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SUMMARY REPORT AND SUGGESTIONS:
DARPA WORKSHOP ON ADVANCED CANNON PROPELLANT (ACP) DIAGNOSTICS

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September 1981

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Liquid Propellant Gun

The central technical difficulty encountered in the LPG program has been the, yet unsolved, problems connected with non-reproducible combustion processes which led to essentially three distinct types of pressure-time histories during the combustion phase of the gun firings, as classified by TRW,[1,2] namely:

alpha 15 60,000

α-type: no delay in ignition, rapid pressure rise to about 1.5 x 10^5 psi with subsequent drop to a reasonable plateau of about 6 x 10^4 to 8 x 10^4 psi; 80,000

beta 3,000 10,000

β-type: ignition delays of about 0.5-1 msec with sporadic pressure rises around 3 x 10^3 to 10^4 psi followed by a very rapid pressure rise to 6 x 10^4 to 1.2 x 10^5 psi and subsequent pressure drop and burn out;

60,000 120,000

gamma

γ-type: typical misfire initiated by an ignition delay similar to that observed in the β-type pressure profiles but without any further pressure rise.

beta

These phenomena were studied at TRW after reorientation of the LPG program with the aim to understand the combined chemical kinetics and fluid dynamics phenomena governing LPG operation during the start-up processes. These experiments were augmented primarily by laboratory studies at CALSPAN

Cont'd

involved

involving visible (high-speed) observations - as far as they were possible under the circumstances of opaque layers being formed in the combustion chambers after ignition - besides heat flux, chamber pressure, igniter voltage and current, and projectile velocity measurements. Additional studies related to non-reproducible gun operation were initiated at BRL with emphasis on the sensitivity of NOS 365 propellants to ignition by pressure pulses when air bubbles were entrained in the liquid, and in order to arrive at acceptable technical specifications for the propellant as well as to obtain a commercial source for a high-grade, constant quality propellant meeting these technical specifications. Simultaneously, PSI was to evaluate new ignition systems, to assess various pressure gauges and to investigate aspects of dynamic loading with little cooperation from CALSPAN and TRW. At the same time, NWC-China Lake was to continue the technical management tasks besides the adaptation of a previously developed electric igniter system to a monopropellant gun.

All of these efforts did not result in a satisfactory resolution of the problems encountered during different phases of the LPG program; they also did not accomplish effectively the tasks they had set out to tackle. Thus, although new hypotheses for the three types of combustion behavior were formulated at TRW, the results obtained at TRW and their interpretations were not not tested and evaluated independently, for example, at CALSPAN. In particular, the erratic behavior appears to depend on the way and the ratio by which hot reaction products, produced in the precombustion chamber, mix more or less rapidly with parts of the main LP charge and form a detonatable mixture of gases and liquids.

The observations at CALSPAN indicated that the combustion processes were very sensitive also to the amount of energy deposited by the igniter system, to the precombustor geometry and to instabilities, including the formation of possible Taylor cavities, in the combustion cycle. At the same time, a limited number of tests at CALSPAN indicated that the addition of an intermediate combustion chamber between the precombustion and the main chamber, particularly when augmented with a crushable, shock-absorbing foam liner, could reduce significantly the initial pressure spikes.

Although considerable calculations and modeling have been done together with the use of CALSPAN observations in order to support the hypotheses for the generation of α-, β- and γ-type pressure profiles, no satisfactory explanation could be given, in particular for the γ-type behavior and for catastrophic events. Therefore, there still exists a need for an explanation of the start-up processes under normal as well as abnormal combustion behavior as function of propellant characteristics, ignition parameters, combustion geometry as well as filler materials.

Thus, a more thorough understanding of the results obtained, particularly at CALSPAN and TRW, is required. This task could be accomplished by bringing together the principle technical people involved at CALSPAN, TRW, PSI and BRL so that they can address together the difficulties encountered in order to come up with technical solutions to these problems based upon the best of their technical expertise. In this context, they should put heavy emphasis on how to avoid - by proper design - many of the problems encountered in the past, rather than to make the past experience an empirical playground for theories and hypotheses without further validation. The objective being to obtain valid data and design criteria necessary for improved igniter and chamber configurations that are not plagued by the instabilities of uncontrolled, gas-liquid phase interactions.

