Electro Thermal Chemical Gun Technology Study

Lead Author
P. Diamond

Contributors
P. Dimotakis
D. Hammer
J. Katz
J. Sullivan

Consultant
F. Egolfopoulos

March 1999

JSR-98-600

JASON
The MITRE Corporation
1820 Dolley Madison Boulevard
McLean, Virginia 22102-3481
(703) 883-6997

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 11, 1998	

4. TITLE AND SUBTITLE

Electro Thermal Chemical Gun Technology Study

5. FUNDING NUMBERS

13-988534-04

6. AUTHOR(S)

P. Diamond, P. Dimotakis, D. Hammer, J. Katz, J. Sullivan
Consultant: F. Egolfopoulos

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The MITRE Corporation
JASON Program Office
1820 Dolley Madison Blvd
McLean, Virginia 22102

8. PERFORMING ORGANIZATION REPORT NUMBER

JSR-98-600

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

US Army Research Office
4300 South Miami Boulevard
PO Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

JSR-98-600

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

Distribution Statement A

13. ABSTRACT *(Maximum 200 words)*

This study of ETC gun technology was performed at the request of Dr. John Parmentola, Acting Director for Research and Lab Management, Office of the Secretary, U.S. Army. Funding for the study was provided by the Army Research Office under the guidance of Dr. Michael Stroscio.

Electro Thermal Chemical (ETC) gun technology refers to the use of plasma devices in place of traditional chemical ignitors to initiate the burning of high energy propellants in a controlled manner. The goal of ETC gun research and development is to provide higher muzzle velocities and more reliable performance for large bore weapons than is possible with existing gun technology.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Contents

1 EXECUTIVE SUMMARY

1.1 Study Background and Scope

Electro Thermal Chemical (ETC) gun technology refers to the use of plasma devices in place of traditional chemical ignitors to initiate the burning of high energy propellants in a controlled manner. It is a practical necessity that the total electrical energy delivered by the plasma ignitors be small compared to the chemical energy released by the propellants. The electrical energy acts as a *catalyst* for releasing the chemical energy of the propellants. The goal of ETC gun research and development is to provide higher muzzle velocities and more reliable performance for large bore weapons than is possible with existing gun technology.

This study of ETC gun technology was performed at the request of Dr. John Parmentola, Acting Director for Research and Lab Management, Office of the Secretary, U.S. Army. Funding for the study was provided by the Army Research Office under the guidance of Dr. Michael Stroscio. Technical briefings by representatives of all the principal academic and government laboratories engaged in ETC studies were organized by Dr. William Oberle of the Army Research Lab. A list of the briefings received by the study group is given in Appendix A. In addition, the study group consulted a number of technical papers provided by the briefers as well as documents selected from a computer database search performed by the Chemical Propulsion Information Agency (CPIA).

ETC gun technology is one sector of a broader U.S. Army R&D program on Electric Gun Technologies. The latter program also incorporates the development of new technology propellant chambers that can withstand higher peak operating pressures than can today's chambers; development of mobile, high power electrical supplies; and research on rail guns.

The ETC sector of the Electric Gun Technology Program currently consists of the XM-291 120 mm gun demonstration project (4 M$ in FY 98, funded equally by ARL and DSWA with a January 2000 completion date), basic research (300 k$ in FY 98) and applied research (600 k$ in FY 98). The latter two program elements support laboratory experimental work and computer modeling. A portion of the funding for the XM-291 demonstration project also supports laboratory experiments and modeling efforts but these are closely related to that project.

In accord with its charge, the study group focused its attention on the current state of understanding of ETC gun technology, its scaling, and its overall potential. The study group was fully briefed on the joint ARL/DSWA XM-291 gun demonstration program but it was not asked to review that program. Similarly, the group study did not examine any sectors of the Army's Electric Gun Technology Program other than ETC guns.

1.2 Conclusions

1. *ETC gun technology is progressing and merits continued R&D support.*

   Experiments in laboratories and at gun test facilities have demonstrated that plasma ignitors used with standard propellants can produce enhanced muzzle velocities for a given bore and projectile weight, especially for cold propellants. Projectile kinetic energy enhancements over conventional ignitors at 60 caliber and at 120 caliber have been achieved at 0°C with the increase in kinetic energy greatly exceeding the electrical energy supplied to the plasma. Lesser enhancements are achieved at room temperatures and with hot propellants. In addition, it has been demonstrated that the variation of muzzle velocity using plasma ignitors is substantially reduced over the temperature range

0-50°C compared to the variability when using conventional ignition technology. A major benefit of ETC is that it virtually eliminates temperature sensitivity.

