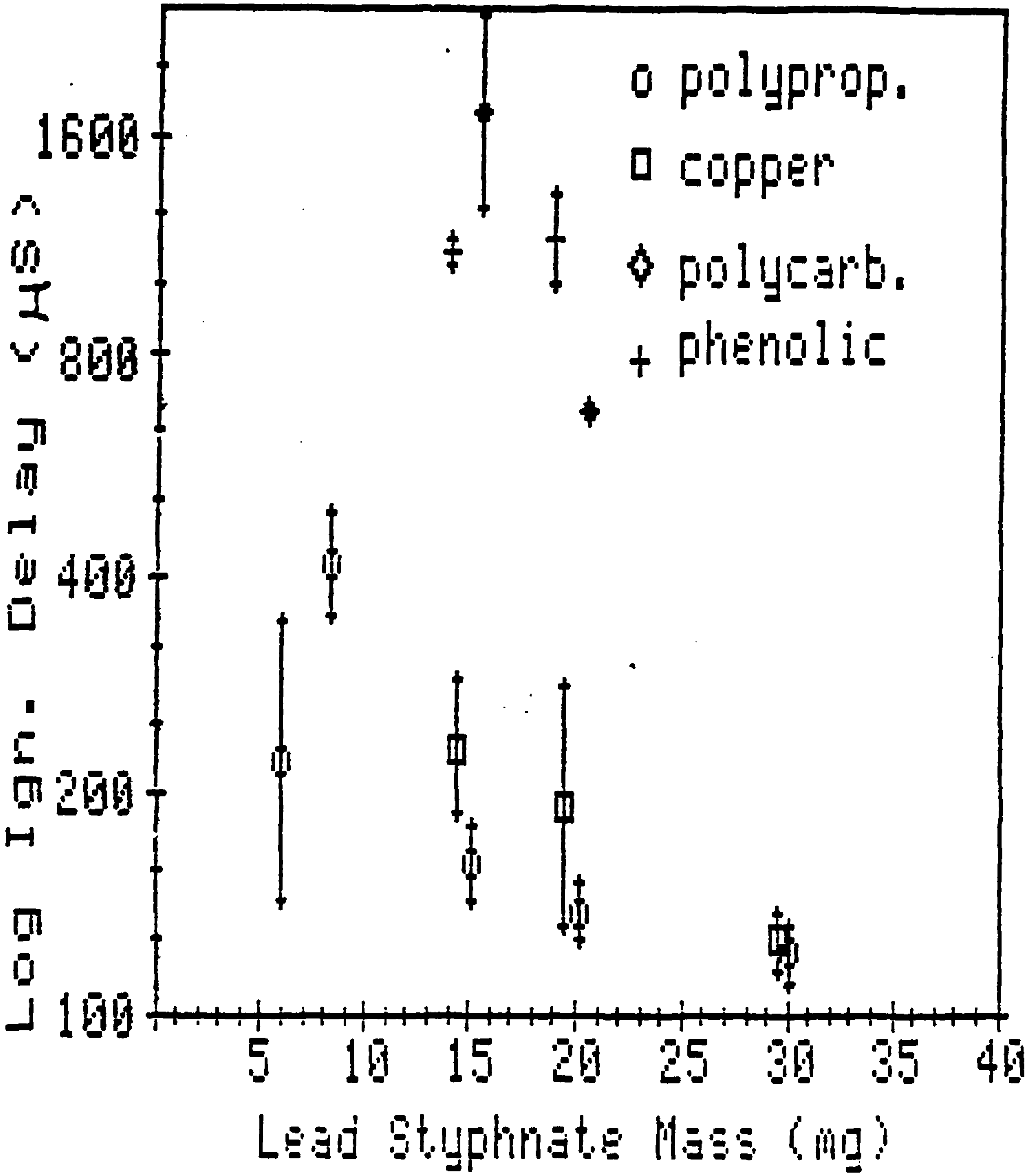


Figure 7. Ignition Delay as a Function of Stage 1 Mass.

the uniformity of the manufacturing process and the materials employed. The Stage 1 and 2 designed developed and demonstrated in this work define the basic primer performance and instrinsic delay.

The results of this investigation may be summarized as follows:

1. The maximum practical energy capable of being coupled into conventional material fiber optics is 4.5 J in a pulse lasting up to about 1 mS. Although this energy is in excess of the requirement for lead styphnate ignition, the possibility exists for development of direct ignition.

2. Lead styphnate is a reasonable Stage 1 material as it exhibits reproducible ignition provided a degree of confinement is provided.

3. A design of attaching lead styphnate to fiber optics has been developed and evaluated as Stage 1.

4. Stage 2 ignition delay and the resultant jitter have been measured as functions of design variables such as Stage 1 mass and case material, etc. The resultant ignition delay of these designs has been determined to be largely a function of Stage 2 confinement and, hence, case material specifications. The minimum ignition delay measured was 120 μS and ignition jitter can be reduced to two percent (2%) by judicious application of the information derived from the present effort.

The conclusions of this effort verify the original projection that designs for laser/fiber optic (LFO) multiple point ignition schemes are possible and within the limits of existing technology. Preliminary designs for Stages 1 and 2 of the LFO approach have been demonstrated in a laboratory environment and continued evaluations of Stage 3 are required to further demonstrate and validate the approach.

BACKGROUND

The Department of Defense has begun new initiatives to explore advanced launch mechanisms for use with self-contained munitions and other indirect fire "smart" projectiles. These new munitions will depend heavily on a variety of sophisticated target acquisition and projectile guidance systems to deliver the warhead to its target and must be designed to be rugged enough to survive launch. Thus, it is necessary to minimize undesirable loads on the projectile during launch and provide as smooth an acceleration up the gun tube as possible so that the effectiveness of the projectile is not compromised. Parallel developments with modular charge designs have identified other difficulties with conventional ignition approaches as well.

Pressure waves formed during the ignition sequence of a granular propellant bed have been shown to be partially responsible for variable projectile velocity. Damage to certain types of sensitive projectiles has also been attributed to this variable ignition. For conventional center-core primer tubes with single-end ignition, the formation of these undesirable pressure waves has been shown to result directly from the high pressure region behind the ignition front as it propagates down the primer tube.[1] Investigations of alternate ignition approaches have been undertaken to explore alternate ignition approaches with varying degrees of success. Rapid Ignition Propagation (RIP) primers which utilize fast burning pyrotechnics or similar materials to produce extremely fast ignition fronts have been effectively used to produce ignition fronts nearly twenty times faster than standard primer assemblies. The results of these experiments, while not yet conclusive, have suggested that failure to consistently produce uniform radial flamespread in conjunction with rapid axial flamespread can lead to extreme pressure wave formation which can have catastrophic results. It appears that uniform radial flamespread with rapid axial propagation is difficult to achieve with conventional pyrotechnics and designs.

For these reasons, an alternative design which avoids the problems associated with primers which depend on fast propagation of deflagration waves is required. One such alternative concept requires ignition of the primer or propellant bed at several points simultaneously. Although some limited experimentation and design thought have been completed using conventional electrically initiated pyrotechnics, it is doubtful that acceptable jitter and, hence, degree of simultaneity can be achieved. In addition, the added safety problems introduced by the inclusion of a large number of electric circuits imbedded in sensitive pyrotechnic materials does not encourage further development of this approach.

