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PREDICTION OF GUN MUZZLE FLASH

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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This report presents some recent work on improving a simple, semiquantitative, muzzle flash predictive methodology developed by Carfagno, in his "Handbook on Gun Flash". The improved methodology was then applied to evaluating several possible solutions for reducing muzzle flash for a new 8-inch propelling charge. Later experimental results showed satisfying agreement with the earlier predictions.

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I. INTRODUCTION

Muzzle flash has been a phenomenon accompanying the use of firearms for centuries. The problem of detection by an enemy has long been accepted as necessary, though undesirable. Only in the more modern history of warfare has it been recognized that extensive muzzle flash is not always a natural and unavoidable consequence, i.e., propelling charges can often be designed to minimize flash. This factor as well as the loss of night vision of an artillery crew and the observation of increased muzzle blast because of muzzle flash have led to some substantial efforts in the past to develop a working methodology for controlling gun flash.

Until the 1950's, the efforts to control muzzle flash had been largely empirical. The approaches fall generally into the categories of mechanical flash suppressors or flash hiders and chemical flash suppressants[1,2,3] either added to the basic propellant formulation or as a separate component of a propelling charge. The substantial progress of the fifties in developing a more satisfying, quantitative, physical, and chemical description is summarized in the reports by Young[4] and Carfagno[5]. The handbook by Carfagno is of special note since it represents an attempt at developing a serious quantitative approach at predicting the occurrence of muzzle flash for a particular gun and propelling charge combination. For a variety of reasons, the methodology developed by Carfagno did not become a routine tool used by propelling charge designers.

In a recent development program of the M188 Propelling Charge for the new self-propelled, 8-inch. Howitzer, M110A2, muzzle flash became an issue. In the engineering development of this charge, muzzle flash had been given a low priority. No serious muzzle flash measurements were made. The implicit assumptions were that, should the extent of muzzle flash prove to be unacceptable, then either more flash reducer will eliminate the problem or the user will waive any muzzle flash requirements.

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[1] *Rudolf Ladenburg, "Report on Muzzle Flash", Ballistic Research Laboratory Report No. 426, Aberdeen Proving Ground, MD, November 1943.*

[2] *Rudolf Ladenburg, "Studies of the Muzzle Flash and its Supression", Ballistic Research Laboratories Report No. 618, Aberdeen Proving Ground, MD, February 1947.* (AD #224762)

[3] *W.S. Gilliam, S.D. Fisher, and H.H. Young, Smoke and Flash in Small Arms Ammunition, Midwest Research Institute, War Department Contract No. W-23-072-ORD-2120, 1948.*

[4] *Henry H. Young, ed., Smoke and Flash in Small Arms Ammunition, Midwest Research Institute, Contract No. DA-23-072-ORD-769, 1954.*

[5] *S.P. Carfagno, Handbook on Gun Flash, The Franklin Institute, Contract No. DA-36-034-501-ORD-78RD, November 1961.*

For the M188 charge, the requirement stated that the muzzle flash was to be no worse than that of the M86A2 Propelling Charge used in the 175-mm Gun. This weapon is known to flash fairly frequently; however, no usable quantitative information was available to adequately define its muzzle flash characteristics. In fact, a well-developed, standardized test methodology was also not available. When the artillery community was exposed to the full extent of the muzzle flash of new 8-inch charge, and a comparison with the 175-mm propelling charge showed that the 8-inch charge was worse, a major reduction in flash was required before the community would accept this charge.

At this point, the authors began collaborating on a systematic methodology for evaluating different options for reducing muzzle flash for the M188 Propelling Charge[6]. Carfagno's "Handbook on Muzzle Flash" proved to be a valuable starting point. Our goal was, therefore, to use whatever rational methodology was available, to adapt or modify it as necessary, and to apply it to the proposed options to eliminate any obviously poor choices. Because of the time available, the development of a complex, transient, viscid flow model with chemical reaction kinetics was obviously out of the question.

