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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A workshop on the Chemical Suppression of Rocket Afterburning and of Gun Muzzle Flash was held at the Ballistic Research Laboratory on 11 and 12 June 1986. It brought together scientists representing six countries to share their collective fundamental understanding of the elementary, controlling processes in the generation of and the suppression of secondary combustion processes. This report is a distillation of the events of that workshop. It consists of short summaries of the 14 papers that form the Proceedings of the Workshop. Additional comments based on the discussion periods are appended to some of these summaries. In addition, an overall assessment of where this community stands and a list of recommendations for future directions and studies is supplied.

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I. INTRODUCTION

The study of the suppression of secondary combustion events in the vicinity of a rocket nozzle or of a gun muzzle has occupied researchers around the world for at least the last 60 years.[1-5] The subject even today is still much of an art. For example, it is known that the simple addition of more alkali salt to a propellant does not scale;[2] but, the fundamental reason why it does not remains obscure. For gun systems one is concerned with: Detection by an enemy, blindness due to flash, especially at night, and blast augmentation associated with secondary muzzle flash. For rockets, in addition to detection of the missile, one is even more concerned with interference of the guidance (whether optical, infrared, radio, microwave, or radar) by the presence of secondary combustion in the missile plume. With the development of new tactical and strategic missiles, and with the development of new gun systems, e.g., artillery, mortar, and airborne cannon, that require ever greater ballistic performance, the designer needs rapid and effective solutions to the problems associated with secondary combustion.[6]

Progress on understanding the fundamental processes that govern secondary combustion and its suppression had, in the past, been hampered by the lack of diagnostic probes and by the extremely difficult enivronment in which these probes must operate. However, in recent years, experimenters have been attempting to use modern techniques, e.g., lasers, with some success. In addition, modeling of the gun events was given a boost by the adaptation of the Low Altitude Plume Predictor (LAPP) code to gun muzzle events.[7] Since researchers are scattered throughout the world and each generally works on but a small piece of the total problem, it seemed reasonable to convene a workshop. The objective of this workshop was to pull together the different pieces of the puzzle and to discover how much of a complete picture of the processes associated with secondary combustion and its suppression is currently available. In addition, since experts from different academic disciplines and from both the gun and the rocket communities would be attending, the workshop would provide the opportunity for synergism to take place.

The initial Workshop on the Chemical Suppression of Rocket Afterburning and of Gun Muzzle Flash took place at the Ballistic Reasearch Labortory on 11-12 June 1986. Twenty seven scientists and administrators representing six countries (see Appendix A) heard and commented on the 14 papers (see Appendix B) that were presented. These papers are contained in the Proceedings of the Workshop.[8]

Below, I have summarized the papers presented at the workshop and have provided additional commentary based on the discussions. More importantly I have supplied an overall assessment of the workshop and have listed recommendations upon which to base future action.

II. SUMMARIES

This section contains summaries of the 14 manuscripts that form the Proceedings of the Workshop.[8] After some of these summaries there are comments from the discussion period that followed each of the oral presentations. References have been selected and more details can be had from the original manuscripts.[8]

Klingenberg (Fraunhofer Institute, EMI-AFB) reviewed what is currently known about flash development and flow in the vicinity of the muzzle. A new hypothesis concerning the source of secondary muzzle flash[5] was presented. In essence this hypothesis states that the ignition source for secondary flash is the temperature of the intermediate flash region. This temperature is controlled by the well-known shock heating as the propellant effluent passes through the Mach-disk[2] and by the assumed combustion reactions that may occur somewhat downstream of the Mach-disk.[5] This hypothesis is attractive because it enables one to understand how a small amount of alkali species can suppress secondary flash; viz. the alkali species interrupt the assumed combustion reactions in the intermediate flash region with the net effect that the ignition temperature for secondary flash is lowered. This hypothesis can be tested in a relatively straightforward fashion. Consider that oxygen can be transported to the core flow of the intermediate flash region. This requires that slip lines are either hindered or rapidly destroyed by the observed turbulence of the flow. This has been found to be the case in very recent measurements of the radial flow velocity of both the precursor and propellant gas flows of the 7.62-mm NATO rifle.[9] Thus, it has been experimentally established that oxygen can be transported to the region just downstream from the Mach-disk; however, there remains the experimental check to determine whether or not sufficient oxygen is transported to make a sensible difference in the observed temperature of the intermediate flash region. Fortunately there is a relatively simple, qualitative experiment to make this determination. The temperature in the intermediate flash region will be measured with three different surrounding atmospheres: air, nitrogen and oxygen. If the assumed combustion contributes in a sensible fashion to the temperature of the intermediate flash region then we expect that the observed temperatures will be ranked in the following order:

$$T \text{ (nitrogen)} < T \text{ (air)} < T \text{ (oxygen)}.$$

Experiments of this type are currently in progress at EMI-AFB. In addition to the above experiments, after two years of setting up, a 20-mm gas gun was made operational and produced the following results which are pertinent to muzzle flash.[10] First, it was demonstrated that suitable mixtures of $H_2/O_2/He$ can produce pressures and temperature at the muzzle that are typical of fielded gun systems. Second, the phenomenon of secondary muzzle flash was observed from the combustion of the hydrogen-oxygen in the gas-gun chamber. The secondary flash had a relatively low intensity, which can be readily explained by the fact that the equilibrium concentration of H_2 is only 9% for the mixtures used. Recall that in fielded gun systems the fuel content ranges from 40% to 70%.[11] In addition, particles, which are known to enhance the secondary flash intensity in the visible and infrared, are absent in the gas-gun simulator. Third, 1% or 2% of K_2CO_3, added to the floor of the gas-gun chamber as a fine powder, is sufficient to suppress the observed secondary flash. These experimental results support the supposition of modellers that only the hydrogen (and possibly the CO) chemistry are needed to adequately describe the kinetics of muzzle flash.[5]

Heimerl and Keller (Ballistic Research Laboratory) discussed the MEFF code[7] and its predictions. They recalled that one of the key features of this code is the incorporation of a suppression network of elementary reactions.[5] This network is capable of evolution as new and presumably better information is obtained concerning:

the important species,
the reactions that describe how these species interact, and
the rate coefficients that determine how fast the species interact.