It is possible that the gun design will have to incorporate an intermediate chamber and additional shock-absorbing materials (like the CALSPAN and early static tests indicated), or that a new design incorporating a solid propellant into the projectile base is more adequate, or a new propellant has to be found which is less susceptible to erratic behavior caused apparently primarily by uncontrollable (in the past) fluid dynamic and combustion problems introduced by the geometry of the gun chambers and the fact that the use of liquid propellants can result in unstable liquid-gas interfaces after ignition if no special design precautions are taken.

The solution of these problems depends critically on the formulation of a concentrated and concerted technical effort aimed at a complete analysis and understanding of the previous failures. This will require close cooperation among all of the experts in the field. A logical structure of a coordinated experimental, engineering, and computational effort is indicated in Figure 1. The boxes which are dashed relating to the kinetics and transport properties of the propellant are items that might be considered of lower properties of the propellant are items that might be considered of lower priority. Stop points, indicated by the crosses, are where the program must be reconsidered before going on further. Of primary interest at the present time - before any more general LPG programs should be conceived - is a technical effort which pins down the actual cause of the previous difficulties related to liquid-gas phase instabilities under combustion and detonation conditions. This can and should be done by efforts combining the laboratory expertise of TRW, CALSPAN in particular, but in collaboration with the engineering backgrounds of PSI, BRL, and NWC-China Lake.

Because of the many typical hardware problems encountered in the past LPG program, its difficulties and problems (as documented in detail in Reference 2) should be used as an empirical basis for "pointing the finger" at critical research and development areas in order to outline a realistic and concentrated ("to the point") efforts for the development of an operable LPG. In this connection, the Tri-Service Plan for Liquid Propellant Technology for Gun Applications,[3] in its version of February 1980, should serve as a valuable general outline of approach. It should be critically evaluated by contrasting it with the actual hardware needs which have to be the main goal for a system which finally has to function under severe field conditions.

As an additional aspect to be explored carefully, we note that if the liquid propellant accidentally produces a fine droplet spray in gaseous pockets produced by either ullage or by entrainment of explosive-gases in the liquid, a highly detonatable mixture results which can also account for some of the phenomena observed. Catastrophic detonation waves have been produced in this fashion by, for example, oil-droplet sprays or even dust clouds in closed rooms. However, we at LJI can only make further fruitful technical recommendations after in-depth discussions with the chief technical personnel at the various test installations.