The use of laser energy coupled to the igniter through a network of fiber optics offers a new approach of accomplishing simultaneous multiple point ignition safely. In addition to allowing all electrical components to be located far from the gun and associated hazards, laser ignition has several other potential advantages over conventional ignition systems for large caliber guns. Among these are reduced and more repeatable ignition delay, insensitivity to stray electrical and RF energy, and greater reliability. The potential for designs applicable to modular charges exists as the number of ignition sites can be easily adjusted as the number of popellant charges dictate.

OJECTIVES OF THE PHASE I WORK

The basic technical objective of the Phase I effort was to develop an ignition concept which would provide the technology required to produce simultaneous ignition at several points within an igniter material or propellant bed. The concept, based on a laser/fiber optic (LFO) scheme, is envisioned to replace a conventional center-core primer tube or omit the center-core concept altogether. The Phase I technical effort is complete and the experimentation conducted to date has demonstrated that multiple point ignition is not only possible, but is indeed capable of being produced within the limits of currently available technology.

Fortuitously, between the time the original proposal was submitted and the Phase I award was made, Geo-Centers, Inc. completed work on a different but technically related project. Due to the high degree of success obtained, we were encouraged by the Army to apply what was learned towards our concept for soft ignition. Thus, the originally proposed Tasks 1-3 were modified slightly and two more tasks were added. As a result, the Statement of Work was amended and changed to:

1. Design a system of attaching laser sensitive igniter materials to 200, 600 and 1000 micron fiber optics, e.g., Stage 1.

2. Verify ignition delay and jitter of Stage 1 ignition as a function of laser-sensitive igniter material mass. Tests performed will utilize a closed bomb with optical access and a pressure transducer.

3. Design a Stage 2 interface with a combustible container and/or vent holes. Investigate performance of small designs configurations, e.g., 100, 500 and 1000 mg of black powder and/or similar materials. Compare performance of several different container designs and volumes.

4. Document the ignition event of Stage 2 with high speed framing and/or shadowgraphic photography. Quantify ignition delay and jitter of designs from Task 3.

5. Depending on the results of Task 4, assemble and test multiple zone center-core LFO primer assemblies. Tests will be designed to establish the degree of simultaneity, reliability and repeatability of the ignition event.

6. Prepare a final report which will include a summary of all tests performed, analysis of the results, and conclusions reached.

The design of the original Phase I concept, shown in Figure 1, was predicated on the ability to ignite conventional igniter materials (e.g., black powder, $BKNO_3$, etc.) directly with laser energy. Limited experimentation has been conducted with direct initiation of black powder and the results are summarized in Figure 2. These data and the data of reference 2 suggest that although direct ignition is possible, significant laser intensities are required to provide a reliable ignition stimulus.

Although considerable experimentation has been conducted in recent years to elucidate the mechanism of laser ignition, most research has concluded that the mechanism is a thermal one.

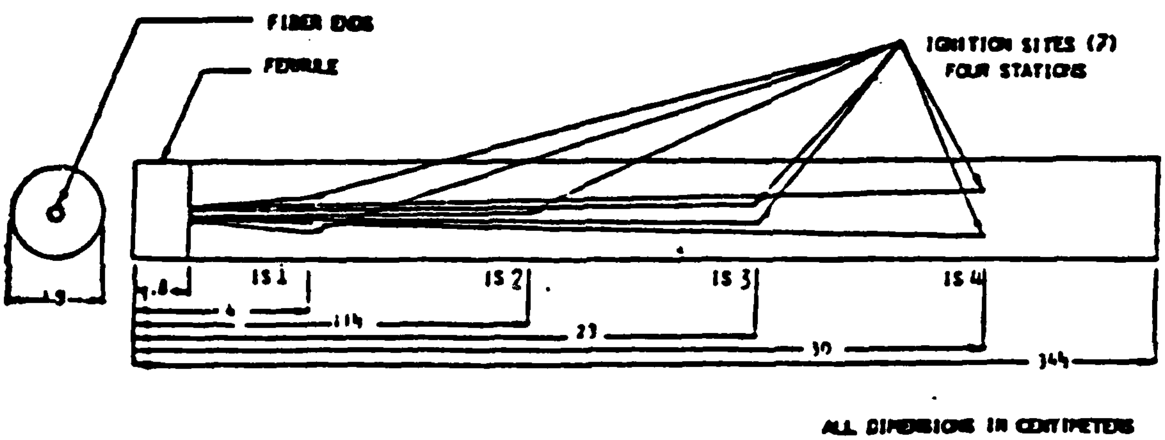


Figure 1. LFO Center-Core Igniter Tube.

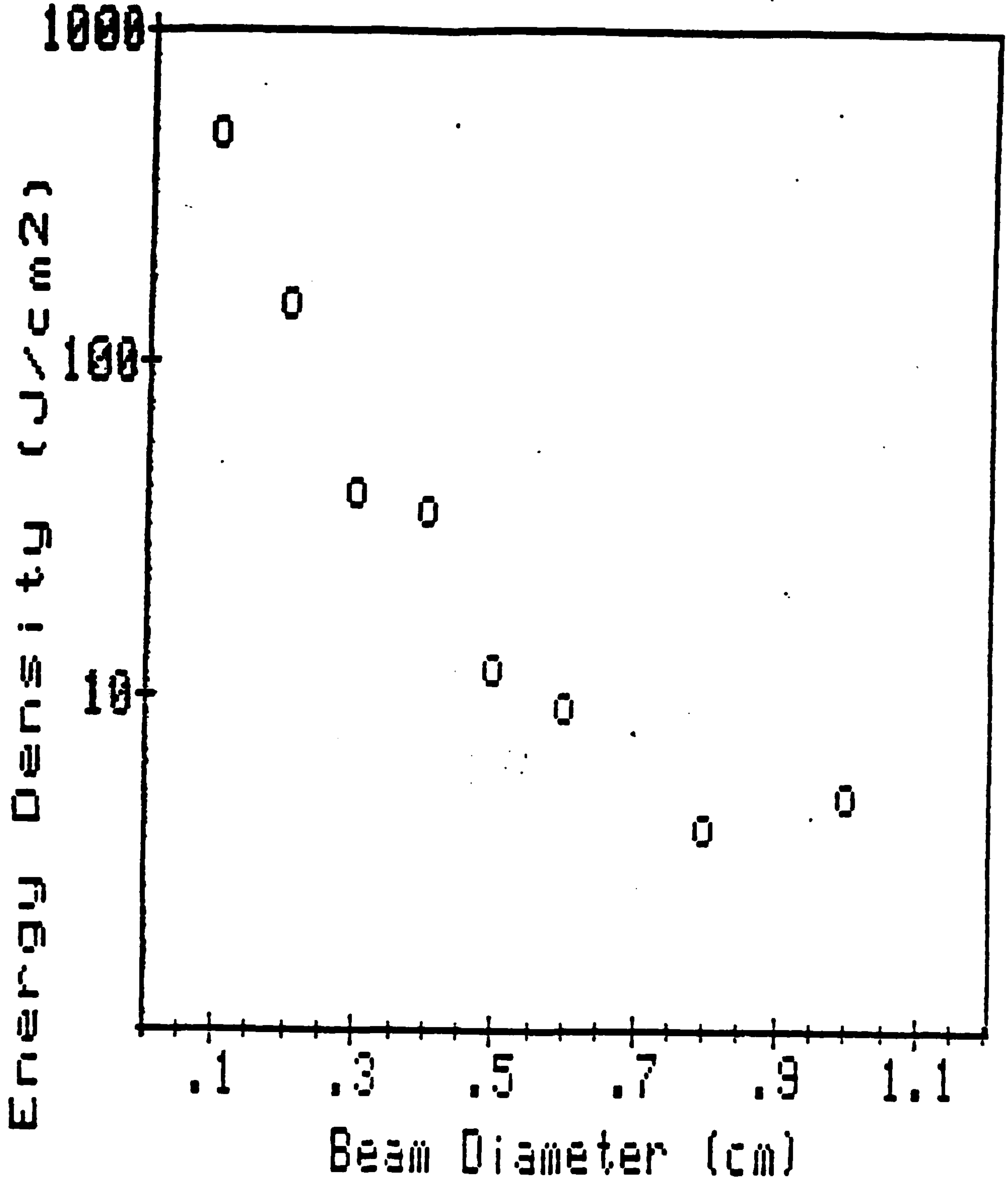
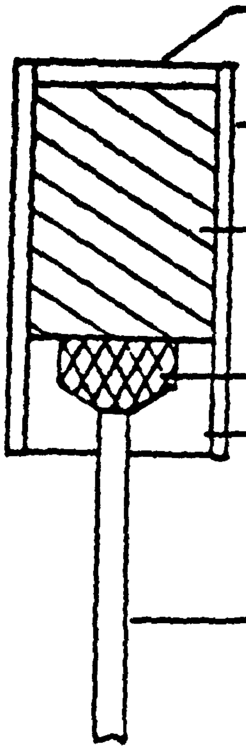