2. *ETC gun technology has significant military potential.*

   Increased muzzle velocity for a given projectile mass provides greater armor penetration capability, improved accuracy, and greater range. Reduced sensitivity to propellant temperature improves accuracy and can result in more efficient use of ordinance. Equally important, plasma propellant technology offers the possibility of precision tailored ignition using new types of propellants not ignitable by traditional means, as well as the possibility of developing insensitive, high energy propellants that could increase the safety of occupants in vehicles carrying such ordinance. These latter two possibilities have not yet been demonstrated.

3. *Basic understanding of ETC gun technology is currently incomplete in several critical areas.*

   The plasmas generated by the devices being developed in the ETC gun program and appropriate for propellant ignition are low temperature (3,000-9,000 K) and are non-ideal (i.e. long range, electrostatic forces are not strongly screened). These conditions define an unusually complex regime of plasma dynamics and radiation transport. Furthermore, after the initiation of propellant burn, the flow takes place in the presence of multiple species of atoms, molecules and radicals that are the intermediate and final products of propellant combustion, thus allowing complex plasma-chemical reactions. At present many fundamental questions are not yet answered: (1) Is the primary energy transfer mechanism between the plasma and the propellant radiative or convective? (2) What are the transport coefficients for such a non-ideal plasma? (3) Is the hydrodynamic flow within the propellant matrix laminar or turbulent?

4. *Current modeling of plasma ignition phenomena suffers from gaps in understanding of the basic technology, sparse experimental data, and the need to deal with three-dimensional geometry.*

   It is quite unrealistic to expect that all of the physical and chemical phenomena potentially important in the propellant chamber dynamics of an ETC gun can be incorporated into a three-dimensional code that would run on any existing or proposed supercomputer. Instead, ETC gun modeling — as is usually the case with complex phenomena — will have to be done by means a suite of 1-D or 2-D models that accurately describe the key physical and chemical phenomena, and others which are genuinely 3-D but grossly simplify all but one or a few of the important physical and chemical mechanisms.

   Until current gaps in basic understanding described above are closed, one cannot have confidence that ETC modeling predictions are valid outside the immediate regime used to fit the models to experimental data. The inability of present models to explain differences observed in 60 mm vs. 120 mm plasma propellant ignition experiments is indicative of the limitations of today's models. One of the most serious current deficiencies is the lack of knowledge of the chemical reaction dynamics. Differences in performance when aluminum vs. copper conductors are used in the plasma devices and differences when propellant type is varied are clear evidence that plasma source chemistry impacts ETC performance.

5. *The scaling of ETC gun performance from demonstrated levels to levels of interest for battlefield systems is uncertain at present.*

   This conclusion follows from Conclusions 3 and 4 above. However, if currently open questions about the basic phenomena are answered in experimental studies, and models which effectively incorporate the new knowledge are developed, we believe that scaling of ETC technologies can eventually become predictive. The phenomenology is so complex, however that realistic scaling "laws" cannot be derived from "first principle" computer models at this time. However, modeling capability is improving and an active program in basic process characterization and modeling should be maintained.

The 120 mm XM-291 gun demonstration project appears to be well on its way of achieving its January 2000 performance goals of a 17 MJ kinetic energy, 10.2 kg projectile, and electrical efficiency of 40%. *Success of the XM-291 demonstration project will not, however, obviate the need to do further basic studies or model development.* Going beyond the goals of the XM-291 project to the vision of a 120 mm ETC tank gun with the armor penetration capability and range of a 140 mm tank gun built with conventional technology will require a much more complete understanding of basic ETC processes than is now available.

1.3 Recommendations

1. *We recommend continued funding of basic ETC technology studies and model development.*

   A coordinated three-prong program consisting of: (1) small scale laboratory experiments, measurements, and parameter studies; (2) model development that incorporates the results from the laboratory studies; and (3) empirical studies needed to explore the full potential of ETC gun technology. The characteristics of the required laboratory experimental program are outlined in the following recommendation.

2. *We recommend that a set of basic laboratory experiments directed to answering critical basic questions concerning the physics and chemistry of plasma-propellant interactions be carried out.*

   Experiments are needed to elucidate critical physical and chemical issues, validate models and codes, and help develop a database for scaling. Many of the needed experiments can be done subscale and can be designed to explore extreme values of parameters that differentiate distinct physical and chemical mechanisms. A set of detailed suggestions for experimental studies are given in Section 4 of this report.

3. *We recommend that increased attention be given to issues of plasma chemistry and its role in ETC phenomena.*

   The need for such research is dramatized by the substantial but unexplained differences between performance with copper and aluminum electrodes.