Because the general construction of these networks is more or less mechanical
once the species are identified, the systematic experimental identification of
the important alkali-containing species is crucial to the development of a
realistic suppression network. In the present work we have had to guess just
what these species are. Included in the present suppression network are the
species: K, KO, KO_2, KOH and KH. There have been two experimental
determinations of the rate coefficient for the reaction[12,13]

$$K + O_2 + M = KO_2 + M.$$
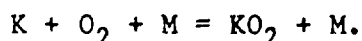
Husain and Plane[12] used time resolved atomic resonance spectrosopy to measure
this rate coefficient at 753 K and 873 K. They then invoked the Troe
formalism[14,15] to extend these meaurements to flame temperatures. Silver,
et al.,[13] have used a flow reactor to measure this rate coefficient over the
temperature range 300-700 K. Their results were extrapolated to higher
temperatures. Comparison of these two values at 2000 K leads to a difference
of about a factor of two, the value of Husain and Plane lying the lower. Here
Heimerl and Keller showed that, with their current reaction network, there was
no practical difference in the MEFF code results concerning the flash/no-flash
predictions for three 81-mm mortar and five 155-mm howitzer cases. (It would
be expected that were the much older estimate of Kaskan and co-workers[16] used
that a difference would show up since this value is some three orders of
magnitude less than either of the ones discussed here.) Heimerl and Keller
also examined the MEFF predictions for these same cases when their suppression
network was entirely replaced by the two-step mechanism proposed by Jensen and
co-workers.[17] These reactions are:

$$H + KOH = K + H_2O,$$

and

$$K + OH + M = KOH + M,$$
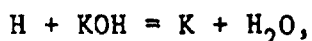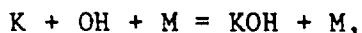
where the recommended[17] rate coefficients were used. By comparison with
observations the results of the MEFF predictions improved relative to the
more extensive supression reaction network for the 155-mm howitzer cases; but
for the 81-mm cases this mechanism leads to predictions that disagree with the
observations. It was suggested that this mechanism is a global one. If this
is in fact the case then it is difficult to see how one might improve upon
it. On the other hand, the general methodology of network development
discussed above, does allow for the evolution and improvement of the kinetic
network.

Khalil, Plett (Asecor, Ltd.), and Gladstone (Defence Research
Establishment, Canada) applied the finite difference code, JET, in order to
compute the transient flow from the 84-mm Carl Gustaf recoilless rifle at
either the breech or the muzzle, but not both.[18] They found that the computed
flow did not agree with experimental measurements. They reasoned that the
major source of this discrepancy lay in the fact that the JET code did not

provide for any reaction kinetics. They implemented the one-step global reaction

Combustibles + Oxygen → Inert Products.

The rate coefficient for this reaction was assumed given by the Arrhenius form: Aexp(-E/RT), where the parameters A and E/R were determined from the global rate of consumption of methane;[19]; i.e., A = 1.0 x 10^{+13} cc/gm-s and E/R = 1840 K. Turbulence was neglected and the ideal gas law was asssumed to hold. Thermodynamic coefficients were taken from standard works and these values were assumed independent of the temperature. The effect of adding a suppressant was taken into account in the form of a constant multiplier that was inserted into the expression for the rate of reaction of the combustibles. It represents the proportion of combustibles in the breech. It was found that a very strong effect on the blast signature was related to the appearance of secondary flash. The blast noise (and secondary flash) increased noticeably as the amount of combustibles in the effluent increased. Thus, even such a simple approach demonstrates the importance of explicitly including kinetics into the computations. Future work will include nitrogen as a separate inert species and the use of flux-corrected transport will eliminate the need for artificial viscosity which the code now requires for reasons of numerical stability. Detailed as opposed to global kinetics will also be added.

Steinberg and Schofield (Quantum Institute, UC Santa Barbara) presented details on the oxidation mechanisms of Na and Li in flat flames. They emphasized that the flame data be taken over the greatest range possible. For example, they operated with 10 different oxygen-rich $H_2/O_2/N_2$ flames whose temperatures spanned the range: 1654-2405 K. They measured the relative values of the seeded Na and the absolute value of the hydrogen atom concentration. Their model of the alkali chemistry considered four alkali-containing species: Na, NaO, NaO_2 and NaOH. They were able to reduce the 17 reactions that connected these species to a more manageable number, five or six. The best computer fits to all the data for the 10 flames led to the following. The reaction rate coefficient for the reaction

Na + O_2 + N_2 → NaO_2 + N_2
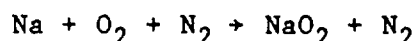
is about a factor of four less than previously published.[20] At 2000 K it is lower than the value determined from Husain's experiments[21] and much lower than the value based on the experimental work of Silver, et al.[13] It is in agreement with the corrected theoretical RRKM calculation made by Patrick and Golden.[22] The reaction rate coefficient for the reaction:

Na + OH + M → NaOH + M

is about an order of magnitude greater than previously published[20] and is in essential agreement with the values from Husain's experiments,[23] if the different efficiencies of the third body, M, are taken into account. It was shown that the value estimated by Jensen and Jones[24] lies about a factor of five greater, and that the corrected theoretical computations of Patrick and Golden lie about a factor of 10 lower. At temperatures lower than 2000 K they find that the Na-containing species in the richer flames are in greater concentrations than predicted by the reaction Na + H_2O alone. They find that

NaO_2 provides an alternate kinetic route for the formation of NaOH. They also find that the NaO is in equilibrium with NaOH and is thus unimportant in flames containing hydrogen atoms. The corresponding Li flames and reaction network has recently been analyzed and the rate coefficients appear self-consistent and of reasonable magnitudes. Finally, a caution: The previously published[20] estimated bond-strength for the alkali-containing species A-OH, A-O and $A-O_2$, where A is an alkali, is to be revised, in some cases severely. Future work will consist of analysis of potassium seeded flames.

H. Mach (Franco-German Research Institute, St.-Louis, France) described the measurements of gas velocities, gas temperatures and infrare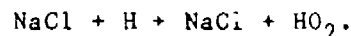d absorption coefficients of CO_2, CO, H_2O and particles along the centerline of the muzzle exhaust of a 7.62-mm rifle. The ammunition used was of two types, with and without suppressant. From the velocity measurements[25] it was found that as the particles passed through the Mach disk their mean particle diameter decreased from 1.3 μm to 0.5 μm, independent of alkali salt addition to the propellant. It was also found that, during the passage through the Mach disk, the particle concentration decreased relative to the CO and the H_2O concentrations; and that this decrease was especially strong relative to CO_2. One can conclude from these data that particle pyrolysis takes place with the formation of gaseous CO_2. Time resolved spectral temperature measurements of the flow were taken at 75, 95, 115, and 150 mm downstream from the muzzle exit. The measurements at 2.7, 4.3, 1.15, and 3.8 μm all showed similar expected trends; however, measurements at 0.589 μm, the Na-D line, led to temperatures that not only were initally higher than the temperatures measured at the other wavelengths but also remained approximately constant as a function of time. For the temperatures derived from other wavelengths there was no difference in the temperature maximum with or without suppressant at locations x = 15 cm and x = 20 cm. But at all locations (15 cm < x < 60 cm) the temperature observed without suppressant remained at its high level for a much longer time than for the case with suppressant. It was found from measurements of spectral absorption coefficients that higher particle concentrations are present without suppressant; the maximum number density was estimated as $2.0 \times 10^{+7}$/cc. Also only at x = 35 cm could detectable quantities of OH be found. They were of order 100-200 ppm. The OH concentration for rounds without suppressant were found to be somewhat higher. It was also concluded that the observed intensity differences with and without alkali additives could be explained in terms of temperature changes alone. Finally, it was found that no significant changes in the particle number density or the concentrations of CO_2, CO and H_2O were detected in the rounds with or without alkali suppressant additive. In the discussion it was brought out that the fact that one could detect OH in absorption leads to optimistic prospects for the use of the more sensitive laser induced fluorescence method.

Kolb, Zahniser, Silver, and Freedman (Center for Chemical and Environmental Physics, Aerodyne Research, Inc.) presented experimental information concerning the production and detection of alkali-containing species (potassium and sodium) and presented a summary of their rate coefficient measurements involving these molecules.[13] Reliable gas phase sources for the production of KO, KO_2, NaO_2, and NaOH have been developed. A source for the production of gas phase KOH has yet to be found. Their summary of measured rate coefficients for reactions that contain alkali species includes the following reactions:
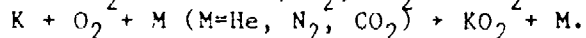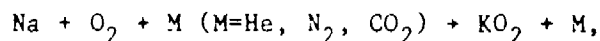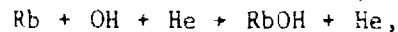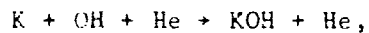
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$$K + O_2 + M \ (M=N_2, \ He, \ Ar) \rightarrow KO_2 + M$$

$$K + H_2O_2 \rightarrow KOH + OH$$

$$K + H_2O_2 \rightarrow KO + H_2O$$

$$Na + O_2 + M \ (M=N_2, \ He, \ Ar) \rightarrow NaO_2 + M$$

$$Na + H_2O_2 \rightarrow NaOH + OH$$

$$Na + H_2O_2 \rightarrow NaO + H_2O$$

$$NaOH + H \rightarrow Na + H_2O$$

$$HCl + NaX \ (X=OH, \ O, \ O_2) \rightarrow NaCl + (H_2O, \ OH, \ HO_2)$$
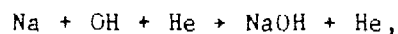
and

$$NaCl + H \rightarrow NaCl + HO_2.$$
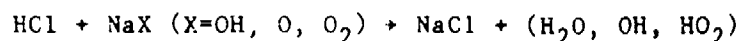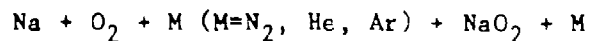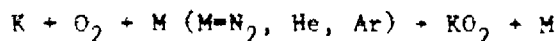
Measurements indicate that the limit for the NaOH + H reaction is at least six times the previous estimate.[24] The reactions with HCl could participate in the flame suppression chemistry of solid propellants that contain halogen containing ingredients, such as ammonium perchlorate. A variety of techniques by which alkali-containing molecules might be detected were examined. Alkali-containing molecules are predicted to have large absorption linestrengths, and so ought to be good candidates for detection in the infrared by tunable diode lasers. By making estimates of the minimal fractional absorption measureable with a tunable diode laser (0.1%) and of the molecular parameters that determine the absorption strength of a given species, the estimated minimum detectable concentrations at a temperature of 1200 K and pressure of one atmosphere were made. This sensitivity analysis indicates that diode laser absorption, operating in the spectral range 350-550/cm, could detect 1-10 ppm of the species: K_2SO_4, Na_2SO_4, NaCl, and NaX and KX where X =)H, O, O_2. (The vibrational frequency of KCl lies at about 278/cm, which is outside the range of commercial diode lasers.) A direct measurement of KF, whose vibrational overtone spectrum is known, demonstrated the feasiblity of this method. Such a detection method holds the promise of being non-intrusive, specific, sensitive and capable of real time detection for these alkali containing species.