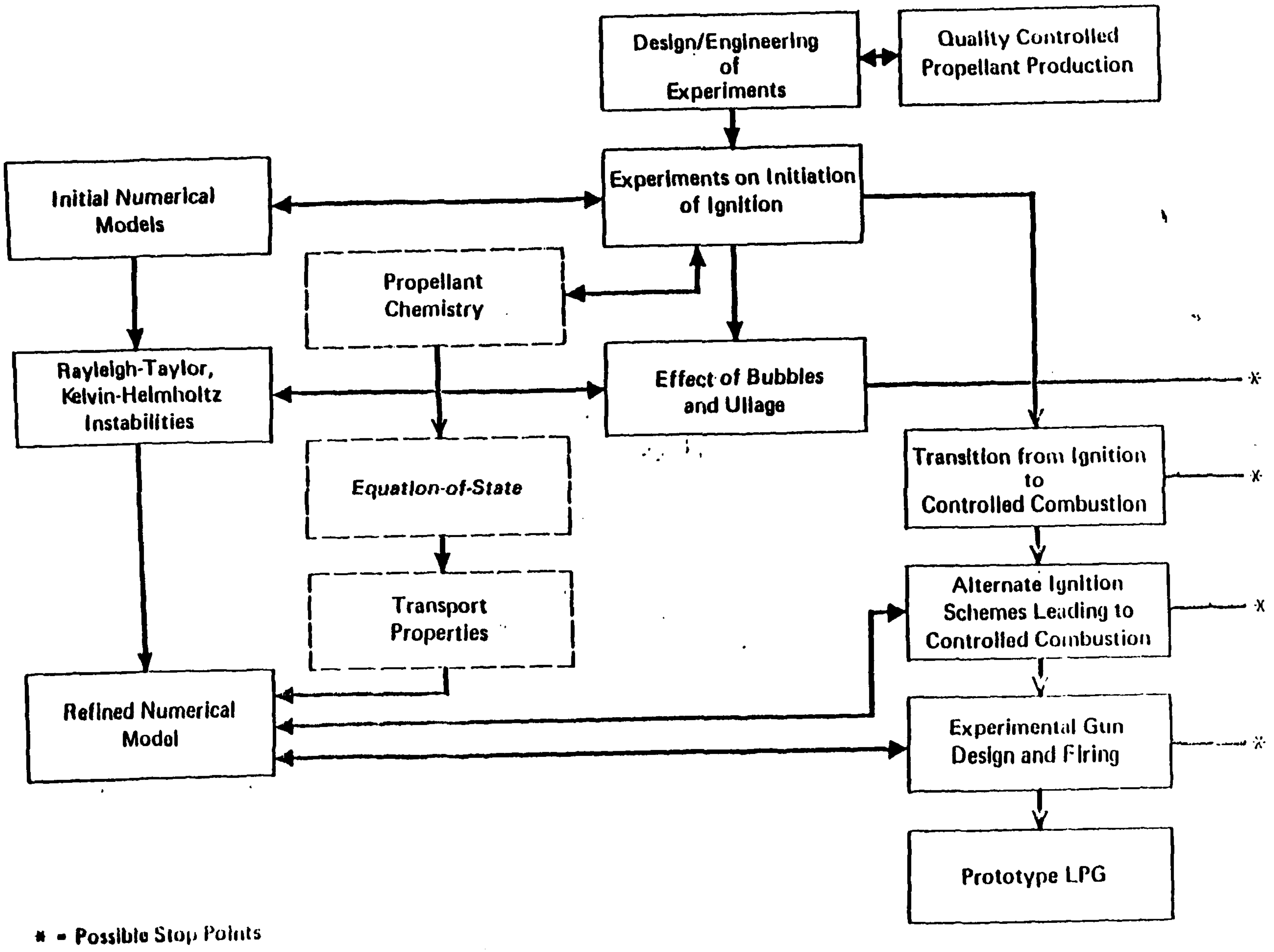

Figure 1. LPG Program Logic

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2. S. Goddard and C. R. Lehner, The DARPA Liquid Propellant Gun Programs, p. 1 of Defense Research, January 1980; previously published as a DARPA Report, January 31, 1978.
3. R. Thorkildsen, Tri-Service Plan for Liquid Propellant Technology for Gun Applications, DDR&E, February 1980.

I. INTRODUCTION

In the following, an independent summary and independent evaluations and suggestions are given about the DARPA Workshop on Advanced Cannon Propellant (ACP) Diagnostics which was held on September 2 and 3, 1981, at the Naval Post Graduate School at Monterey, California. The ideas, thoughts and suggestions arrived at by the author are the outcome of many fruitful interactions he had during the Workshop and were partly conceived and clarified because of these exchanges and discussions. Nevertheless, the following written document is a personal re-evaluation and condensation of the large body of information exchanged at the Workshop and the conclusions arrived at remain, therefore, the sole responsibility of the writer.

II. SUMMARY OF WORKSHOP PRESENTATIONS AND RECOMMENDATIONS

After opening statements by Dr. Daniel F. McDonald, Corporate Vice-President of the BDM Corporation, LTC René Larriva, the new Manager at the DARPA Tactical Technology Office in charge of the liquid propellant gun effort addressed the participants of the Workshop which was held at the Naval Post Graduate School at Monterey, California on September 2 and 3, 1981.

Subsequently, Dr. Terry Goddard, the BDM Corporation, Monterey, California, gave a program progress report in which he outlined the ACP concept and gave reviews on the previous ACP Workshop on Fluid Gun Propellants (July 1980), the ACP Library Effort (June 1981), and the ACP Liquid Gun Propellant Characterization Methodology Study (August 1981 and ongoing).

In summarizing the conclusions reached at the 1980 ACP Workshop and in order to provide succinct guidance to DARPA about the important aspects and problems which have to be addressed, I want to emphasize the key issues among the items elaborated on in the outline of the program structure; details of the complete presentations can be found in the respective copies of material which were handed out during the Workshop.

First, as has been pointed out by us before,[1,2] there remains as a top priority the need for experimental studies by modern diagnostic techniques in order to determine phenomenologically the features of the all-important ignition processes and of the combustion processes in the propellant charge under realistic conditions (including projectile motion) so that future modeling efforts (see below) can deal with reality rather than with preconceived ideas. This sentiment was shared by all participants and, in this connection, I still wonder why there is no general gun laboratory, like a National Gun Laboratory, in which new concepts can be explored and in which new experimental techniques can be transferred from other fields to experimental test-fixtures and be adopted and developed; or why the Services Laboratories have not in the past made concerted efforts - under competent technical management - in the field of technology transfer for their needs by tapping such available resources like the Lawrence Livermore National Laboratories (LLNL) as well as other national and foreign efforts.