4. *Innovative technology research, such as that leading to the FLARE ignitor concept, should be encouraged as part of the ETC program.*

2 INTRODUCTION

Electro-thermal chemical (ETC) propellant ignition works; it improves the performance of conventional propellants, particularly reducing the penalty imposed by low ambient temperature, and permits the ignition of advanced high density (and high energy density) propellants. It is not understood how and why it works in any detail. Detailed understanding is necessary in order to maximize the benefits of ETC technology. In addition, if electro-thermal ignition fails, a more detailed understanding will be necessary in order to remedy the failure.

3 SCIENTIFIC ISSUES

3.1 Two Approaches to Understanding

There are two different methods of approaching a complex problem like ETC. One is theoretical and computational: determine all the significant physical processes (electric discharge physics, radiation transfer, fluid flow of the air, discharge plasma, and burnt propellant gases, elastic-plastic flow of unburned propellant, burn, turbulent mixing and heat transport, etc.), calculate from first principles or find and calibrate a phenomenological model for each, and finally integrate all these pieces into a two-dimensional (in some cases, three-dimensional) hydrodynamic code. If this is done successfully the resulting code is a powerful tool which can be used to calculate the effects of any changes in the initial conditions and parameters and to optimize system performance.

The second method is empirical, and is the way engineering design of complex systems was generally done before fast computers became available. It is still the method of choice when the microscopic physics of a problem is unknown or incalculable, as, for example, in the strength of materials. The important properties of the system in question (in this problem time history of the propellant pressure) are measured for various values of the controllable parameters. These values are chosen to span regions of parameter space considered promising. Phenomenological models are fitted to the data. Over a limited range between the (necessarily few) measured data the performance is estimated by interpolation; to a limited extent it may be estimated outside these ranges by extrapolation. In addition, by doing appropriate experiments it may be possible to determine which physical processes are important, and thereby to develop a simple but useful model of complex processes.

In general a combination of these two approaches is followed. For example, an empirical approach may be used to describe the critical physical processes, and a computational code based on this. We feel that in ETC the balance is too heavily skewed in the direction of computation. This is a problem in which experiments, particularly at reduced scale, are comparatively quick and cheap, while the computational problem is very complex and difficult, probably more so than that of nuclear weapons design.

The computational problem contains many components, several of which are either beyond the computational state of the art or are not themselves understood in detail. In each case empirical and phenomenological models are used. As a result, the computational approach is not in fact based on first principles, but is in essence also empirical. This is particularly true when the models are themselves only rough approximations to very complex physics. Perhaps the most extreme example of this is the burn model. A fundamental understanding of combustion, at the level of calculating the abundances of all the important chemical species (mostly free radicals) and the rates of all the important chemical reactions, does not exist for any molecule more complicated than propane. Even in this case roughly 100 species and several times that many reactions must be considered. It is clear that the combustion of actual solid propellant will not be calculated at this level of detail in the forseeable future. A similar resort to phenomenology and empiricism is necessary in such processes as turbulent mixing and heat transport, which are also essential components of the ETC problem.

For these reasons we believe that the apparent understanding provided by large scale "all up" numerical hydrodynamic calculations of interior ballistics may be deceptive. At present even the mechanism of electro-thermal ignition remains uncertain; it could be radiative heat transport, catalysis by free radicals or free charges, particulate abrasion, resistive heating, the overpressure of the discharge plasma, ultraviolet photochemistry, or perhaps something else. Until this question is answered computation can only disguise the uncertainty, and mask the empiricism behind the computation. We suggest that empiricism be embraced openly, at least to determine the fundamental mechanisms of ETC ignition, and perhaps also as a guide to optimizing its performance.

3.2 Plasma Initiation

3.2.1 FLARE (Flashboard Large Area Emitter)

Flashboards were originally developed as low density plasma and UV sources for use in vacuum with microsecond pulses. There, the idea was (and still is) that each short gap between a string of metal (usually Cu) diamonds breaks down, vaporizing and ionizing material both from the conductor and the underlying surface, which was typically PC board, but it could also be a sheet or tube of plastic. The return conductor is on the opposite side to drive the plasma away from the surface into vacuum.

Flashboards were (and are) often run as several parallel strings in order to provide a large area of plasma and/or UV. Flashboards can be used in planar geometry, or on the inside or outside of tubes. When mounted on tubes, the diamonds can be oriented to have their gaps along the tube axis or azimuthal (or even helical if that were desirable). In high pressure air, the plasma initiation is believed to be (and probably is) the same, but once the current starts flowing, the only way the discharge can move away from the source is to push air out of the way and/or involve the air in the discharge. The discharge geometry is azimuthal when FLARE is used to ignite propellant.