Husain (Department of Physical Chemistry, University of Cambridge, England) described his absolute rate measurements for three classes of reactions.

CLASS I:[21,12]

$$Na + O_2 + M \ (M=He, \ N_2, \ CO_2) \rightarrow KO_2 + M,$$
$$K + O_2 + M \ (M=He, \ N_2, \ CO_2) \rightarrow KO_2 + M.$$

CLASS II:[26]

$$Na + OH + He \rightarrow NaOH + He,$$
$$K + OH + He \rightarrow KOH + He,$$
$$Rb + OH + He \rightarrow RbOH + He,$$
$$Cs + OH + He \rightarrow CsOH + He.$$

CLASS III:[27]

K + I + He → KI + He,
Rb + I + He → RbI + He,
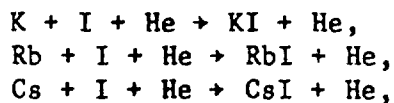Cs + I + He → CsI + He,
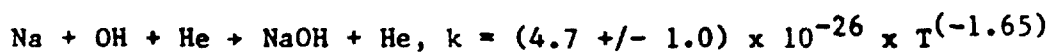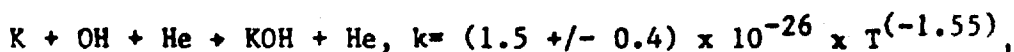
They are characterized by the fact that each was able to be studied in isolation and in real time with direct spectroscopic monitoring. The values obtained[21] for the reaction Na + O_2 + N_2 were extended from the range of temperatures of the measurements (570-1016 K) by employing the Troe formalism.[14,15] The rate coefficient so defined is:

$$\ln (k) = [-0.3225 (\ln T) + 2.133] (\ln T) - 69.21,$$

where k, the rate coefficient is in units of cm-molecule-second. Similarly the rate coefficients for the following reactions were found to be:

Na + OH + He → NaOH + He, $k = (4.7 +/- 1.0) \times 10^{-26} \times T^{(-1.65)}$

and

K + OH + He → KOH + He, $k = (1.5 +/- 0.4) \times 10^{-26} \times T^{(-1.55)}$,

respectively.[26] The reactions involving iodine[27] are of fundamental interest in the study of recombination reactions of alkali atoms. They point the way to future measurements with halogens of more relevance to suppression, e.g., Cl. In the discussion, possible sources for excited sodium and potassium atoms were presented. The reactions: NaO + O,[28] NaO + CO and 2H + Na and their potassium counterparts could all lead to excited atomic alkali atoms.

Slack, Cox, Grillo, Ryan (Grumman Corporate Research Center), and Smith (Department of Chemical Engineering, UCLA) reported on experiments using a flat flame burner to study the effect of adding potassium to $CH_4/O_2/Ar/N_2$ flames at atmospheric pressure.[29] Potassium was added to the flame in the form of an aerosol of aqueous K_2CO_3. The temperature, potassium atom and OH concentrations were measured above these flames. They found that the addition of potassium accelerates the axial decay of the OH radical downstream from the flame front, that the efficiency of potassium in accelerating the OH decay rate decreased with continued potassium addition. They also found that, for a given amount of potassium added to the flames, the influence of the potassium increased with increasing fuel-to-oxidizer ratio in the range 0.9 to 1.1. In addition, they found, in preliminary studies, that the sodium is just about as effective as potassium in accelerating the OH decay rates. These results can be used to validate the kinetic suppression network used in models. Thus far they have examined only one kinetic mechanism. It has been shown that the simple two-step reaction suppression mechanism[17] does not reproduce the observed nonlinear influence on the OH concentration, suggesting that this mechanism is perhaps global in nature. Future work includes comparison of their data with other kinetic networks. In the discussion the following reactions were mentioned as being very fast, i.e., about 1.0×10^{-11} cc/molecule-sec at room temperature: NaO + H_2, NaO + H_2O and NaO + CO.

Vanderhoff, Peterson, and Kotlar (Ballistic Research Laboratory) addressed the experimental question of how to measure the temperature in the

muzzle exhaust gases of a short barrel, 7.62-mm rifle. Coherent anti-Stokes Raman spectroscopy (CARS) appeared to be well suited because:

it is non-intrusive,
it has a potentially high signal-to-noise ratio, and
it has a high degree of spatial and temporal resolution.

For experimental convenience and for simpler data analysis CO was chosen as the molecule to study. The single-shot CARS temperature[30] obtained in the intermediate flash region was lower than was expected from other separate emission measurements in the muzzle flow field. It was concluded that extreme density and temperature changes caused index of refraction gradients in the flow of the muzzle gases. These gradients in turn provide a mechanism by which wavelength dependent beam steering takes place, with the result that the location of the measurement volume becomes uncertain. And so as a simple, reliable diagnostic for muzzle flash studies, the CARS technique is not recommended. In the discussion it was suggested that the CARS beams might be able to be brought into the core flow region by use of an intrusive light pipe; and so, one might be able to minimize the beamsteering difficulties.

