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Implications of EMP from H.E. Detonation

L. F. Wouters

January 15, 1970

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Symposium Proceedings
AFSWC Symposium, Albuquerque, New Mexico
March 12-13, 1970

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Abstract

Implications of EMP from H.E. Detonation

L. F. Wouters

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Estimates of charge densities and dipole moments are made for the high explosive tests observed by Walker. (UCRL 72150 - Ref. 6) The main field generation mechanisms appear to be associated with ionic charge separation mechanisms. Electronic conductivities are too high during the first tens of microseconds to support a significant internal field stress. A hypothesis is proposed and tested for the later, millisecond - scale fields, which is based on negative-charge "sweeping" by atmospheric O_2 . This is closely associated with hydrodynamic air mass displacement effects, in semi-quantitative agreement with observations.

Implications of EMP from H.E. Detonation

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Introduction

Reports of observation of electromagnetic energy from H.E. detonation extend as far back as the first World War. Most such reports are highly subjective and non-quantitative. Since the second World War, a number of modest observations have been made using appropriate equipment (that is, oscilloscopes).^(1,2) Generally these displayed an em signal as an apparently random pattern of very high frequency noise of small local field amplitude. The reported difficulties in obtaining consistently repetitive data, and the problems in relating such observations to plausible source models, tended to discourage extensive studies. H.E. EMP acquired an aura of hashy mystique.

Two recently reported sets of observations significantly changed this picture. Both exercises produced extensive and relatively reproducible em pulse waveforms of coherent low-frequency content:

(1) The Soviet work by members of the Dremmin Laboratory.⁽³⁾ Figure 1 is a trace reproduction of one of their oscillograms of the local E-field generated by a 1.3 kg cylindrical charge for which $h/d = 1$.

(2) The "Sailor Hat" observations by a team from AWRE (U.K.)⁽⁴⁾ and by a BTL group.⁽⁵⁾ Sailor Hat Event D was a 500-ton, hemispherical H.E., surface detonation. A typical AWRE record taken at 300 feet is shown in fig. 2. There had also been some marginal evidence on Snowball, an earlier similar event.

The Soviet work in particular, suggested that there might be some prospect of correlating the em wave form with certain hydrodynamic phases of a test H.E. explosion. However, that report is somewhat deficient as to certain quantitative specifications.

The LRL program was thus undertaken to:

- Verify and extend the Soviet experiments.
- Obtain additional, related phenomenological data.
- Identify possible applicational significances.
- Attempt to develop a source/generator concept.

As we have seen⁽⁶⁾, the most significant addition to this business, is the time-synchronous fast photography. These observations do permit point-to-point correlation of the em waveform with optical explosion features. Our experiments have also more precisely defined the time scales of various dynamic features relative to the instant of firing: It was easy to identify the initial small signal contribution as being related to the firing system.

Applicational aspects here include instrumentational problems, such as those sometimes experienced in H.E. simulation and hydrodynamic experiments. Time-dependent observations in such work, include close-in shock TOA, pressure, particle velocities, material stress, and so forth. A certain fraction of such measurements exhibit strange interference in the forms of hash in the wrong place, multiple triggers, unexplained base line shifts, etc.⁽⁷⁾

In such applicational connection, it is useful to have a scalable source model. In past H.E. work, em field generation has usually been summarily attributed to separation of charges due to differential velocity effects. Here I will attempt to attach a somewhat more definitive and quantitative description to that primitive concept.

To that end, the philosophy adopted in interpreting the LRL experiments, is one of accepting the least complex alternative which is not contrary to the data, and of not turning to exotic and mysterious explanations until all orthodox avenues were closed. (Fortunately, this has not been necessary!)

Some Early Charge Numerology

First, let me develop some rough numbers which a source mechanism is to satisfy. These can be rather directly inferred from the general character of our data and from known H.E. detonation properties.

Dipole Moment. In initial evaluations of strange em sources, it is customary to adopt a multipole approximation as a reference model. For a number of reasons, this appears to be a rather good approach here. The wavelengths are very large as compared to the source dimensions. The polarizations, distributions, weakness of close-in magnetic components, and the time-scale of the local fields, turn out to be almost uniquely satisfied by a vertical electric dipole moment.