II. BACKGROUND

The phenomenology of muzzle flash is usually described in terms of three different and distinct types of flash. Primary flash is considered to be largely the result of radiation being emitted from the hot gases just as they are exiting the muzzle. Intermediate flash is thought to be due to the emission from recompressed and reheated gases passing through a shock disc typical of highly under-expanded flow fields. Recent experimental work by Klingenberg[7] as well as some early work by Ladenburg[1] show evidence of shock-induced reactions due to recompression of the incompletely burned propellant gases as the physical cause of intermediate flash. Secondary flash is defined as the ignition, due to interaction with shock waves, of the mixture of fuel-rich exhaust gases and entrained ambient air. It is this combustion process which results in the extensive, undesirable, and usually unacceptable muzzle flash.

[6] *Ingo W. May, Alan R. Downs, Emerson V. Clarke, Jr., and Jerome M. Frankle, "Review of Study Plan for Vulnerability Assessment of the M110E2 Due to Muzzle Flash", Ballistic Research Laboratories Interim Memorandum Report No. 153, Aberdeen Proving Ground, MD, May 1976.*
(Not Available)

[7] *G. Klingenberg, "Analysis of Gun Muzzle Flash Phenomena", Proc. 4th International Symposium on Ballistics, Monterey, CA, Oct 17-19, 1978.*

The parameters which determine whether a gun is likely to flash are summarized by Carfagno[5] as follows:

1. Propellant Flame Temperature: This propellant variable to a large extent drives the muzzle temperature. Everything else being equal, a propelling charge with a high flame temperature propellant is more likely to flash than one with a cool propellant.

2. Thermodynamic Efficiency: A gun which extracts more energy from the propellant leaves less residual energy in the exhaust gases; hence, the muzzle gases will exit with a lower temperature. Operating a gun at higher pressures or increasing the expansion ratio, i.e., travel, are typical ways of increasing thermodynamic efficiency.

3. Concentration of Combustibles in Muzzle Gases: The concentration of hydrogen and carbon monoxide, the main fuel ingredients in the exhaust stream, affects the ignition limits for the mixture of air and muzzle gases. However, for most gun propellants, the combustibles concentration ranges from 40 to 70 percent. Over this region the ignition limits are only weakly affected.

4. Chemical Flash Reducer: Salts such as potassium sulfate or potassium nitrate have long been known to be effective in suppressing muzzle flash via a free radical chain-breaking mechanism which interferes with the hydrogen-oxygen combustion process. This has the effect of increasing the critical ignition temperature (or ignition delay time) for the combustion of the mixture. Although chemical flash reducers seem like the ideal solution to muzzle flash problems, it must be kept in mind that the efficient potassium salts do cause significant amounts of smoke, which, during daylight gun operation, may be quite troublesome. The addition of an inert salt also causes a slight energy penalty.

The effects of the last two parameters on the critical ignition temperature T_c are depicted in Figure 1. One conclusion, drawn by Carfagno, from these data derived from extensive shock tube ignition studies, is that flash reducer concentrations exceeding two percent are probably ineffective.

The concept for muzzle flash prediction as used by Carfagno is depicted in Figure 2. The basic idea underlying this concept is that muzzle flash can occur if the physical heating of the gases due to recompression exceeds the chemical ignition limits.

The problem then reduces to one of obtaining good estimates for the physical heating temperatures developed in the flow field before secondary combustion occurs.