In this connection, it is gratifying to see the establishment of centralized documentation in the form of an ACP Library. However, the User's Guide prepared by the BDM Corporation does not show any literature or references to foreign efforts including, for example, Russian, W.-German and British research and development. Maybe of value here would be the U.S. Air Force Foreign Technology Division at Dayton, Ohio, and the foreign technology documents at most of the agencies mentioned under Section "D, Other Documents and References" in the User's Guide.

I think that by now everyone realizes and agrees that a technically well managed experimental program is needed[1,2] for the development of at least two test-fixtures which have to be well instrumented and should utilize already available liquid propellants. This program is most important in order to obtain phenomenological information and data about the ignition mechanisms and the charge-combustion processes which are at present not understood even from the viewpoint of their overall phenomenology,[1,2] since the models adopted for the assessment of gun performance commonly lack physical understanding. The latter is required if one wants to establish parametric performance characterizations. Thus, in a nutshell, the real problems which still remain to be addressed by a concerted experimental and theoretical effort for the liquid propellant gun program are:

(a) The lack of a fundamental, physical understanding of how propellant characteristics, ignition variables and geometric parameters affect ignition and propulsion processes.

(b) The lack of a reasonable model describing quantitatively the processes occurring from ignition to combustion for known liquid propellants even from a heuristic and globabl point of view.

(c) The lack of understanding of the effects of mixed phases, fluid turbulence, liquid- and gas-phase shock-waves, entrained impurities, local and global energy deposition, geometric factors, radiation phenomena, etc. on the synergetics of the ignition and operation of guns using liquid propellants.

(d) The inability to formulate realistic specfications for liquid gun propellants due to the lack of knowledge and information given above.

Because of these pervading and unresolved problems, the gun and interior ballistics experiments and developments should be separated from the developments of new propellants. The preliminary ACP Propellant Characterization and Test Program for the screening of new propellants should have a very low priority, particularly since there exist ongoing tests and screening efforts for new propellants, for example, at Los Alamos Scientific Laboratories (LASL) and other establishments. The work at these laboratories should be understood first before any new extensive efforts are launched.

Thus, the present ACP Characterization Test Program as proposed by Dr. T. Goddard should be critically re-examined, and should be limited, at best, to desirable prototypes of propellants without going into new chemistry efforts since new propellant development and characterization, mostly by standard methods, is not the important issue at the present time.

In this connection, it should be noted again that ACP's are metastable materials which, once stimulated to a threshold, decompose with the liberation of energy at a rate which increases "exponentially" with temperature. The quantitative aspects of the initiation and growth-to-combustion and detonation are extremely complex and cannot be predicted with existing theories. Therefore, "cranking" large computer codes and testing new chemicals will not lead to any breakthrough in our understanding of the phenomena involved. For this reason, a wide variety of tests for the experimental fixtures are desired for available liquid propellants which take into account the variables of ignition stimuli and chamber geometry. They should establish all the necessary empirical understanding of the processes with sufficient time resolution from the trigger-event through the early ignition history to full combustion and/or detonation stages so that simplified, global modeling efforts can be undertaken (see below).

1. Test Fixtures

In order to obtain empirical insight into the triggering and ignition phenomena, "transparent" fixtures are required so that highly time-resolved shadowgraphs, self-illuminated picture and, preferably, also Schlieren picture sequences can be obtained. As was pointed out correctly by Mr. Stanley Goddard in his discussion of the general Diagnostic Methodology Issues, only the very early stages of the ignition and burn histories may be amenable to observation by either self-illuminated or light-transmission methods in the visible (and/or ultraviolet and infrared) region of the spectrum. However, this state of affairs is not really detrimental to the effort since, according to the earlier investigations by Mr. Ed Fisher at the Calspan Corporation, which involved coupled visible observations with pressure measurements, only about the first 500 microseconds after the trigger event are important and determine the fate of the later combustion stages. I consider the effort at Calspan as the only sensible approach in the past which should be looked upon as a "zero-order" approximation for further laboratory studies.

The future experiments should be conducted in, if necessary, disposable fixtures which are based upon the latest developments in Kevlar-carbon-fiberglass fixture designs as developed to a high degree of perfection in W.-Germany and adopted here by, for example, Mr. Ingo May at ARRADCOM, Otto Heiny at the Eglin Air Force Base, and at BRL. However, new talent should be brought early into the design and development stages by making full use of other resources, like the Lawrence Livermore National Laboratories and the Los Alamos Scientific Laboratories (LASL) in order to generate new ideas and more enthusiasm for new techniques than can usually be mustered by reliance upon the "old brass" only.