For such an equivalent source, we can scale the observed peak fields according to:

$$E_{\theta} = \frac{1}{4\pi k_0} \frac{p}{r^3} \sin \theta$$

where $p = \delta q h$, the dipole moment. In the case of the shots of "central" geometry ($d \sim h$), $E_{\theta} \sim 10$ v/m at 10m, and we find: $p \sim 10^{-6}$ coulomb-meters.

From the photographic records, the em source dimensions appear to be of the order of one meter (h). Note also fig. 3. This then at once would require that the differential charge (δq) should be of order 10^{-6} coulomb. Of course, this says nothing about how this charge becomes differentiated, nor about its detailed history.

Ion Densities. We can obtain a similar number for the charge population by considerations borrowed from first-order theory of stellar atmospheres. The dynamic equilibrium for a "simple" ionized gas is:

$$\frac{n_1 n_e}{n_0} = v f_e e^{-x/kT} \sim \frac{n_e^2}{n_0}$$

This describes the population of components of form:

Also:

v is a ratio of statistical weights for the eligible states -
(a fraction not far from unity).

x is the ionization potential (~ 13.5 ev)

f_e is the electronic partition function written:

$$f_e = \left(\frac{\sqrt{2\pi mkT}}{h} \right)^3$$

The HE reaction temperature here is of the order of 4600°K. The temperature of isothermally contained products (behind the burn front) is indicated to be about 2/3 this⁽²⁾, so I will use $T \sim 3200^\circ\text{K}$. Then $f_e \sim 10^{21}$ (cgs). I use the ionization potential for Hydrogen here because it appears that the x values for explosion products lie in the range 12 to 15 ev. The exponential term is then $\sim 10^{-22}$ and:

$$\frac{n_e^2}{n_0} \sim .03$$

The ionized fraction:

$$\frac{n_e}{n_0} \sim \frac{.03}{\sqrt{n_0}}$$

is seen to be relatively insensitive to matter density, so that uncertainty in the assignment of n_0 at early times is not critical. Thus:

$$n_0 \sim 3 \times 10^{19} \text{ (normal air)} \quad n_e/n_0 \sim 5 \times 10^{-12}$$

$$n_0 \sim 3 \times 10^{22} \text{ (solid HE)} \quad n_e/n_0 \sim 2 \times 10^{-13}$$

The fraction of ionized matter is thus of order 10^{-12} and $n_1 \sim n_e \sim 10^9/\text{cm}^3$.

Note that in normal air, the stagnant ionization density is of order $10^2/\text{cm}^3$.

Examination of the "fireballs" in the fast photo records suggests that they represent a volume of hot gas of about 3 m^3 . This would involve $\sim 3 \times 10^{15}$ ions or $\sim 3 \times 10^{-4}$ coulombs of "plasma". We then require a charge separation or distribution asymmetry of only a few per cent to account for the observed dipole moment.

It is worth noting that this estimate is based on a theory applicable to an essentially stationary energy state in a gas. This may not be too far from reality for a short period just following the burn (30-50 μsec) and before hot gas expansion has begun. There is some comfort in that most of the functions in this description are relatively insensitive to precise definition of parameter values. Of course, the volume of ionized gas does extend somewhat beyond the fireballs and no doubt includes the central "doughnut".

These numbers illustrate a striking feature: We are dealing with a source mechanism in which something like 10^{-12} of the matter is involved in an asymmetric distribution, yet the phenomenology appears to be reasonably reproducible and exhibits rational trends. Certainly our experiments were not intentionally controlled in most physical or material tolerances to better than $1:10^3$. It even seems somewhat immune to Soviet-U.S. differences! (Fig. 4)

You will note that there seems to be some ambiguity in this discussion thus far, as to free electrons and ions. This simple model only estimates free negative electron and positive ion densities. The (weak) electron attachment coefficients for burn products such as CO, CO₂, NO, NO₂, are nevertheless significant on this time scale, such that the free electron lifetime would be in the range 10^{-7} to 10^{-6} sec. Thus there is an additional competitive mechanism:

which should shift the ionization equilibrium towards higher ion densities

at early times. (30 to 100 μ sec) This is consistent with high internal conductivities, a neutral plasma model, and no observed field in this time regime.