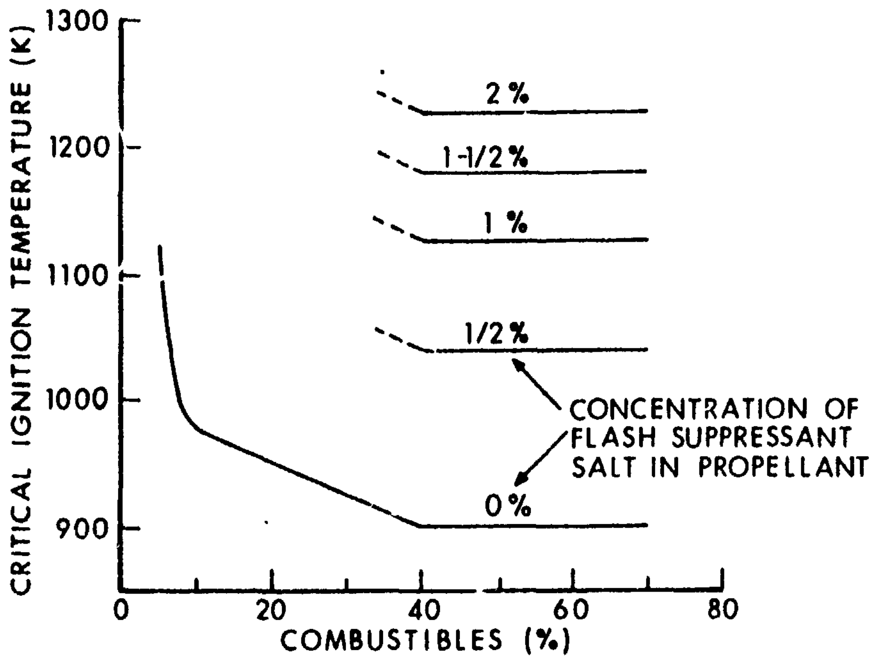

Figure 1. Effects of Flash Reducer and Gun Exhaust Combustibles on Ignition Temperature

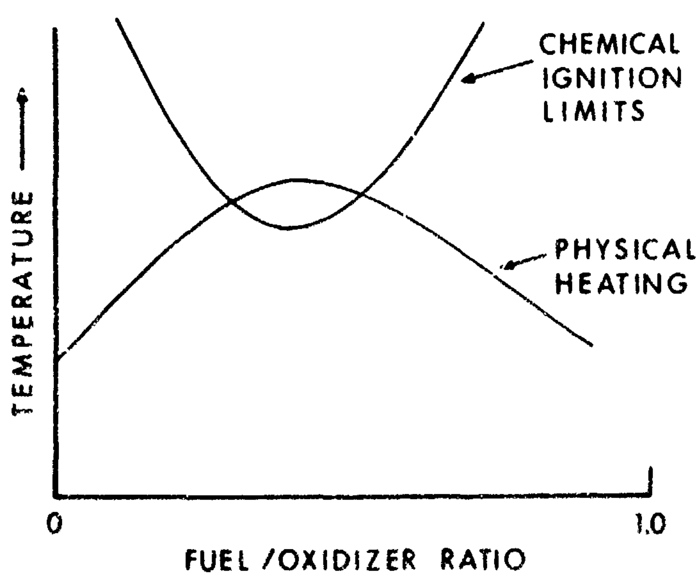

Figure 2. Basic Carfagno Concept for Predicting Muzzle Flash

III. CARFAGNO'S METHODOLOGY

Carfagno''s methodology is reviewed in this section and an error is corrected. A simplified deviation is presented for the temperature equations.

A representative snapshot schematic of the muzzle flow field shown in Figure 3, is taken from an informative review by Schmidt[8]. The important factor to be noted is the complexity of this 2-D, axisymmetric flow field, its transient nature, and the turbulent mixing with the ambient air. If reaction chemistry is now superimposed, one has an essentially intractable situation, at least from a rigorous modeling standpoint considering today's state-of-the-art.