2. Diagnostic Techniques

The excellent presentation on "Overview of Radiographic Techniques" by Mr. Robert Bracher and his very useful and technically suggestive workshop direction on "Radiographic Techniques" made it very obvious that X-ray imaging techniques should certainly be incorporated into the test-fixture instrumentation. Here again, ideas and methods should be incorporated which have been developed at the various National Laboratories. Also, as pointed out by Mr. Bracher, four time-regimes for available image-converter framing camera observations should be considered:

(a) trigger and early ignition stage

frame interval: ∿4 μsec
total frame number: 20
time interval covered: 0 - 80 μsec

(b) post trigger regime

frame interval: ∿10 μsec
total frame number: 20
time interval covered: 200 μsec
(should be shifted to overlapping 200 μsec intervals)

(c) overall ignition regime

frame interval: ∿50 μsec
total frame number: 20
time interval covered: 1 msec
(should be shifted if necessary)

(d) overall iginition and burning events

frame interval: ∿100 μsec
total frame number: 20
total interval covered: 2 msec
(should be shifted if desirable)

Particularly, the regimes under (a) and (b) are of most interest for the early experimental studies and variations of the suggested observational intervals have to be considered whenever the observed phenomena require to do so.

Image intensifiers, converters and scintillators combined with framing cameras are available now commercially for regular photography, shadowgraphy, Schlieren photography, as well as X-ray and neutron radiography which can provide resolutions of 15 to 20 lp/mm at frame rates of up to 2.5 MHz and exposure times down to 100 nsec at optical gains of at least a factor of 10^4 by intensifiers and factors of 50 to 100 by cameras. This is particularly useful if point-source X-ray sources are considered for improved image sharpness because of their relatively low power output. Shorter exposure times down to 300 psec can be obtained in principle, albeit at the expense of loss in resolution to about 4 lp/mm. Thus, many observations about the initiation and ignition processes become possible as long as fixture breeches and barrels with sufficiently strong observation ports and/or sufficient X-ray or neutron transparency can be constructed. The use of now avabilable rod lenses (American Optoscope Comp., Selfoc in Japan, NGA in New Jersey), fiberoptics, sapphire windows and Kevlar-carbon-fiberglass combinations, as mentioned by Mr. Stanley Goddard during the Instrumentation Workshop, are of particular interest here for the design of new test-fixtures. It should be noted, however, that due caution has to be exercised where doping of propellants with "contrast materials" is considered, since particle suspensions in the liquid may cause gross changes in the ignition characteristics; hence, chemical rather than physical doping should be emphasized if contrast materials cannot be avoided altogether. In this connection, new but workable and/or proven experimental designs and procedures should be considered by an educated selection of methods in use at modern laboratories and by chosing techniques which are well understood so that "blind alleys" can be avoided from the outset; the vast variety of resources at National Laboratories should be consulted, in particular, at the Lawrence Livermore National Laboratories (LLNL) and at the Los Alamos Scientific Laboratories (LASL).

It is my considered opinion that experimental studies of the propellant chemistry relevant to the ignition and final combustion stages should be considered only from the point of view of global modeling of these events since (a) practically nothing is known about the chemical reactions starting far from equilibrium in dense gases and liquid and (b) detailed modeling of the chemistry, even in the limit of a simple gas phase, is a non-unique, long term proposition for which appropriate <u>in situ</u> diagnostics will be much too complicated, expensive and time consuming (see also below). The chemical overall decomposition and overall oxidation of the liquid propellant can, whenever necessary, be studied under controlled laboratory conditions by the same and/or similar methods which are presently in use for other propellants and explosives, for example, at BRL, LLNL, LASL, NASA Labs., etc., so that overall rates as functions of boundary parameters (pressure, temperature and composition) as well as overall activation energies (as functions of composition and pressure) can be obtained.

For the initial understanding of the initiation, ignition and subsequent burning and/or explosion processes, localized and time-resolved temperature measurements should be implemented by optical or spectroscopic methods. There exists the possibility to perform temperature measurements by absolute radiation intensity measurements in spectral regions where the medium is optically thick ("black"); this is not the case during the initiation and ignition phases for transparent liquid propellants which are advantageous for optical and Schlieren observations. However, they could be doped (preferentially chemically by molecular or atomic species rather than physically by particles) by very small amounts of, for example, sodium or other compounds so that locally a spectral non-transparency is achieved (unit spectral emissivity). The advantage of these methods lies in the fast reponse times ($\lesssim$ microseconds) available with modern visible and infrared photodetectors.