What about O_2^- and recombination?

O_2 Attachment. Elementary hot atmosphere theory does not take account of the consequences of singular molecular forces, such as is responsible for the affinity of the oxygen molecule for free electrons in the 3000°K domain. In the self-consistent model which I am about to discuss, this O_2^- mechanism is a dominant source feature; fig. 5 displays the behavior of the (3-body) attachment coefficient for $e^- + O_2 \rightarrow O_2^-$. This corresponding attachment rate in STP air is $\sim 2 \times 10^8 \text{ sec}^{-1}$. It is a sufficiently strong affinity as to successfully compete for electrons weakly bound to burn products and microscopic debris fragments.

Ionic Recombination. The ionic recombination rate is much smaller ($X^+ + Z^- \rightleftharpoons X + Z$). For STP $N_2^+ + O_2^-$, it is measured by a mean lifetime of order 10^{-4} to 10^{-3} sec. Inasmuch as the recombination energy is of the order of the thermal energies involved here, it is likely that this equilibrium is also shifted in favor of longer plasma lifetime (i.e. to the left). Of course, recombination is a higher order function of the ion densities; but at very low levels, it is controlled by charge exchange transport in the local ion fields.

On the time scale of the em waveforms, the explosion products become well mixed with air (and hence O_2). The mass of air which eventually comes into thermal equilibrium with those products is of the same order as the masses of explosive used here.

An alternative hypothesis attributes plasma creation to photoionization due to U.V. emitted by the reactants. A brief consideration of the thermo-

dynamics of radiation in the presence of a virtual continuum of matter quantum states (of similar weights) suggests that it could not depart far from a black-body thermal spectrum (on a microsecond time scale). Of course, such a plasma model also does not say anything about macroscopic dipole moments.

Mobilities & Conductivities

Another approach to the dipole source description is that borrowed from antenna radiation theory, in which the radiative element is described in terms of a rate: $I = \frac{\delta q}{\delta t}$, where δt is characteristic of the source pulse time. In such a treatment, δt carries through the entire description, and the physical outcome is no different. But we have more or less implicitly assumed thus far, that the (instantaneous) dipole moment (and hence charge separation) is proportional to the total charge density.

Thus the source current representation has merit in assessing the importance of internal conduction currents. That is, must we write:

$$I_{\text{net}} = \frac{\delta q}{\delta t} - i_{\sigma} ? \quad \text{Or, since the time scale is so long:}$$

$$p_{\text{eff}} = h_{\text{eff}} (\delta q - \sigma E_{\text{int}} \delta t)$$

Evidently "proportionality" fails when σE_{int} approaches $\frac{\delta q}{\delta t}$. Turning to our data for guidance as to this "effective antenna current", I find:

$$\frac{\delta q}{\delta t} = 10^{-6} / 10^{-4} \sim \underline{10^{-2} \text{ amps}}$$

For effective dipole currents approaching or exceeding this number, the internal currents need to be taken into account, whether they arise as "breakdown" or as diffuse charge transport.

There are several ways to estimate E_{int} . As a start here, I simply scale inward ($\frac{1}{r^2}$) from 10 m., obtaining $\sim 10^4$ v/m. (This is good to $\sim \times 2$.) And so we come to the question of σ and charge mobilities.

In STP air, the electron mobility is $\sim .2$ m/sec per v/m. It changes relatively slowly with density and composition, so that it is a reasonable number to use for approximation purposes for early electronic conductivity in the product gases.

Then: $\sigma_e = n_e e \mu \approx 10^{-4}$ mho/m

This leads at once to $\sigma_e E_{int} \rightarrow 1$ amp/m² and it is self-evident why no significant dipole moment can be generated in the early, hot burn, plasma. The corresponding plasma time constant is $K_0/\sigma \approx 10^{-7}$ sec, so that plasma neutrality can easily follow the hydrodynamic phenomena. Evidently $i_\sigma \approx \frac{\delta q}{\delta t}$ always. In contrast, the ionic mobilities are of the order of 1/1000 that of the electrons ($\sim 3 \times 10^{-4}$ m/s per v/m.) One obtains late conductivities in the range 10^{-9} to 10^{-7} mho/m. Now:

$$\sigma_i E_{int} \approx 10^{-4} \text{ amp/m}^2$$

It appears that ionic conduction currents are just neglectable, at least to first order.