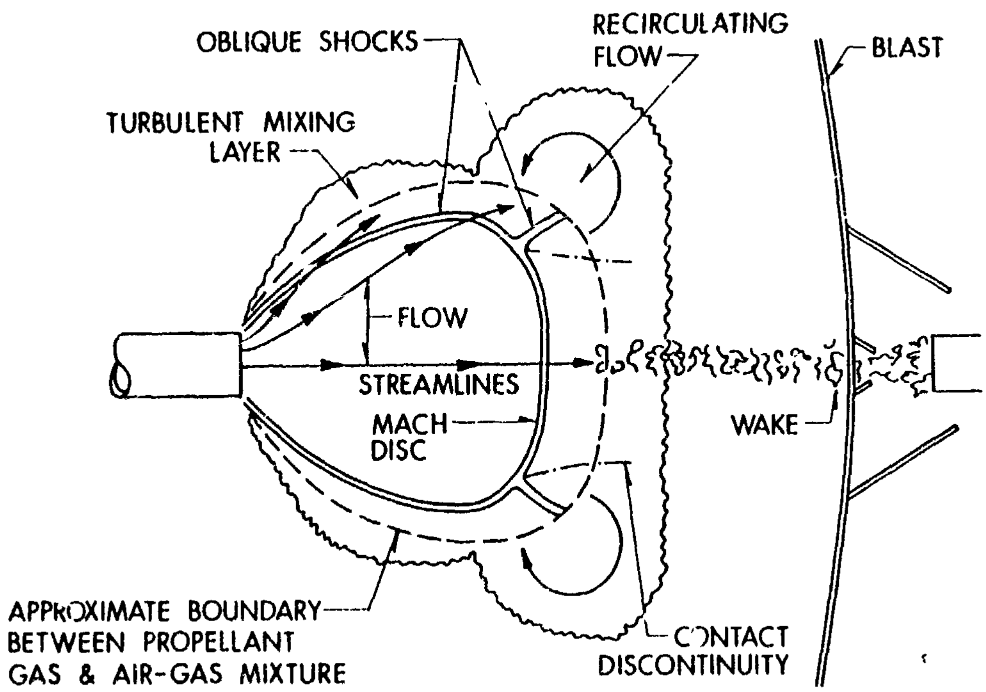

Figure 3. Schematic of Propellant Gas Ejection Flow

Carfagno simplified this complex flow field into three different, one-dimensional shock tube model approximations. These approximations, illustrated in Figure 4, referred to as Cases A, B, and C, differ in whether shock heating is allowed, and whether mixing occurs before or after shock heating. In Case A, the flow field is without any shock formation; only isentropic expansion to atmospheric conditions is considered with mixing occuring after expansion. This case was rejected by Carfagno both on physical as well as empirical grounds. It may, however, be useful as limiting case for analyzing muzzle devices which attempt to eliminate shock formation. Cases B and C are also illustrated in

[8] *Edward M. Schmidt, "Muzzle Devices, A State-of-the-Art Survey, Vol. I: Hardware Study", Ballistic Research Laboratories Memorandum Report No. 2276, Aberdeen Proving Ground, MD, February 1973.* (AD #909325L)

Figure 4. Because he obtained better agreement betwee his analysis and experiment, Carfagno chose Case B as more suitable for flash predictions. For this case, as well as for Case C, "ideal" gun muzzle gas temperature and pressure are computed if one is given the total propellant energy, the kinetic energy imparted to the projectile, and the total gun volume assuming ideal gas equation of state. The muzzle gas is then expanded to atmospheric conditions, mixed with an arbitrary ratio of air, and then passed through the shock disc where recompression, reheating, and subsequent expansion occur. The temperature of the expanded flow, computed for all mixture ratios, is then compared with the critical ignition temperatures shown in Figure 1. A flash assessment is then made. There are, however, several difficulties with the Case B analysis. The experimental work by Schmidt[9] indicates that mixing occurs largely after the muzzle gases pass through the shock bottle. If shock heating of the mixture did occur, then ignition of the mixture is virtually always predicted during recompression