A closed bomb vented by a short barrel[31] was used by Salo and Bracuti (Army Research, Development and Engineering Center) to simulate artillery and mortar propelling charges. With this apparatus they obtained relative flash intensity measurements for six potassium containing species and 11 non-alkali species. Ammonium bicarbonate and potassium bicarbonate were found to be the most effective flash reducers. A rudimentary modeling of the flash event indicated that the main suppression activity occurred outside the gun tube rather than within the tube. In the discussion it was suggested that the effectiveness of the ammonium bicarbonate might be brought about by two mechanisms. The first a physical one since the equilibrium products of the ammonium compound are: CO_2, H_2O and NH_3. The CO_2 and H_2O tend to serve only as energy sinks and so depress the temperature. The second mechanism is chemical. The ammonia, through the species: NH and NH_2 could react with NO or NO_2 (in the absence of O_2) to form N_2 and H_2O; and so, some mild form of chemical suppression is also possible. It was brought out that the simple monitoring of the visible light is not a reliable guide to the ability of a salt to suppress secondary combustion (See Reference 2, page 4). The reason is that a salt like ammonium bicarbonate is probably acting to depress the temperature as discussed above but in the case of the the alkali salts the atomic species is freed, which is known to be excited, and so adds to the visible intensity. One could spectrally resolve to account for these effects or perhaps measure the changes in the temperature due to the different additives.

Henning (RARDE, Fort Halstead, Seven Oaks, England) reported[8] that:

"In the past, flash and flash suppression have not been studied as a specific research topic but have been examined on a project by project basis. ... It is now the intention of the Internal Ballistics Branch at RARDE (Fort Halstead) to take a more active interest in this subject..."

The two major experimental facilities currently available to study in-bore and muzzle flows, flash and blast are the following. The High Enthalpy

Blast Simulator provides the opportunity for studying simulated muzzle flows under varying conditions with inert gases. For example, with oxygen-free nitrogen pressures and temperatures typical of those in fielded guns can be attained. The reflection and confinement of blast flows in enclosed spaces, blast suppression, muzzle brake development and visualization of sabot separation are all part of the current program. The RARDE Ballistic Simulator consists of a driver chamber and a tube section. This 21-mm diameter tube can be augmented in one meter lengths. The adaptor that provides a smooth transition from one section to the next also contains provisions for instrumentation. Current studies include the effects of wear and flash reducing additives for cased and uncased propellants. In addition a Laser Doppler Anemometry system devised by Smeets and George[25] is available. The particle velocity can be measured directly and in real time. This instrument can also be adapted for two color measurements of the temperature. A temperature range of 500-5000 K is computed for the wavelengths of 488 and 514.5 nm.

Jones and Mace (RARDE, Westcott, Aylesbury, England) presented a summary and review of the last few years work in flame suppression by the Plume Technology Group.[17,24,32-35] The chief tool developed and used has been the Rocket Exhaust Program (REP3).[36] They have computed that the concentrations of the major species: H_2, CO, CO_2, H_2O, and N_2 do not vary significantly with the proportion of potassium-containing additives in the rocket propellant. Minor species were found to decrease with increasing amount of additive. They also noted slight changes in the temperature and pressure at the nozzle exit with the level of the additive. The code results for signatures show the following. The level of radiation from the whole exhaust in the CO_2 band at 4.1-4.9 μm was reduced by a factor of 40 when secondary combustion was suppressed. The peak intensities of both the potassium and the sodium resonance lines were reduced by factors of about 1000 when suppression occurred. Both the attenuation and the scattering of microwave radiations are significantly reduced when afterburning suppression occurs, because there is a significant reduction in the electron concentration. One can ask the more difficult question: what is the minimum amount of additive required to suppress the secondary combustion? The minimum weight percent of potassium salt additive in the propellant required for afterburning suppression has been measured to be about 0.3%. The code predictions compute a value that is too high by a little less than six times. Here, Jones and Mace show that the assumption of the coupling of the fluid dynamic and chemical effects by combining local time-mean values leads to a significant loss of physical realism and perhaps is the major source of the discrepency just noted. A new turbulence sub-model has been formulated[37] that attempts to adequately describe the process of large eddy formation and the influence of turbulence induced fluctuation in concentrations and temperature on the chemical rate processes. This sub-model has not yet been tested.

Kubota reported on some recent experiments involving afterburning suppression in rocket motors.[4] For these studies he selected two double-based propellants whose burn rates are significantly different; i.e., he selected a low and a high energy propellant. To each of these, potassium salts were added during their manufacture. He found that there is no afterburning for the propellants with no additive if the expansion ratio exceeds a certain value. This value depends on the propellant used. By varying the amount of suppressant additive for a fixed expansion ratio, he was able to show that one

could obtain curves similar to those obtained by changing the expansion ratio of the nozzle. However, the expansion ratio is fixed by other constraints in the design phase of a rocket motor; and so, it is not available as a practical mechanism for afterburning suppression. He found on the one hand that the alkali salts have no significant influence on the burning characteritics of the propellants, but on the other hand they do prevent the formation of the flames (i.e., secondary combustion) after the gases have left the nozzle. He concluded that the potassium addition has the effect to move the point where the flame ignites away from the nozzle; i.e., the potassium causes a time delay in the spontaneous combustion of the exiting gases. Kubota also showed a motion picture of the surface of a burning propellant that had been manufactured with alkali salt suppressant. What was pointed out was the formation of rather large droplets that were independently identified as KO_2. In the discussion it was remarked that such droplets had also been seen in black powder studies at the BRL. The net effect was to call into question the actual amount of alkali that entered into the suppression process. These results would indicate that it could be less than the known amount added.