Later, we will see an implication of internal fields perhaps as high as 10^5 v/m. The "waveform" truncations on certain peaks is believed due to internal Townsend breakdown, perhaps enhanced by the presence of this weak plasma.

The corresponding plasma time constant is then in the range 10^{-4} to 10^{-2} sec, which would be characteristic of unconstrained recovery and plasma oscillation damping. The "tails" of each waveform component should then represent the combined consequences of this "frictional damping", and of ion recombination.

About Burn Products & "Debris". These considerations say little about ionic species, and nothing about the manner in which energy is pumped into the internal field stress associated with their separation, or the polarization of the medium. There is a mixture of burn products here (CO, CO₂, NO, NO₂, H₂O, etc.), whose electron affinity is poorly known. O₂⁻ is a particularly well-researched species. While I hope to show why it is probably the really significant em source constituent here, it is certainly possible that other electronegative (or positive) species may play a competitive, and mechanistically very similar role.

H.E. detonation is not 100% efficient in combustion; our films show evidence of much particulate debris and unoxidized carbon (as "smoke"). Such debris fragments are thought to be in the range of 1 to 100 microns

in diameter. These can also acquire a charge. The electron cross-section behavior of O_2 and N_2^+ , is such as to favor electron scavenging from such charged debris (to O_2^- and N_2). This would lead to a "late, warm, plasma" composed of $Frag^+$ and O_2^- .

Specific Source Model Considerations

Now I will examine the diagnostic evidence in more detail in an attempt to depict a "not-inconsistent" source hypothesis - and I want to stress "hypothesis". The various parametric tests described in the experimental paper⁽⁶⁾, appear to lead to a complex interpretational matrix. I will examine each portion of the waveforms more-or-less separately, making the following identifications (Note again fig. 4):

The firing precursor

The first pulse

The second pulse

For reasons which will become evident, the "unity" h/d waveform is used as a comparative reference.

In some test cases (e.g. Sailor Hat - fig. 2), these components may not be separable in the records.

The significant observational features may be categorized as follows:

1. General field properties:

Vertical E field polarization

No observable H field

Peak E field values: ~ 2 v/m at 10m, first pulse

~ 15 v/m at 10m, second pulse

Field polarities have a complex behavior

2. Waveform features and timing:

First pulse starts at 200 to 500 μ sec, well after the initial burn ~ 15 μ sec. Its duration is ~ 700 μ sec.

Second pulse starts at 2 to 5 msec., following stagnation.

The explosion debris appears relatively motionless. Its duration is ~ 10 msec.

Both pulses are identifiable by general shape throughout the tests, even though there are extensive variations in their detail.

3. Geometrical parameter effects

h/d - There are recognizable trends as this ratio is varied. In particular, geometries near unity appear to maximize the energy content of the second pulse. The first pulse is altered mainly as to polarity. These geometries also exhibit the greatest vertical debris distribution (jetting), and the strongest reflected shock (as seen in the fast photo records).

Height - At 4 meters, the second pulse disappears, without much change in the first pulse.

Symmetry - Both waveform components are suppressed on the spherical shots. (Note fig. 6) But the first pulse is reduced by $\sim 10^2$, while the second pulse changes by only ~ 10 .

4. Hydrodynamic correlations:

First pulse starts somewhat before the end of "fireball expansion" (in reference to spherical case).

Second pulse starts when the ground-reflected shock arrives at the lower fireball. The timing between + & - waveform phases closely corresponds to the shock travel time from lower to upper fireball (in reference to unity cylinder case).