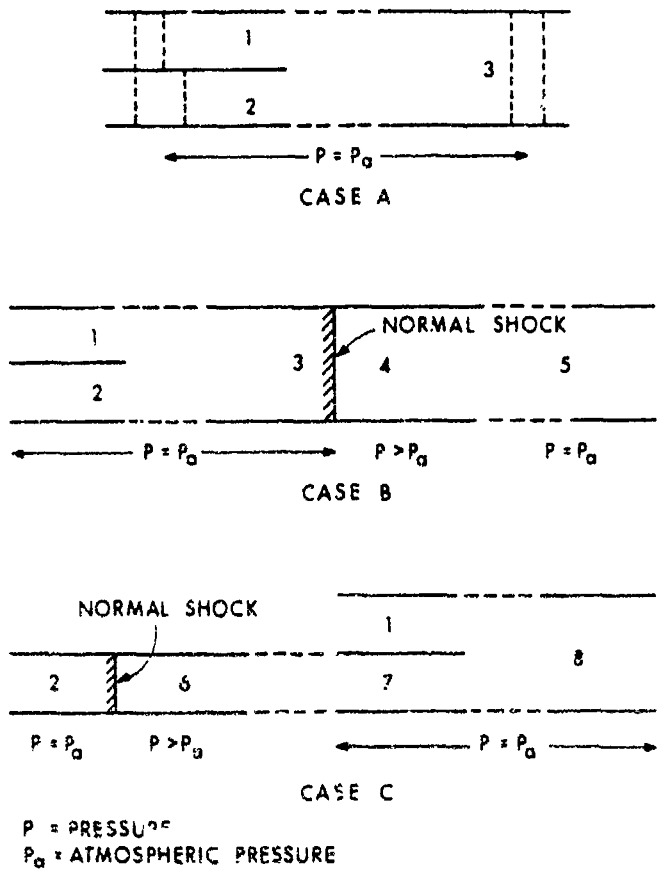

Figure 4. Carfagno 1-D, Idealized Flash Models

[9] *Edward M. Schmidt and Donald D. Shear, "The Flow Field About the Muzzle of an M-16 Rifle", Ballistic Research Laboratories Report No. 1692, Aberdeen Proving Ground, MD, January 1974.* (AD #916646L)

in the shock region. One has to invoke some sort of residence time requirement to avoid this difficulty. Hence, on physical grounds, Case B should be rejected. Nevertheless, Carfagno obtained better agreement with experiment using the Case B than with the Case C analysis, which is performed in a similar manner except that mixing is introduced after shock heating and expansion. The reason became obvious when we found that Carfagno computed the temperatures for Case C incorrectly. Basically, he used the jump condition relation of the "mixed" Case B analysis for computing the "unmixed" Case C jump condition.

In addition to correcting the error by Carfagno, we at the same time computed more realistic input conditions for the muzzle temperature and pressure. They are obtained from typical interior ballistic simulations[10] which use a more realistic equation of state, incorporate a realistic pressure gradient description, and account for losses due to friction and heat transfer. With these modifications, as will be shown in the next section, the more realistic Case C (Real) analysis results in computed flow temperatures similar to the ideal gun, ideal gas Case B (Ideal) analysis. Hence, the good correspondence found by Carfagno between his Case B analysis and the observed flash characteristics for approximately 70 gun systems must be considered somewhat fortuitous. A closer examination indicates that a good part of this coincidental agreement is due to the powerful influence of the propellant flame temperature on the muzzle as well as the flow field temperatures.

IV. MODIFICATIONS

In order to obtain a simple closed form analytical expression, Carfagno's derivation of the equations, describing all the simplified flow fields, had become somewhat involved. For this reason, a streamlined, independent derivation is given below for Case C using the normal shock relations found in McCormack and Crane[11] while retaining Carfagno's flow field nomenclature shown in Figure 4.

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[10] *Paul G. Baer and Jerome M. Frankle, "The Simulation of Interior Ballistic Performance of Guns by Digital Computer Program", Ballistic Research Laboratories Report No. 1183, Aberdeen Proving Ground, MD, December 1962.* (AD #299980)

[11] *P.D. McCormack and Lawrence Crane, Physical Fluid Dynamics, Academic Press, New York and London, 1973, Ch. 9.*

1. Compute muzzle temperature, T_m, and pressure, P_m, using a standard interior ballistic code. Gas velocity, U_m, at projectile exit is given by the projectile muzzle velocity.

2. Compute stagnation temperature, T_s, at muzzle exit:

$$T_s = T_m + U_m^2/(2C_{pm}) \qquad C_{pm} = \text{specific heat of muzzle gases.}$$

3. Compute temperature, T_2, after isentropic expansion to atmospheric pressure, P_a:

$$T_2 = T_m(P_a/P_m)^{(\gamma-1)/\gamma} \qquad \gamma = \text{specific heat ratio}$$