In the tests described to us, the propellant is in the form of annular 'cookies' which are described elsewhere in this report, and the FLARE surrounds these cookies at a 1 mm larger radius. The current geometry involves two heavily insulated bus wires, one of which carries the current to one end of each of the azimuthal strings of flashboard diamonds in parallel, and the other of which re-collects the current after it has traveled around each string, thereby ensuring that the discharge will remain azimuthal rather than axial.[1] The hot gas/plasma mix and the radiation from the flashboard as well as the gas/plasma impinge upon the propellant, heating it by radiation, convection and conduction. The energy density delivered by the FLARE to the circumferential area of the plasma and heated gases will also flow down between the cookies and pre-heat those surfaces as well, probably mostly by convection from the high pressure gas/plasma pushing the atmospheric pressure ambient air ahead of it. The energy flux of plasma and radiation into those gaps is likely to be dwarfed by the chemically-driven energy coming from the circumferential region of the cookies as soon as it is ignited by the plasma. [1] Rex Richardson, personal communication, July, 1998.

3.2.2 TCPI (Triple Coaxial Plasma Igniter)

A coaxial plasma igniter consist of a center conductor surrounded by an insulator (like a coaxial cable with the outer jacket and braid stripped off) on which are 4 strips of Al foil. This combination is contained within an insulating tube (about 1.6 cm in diameter) which is perforated with small holes in an array that has about a 2 cm center-to-center distance all around it. The current flow from the external pulse-forming network passes up through the center conductor (not worrying about which end is the anode or the cathode) and back down through Al foil strips, exploding them into a vapor and then breaking them down into a plasma. The plasma escapes through the holes and impinges upon the surrounding propellant. The TCPI involves three such sources such that they fit around the projectile tail in between the fins.

The TCPI design is no longer being used because it has several disadvantages relative to FLARE, including the following: it was not as easy to arrange to have a higher packing fraction of propellant; it does not deliver its energy as fully to the surrounding propellant; and it evidently damaged the projectile fins.

3.3 Radiative Heating

One possible mechanism of ETC ignition is heating of the propellant by visible and near-UV radiation from the hot plasma. A number of estimates of the energy delivered by FLARE are available. The relevant energy is that in the near-UV, for which the absorption length in propellant has been estimated to be 30μ (but dependent on wavelength).

1. 10% of a 10,000 °K black body for 1 ms. This delivers 6×10^7 erg/cm^2, or 2×10^{10} erg/cm^3 to the surface layers. The resulting estimated temperature rise ΔT is between 1,000 °K and 2,000 °K, which heats the propellant to much more than the 400 °C estimated ignition temperature.

2. In one experiment 50% of the stored energy of a 75 kJ capacitor bank was radiated, half of it in the near-UV. These 20 kJ were delivered into roughly 300 cm^2 (a 15 cm length of cylinder 60 mm in diameter). The resulting deposition of 7×10^8 erg/cm^2, or 2×10^{11} erg/cm^3 in the surface layers, raises the temperature by ΔT estimated to be between 10,000 °K and 20,000 °K, many times the amount required for ignition.

3. In one experiment a power of 40 MW was radiated for 0.2 ms into 400 cm^2. The energy radiated is 8 kJ, and the energy per unit area is 2×10^8 erg/cm^2, or 7×10^{10} erg/cm^3 into the surface absorption layer. The estimated temperature rise ΔT is roughly 5,000°K, again ample for ignition.

The thermal diffusivity D of propellant is the ratio of its thermal conductivity to its volumetric heat capacity. Adopting plausible estimates of 0.1 W/m°K for the conductivity and 1.3 J/cm^3°K for the heat capacity leads to $D \approx 10^{-3}$ cm^2/s. In $t = 1$ ms the thermal diffusion length $\Delta x = (Dt)^{1/2} \approx$ $10\,\mu$m. This is smaller than the estimated radiative absorption length, so that thermal conduction has little effect on the temperature distribution in the propellant. Thermal conduction would need be considered only if the absorption length were less than Δx, in which case it would be a fair approximation to assume the absorbed energy to be spread over the thickness Δx, as if that were the absorption length.

These three estimates show that radiative heating by the plasma source is sufficient to ignite the propellant where it is exposed to that radiation. In reaching this conclusion it was essential that a significant part of the radiated energy be emitted in a region of the spectrum (near-UV) in which the propellant is opaque, absorbing the radiated energy in a thickness of 30 μm. If the absorption were ten times less (an absorption length of 300 μm) ignition might be uncertain. It is thus seen that the fit of the spectral distribution of the radiation to the frequency-dependent absorption coefficient of the propellant is essential to ignition.

The experimenter has some control over both these variables. The emission spectrum of the plasma may be controlled by choosing the elements (in electrode, gas and propellant) from which the plasma is made. The gas density affects the plasma temperature by controlling the amount of cold gas with which the electric discharge plasma mixes. The absorption of the propellant may be altered, or at least increased, by varying its composition. Although the freedom to do this is limited by the need for the propellant to burn properly, it is probably feasible to increase its opacity, if that is required, by adding small quantities of opaque substances such as carbon black.