Figure 2. Laser Ignition Boundary of Black Powder.

Furthermore, the mechanism is rather inefficient and can require 100 J/cm^2 or more of laser energy. In addition to the high laser fluence requirement, long initiation or ignition delay periods appear to be characteristic of this ignition mechanism. These major drawbacks indicate that a direct ignition system for propellant formulations is not yet technically feasible at conventional, visible to IR laser wavelengths. Recent multiphoton ionization studies conducted in the UV have shown some promise but is still in the exploratory stages.[3] Our preliminary experiments with black powder and other experimentation conducted with solid propellants have borne out this conclusion.

For these reasons, the scope of the Phase I experimentation was modified slightly to include a laser sensitive material employed in a pyrotechnic ignition train to accomplish propellant ignition. Although a number of common explosive materials exhibit low laser initiation requirements, reference 2 has shown lead styphnate to have a very low energy requirement (1 J/cm^2). Lead styphnate is easily blended with 10% nitrocellulose and 10% butyl acetate to form a paste-like material which is easily formed and applied. Thus, with the addition of about 1% carbon black, this composition was selected as the base material for the Stage 1 igniter. Geo-Centers, Inc. has experimented with this formulation in the past and has found it easy to ignite with laser energy communicated through a small fiber optic but with certain operational limitations.[4]

Figure 3 shows the physical configuration and the geometric variables employed in this series of experiments to determine the optimum mass of the Stage 1 material. Since the small amount of laser sensitive material included in the Stage 1 formulation does not provide sufficient thermal energy to ignite



STAGE 1 TEXT MATRIX

Design Number	Hole Diameter (inches)	Volume (cc)	Lead Styphnate Mass (mg)
1	0.050	0.0022	6.0
2	0.060	0.0028	8.4
3	0.077	0.0050	15.1
4	0.088	0.0067	20.1
5	0.109	0.0100	30.0

Figure 3. LFO Stage 1 and Geometric Variables.

a propellant formulation directly, a second or Stage 2 ignition step is necessary. Black powder ignites well via lead styphnate and currently manufactured primer assemblies utilize this material extensively. As is shown in Figure 3, the case and the bushing containing the Stage 1 material of the LFO primer is a combustible material which is readily burned after ignition of the black powder. Note that the Stage 2 case is closed to permit pressurization during the black powder ignition. Finally, the third stage of the LFO concept includes the LFO primer-propellant/igniter material interface and is shown in Figure 4 in two configurations. Figure 4(a) shows the center-core primer configuration and Figure 4(b) shows the alternative to the center-core primer approach.

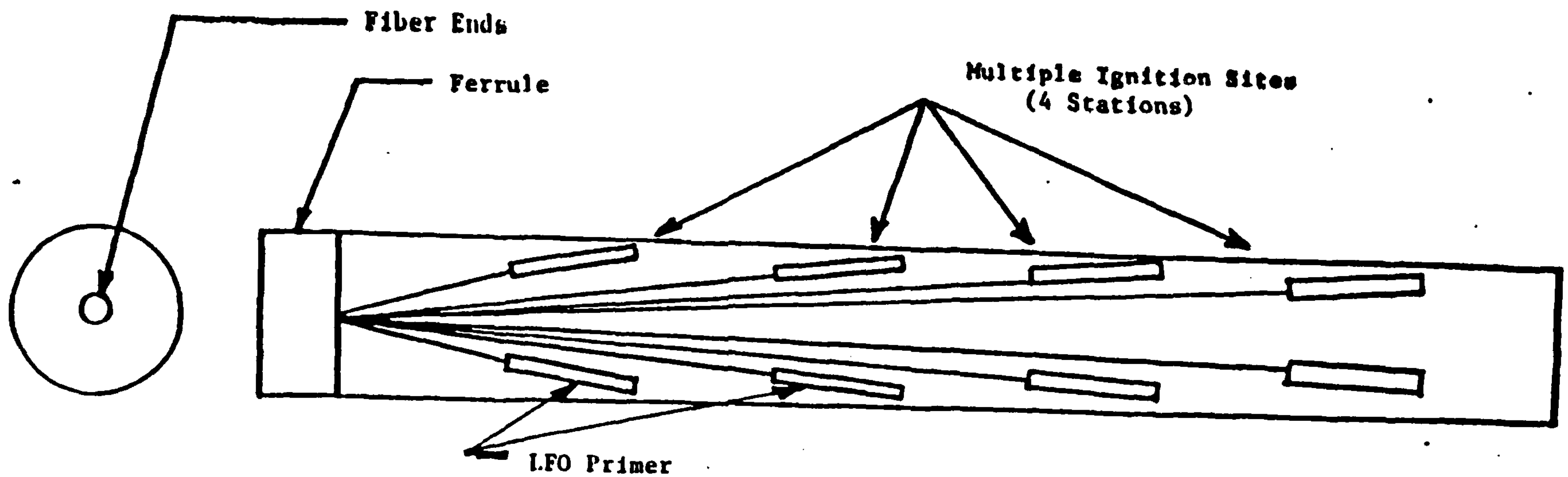


Figure 4(a). Revised LFO Concept for Center-Core Igniter Tube.