Although the adaptation of acoustic microscopy and laser-scanning acoustic microscopy has not been discussed in the Workshop, it may still me worthwhile to investigate the applicability of this method for observations during the initiation and early ignition phases, since it can provide in principle with acoustic micrographs and/or interferograms of the liquid which reveal changes and gradients in the modules of elasticity, the density, and the viscoelasticity on microscopic scales. Presumably, experience in the method exists at least at LLNL for material control, and the potential for the adapation of the technique for liquid fuel investigations should be explored at least on paper. Maybe the method can be combined with visible light observations for acousto-optical visualizations of structures, pressure waves and shock waves, etc. in the liquid during the early ignition regime before acoustical and/or optical transparency is lost.

The main problems connected with <u>in situ</u> chemical diagnostics are primarily caused by the fact that initially a liquid phase is present which is transformed into a mixture of liquid and gas phases at high pressures and finally into a high pressure gas phase with soot and, maybe, other particulates present. Therefore, spectral features in absorption and in emission in the later burning phases will be smeared out considerably; in addition, overlap of different absorber/emitter bands will degrade the specificity for spectral species identification and make quantitative concentration-time measurements difficult, if not impossible.

Nevertheless, if transparent fixtures and/or visible and infrared transparent windows are to be used in conjunction with "transparent" liquid propellants, I consider it worthwhile to obtain, first of all, spectral scans for the ultraviolet, visible and infrared transmissions of the liquid in order to ascertain where "optical windows" are available for transmission observations and measurements as well as for potential future spectroscopic studies. These studies together with spectroscopic observations during and after ignition will also provide information about useable spectral regions with unit emissivity for temperature measurements. Furthermore, spectral features present in the "transparent" liquid propellant before iginition are bound to change after ignition. These changes, as functions of time, should be useful for diagnostic purposes in connection with the structure and physical state of the liquid as well as for rudimentary in situ chemical analyses. Only once the spectral features of the propellant before, during and after ignition are at hand, may one be able to consider more sophisticated spectroscopic measurement techniques; these can range from the less expensive and usual absorption and emission techniques to various, very expensive Raman scattering techniques and to potential pico-second techniques which are presently employed or contemplated for use primarily in combustion and rocket studies.[3,4,5] Again, valuable knowledge and expertise in these areas are available at many of the National Laboratories.

Additional, continuous projectile-velocity measurements can be achieved by "head-on" laser-velocimetry. The technique is based upon laser-inferometry and can be implemented by reflecting a laser-beam off a corner-cube mounted at the tip of the projectile and by mixing parts of the emitted and reflected beams on a photodetector in order to obtain a continuous Doppler signal from the moving projectile. With sufficiently high frequency response in the required frequency-analyzer equipment, it should also be possible to detect any pressure waves and shockwaves which may hit the projectile, as long as they impart velocity changes. Similarly, if local velocity measurement in the liquid and/or gas phase of the propellant are desirable, well-known laser anenometry techniques can be adopted.

Furthermore, it should be noted, that shock-tubes have been used in the past to produce shock waves in liquids[6] so that there exists the interesting additional possiblity to study the effects of shock waves and their interaction with the geometry on the detonability of liquid gun propellants separately and without using ignition devices. For example, by injecting shock waves at the usual location of the ignitor into realistic breech configurations, one could separate the effects of local and volume depositions of chemical energy and shock-wave interactions on the initiation and ignition of processes of energetic liquids. This approach should be considered seriously since it could also be used for the development of a shock-wave ignitor for reproducible ignition-initiation in lieu of the more conventional deposition schemes for chemical energy. Electrical (spark) generation of the shock-waves could be one method. Consultation with experts at LASL should be particularly valuable in this connection.