4 RECOMMENDED EXPERIMENTS

We suggest an experimental program to determine the dominant physical processes in ETC ignition and also experimental studies to explore further improvements to the plasma ignition devices.

4.1 Fundamental Experiments

Because these are fundamental experiments, rather than development tests for a final design, they may be performed at reduced scale. A basic program would include the following experiments:

1. Reduce the air pressure in and around the propellant. In a series of experiments values of pressure may be chosen ranging from near-vacuum to atmospheric. Reducing air pressure reduces the cooling of discharge plasma by mixing and facilitates the flow of plasma between the propellant layers, but reduces the Reynolds number of that flow. It changes the radiative properties of the hot gas.

2. Replace air by other gases, including noble gases and halogenated hydrocarbons. These substitutions change the radiative properties of the gas (for example, helium hardly radiates at all at temperatures $< 30,000^\circ$ K). Halogenated hydrocarbons tend to seize and inactivate free electrons and free radicals (hence the use of freon and carbon tetrachloride in fire extinguishers). These substitutions will permit tests of the hypotheses that radiative energy transfer, free electrons and free radicals are required for ETC ignition.

3. Substitute other metals for copper in the electrodes. These will change

the ionization state and radiative properties of the plasma, testing the effects of radiative heating and ionic catalysis.

4. Roughen the surfaces of the propellant discs. This will assist the onset of turbulence in the gas flow between these layers (we roughly estimated Reynolds numbers in the range 10^3–10^4, a range in which this onset depends on surface roughness), and will test the hypothesis that turbulent heat transport is involved in ETC ignition.

5. Place the return current electrode (in a FLARE design) along the axis of the propellant, and provide for current paths to it by vapor-depositing thin conducting layers on the surfaces of the propellant discs or providing thin radial wires. This will make the discharge flow radially between the discs, rather than at their periphery, and may accelerate ignition. By striking the discharge between the discs it will provide increased radiative heating and turbulent heat transport to the discs, without requiring the plasma to flow between them from the FLARE electrode at the periphery of the shell. This experiment does not test any specific physical process, but does investigate an alternative design.

The above experiments are selected to further understanding of ETC ignition. Some may also give results that suggest ways to improve performance, and, if so, the insights should be incorporated into the ETC program.

4.2 Optimization of FLARE Igniters

While an impressive amount of work has already been done in developing the FLARE ignition devices and they may be more than adequate for the XM-291 demonstration project, it is unlikely that FLARE has reached anything near an optimal design. The following remarks explore some possible directions of improvement.

First, it is useful to discuss the ways plasmas can be contributing to the ignition of the propellant in more depth than simply saying the words radiation, convection and conduction.

Plasmas can affect propellant chemistry by:

- radiation – heating as well as photochemical effects
- delivering mechanical energy and heat directly
- stirring up the burning propellant gases by driving gas flow
- providing increased pressure early in the chemical discharge
- charged particle effects.

Plasma radiation from partially ionized plasmas can deliver heat to the surface of a solid via UV radiation. The absorption length is 0.01–0.1 mm for UV radiation, making this energy delivery mechanism ideal for propellant ignition. Any low temperature plasma with species like Cu and the constituents of air will be a copious emitter of radiation. However, to maximize UV emission: (1) Cu may not be the best electrode material, (2) one atmosphere is unlikely to be the optimum gas pressure, given the bank energy available, and (3) air may not be the best gas mixture. For example, an alloy such as brass may provide more lines in the UV (as well as the visible), and a lower pressure (e.g. = 0.1 atm) may enable UV lines of nitrogen and oxygen to be excited. Perhaps an argon backfill to pressures like 0.01-0.1 atmospheres, for example, would be good to try. Clearly such tests could and should be done with just the current FLARE before trying it even with subscale rounds, although the geometry should be the same as was used for the previous radiation measurements for ease of comparison.

Once the vapor has ignited and chemical burn begins, the energy density delivered by the chemical reactions to the solid surface ought to greatly exceed the UV energy density, assuming that the UV isn't absorbed in the burning gases before it gets to the solid surface. Thus, gas mixing induced by plasma jetting and/or turbulent flow ought to be more important than UV after initiation. However, the UV could still contribute to increasing the propellant burn rate by breaking chemical bonds (e.g. in oxygen molecules) and creating radicals in the vapor or at the surface. Visible emission is also plentiful, but the absorption length is a few mm, which implies a much lower energy density. This wavelength range can break $\sim 1.5 - 2.5$ eV bonds, and so it may create radical species that enables the propellant to burn faster. However, it may merely serve to pre-heat the propellant so that its burn rate becomes independent of its initial temperature. Kevin White [2] showed a figure for JA2 propellant grains that has not actually burned has nevertheless had been physically modified to a depth of 4-5 mm. Perhaps this arises from visible emission. The same thoughts concerning optimizing the total radiation output of the plasma-FLARE conductor combination come up here as came up in the discussion of UV.