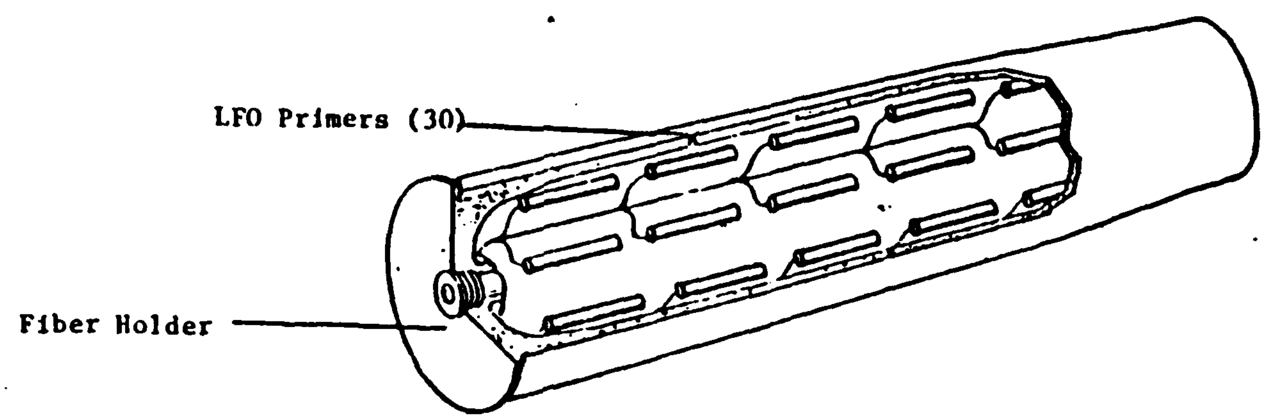


Figure 4(b). LFO Concept for 105 mm Cartridge.

RESULTS OF THE PHASE 1 WORK

The initial work, completed prior to actual Task 1 objectives, centered on determining the coupling efficiency of the laser pulses into small diameter fiber optics. Thus, in an effort to identify and quantify the damage mechanisms which will ultimately limit the propagation of high power laser pulses in transparent media (absorption coeffient 10^{-5} to 10^{-1} cm^{-1}), the dielectric breakdown in glass has been reviewed. To date these theoretical studies have been limited to intrinsic phenomena in which case the onset of light-induced damage is generally due to the occurrence of self-focusing.

The parameters determining the onset of self-focusing have been reviewed and the power threshold has been estimated. Various geometric configurations have been analyzed for light entering bulk glass and a concept which may correct for self-focusing has been determined. The intrinsic breakdown mechanism has been identified as avalanche ionization which is analogous to low frequency electric breakdown in insulating materials. Experimental data for the intrinsic rms breakdown field strength have been used to estimate the maximum pulse intensity, energy and power. Surface effects have also been studied and our experimental results have been compared to other researchers and found to be in good agreement.

Several coupling approaches have been explored to complement our theoretical predictions. In the planar coupling configuration, the ends were prepared in one of three ways -- simple cleaving, polishing, and forming a lens on the end. Cleaving was accomplished with a silica-carbide knife edge which is used to score the fiber around its circumference. By pulling slightly along the fiber axis and simultaneously creating a slight bending moment at the score, a crack will propagate through the fiber resulting in a perfectly smooth surface. Polishing was accomplished with aluminum oxide lapping films on glass plates. Rough grinding was accomplished with 30 μm film, intermediate with 15 and 3 μm, and final polishing with 0.3 μm film followed by 0.1 grit on a polyurethene polishing pad. Lenses were formed by carefully heating a cleaved end. After some practice, the surface tension of the molten glass can be made to form a hemispherical lens. The performance of these surface preparations was evaluated both in air and in vacuum.

The results of these tests are summarized in Figure 5 and the approacn explained in detail in Appendix 1. It is clear from these data that 3 to 4 (10^8) W/cm^2 is the maximum output limit regardless of the incident energy or surface preparation. Consistent with our theoretical predictions, an upper boundary is observed. However, our results to date are roughly two orders of magnitude lower than the predicted intrinsic threshold. Since intense plasma discharges are noted at these intensities, it was postulated that this plasma was absorbing the laser energy prior to its entering the fiber. Experiments were conducted both in vacuum and with a nitrogen jet displacing the plasma plume. These experiments did not produce higher energy transmission and serve to reinforce the hypothesis that the losses occur inside the fiber rather than on the surface.