Weaver and Singh (US Air Force Rocket Propulsion Laboratory) discussed their program to study the inhibition mechanism of $H_2/O_2/N_2$ flames seeded with HBr, KCl and KOH. Since the experimental work is still in progress only the experimental appratus was mentioned. This included the following lasers: an eximer, a YAG and an argon-ion. Raman, Rayleigh scattering and laser-induced flourescence techniques are planned to obtain concentration and temperature measurements of major species and of the OH radical. The suppressant HBr was the initial point of the computational studies in order to calibrate both the theoretical model and the experimental observations with those of other workers. Only the computational work was reported here. They had employed two code formulations available from the literature.[38,39] For the case of no additive both code results agreed. However the ARBRL code could not be made to converge when HBr was added. Special precautions had to be taken with the Sandia code to ensure its convergence. They found: That the computed burning velocity and the peak mole fractions of both H and OH decreased with increasing HBr in fuel-rich and fuel-lean flames; that the burning velocity for fuel-rich flames is greater than the corresponding velocity for fuel-lean flames; and that, when HBr is added, the primary flame zone is stretched relative to the case with no addition, leading to a lower rate of temperature rise, fuel and oxidant decay, and production of product species. Their next step is the comparison of the computations with experimental data. The studies with potassium salts are for future work. In discussions it was brought out that the most likely reason that there was a non-convergence of the ARBRL code in the additive cases lay in the fact that the computational space of the solution must be adjusted so that the solution profiles at the "ends" of this space have a near zero derivative.

III. ASSESSMENT

The summary given above together with the more detailed proceedings form the data base to determine where we are now in our collective understanding of the fundamental processes relevant to the suppression of secondary combustion phenomena. The amount of progress that has been made in the assault on this important technical question during the past few years is nothing short of amazing. This scientific community appears on the threshold of firmly

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establishing the fundamental flow and alkali-suppression processes. Let me be specific.

There are several recognized weaknesses with the MEFF muzzle flash prediction code. Two of the most important are the kinetic reaction network that describes the alkali suppression and the handling of the turbulence. The basic problem with the kinetic schemes lies in the lack of information regarding the identity of the alkali-containing species. In the paper by Kolb and coworkers, there is the promise of being able to monitor and detect alkali species of interest in the suppression phenomenon. The paper by Jones and Mace describes an initial attempt to get a handle on the "proper" way to include the turbulence.

Another serious limitation of the MEFF approach is that it is a steady-state solution to a dynamic problem. The development of the JET code already includes the temporal development of the Mach disk. Eventually, it will include, in a modular fashion, both kinetics and turbulence. The JET code offers promise for the future.

The role of particles has not been determined. It has been assumed that the suppression mechanism obtains only in the gas phase. But the gas-gun simulator, whose muzzle pressures and temperatures are characteristic of fielded guns, has just been brought into operation at EMI-AFB. There is the expectation that one can now study in a controlled fashion the properties of muzzle flows that are pure gas phase, seeded with inert particles or seeded with reacting particles. In this manner the specific effects of particles upon suppression can be learned. Mach reported on the measurements of the gas velocities and temperatures, as well as selected absorption coefficients, in a fielded 7.62 mm rifle. At RARDE, Fort Halstead, other flow simulators are coming up to speed to address these and other questions concerning secondary combustion.

The groups associated with Schofield, Slack, and Weaver have each developed flat flame burners and a variety of diagnostics to study the effects of inhibition and suppression in the more benign but better controlled conditions in the laboratory. They are at different stages of maturity and they each attack the suppression problem from different but complimentary viewpoints. They all use detailed modeling of the event to guide the experiments and to help interpret the data obtained.

The measurement of rate coefficients for reactions that involve alkali species, while not yet routine, has made great strides in the laboratories of both Husain and Kolb. For example, in 1981 virtually nothing was known concerning these rate coefficients except an inferred rate for the key reaction:

$$K + O_2 + M = KO_2 + M,$$
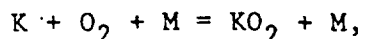
which has since been shown by measurement to be three orders of magnitude too small.

End products, such as the MEFF code at BRL and the JET code in Canada, are now being applied (albeit with much caution and trepidation) to help in the solution of systems problems, such as the 81-mm mortar and the 84-mm

Carl Gustaf recoiless rifle. In addition to the information discussed above, other improvements to these "end-use" codes are contemplated to make them even more useful; e.g., a post processor for the MEFF code to help unravel the details of the kinetics.

IV. RECOMMENDATIONS

The following areas have the most promise for further advancement of our understanding. Information gleaned in these areas will ultimately lead to credible, validated codes that accurately predict secondary combustion suppression.

1. The identification and quantification of alkali-containing species in inhibited flames, rocket motor plumes and/or gun muzzle effluent.

2. The experimental determination of the role that particles play in the processes of the suppression of secondary combustion.

3. The determination of rate coefficients for reactions (most of which will involve alkali-containing species) that detailed modeling indicates are important.

4. The investigation as to whether turbulence phenomena are important in the models of secondary suppression; and, if so, how should one incorporate them into the codes.

5. The measurement of the temperature in the intermediate flash region for atmospheres of air, pure nitrogen and pure oxygen should be independently verified. This notion is important and could govern the thinking in the muzzle flash suppression for years to come. Indeed, should the hypothesis concerning the role of combustion in the intermediate flash region prove correct, then consideration must be given as to how this phenomenon could be incorporated into a muzzle flash code.