On the basis of this semi-quantitative set of facts, we quickly jumped to some "strawman" conclusions:

During the burn phase (and for some time after), the gas behaves as a neutral plasma. This period is long enough to ensure that subsequent mechanisms are ionic in character. The time-scale and parametric behavior of the first pulse indicates that its source is almost entirely associated with the expanding gas/debris region. It is presently believed to be related to the pressure-density recovery of the rarefied central regions.

For our purposes here, it is supposed that the source region returns to a neutral plasma state between first & second pulses.

In the further course of interpretation, our attention focussed on the second component. Its larger apparent field energy content suggested a greater applicational significance. Its phenomenology is less obscured in the film data, and it seems to be strongly and obviously associated with (reflected) shock wave passage. If we "understood" it, perhaps this would in turn clarify the first pulse; indeed that seems to be the case.

The Second Pulse. The second pulse is almost certainly a consequence of the passage of the reflected shock through the quasi-stable explosion products. It is thus environment-related as well. The negative polarity of the large waveform change associated with shock passage from lower to upper fireball, furnishes perhaps the strongest single clue to source model delineation.

In our early thinking, many hypotheses for charge separation (or current production) of varying complexity and inelegance, were tested and discarded. The character of the quasi-plane reflected shock wave finally suggested that we might be dealing with something like a traveling dipole layer structure, in which the induced polarization is distributed through the shock front. Similar mechanisms have been suggested in the past in connection with other strong-shock situations.

The waveform polarity suggested that this shock interaction was differentially moving the negative charges ahead of the positive ones. In view of the salient role of O_2^- in other long-period em considerations, it was not difficult to conjecture a mechanism sequence in which atmospheric oxygen captures electrons from the debris, and is subsequently swept out of the relatively stagnant cloud of heavy positive debris particles, as O_2^- . Hence the late plasma model outlined earlier.

Indeed, our films show that the visible debris is not displaced (upward) very far by the reflected shock - perhaps one or two cm. The negative ion separation is then presumed to be associated with the gas displacement "wind" behind that shock - perhaps 5 to 10 cm. (rather than with the shock region itself).

This model suggests a slight revision of the reference dipole outlined at the beginning. The dipole moment can be equally well generated as a result of a polarization or net charge gradient moving vertically along the length of the source region. Imagine a source plasma cylinder of uniform charge density (O_2^- and $Frag^+$). (Fig. 7) Evidently as the dipole layer moves incrementally upward, each incremental layer returns to neutrality as the interaction region moves out. However, we are eventually left with the same quantity of initially displaced charge, now separated by the height of the cylinder. Thus results the slow build-up of the (negative) dipole moment as exhibited in the second pulse traces.

The self-consistent value for the polarization here, is $\sim 10^{-7}$ coulomb/m² and the corresponding instantaneous charge displacement (or dipole layer thickness) would be ~ 10 cm. This leads to a peak field internal to the dipole of order 10^5 volts/meter, which is sufficiently high to invoke field limiting mechanisms, such as Townsend discharge. At this time, this model feature and the data are too qualitative to do more than indicate a consistency with the very apparent waveform peak-clipping in the data.

The smaller second pulses observed for the "tall" h/d case and the spherical tests, most probably manifest the greater dispersion in debris distribution and the greater divergence in reflected shock for those cases. Our apriori selection of test geometries did not anticipate this effect of a strong reflected shock on otherwise spherically-symmetric shot debris.

But this model is far from perfect. Aside from its qualitiveness, there are some evident gaps and inconsistencies. In certain cases, the second pulse first goes positive just as the shock returns to the visible debris region. Perhaps there are other, positive ions also involved; perhaps there are "striations" in the debris distribution. Certainly there are temperature-composition gradients here which have not been taken into account. It is possible that this is a temporary local quadrupole effect due to initial O_2^- displacement into the dense, relatively conductive HE plasma. The ground surface field would then have positive polarity, as seen by our sensors. (Which also "work against ground.")

The First Pulse. The conditional success of that second-pulse model provided some strong inference with respect to first-pulse interpretation. Another clue came from the detailed explosion calculations for the spherical tests, one of which appears in fig. 8. As seen there, the first pulse occurs somewhat prior to initial fireball stagnation ($\sim 700 \mu\text{sec}$), and about at the time that the shock front is no longer able to sustain a large pressure differential. Extensive inward air penetration then occurs.