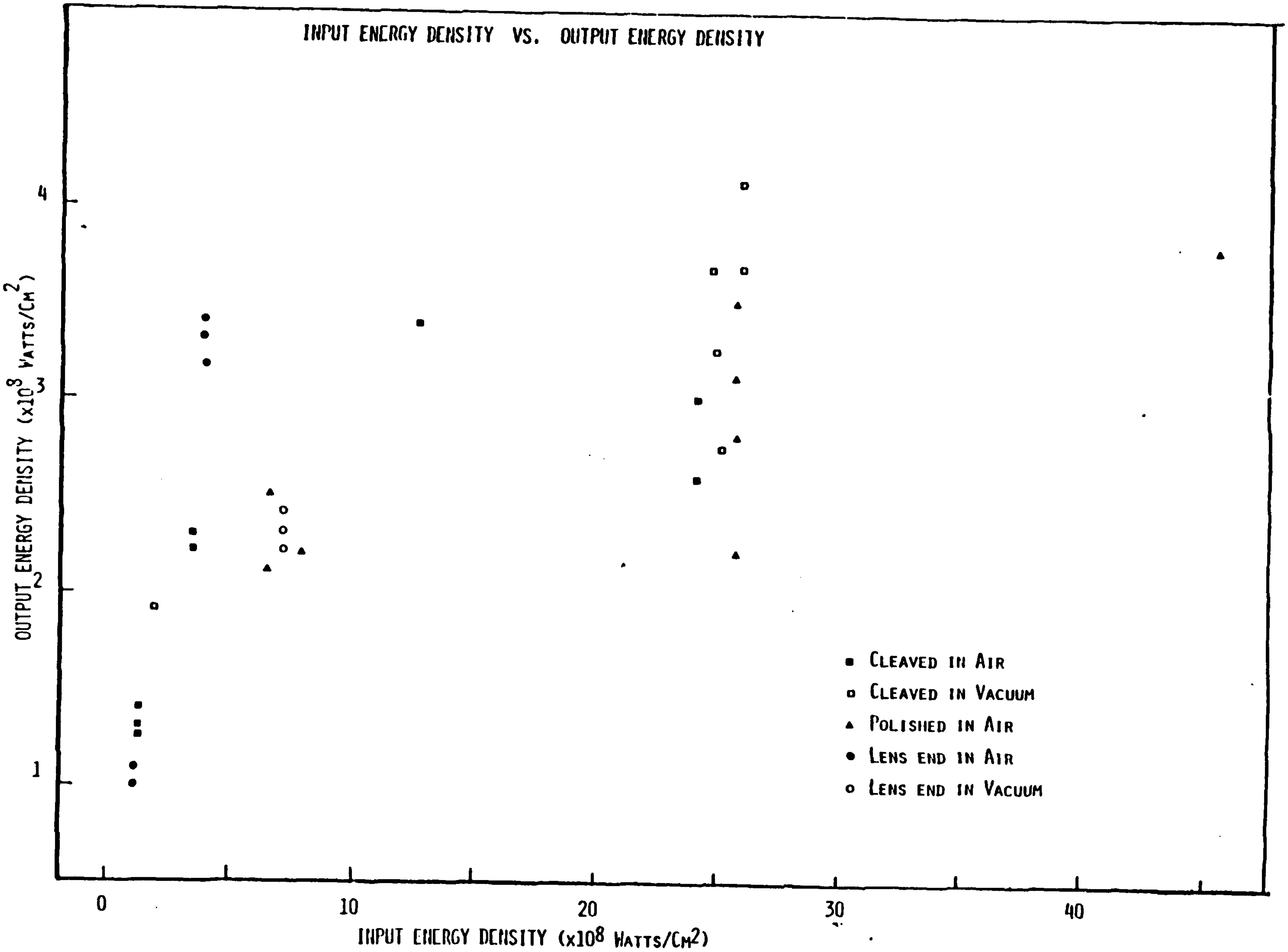


Figure 5, Coupling Efficiency.

Thus, our current hypothesis maintains that the disparity is due to self-focusing effects which are aggravated by the multi-mode operation of our laser. Experiments to validate this hypothesis could be accomplished with the laser operating with a Gaussian beam.

The most efficient surface configuration evaluated was the lens which is formed directly on the fiber end. This surface produced a coupling efficiency of better than 80% at 3.5 (10^8) W/cm^2 and holds good promise for future development. However, this configuration was the most sensitive to alignment and the slightest deviation would cause catastrophic failure via the self-focusing mechanism. Thus, it is not clear whether the lens or the improved surface provided by flame polishing is important. Alternatively, by using a simple cleaved-end, more latitude in alignment is available and, by pumping the system harder (e.g., at lower efficiency), equivalent output energies are produced. Therefore, since the high input energy required at this reduced efficiency is available with our laser, this was the surface preparation technique which was employed for subsequent tests.

TASK 1: Design a system of attaching laser sensitive igniter materials to 200, 600 and 1000 micron fiber optics, e.g., Stage 1.

Figure 3 schematically shows the evaluated design of the first ignition stage of the proposed LFO primer concept. Based on our previous research and confirmed by the present work, the degree of confinement affects the performance of the lead styphnate in possibly two ways. First, if the lead styphnate is not rigidly held in position during the ignition sequence, it has been observed to occasionally "blow off" prior to its full ignition. Secondly, based on our observations, it appears that increasing local pressure accumulation enhances the opportunity for complete ignition and therefore, reduces ignition delay and jitter. The design depicted was developed primarily to offer a degree of confinement for the Stage 1 material. Furthermore, this design lends itself easily to closely controlled manufacture as the mass of the Stage 1 material can be controlled by the volume of the cavity machined into the bushing. Finally, the material properties of the bushing can be judiciously selected to provide good adherence to both the jacket of the fiber optic and the Stage 1 material. Obviously, the bushing design can readily accommodate any fiber diameter and infinitely variable Stage 1 material volumes. This variability has significant merit due to the unknown fiber diameter requirements as a result of incomplete evaluations of suitable Stage 1 materials. For these reasons, the design shown was proposed and was subsequently evaluated as Stage 1 with the geometric variables listed in Table 1.

TASK 2. Verify ignition delay and jitter of Stage 1 ignition as a function of laser-sensitive igniter material mass. Tests performed will utilize a closed bomb with optical access and a pressure transducer.

Experimental determination of ignition delay and jitter of the Stage 1 design (from Task 1) was conducted. The experimental variables of the LFO Stage 1 are shown below in Table 1.

TABLE 1 - LFO STAGE 1 AND GEOMETRIC VARIABLES

Design Number	Hole Diameter (inches)	Volume (cc)	Lead Styphnate Mass(mg)
1	0.050	0.0022	6.0
2	0.060	0.0028	8.4
3	0.077	0.0050	15.1
4	0.088	0.0067	20.1
5	0.109	0.0100	30.0

The ignition delay measurements as a function of mass were completed with the closed bomb and related apparatus which are shown schematically in Figure 6. A small volume (20 in^3) PAR (Model 101A6427) closed bomb was modified to accept

1. the fiber optic lead of the LFO primer,
2. a Piezotron (Model 112A03) pressure transducer, and
3. a fiber optic to deliver ignition event light to an EG&G (Model SGD-100A) fast photo diode.

These data were recorded on a Nicolet Model 4094 digital oscilloscope in addition to complementary data relative to laser pulse shape and timing.

The laser pulse is introduced to the fiber in exactly the same fashion as was described in the previous section. Due to the small mass of Stage 1 material utilized and the relatively large bomb volume, it was not possible to determine the ignition point based on the observed pressure trace. For this reason,