Note Added in Proof: The expected temperature inequalities shown on page 6 have been experimentally verified, and so the hypothesis is proved.

ACKNOWLEDGEMENTS

REFERENCES

1. C. Cranz, Lehrbuch Der Ballistik, Vol. 2 "Innere Ballistik," Julius Springer Pub., Berlin 1926.

2. S.P. Carfagno, Handbook on Gun Flash, The Franklin Institute, Nov 1961.

3. H. Kesslau, "Das Muendungsfeuer bei Geschuetzen und Raketen," Institut Saint-Louis, Report 11/48, 19 July 1948. See also: J.M. Heimerl, "The Muzzle Flash of Guns and Rockets: A Translation," Special Publication BRL-SP-50, Dec 1985.

4. Y. Iwao, N. Kubota, I. Aoki, T. Furutani, and M. Muramatsu, "Inhibition of Afterburning of Solid Propellant Rocket," Journal of the Industrial Explosives Society Japan (Explosion and Explosives) Vol. 42, pp. 366-372, 1981. See also: J.M. Heimerl, G. Klingenberg and F. Seiler, "Inhibition of Afterburning of Solid Propellant Rocket. (An English Translation)," Fraunhofer-Institute fuer Kurzzeitdynamik, EMI-AFB Report T 3/86, April 1986.

5. J.M. Heimerl, G.E. Keller and G. Klingenberg, "Muzzle Flash Kinetics and Modelling," Fraunhofer-Institut Fuer Kurzzeitdynamik, EMI-AFB Report 1/85, May 1985.

6. See for example, L. Cash, "Developmental Testing Phase II (DT II) of the XM819 Red Phosphorous (RP) Smoke Cartridge for the M252, 81mm Mortar," AMSAA Independent Evaluation Report (IER) No. 5-86, March 1986.

7. V. Yousefian, "Muzzle Flash Onset," Ballistic Research Laboratory, Contract Report ARBRL-CR-00477, Feb 1982.

8. Proceedings of the Workshop on the Chemical Suppression of Rocket Afterburning and of Gun Muzzle Flash, J.M. Heimerl, Editor, Ballistic Research Laboratory, Special Report, BRL-SP-0059, September 1986.

9. J.M. Heimerl and G. Klingenberg, "New Evidence for the Role of Turbulence in the Ignition of Secondary Flash," Proc. 9th International Symposium on Ballistics, Royal Military College of Science, Schrivenham, England, 29 April-1 May, 1986.

10. G. Klingenberg, J.M. Heimerl and E. Schmolinske, "Simulation Experiments - Gas Gun Simulator," Proc. 9th International Symposium on Ballistics, Royal Military College of Science, Schrivenham, England, 29 April-1 May, 1986.

11. S.P. Carfango and O.N. Rudyj, "Relationship Between Propellant Composition and Flash and Smoke Produced by Combustion Products," Franklin Institute Final Report F-A2132, for the period Jan 13, 1958 to Dec 13, 1960.

12. D. Husain and J.M.C. Plane, " Kinetic Investigation of the Third-Order Rate Processes between $K + O_2 + M$ by Time-Resolved Atomic Resonance Absorption Spectroscopy," J. Chem. Soc., Faraday Trans. 2, Vol. 78, pp. 1175-1194, 1982.

13. J.A. Silver, M.S. Zahniser, A.C. Stanton, and C.E. Kolb, "Temperature Dependent Termolecular Reaction Rate Constants for Potassium and Sodium Speroxide Formation," Twentieth Symposium (International) on Combustion, The Combustion Institute, pp. 605-612, 1984.

14. J. Troe, "Predictive Possibilities of Unimolecular Rate Theory," J. Phys. Chem., Vol. 83, pp. 114-126, 1979.

15. J. Troe, "Theory of Thermal Unimolecular Reactions at High Pressures," J.Chem. Phys., Vol. 75, pp. 226-237, 1981.

16. K.S. Iya, S. Wollowitz, and W.E. Kaskan, "The Mechanism of Flame Inhibition by Sodium Salts," The 15th Symposium (International) on Combustion, pp. 329-336, 1975.

17. D.E. Jensen, G.A. Jones, and A.C.H. Mace, "Flame Inhibition by Potassium," J. Chem. Soc. Faraday Trans. I, Vol. 75, pp. 2377-2385, 1979.

18. D.H. Gladstone, M.B. Khalil, and E.G. Plett, "The JET Code: A Useful Tool for Intermediate Ballistic Analysis," Proc. 9th International Symposium on Ballistics, Royal Military College of Science, Sch-ivenham, England, 29 April-1 May, 1986.

19. R.E. Peck, "Eddy Viscosity Modelling in the Prediction of Combustion-Chamber Flows," Ph.D. thesis, University of California, Irvine, 1976.

20. A.J. Hynes, M. Steinberg, and K. Schofield, "The Chemical Kinetics and Thermodynamics of Sodium Species in Oxygen-Rich Hydrogen Flames," J. Chem. Phys., Vol. 80, pp. 2585-2597, 1984.

21. D. Husain, P. Marshall, and J.M.C. Plane, "Temperature Dependence of the Absolute Third-Order Rate Constant for the Reaction Between $Na+O_2+N_2$ Over the Range 571-1016 K Studied by Time-Resolved Atomic Resonance Absorption Spectroscopy," J. Chem. Soc., Faraday Trans. 2, Vol. 81, pp.301-318, 1985.

22. R. Patrick and D.M. Golden, "Thermolecular Reactions of Alkali Metal Atoms with O_2 and OH," International J. of Chem. Kinetics, Vol. 16, pp. 1567-1574, 1984.