4. Compute Mach Number, M_2, of flow entering shock:

$$M_2^2 = [2T_s/T_2(\gamma-1)] - 2/(\gamma-1)$$

5. Compute after shock conditions, M_6, T_6, P_6:

$$M_6^2 = (M_2^2 + \frac{2}{\gamma-1})/(\frac{2\gamma}{\gamma-1} M_2^2 - 1)$$

$$T_6 = T_2 (1 + \frac{\gamma-1}{2} M_2^2)/(1 + \frac{\gamma-1}{2} M_6^2)$$

$$P_6 = P_a[1 + \frac{2\gamma}{\gamma+1} (M_2^2 - 1)]$$

6. Expand isentropically to atmospheric pressure and compute temperature, T_6:

$$T_7 = T_6 (P_a/P_6)^{(\gamma-1)/\gamma}$$

7. Compute the flow velocity, U_7, after expansion:

$$U_7 = [(T_s - T_7)2C_{pm}]^{1/2}$$

8. Compute specific heat, C_{p8}, and velocity, U_8, of mixture as function of mass mixture ratio, r:

$$C_{p8} = rC_{p1} + (1-r)C_{pm}$$ C_{p1} = specific heat of air

$$U_8 = rU_1 + (1-r)U_7$$ U_1 = velocity of air = 0

9. Compute stagnation temperature, T_{s8} of mixture:

$$T_{s8} = r\,(C_{p1}/C_{p8})\,T_{s1} + (1-r)\,(C_{pm}/C_{p8})T_s$$

T_{s1} = stagnation temperature of air = T_a

10. Definition of T_{s8} is:

$$T_{s8} = T_8 + (U_8^2/2C_{p8})$$

11. Compute temperature, T_8, for Case C analysis:

$$T_8 = r(C_{p1}/C_{p8})\,T_a + (1-r)(C_{pm}/C_{p8})\,T_s - (1-r)^2U_7{}^2/2C_{p8}$$

These equations give results virtually identical to the corrected, but more cumbersome Carfagno equations.

V. APPLICATION OF METHODOLOGY

The methodology for predicting the occurrence of muzzle flash was applied to the 8-inch, M188 Propelling Charge and the results are discussed in this section along with the limitations of the methodology.

The main options considered for reducing or eliminating flash for this charge were to increase the concentration of flash reducer in the basic propellant formulation, to use a cooler propellant, or a combination of the two. Previous attempts of increasing the amount of additional flash reducer as a separate component to the propelling charge had proven to be unsuccessful. Table 1 lists the four cases considered for the M188 flash reduction program.

Table 1. M188 Charge Cases Considered for Muzzle Flash Calculations

Case	Propellant Type	Flame Temperature (K)	Flash Reducer (%)	Muzzle Velocity (m/s)	Muzzle Pressure (MPa)	Muzzle Tempperature (K)
1	M30A1	2995	1.0	710.5	44.0	1791
2	M30A2	3029	2.7	709.0	42.9	1805
3	M31	2570	0.3	707.7	43.0	1469
4	M31E1	2545	1.0	708.4	44.3	1467

In this table are listed the main variables of propellant flame temperature, flash reducer concentration, and exit conditions. The first case represents the unacceptable muzzle flash baseline case. In Case 2, the flash reducer is increased. Case 3 is a cool propellant option, and Case 4 represents a combination of cool propellant and a more substantial flash reducer concentration. For the purpose of this analysis, concentrations in excess of two percent are not considered effective based on Carfagno's observations.

In Figure 5 are plotted the results of the modified muzzle flash analysis. For Cases 3 and 4, the cool propellant options, and for Cases 1 and 2, maximum final temperatues, T_5 and T_8, computed as a function of the mixture ratio, are essentially independent of the flash reducer concentrations. This is to be expected since the muzzle conditions are designed to be independent of the flash reducer. Also, the hot propellant temperature curve is significantly above the cool propellant curve, again a result of the differences in the starting conditions. Superimposed on the physical heating curves are critical ignition temperature levels corresponding to the three different levels of effective flash reducer concentrations. These levels have been biased downward by a 100-K safety factor similar to that which Carfagno used in his previous analysis of approximately 70 different gun systems. This bias is an obvious empirical device designed to compensate at least to some extent for the many oversimplifications of the model as well as some deficiencies in the input conditions.