3. Modeling Efforts

It is apparent that the liquid-propellant (as well as any other) gun is a classical example of a device which is too complex for a detailed, quantitative description. The situation is similar to, or even more difficult than that which had to be faced in the past by the rocket propulsion community,[7] since the real challenge arises because "it is so easy to invent a problem and to study the invention and so difficult to construct a meaningful approximation to the real thing".[8] Therefore, I think a two-pronged approach is desirable whereby experimental findings are first modeled by simple, "back-of-the-envelope type" interpretations. They should be based upon physical insights and the use of overall laws of conservation of mass, momentum and energy in order to arrive at global models rather than intricate and detailed "flow descriptions" which require elaborate computer programs in addition to many underlying, questionable assumptions. The model interpretations will inevitably have predictive consequences which should be tested experimentally in order to weed out wrongly conceived ideas, structures and mechanisms. The emphasis for these efforts should be guided by the principle of simplicity in the sense of well-defined and new physical ideas and concepts rather than elaborate efforts devised to crank old and mostly non-applicable complicated fluid dynamics codes for yet another higher-order approximation which can lead only one ε-step further away from a practical solution to the problems at hand.

The reason for this critical statement is based upon the fact that initiation and ignition of a liquid (and any other) propellant is a forcing process on a system far removed from equilibrium. At the present time, we do not even know the phenomenological laws which govern the complex coupled processes of chemical kinetics and transport phenomena occurring in energetic liquids and energetic liquid-gas mixtures, suspensions and interfaces. For example, although progress has been made in the study of chemical reactions initially far from equilibrium in dilute gases, essentially nothing is known about the kinetics in dense gases, liquids and solids.[9] Chemical instabilities are known to occur in coupled chemical reactions driven far from equilibrium and, for example, photon and phonon induced chemical instabilities may occur.

Hence, there exists the possibility of combined chemical and hydrodynamic instabilities[10] in two-phase systems, many of which may still have to be uncovered and/or formulated and which cannot be derived by the usual computer codes which couple the Navier-Stokes equation for the gas-phase with various sets of chemical reactions and which can include two-phase phenomena only marginally or heuristically. These phenomena may perhaps be described in the context of global dynamic systems theories[11] in the sense of generalized Ginzburg-Landau-type equations which are customary for bifurications and nonlinear stability problems.[11] Therefore, I recommend that a small-scale workshop be held in which the past modeling efforts are reviewed and discussions are held about the future modeling efforts required for a more or less simplified heuristic understanding and quantitative treatment of the initiation, ignition, burning, explosion and/or detonation phenomena related to liquid gun propellants. Maybe Dr. Martin Summerfield from the Princeton Combustion Research Laboratory could organize such a meeting, together with experts from the liquid propellant combustion community and the additional help by more theoretically inclined experts who are familiar with nonlinear systems, like Professor E. Montroll from the Department of Physics at the University of Rochester, Professor I. Oppenheim from the Department of Chemistry at M.I.T., Professor J. Ross from the Department of Chemistry at the Stanford University, etc. Of course, this workshop can only be exploratory in the sense that it can provide the liquid-propellant gun community with state-of-the-art knowledge about new theoretical approaches; therefore, the expertness available at, for example, LASL should be consulted for state-of-the-art information. At the same time, this workshop should be tailored toward the practical needs which will arise from the insights and data obtained from new and well equipped future test facilities (see above), and it should be steered towards the elucidation of approaches toward simplified descriptions of the admittedly complex phenomena at hand. Whether simple concepts (like a model of two systems in contact with each other and augmented by transport relations and nonlinear connecting global rate laws) can be applied, remains to be studied in detail.

However, it should be kept in mind that, gauging by the progress made in the past by the liquid and solid rocket propulsion community, significant progress can and should be made by studying the phenomenology of the ignition processes since engineering concepts for reliable liquid-gun operation will inevitably emerge from well instrumented empirical studies regardless of theoretical developments. Again, it should be emphasized that full use of all community resources is important for both the experimental and theoretical investigations so that new ideas, concepts and approaches become available and stagnation by the pursuit of pet-ideas or of methods along old and beaten paths is avoided.

III. CONCLUSIONS

From the foregoing discussion we conclude that the all pervading and still unresolved problems plaguing the Advanced Cannon Propellant (ACP) Program may be summarized as:

(a) The lack of a fundamental physical and phenomenological understanding of how propellant characteristics, ignition variables and geometric parameters affect the ignition and propulsion processes.

(b) The lack of a reasonable model describing quantitatively the processes occurring from ignition to combustion for known liquid propellants even from a heuristic and global point of view.

(c) The lack of understanding of the effects of mixed phases, fluid turbulence, liquid- and gas-phase shock-waves, entrained impurities, local and global energy deposition, geometric factors, radiation phenomena, etc. on the synergetics of the ignition and operation guns using liquid propellants.

(d) The inability to formulate realistic specifications for liquid gun propellants due to the lack of knowledge and information given above.