Again, we postulate that a similar molecular mechanism takes place as for the second pulse. The atmospheric oxygen picks up electrons on the way in, leaving a positive fragment shell behind. (Fig. 9) If the situation was perfectly symmetrical, all the field would be internal. In these tests, some hydrodynamics asymmetry was unavoidable, due to the firing fuse and the nylon suspension, resulting in the small observed signal.

The cylindrical geometry can be rationalized as a vertical, conical, solid segment of the spherical situation. (Also shown in fig. 9.) In those cases, this sequence should occur at an earlier time, since the shock/debris distribution has a much greater surface to volume ratio (and it does). The charge distribution asymmetry is obviously much greater, both in the individual upper & lower axial fireballs, and in their net difference. (Note fig. 3) There is perhaps a hint of a quadrupole component, but this descriptive hypothesis represents the limit of our present state of interpretation.

We can obtain a first-order estimate of the electric dipole moment for the first pulse, via a simple geometric approximation. The volume asymmetry is depicted as a "nest of cylinders" (fig. 7):

$$\frac{V_{\text{top}} - V_{\text{bot}}}{V_{\text{disc}} + V_{\text{top}} + V_{\text{bot}}}$$

For this illustrated 2:1 case, this obtains 2%.

Next, the total charge quantity is $\sim 3 \times 10^{-4}$ coulombs (taken from previous estimates, above). Then the amount involved in asymmetric volume distribution is $\sim 5 \times 10^{-6}$ coulombs. The charge separation is $\sim .2$ m, on the basis that the top of the cylinder encounters the incoming sides at about that distance. This effect also controls the quantity of matter involved in charge exchange due to "oxygen sweeping". First-order account is taken of this by a factor $\frac{h}{r_0} \sim .2$. (r_0 is related to the spherical case radius at penetration time.) Thus we get: $\sim 2 \times 10^{-7}$ coul.-met. This number is very sensitive to the geometric and physical details; it only establishes the order of magnitude. At 10 m, this predicts ~ 2 v/m. The observed peak value was 3 v/m. (This is more fortuitous than intentional!) Again, much the same reservations (as to completeness and "perfection") apply to this "explanation", as I invoked on the second pulse model.

It is interesting to note that the initial polarity of the Sailor Hat waveforms, is positive, as one would require from this model. In those 500-ton surface tests, it is hardly appropriate to speak of a "second-pulse" in the same sense as for our 3 lb. suspended charges.

Thus we see that so far, conventional atomic physics appears to furnish first-order source hypotheses which grossly satisfy the observations, without great strain. As yet, there seems to be no reason to appeal to "magick".

* Work performed under the auspices of the U.S. Atomic Energy Commission.

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FIGURES

- (1) Typical Soviet Trace
- (2) Typical AWRE Record
- (3) Explosive Profile for $h/d = 2$
- (4) LRL Record for $h/d = 1$
- (5) Three body attachment coefficient, etc.
- (6) LRL Record for Spherical case.
- (7) Plasma cylinder approximation for "Second Pulse Model"
- (8) Shock History, Spherical case (Hydrodynamic Calculation)
- (9) Spherical segment approximation for "First Pulse Model"

Fig. 1
Typical Soviet Trace ($H/D = 1.0$)

Vertical electric field at 300 feet.
Fig 2 TYPICAL AWRE RECORD

Fig.3 EXPLOSIVE PROFILE FOR $H/D=2$
outlines of opaque boundary

Fig.4 LRL RECORD FOR $H/D=1$

Soviet data shown dashed

Fig.5 Three-body attachment coefficient for molecular oxygen as a function of temperature

Fig.6 LRL RECORD FOR SPHERICAL CASE

1/8 mass case shown dashed

Fig.7 PLASMA CYLINDER APPROXIMATION
FOR "SECOND PULSE MODEL"

Fig. 8 SPHERICAL CHARGE GROWTH CURVE

Fig.9 SPHERICAL/SEGMENT APROXIMATION
FOR "FIRST PULSE MODEL"

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