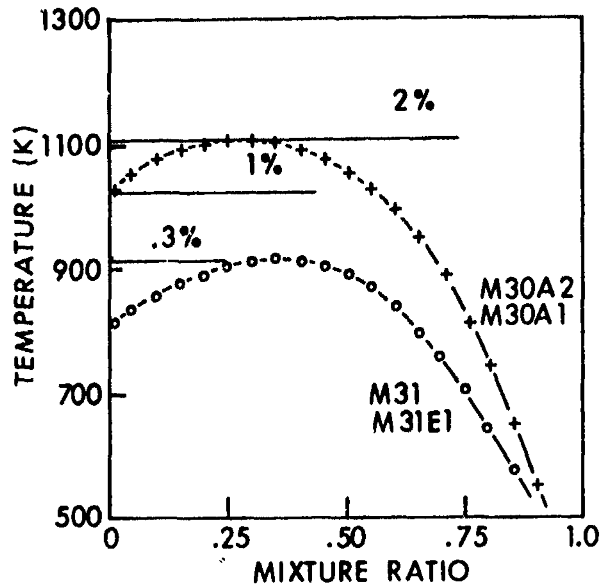

Figure 5. Muzzle Flash Prediction Map

oooo T_8 for M31 and M31E1
++++ T_8 for M30A1 and M30A2
—— Ignition temperature for several levels of flash reducer concentration.

Table 2 then summarizes the flash analysis work, as well as the experimental results obtained after the predictions. In this table, T_5 (ideal) is the temperature using the standard Carfagno analysis. T_5 (real) corresponds to the Carfagno analysis using more realistic muzzle conditions. T_8 (ideal) is computed using "ideal" gun exit conditions coupled to the correct flow analysis. T_8 (real) is, of course, the correct Case C flow field analysis with more realistic muzzle conditions. A large positive T* value indicates a probable flash situation. Values of T* near zero should be considered as unreliable. As can be seen, the agreement of the prediction with experimental flash observation is quite satisfying.

VI. LIMITATIONS OF METHOD

There are some obvious deficiencies in this simplistic approach to muzzle flash predictions. The computation of the muzzle exit conditions could be substantially affected by inert components typically found in bag charges. Furthermore, the exit conditions are really transient, and not a steady state nature as assumed. The chemical ignition temperatures used should really be treated as time-dependent parameters. A qualitative observation is that this may result in lower ignition temperatures for large caliber weapons because the flow field is of

Table 2. Summary of Results

Propellant	Flash Reducer (%)	Combustibles (Mole %)	Critical Ignition Temperature (K)	Maximum Temperatures T_5 (Case B) Ideal	Real	T_8 (Case C) Ideal	Real	T* (K)	Flash Pred	Observ.
M30A1	1.0	40.2	1125	.178	1043	1250	1111	+86	Yes	Yes
M30A2	2.7	39.1	1225	1191	1055	1262	1122	- 3	?	Occas.
M31	0.3	50.5	1000	962	843	1037	911	+11	?	Occas.
M31E1	1.0	49.5	1125	959	842	1035	912	-113	No	No

$T^* = T_8 \text{ (Real)} - (T_c - 100)$

100-K Safety Factor Is Similar To That Used By Carfagno.

much longer duration than for small caliber guns. The influences of unburned propellant, blow-by, and other hot solid residue, typical for all guns, are also ignored. Finally, the analysis is simply of a go/no-go type; the magnitude and temporal characteristics of flash, also desirable quantities, are not computed. The effect of muzzle brakes on muzzle flash is also not taken into account. Hence, any predictions for gun systems with muzzle brakes should be treated with more than the usual caution.

VII. CONCLUSIONS

An improved, semiquantitative guide for muzzle flash prediction has been developed. This useful tool is now a part of the repertoire of Army propelling charge designers. It must be admitted that the predictions still require some judgement. Specifically, unless the predicted temperature values and the chemical ignition limits are significantly different, testing is still the only reliable way to determine the flash characteristics. As an evaluating or ranking tool, the analysis should prove to be useful. However, a more rigorous, perhaps 3-D, transient, viscid muzzle flow analysis with chemical kinetics appears desirable. This may not be quite within today's state-of-the-art.

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