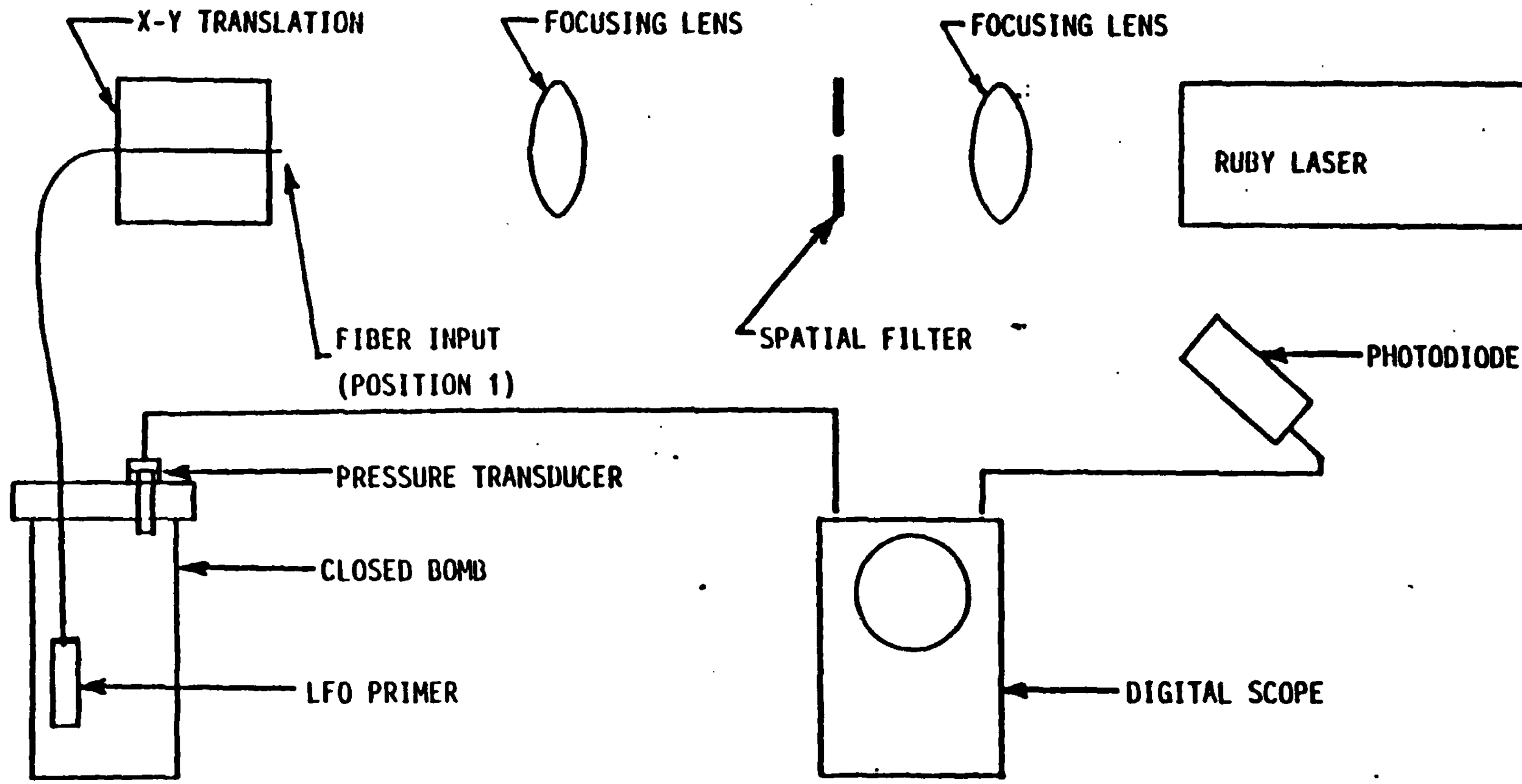


Figure 6. Ignition Delay Test Apparatus.

all reported ignition delay measurements were made by employing a complete LFO primer (Stage 1 and 2) and therefore, represent the total system delay and jitter. However, for these tests, the mass of the Stage 2 material was reduced to 250 mg of Class 5 black powder which was found to give acceptable pressure traces while minimizing systematic error introduced by this additional interface. Figure 7 shows the results of the ignition delay tests completed which are based on the test matrix described in Table 1. Comparison of these data with data reported previously[4] and reproduced as Figure 8 demonstrate good agreement in terms of reduction of ignition delay and jitter with increasing the Stage 1 material mass.

The improved design of Stage 1 performs much better than the earlier design as ignition delay and the subsequent jitter are reduced more than an order of magnitude. Consistent with the earlier work, reducing the mass of lead styphnate still adds mass uncertainty as shown by the error bars but this variation is held to a more acceptable level. Figure 9 shows the peak bomb pressure as a function of Stage 1 mass. As expected, providing higher rates of pressure accumulation in the primer raises the peak bomb pressure. Based on these and other supporting data, it is felt that a good compromise between peak pressure and ignition delay can be obtained with this approach. Based on these data, Stage 1 configuration #4 (mass = 20 mg, bushing volume=0.0067 cc) has been selected for further experimentation.

TASK 3. Design a Stage 2 interface with a combustible container and/or vent holes. Investigate performance of small designs configurations, e.g., 100, 500 and 1000 mg of black powder and/or similar materials. Compare performance of several different container designs and volumes.

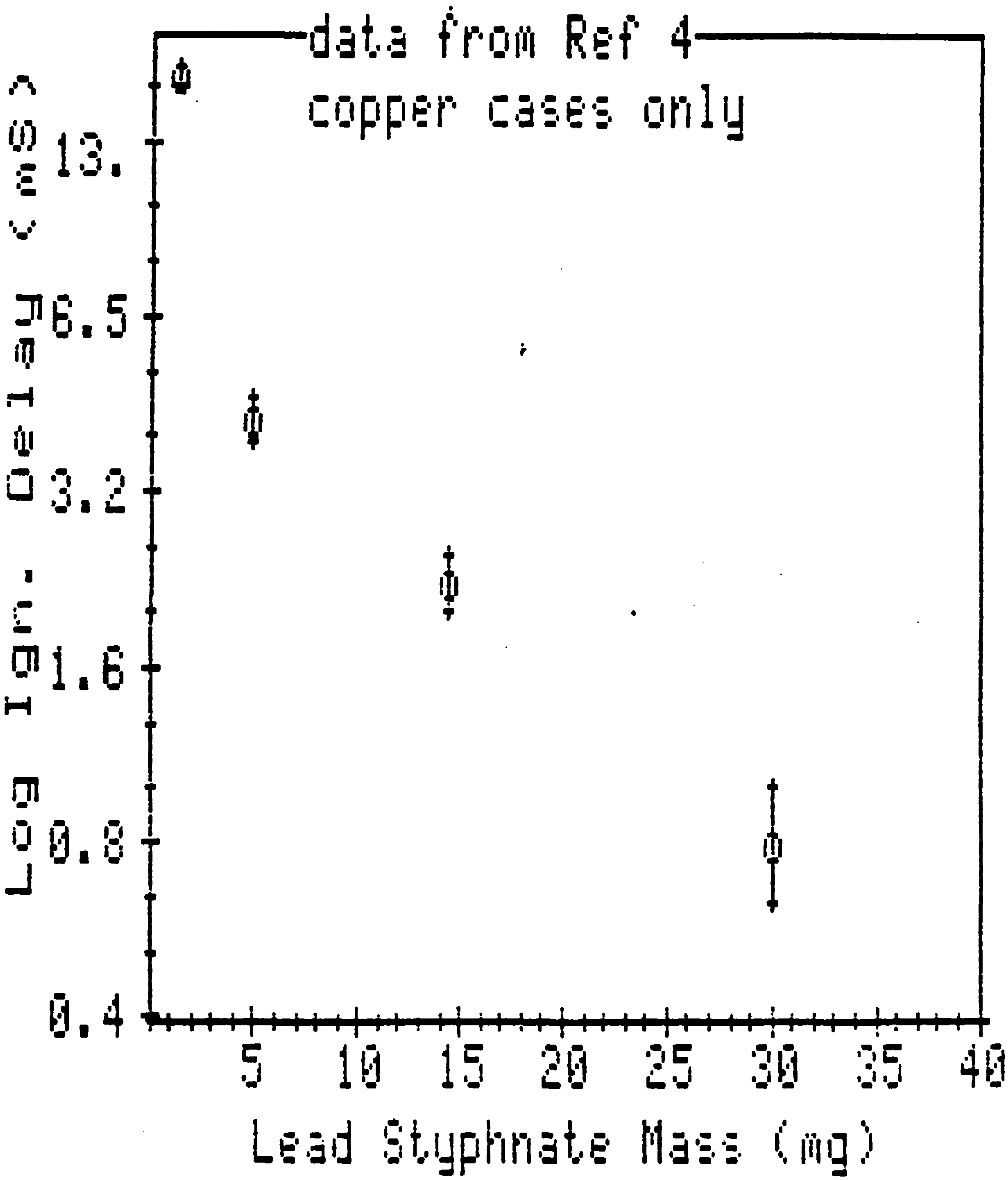


Figure 8. Ignition Delay vs Lead Styphnate Mass.