Energy can also be delivered to the propellant surface by the plasma by convection and/or conduction. Both will serve to raise the temperature at and near the surface, contributing to the propellant vaporization and ignition along with the UV. Although the UV reaches the surface effectively instantly, on a 1 ms time scale, especially from a distributed source like FLARE, the plasma itself can also reach the surface if its pressure is high enough to push the ambient air ahead of it. (It would be interesting to see what would happen if the ambient air density were lowered in order of magnitude steps.)

Because there can be substantial jetting of plasma toward the propellant surface in some plasma sources, including at early time from FLARE, it is possible that turbulent flow is induced in the reacting gas cloud that is moving away from the propellant towards the source, and even between the "cookies". This may enhance heat flow from the hot gases to the surface, as well as mixing the vapor from the various grains in the propellant more thoroughly as they vaporize. This suggests roughening surfaces, especially between cookies, changing the gas pressure, etc.

If the plasma densities and temperatures are as high as estimated, the plasma could provide a significant back-pressure on the reacting vapor early on, possibly increasing the initial burn rate by increasing the density in the vapor cloud. The peak plasma pressure on p. 111 in the JANNAF report [3] is certainly significant (over 100 atmospheres). The geometry makes it look like the high peak pressure may be kinetic pressure, not static pressure, so that jetting may still be the more important effect. Finally, consider the possible effects on propellant burn of the charged particle species in the plasma because they are charged particles. Thus, we are not referring to the fact that they carry current, enabling energy transfer from the capacitor bank to the plasma, or the fact that $j \times B$ forces in the plasma may push plasma into the propellant or cause turbulence and improve mixing of hot gases, or any of the other effects already discussed. The main point here is that we expect the plasma to be weakly ionized. One atmosphere of air (about 10^5 Pa) equates to a gas density of about $2.7 \times 10^{19}/\text{cm}^3$ at standard conditions, and is mostly diatomic molecules. Vaporized propellant close to the solid propellant surface is going to be higher density than this. Because oxygen and nitrogen molecule dissociation energies are only a few eV, in a ms discharge at 1-2 eV, these molecules are probably fully dissociated. We have obtained some calculations of the various species present in Cu and Al discharges at various temperatures near 1 eV, in equilibrium, assuming equal mole fractions of Cu or Al and gas atoms initially. Those calculations show a high level of dissociation and an electron density of 10-20% of the initial neutral density. Since we have a pulsed, dynamic plasma at 1 eV in contact with surfaces 1 mm apart in high pressure gas, the ionization fraction could well be considerably less than this amount. The reason is that at low temperature, the plasma requires $\sim$ 100 eV per electron-ion pair generated

[4] (because there is so much radiative energy loss relative to energy that goes into ionization). Therefore, only if the input power can balance the plasma loss processes and maintain the species balance, and specifically the ionization, can the equilibrium conditions be maintained and the electron density be as high as 10-20%. A proper calculation of this balance is beyond the scope of the present discussion (and of the state-of-the-art of present modeling capabilities).

Assuming the fractional ionization is relatively low, there simply will not be enough charged particles to induce much chemistry compared with the number of O radicals, UV photons, etc. Therefore, the effects of having electrons, positive ions and negative ions around is likely to be relatively small as a direct effect. [4] See, for example, M.A. Lieberman and A.J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing* (Wiley, New York, 1994), p. 81.

The gaps between the cookies are purposely made narrow in order to maximize the propellant packing fraction. Therefore, it could be beneficial especially for harder-to-ignite propellants to actively generate plasma in between the cookies. This could be done by running a return current path back up the center (perhaps using the part of the projectile that passes through the middle of the propellant) and depositing thin film stripes of Al on the faces of the cookies. In that case, once the circumferential plasma has formed and moved into the surface of the cookies, could flow through the Al stripes to the center, and form some highly radiating Al plasma between the cookies.

Another possible variation to test is motivated by a Rex Richardson comment [1] that the Cu seems to be eaten away by the discharge faster than is expected from Ohmic heating. This could be either good or bad, depending upon whether the vaporized Cu participates in the discharge and contributes to the UV radiation, plasma flow, etc., or forces the discharge out of the Cu and into the gas, which may not be so good if radiation is important. Testing a material like Al as the conductor should make a major difference both because it vaporizes at lower temperature and because (at least in the exploding wire experiments at Cornell University) it expands considerably faster than Cu, and should break down more easily and form a larger volume of metal-ion-containing plasma. It is not obvious whether this will turn out to be better or worse for igniting a propellant. However, if laboratory experiments with proper instrumentation are done in advance so that it is known how the FLARE characteristics are actually changed, the experiments with propellant may tell us what the important discharge factors are for optimizing projectile performance.