In view of this situation, the following independent overall conclusions and suggestions have been derived.

The Preliminary ACP Propellant Characterization and Test Program for the screening of new propellants should have a very low priority; exploratory work in this connection is going on elsewhere (LASL), and useable liquid propellants are available. The latter should be used first for the all-important task of establishing empirically the phenomenological understanding and quantitative bases necessary for the successful use of these propellants in test-fixtures and workable guns.

Consequently, the development of "transparent" test-fixtures should be given the highest priority together with the development and/or adaptation of modern, new and proven diagnostics for empirical studies of the phenomena occurring from the moment of ignition initiation to the fully developed combustion and/or detonation phases, In particular, the methods of high speed X-ray radiography, regular photography, shadowgraphy and Schlieren photography, should be incorporated into test-fixtures in consultation and in cooperation with the expertness available at various National Laboratories, particularly at LLNL and at LASL.

Since detailed in situ chemical diagnostics is expected to be much too difficult, required chemical analyses and overall rate determinations should be conducted outside of the test-fixtures. Appropriate laboratory methods for the decomposition and deflagration of the propellants are routinely available at many laboratories and should be used for providing engineering data for the effective overall activation energy and the rate of energy deposition as functions of temperature and pressure which are useful for global rather than detailed modeling efforts. Time-resolved spectral emission and/or absorption data should, nevertheless, be attempted in the ultraviolet, visible and infrared during the initiation and ignition phases so that "optical windows" can be determined and general and coarse changes in the state of the propellants can be observed.

Proven laser methods should be adopted for continuous measurements of the projectile velocity and acceleration and for potential local velocity and acceleration measurements in the liquid and gaseous phases of the propellant. Here again, existing knowledge and methodology should be extracted from the National Laboratories. These laboratories (particularly LLNL and LASL) should also be tapped for new methods developed in conjunction with their explosives programs and which could be adapted for the design and development needs for the actual liquid-propellant guns.

Furthermore, the possible coupling of shock-waves with the liquid propellant in the ignitor and in the burning chambers should be investigated (a) in order to achieve the decoupling of the effects of local or volume depositions of chemical energy from those caused by shock-wave interactions with the geometry and/or impurities on the ignition and burning characteristics of energetic liquids and (b) for the potential development of shock-driven, reproducible ignition initiation by, for example, spark-generaged shock waves in lieu of the more conventional deposition of chemical energy.

The liquid-propellant (as well as any other) gun is a classical example for a device which is too complex for detailed, quantitative descriptions so that "it is so easy to invent a problem and to study the invention and so difficult to construct a meaningful approximation to the real thing"; therefore, a two-pronged approach towards global modeling of observations should be implemented. Experimental findings should first be modeled by simple, "back-of-the-enevelope" type interpretations based upon the conservation laws of mass, momentum and energy, and the predictive consequence of the resulting models should be tested experimentally. Elaborate modeling efforts should be avoided at the outset, since most of the available computer codes are designed to "crank" old, and mostly non-applicable, complicated fluid-dynamics and gas-phase chemical equations which have nothing to do with the realities prevailing during ignition in the complicated system at hand. Here, new and imaginative approaches are required since initiation and ignition of liquid propellants are forcing processes on a system which is far removed from equilibrium and which responds nonlinearly by evolving into two phases with attendant complex chemical and transport processes which are not understood at the present time.

It is suggested that a workshop be organized for the discussion of simplified and/or programmatic global modeling efforts relevant to liquid propellant ignition and burning by utilizing the expertness available in the academic community and at National Laboratories dealing with explosives, in particular, at LASL.

Finally, the experimental efforts involving test-fixtures should also be geared to arrive at hardware solutions by utilizing the experience gained from the phenomenological studies in the test-fixtures without necessarily having to rely on a modeling backup. After all, engineering solutions should be the primary aim, since the understanding to the point of detailed descriptions and prescription will always take considerable time. It usually takes much more engineering intuition and inventiveness in order to succeed (which involves shouldering of responsibilities) rather than lengthy and doubtful computer studies and committee decisions (which involve shunning of responsibilities) in order to carry through a concept from the drawing board to the final hardware stage. Maybe, the efforts of a dedicated task force of knowledgeable people could be much more fruitful and effective for less money in the long run than the usually diffuse efforts administered through too many channels and resulting often in lack of enthusiasm, cohesiveness, close cooperation of individuals, and a sense of urgency.

IV. REFERENCES

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