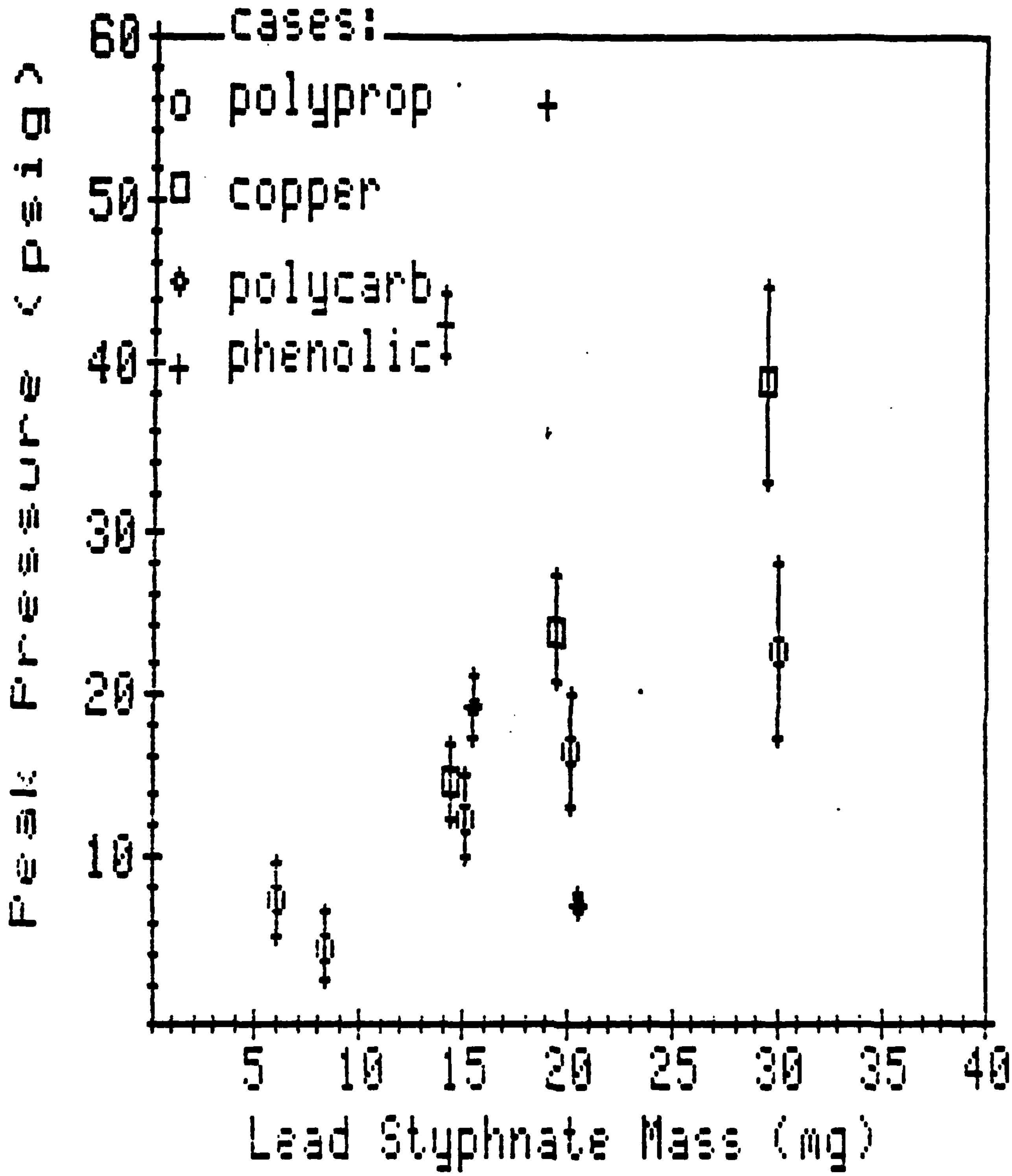


Figure 9. Peak Pressure vs Stage 1 Mass.

Limited evaluations have been completed to assess the performance of the LFO primer at the Stage 2 interface. As is shown in Figure 3, the casing of the primer was constructed with either polypropylene, copper, polycarbonate, or cloth-filled phenolic tubing and tests have been completed to evaluate these variables. These data are also included in Figure 7 and are summarized in Table 2.

Predictably, the plastic-cased configurations (polypropylene, polycarbonate, and phenolic) generally exhibited shorter and less variable ignition delay. As these experiments were designed to evaluate the overall Stage 1 and 2 ignition delay, the mass of the Stage 1 material was held constant at 0.25g. Thus, the data of Figure 7 and Table 2 are not singularly conclusive as they may not represent the performance of primers filled with larger amounts of black powder. However, these data do suggest that longer ignition delays are associated with higher peak pressures. By designing for short ignition delay, peak pressure may be compromised. Therefore, in addition to shortening the overall ignition delay, such designs may inhibit the complete ignition of the Stage 2 material, particularly when larger amounts are used.

Post test examinations of the prototypic primers have revealed several failure mechanisms which suggest additional design development. For example, the end plug is generally blown out of the polypropylene case, whereas the plug remains fixed in position with the other harder case materials. Thus, the polypropylene-cased configurations did not experience high internal pressure accumulation and the expanding gasses generated by the burning black powder simply created pressure in the bomb earlier resulting in shorter observed ignition delay.

TABLE 2. IGNITION DELAY & PEAK PRESSURE SUMMARY

Lead Styphnate Mass (mg)	Pressure (psig)	Ignition Delay (S)	% Ignition Variability	Case Material
6.0	7.4+/-2.4	221.3+/-148	67	Polypropylene
8.4	4.4+/-2.1	414.0+/-71	17	"
15.1	12.5+/-2.5	161.5+/-21	13	"
20.1	16.5+/-3.4	137.5+/-14	10	"
30.0	22.6+/-5.3	119.9+/-11	9	"
15.1	14.6+/-2.3	232.4+/-55	24	Copper
20.1	23.9+/-3.3	192.0+/-90	47	"
30.0	38.8+/-5.8	125.0+/-12	10	"
15.1	19.2+/-2.0	1714 +/-596	35	Polycarbonate
20.1	7.1+/-0.6	671.0+/-11	2	"
15.1	42.3+/-2.0	1107 +/-51	5	Phenolic
20.1	55.6+/-12	1146 +/-167	15	"

As more pressure accumulated in the hard-cased configurations, the longer ignition delay times reported are, therefore, reasonable. Obviously, the design trade-offs impact the ignition and complete combustion of the Stage 2 material and more qualitative judgments regarding the primer's performance must be made. Our post test examinations have suggested that materials such as phenolic are good candidate materials for two major reasons:

1. A reasonable compromise of peak pressure, ignition delay and more importantly, ignition jitter is possible.

2. In all tests completed, the phenolic and the black powder contained burned completely which suggests good Stage 3 ignition performance.

It is possible that some of the variability noted in Table 2 and the complementary figures were caused by the variable pressure required to produce case failure and the subsequent pressure accumulation in the closed bomb. In some cases, variability in blow out of the end plug is caused by variable amounts of glue employed to fix the plugs to the case. In other cases, variations in lead styphnate and black powder mass can account for some of the ignition delay jitter.