We suggest running a return current path back up the center and depositing thin film stripes of Al on the faces of the cookies. In that case, once the plasma has reached the outer circumference, current could flow through the Al strips to the center, and form some highly radiating plasma between the cookies from the Al. This should be tested.

An important point illustrated by these suggestions is that it will be very difficult to improve tank cannon performance by starting from first principles for many, many years. Therefore, empiricism guided by hypotheses and the results of small scale laboratory experiments, is more likely to lead to scaling improved tank cannon and artillery shell performance in the next several years than trying to carry out very difficult computer modeling of as yet poorly understood processes. In fact, such an empirical approach is a good way to help modelers determine the important physics and chemistry that needs to be included in their codes.

References

[1] Rex Richardson, personal communication, July, 1998.

[2] Kevin White, presentation to the JASON Study, July 9-10, 1998.

[3] Oberle, W., K.J. White, and J. Powell, "JANNAF Combustion Subcommittee Workshop: Plasma Propellant Temperature Sensitivity Reduction Using Electrothermal-Chemical (ETC) Propulsion Concepts", ARL-TR-1579, December 1997.

[4] Liberman, M.A. and A.J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing* (Wiley, New York, 1994), p. 81.

A APPENDIX: LIST OF BRIEFERS

The study group received a comprehensive set of technical briefings from the scientists and program managers involved in developing Electro Thermal-Chemical (ETC) gun technologies. The briefings were given over the two-day period July 9–10, 1998 in San Diego. Briefers, institutional affiliations, and presentation titles are listed below.

- William Oberle (Army Research Laboratory), "Electro Thermal-Chemical (ETC) Gun Propulsion: Background and Program Overview."
- Robert Shaw (Army Research Office), "Army Research Office Workshop on Plasma/Propellant Interaction for Ignition." [Presentation given by W. Oberle]
- David R. Lewis (Defense Special Weapons Agency), "ETC Propulsion Activities Overview."
- Gary T. Phillips (Science Applications International Corporation), "Army/ DSWA ETC Direct Fire Joint Program."
- Kevin White (Army Research Laboratory), "ARL Efforts in Plasma-Propellant Interaction."
- Rex D. Richardson (Science Applications International Corporation), "PPI Experimental Efforts Under Joint Army/DSWA Direct Fire Program."
- Philip L. Varghese (University of Texas at Austin), "Emission Spectroscopic Measurements and Analysis of a Pulsed Plasma Jet."
- Mohamed Bourham (North Carolina State University), "NCSU Efforts in Plasma-Propellant Interaction."

- Rose Pesce-Rodriguez (Army Research Laboratory), "Overview of ARLs FY99 PPI Basic Research Program." [Presentation given by W. Oberle]
- Gloria Wren (Army Research Laboratory), "ETC Modeling and Simulation Overview."
- Lindsey Thornhill (Science Applications International Corporation), "Plasma Generator - Injector Modeling."
- Gloria Wren (Army Research Laboratory), "Influence of Radiation on Propellant Heating."
- Michael J. Nusca (Army Research Laboratory), "Plasma Flow and Convection in the ETC Gun." [Presentation given by G. Wren]
- Chia-Chun Hsiao (Science Applications International Corporation), "ETC Modeling Summary."

In addition to the presenters listed above, Richard F. Johnson (United Defense LP) and Fred Su (Science Applications International Corporation) participated in the discussions at the briefings provided helpful information to the study.

DISTRIBUTION LIST

Director of Space and SDI Programs
SAF/AQSC
1060 Air Force Pentagon
Washington, DC 20330-1060

CMDR & Program Executive Officer
U S Army/CSSD-ZA
Strategic Defense Command
PO Box 15280
Arlington, VA 22215-0150

Superintendent
Code 1424
Attn Documents Librarian
Naval Postgraduate School
Monterey, CA93943

DTIC [2]
8725 John Jay Kingman Road
Suite 0944
Fort Belvoir,VA 22060-6218

Dr. A. Michael Andrews
Director of Technology
SARD-TT
Room 3E480
Research Development Acquisition
103 Army Pentagon
Washington, DC 20301-0103

Dr. Albert Brandenstein
Chief Scientist
Office of Nat'l Drug Control Policy
Executive Office of the President
Washington, DC 20500

Dr. H. Lee Buchanan, I I I
Assistant Secretary of the Navy
(Research, Development & Acquisition)
3701 North Fairfax Drive
1000 Navy Pentagon
Washington, DC 20350-1000

Dr. Collier
Chief Scientist
U S Army Strategic Defense Command
PO Box 15280
Arlington, VA 22215-0280

D A R P A Library
3701 North Fairfax Drive
Arlington, VA 22209-2308

Dr. Victor Demarines, Jr.
President and Chief Exec Officer
The MITRE Corporation
A210
202 Burlington Road
Bedford,MA01730-1420

Mr. Frank Fernandez
Director
DARPA/DIRO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Mr. Dan Flynn [5]
Deputy Chief
OSWR
CDT/OWTP
4P07, NHB
Washington, DC 20505

Dr. Paris Genalis
Deputy Director
OUSD(A&T)/S&TS/NW
The Pentagon, Room 3D1048
Washington, DC 20301

Dr. Lawrence K. Gershwin
NIO/S&T
2E42, OHB
Washington, DC 20505

Mr. David Havlik
Manager
Weapons Program Coordination Office
MS 9006
Sandia National Laboratories
PO Box 969
Livermore, CA94551-0969

Dr. Helmut Hellwig
Deputy Asst Secretary
(Science, Technology and Engineering)
SAF/AQR
1060 Air Force Pentagon
Washington, DC 20330-1060

Dr. Robert G. Henderson
Director
JASON Program Office
The MITRE Corporation
1820 Dolley Madison Blvd
Mailstop W553
McLean, VA 22102

DISTRIBUTION LIST

J A S O N Library [5]
The MITRE Corporation
Mail Stop W002
1820 Dolley Madison Blvd
McLean, VA 22102

Mr. O' Dean P. Judd
Los Alamos National Laboratory
Mailstop F650
Los Alamos, NM 87545

Dr. Bobby R. Junker
Office of Naval Research
Code 111
800 North Quincy Street
Arlington, VA 22217

Dr. Martha Krebs
Director
Energy Research, ER-1, Rm 7B-058
1000 Independence Ave, SW
Washington, DC 20858

Dr. Ken Kress
Investment Program Office (IPO)
1041 Electric Avenue
Vienna,VA 20180

Lt Gen, Howard W. Leaf, (Retired)
Director, Test and Evaluation
HQ USAF/TE
1650 Air Force Pentagon
Washington, DC 20330-1650

Dr. John Lyons
Director of Corporate Laboratory
US Army Laboratory Command
2800 Powder Mill Road
Adelphi,MD 20783-1145

Dr. Arthur Manfredi
ZETA Associates
10300 Eaton Drive
Suite 500
FairfaxVA 22030-2239

Dr. George Mayer
Scientific Director
Army Research Office
4015 Wilson Blvd
Tower 3, Suite 216
Arlington, VA 22203-2529

Ms. M. Jill Mc Master
Editor
Journal of Intelligence Communication
Investment Program Office (IPO)
1041 Electric Avenue
Vienna,VA 20180

Dr. Thomas Meyer
DARPA/DIRO
3701 N. Fairfax Drive
Arlington, VA 22203

Dr. Bill Murphy
ORD
Washington, DC 20505

Dr. Julian C. Nall
Institute for Defense Analyses
1801 North Beauregard Street
Alexandria, VA 22311

Dr. Ari Patrinos [5]
Associate Director
Biological and Environmental Research SC-70
US Department of Energy
19901 Germantown Road
Germantown,MD 207874-1290

Dr. Bruce Pierce
USD(A)D S
The Pentagon, Room 3D136
Washington, DC 20301-3090

Mr. John Rausch [2]
Division Head 06 Department
NAVOPINTCEN
4301 Suitland Road
Washington, DC 20390

Records Resource
The MITRE Corporation
Mailstop W115
1820 Dolley Madison Blvd
McLean,VA 22102

Dr. Victor H Reis [5]
US Department of Energy
DP-2, Room 4A019
Mailstop 4A-028
1000 Independence Ave, SW
Washington, DC 20585

DISTRIBUTION LIST

Dr. Fred E. Saalfeld
Director
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Dr. Dan Schuresko
O/DDS&T
OSA/ATG
Room 23F20N, WF-2
Washington, DC 20505

Dr. John Schuster
Submarine Warfare Division
Submarine, Security & Tech
Head (N875)
2000 Navy Pentagon Room 4D534
Washington, DC 20350-2000

Dr. Michael A. Stroscio
US Army Research Office
P. O. Box 12211
Research Triangle Park,NC27709-2211

Ambassador James Sweeney
Chief Science Advisor
USACDA
320 21st Street NW
Washington, DC 20451

Dr. George W. Ullrich [3]
Deputy Director
Defense Special Weapons Agency
6801 Telegraph Road
Alexandria, VA 22310

Dr. David Whelan
Director
DARPA/TTO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Dr. Edward C. Whitman
US Naval Observatory
Nval Oceanographers Office
3450 Massachusetts Ave, NW
Washington, DC 20392-5421