Figure 8 shows the relationship of initial pressure rise vs mass of lead styphnate and supports the conclusions drawn from Figure 7. It is clear from these data that higher masses of lead styphnate will ignite black powder more uniformly which results in shorter, sharper rates of pressure rise. A linear relationship exists between initial pressure rise and mass of lead styphnate. As in the previous experiment, these data also support the hypothesis that higher pressures generated with the copper cases indicate that more black powder is ignited before the pressure in the bomb begins to rise. The error bars of Figure 7 are included to depict the uncertainty of lead styphnate mass. Obviously, tighter manufacturing controls will further reduce performance variability.

Predictably, increasing the mass of the Stage 2 material raises the pressure of the bomb, but seems to have little affect on the ignition delay jitter within the variability of the experiment as shown in Table 3. A four-fold increase in black powder mass increases bomb pressure by 72%, increases delay by 41%, but only affects ignition jitter by two percent (2%).

TABLE 3. IGNITION PERFORMANCE OF VARIABLE STAGE 2 MASS. CASE MATERIAL IS PHENOLIC AND STAGE 1 MASS IS 20.1 MG.

Black Powder Mass (mg)	Pressure (psig)	Ignition Delay (μS)	% Ignition Variability
0.25	55.6 +/-12	1146.4 +/-167	15
1.0	95.9 +/-21	1614.8 +/-270	17

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CONCLUSIONS

The results of this investigation may be summarized as follows:

1. The maximum practical energy capable of being coupled into conventional material fiber optics is 4.5 J in a pulse lasting up to about 1 mS. Although this energy is in excess of the requirement for lead styphnate ignition, the possibility exists for development of direct ignition.

2. Lead styphnate is a reasonable Stage 1 material as it exhibits reproducible ignition provided a degree of confinement is provided.

3. A design of attaching lead styphnate to fiber optics has been developed and evaluated as Stage 1.

4. Stage 2 ignition delay and the resultant jitter have been measured as functions of design variables such as Stage 1 mass and case material, etc. The resultant ignition delay of these designs has been determined to be largely a function of Stage 2 confinement and, hence, case material specifications. The minimum ignition delay measured was 120 μS and ignition jitter can be reduced to two percent (2%) by judicious application of the information derived from the present effort.

The conclusions of this effort verify the original projection that designs for laser/fiber optic (LFO) multiple point ignition schemes are possible and within the limits of existing technology. Preliminary designs for Stages 1 and 2 of the LFO approach have been demonstrated in a laboratory environment and continued evaluations of Stage 3 are required to further demonstrate and validate the approach.

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APPENDIX 1

COUPLING EXPERIMENTATION

The experimental schematic is shown in Figure 10. In most experiments, the laser system employed was a Korad K1 ruby (6943 Å) operating with an open cavity. Maximum energy output was about 12 J in a pulse lasting up to 1.5 mS. For the single LFO primer experiments conducted, the collimated 0.7 cm diameter beam emitted from a beam reduction telescope is focused by a long focal length lens onto either a 600 or 1000 micron fiber. The beam splitter is a standard microscope cover glass which reflects approximately four percent (4%) of the laser energy into a Holobeam photodiode array. The output of the photodiode array was displayed on a Tektronics Model 4034 storage oscilloscope which was triggered from the laser's timing circuits. The performance of the laser was, thus, monitored which allowed rejection of sporadic and inconsistent laser pulses from the data base. The balance of the laser energy is passed through an optical system comprised of neutral density filters, lenses and spatial filters as required. Thus, the energy and geometrical properties of the laser pulse could be adjusted for evaluation of these effects on coupling efficiency.

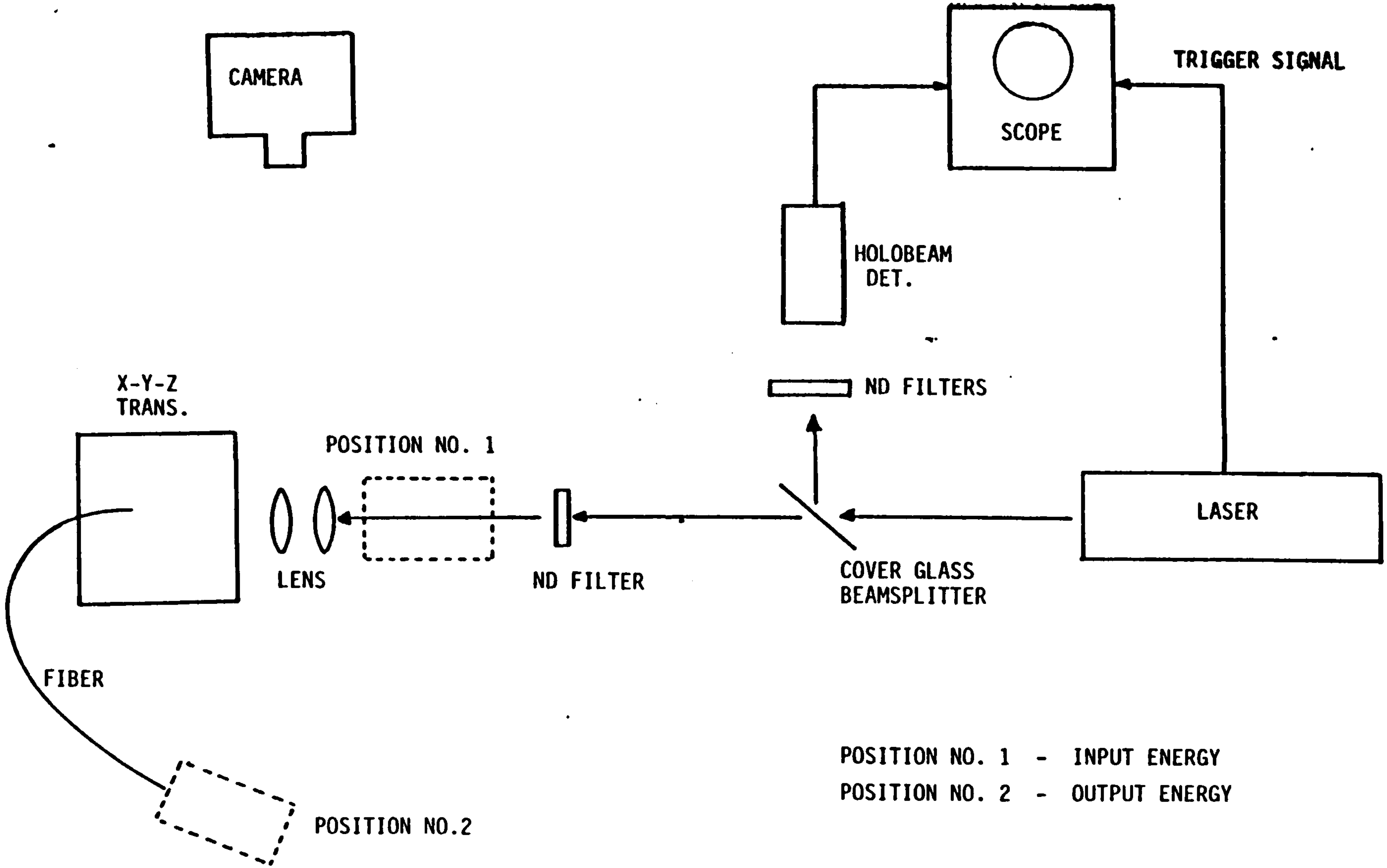

Figure 10. Experimental Schematic.

END

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