23. D. Husain, J.M.C. Plane, and C.C. Xiang, "Determination of the Absolute Third-Order Rate Constant for the Reaction Between Na+OH+He by Time-Resolved Molecular Resonance-Fluorescence Spectroscopy, OH (A-X), Coupled with Steady Atomic Fluorescence Spectroscopy, Na (3P-3S)," J. Chem. Soc., Faraday Trans. 2, Vol. 80, pp. 1619-1631, 1984.

24. D.E. Jensen and G.A. Jones, "Alkali-Metal Copmpounds in Oxygen-Rich Flames," J. Chem. Soc., Faraday Trans. I, Vol. 78, p. 2843, 1982.

25. G. Smeets and A. George, " Michelson Spectrometer for Instantaneous Doppler Velocity Measurements," J. Phys. E: Sci. Instrum., Vol. 14, p. 838, 1981.

26. For summary see: D. Husain, J.M.C. Plane, and C.C. Xiang, "Measurement of the Absolute Third-Order Rate Constant for the Reaction Between Cs+OH+He Determined by Time-Resolved Molecular Resonance-Fluorescence Spectroscopy, OH (A-X), Coupled with Steady Atomic Resonace Fluorescence, Cs (7P-6S)", J. Chem. Soc., Faraday Trans. 2, Vol. 81, pp. 769-782, 1985.

27. For summary see: J.M.C. Plane and D. Husain, "Absolute Third-Order Rate Constants for the Recombination Reactions Between Alkali-Metal and Iodine Atoms and the Measurements for Rb+I+He," J. Chem. Soc., Faraday Trans. 2, Vol. 82, to be published, 1986.

28. J.H.C. Plane and D. Husain, "Determination of the Absolute Rate Constant for the Reaction $O + NaO \rightarrow Na + O_2$ by Time-Resolved Atomic Chemiluminescence at 589 nm," submitted to J. Chem. Soc., Faraday Trans. 2, 1986.

29. M. Slack, J. Cox, A. Grillo, R. Ryan, and O. Smith, "Influence of Potassium on OH Decay Rates in Metyhane-Air Flames", Grumman Corporate Research Center Report MP-1019, March 1986.

30. A.J. Kotlar and J.A. Vanderhoff, "A Model for the Interpretation of CARS Experimental Profiles," Applied Spectroscopy, Vol. 36, p. 421, 1982.

31. A.J. Bracuti, L.A. Bottei, and R. Davis, "Evaluation of Potential Multipurpose Propellant Additives: Flash-Erosion Suppressant", J. of Ballistics, Vol. 7, pp. 1609-1626, 1983.

32. D.E. Jensen and G.A. Jones, "Reaction Rate Coefficients for Flame Calculations," Combustion and Flame, Vol. 32, p. 1, 1978.

33. D.E. Jensen and G.A. Jones, "Theoretical Aspects of Secondary Combustion in Rocket Exhausts," Combustion and Flame, Vol. 41, p. 71, 1981.

34. D.E. Jensen and G.A. Jones, "Kinetics of Flames Inhibition by Sodium," J. Chem. Soc., Faraday Trans. 1, Vol. 78, p. 2843, 1982.

35. D.E. Jensen and A.S. Wilson, "Prediciton of Rocket Exhaust Flame Properties," Combustion and Flame, Vol. 25, p. 43, 1975.

36. J.M. Cousins, "Calculation of Conditions in an Axisymmetric Rocket Exhaust Plume: The REP3 Computer Program," PERME(W) Report TR-227, 1982.

37. A.C.H. Mace, "Turbulence-Chemistry Interactions in Rocket Exhaust Plumes," RARDE Report 7/85, 1985.

38. T.P. Coffee and J.M. Heimerl, "Sensitivity Analysis for Premixed, Laminar, Steady-State Flames," Ballistic Research Laboratory Report ARBRL-TR-02457, Jan 1983.

39. R.J. Kee, J.F. Grcar, M.D. Smooke, and J.A. Miller, "A Fortran Program for Modelling Steady Laminar One-Dimensional Premixed Flames", Sandia Report SAND85-8240, Dec 1985.

APPENDIX A.   LIST OF ATTENDEES

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APPENDIX B. TITLES AND AUTHORS OF WORKSHOP CONTRIBUTIONS

APPENDIX B
TITLES AND AUTHORS OF WORKSHOP CONTRIBUTIONS

1. "Gun Muzzle Flash Research at the Fraunhofer-Institute EMI-AFB" by
   G. Klingenberg

2. "Kinetics Networks and MEFF-Code Predictions: A Progress Report" by
   J.M. Heimerl and G.E. Keller

3. "Flash Simulation with a Global Reaction Model for Transient Flow from
   the 84 mm Carl Gustaf Rifle" by M.B. Khalil, E.G. Plett, and
   D.H. Gladstone

4. "Detailed High Temperature Oxidation Chemistry of the Alkali Metals In
   Flames" by M. Steinberg and K. Schofield

5. "Spectoscopic Measurements in the Exhaust Flow of a 7.62 mm Rifle Using
   Propellants With and Without Chemical Flash Suppressants" by H. Mach

6. "Chemical Kinetic Studies and Infrared Laser Detection of Potassium and
   Sodium Species Relevant to Muzzle Flash and Rocket Plume Afterburning
   Suppression" by C.E. Kolb, M.S. Zahniser, J.A. Silver, and A. Freedman

7. "Kinetic Studies of Recombination Reactions of Alkali Atoms by Time-
   Resolved Spectoscopic Methods" by D. Husain

8. "Influence of Potassium on OH Decay Rates in Methane-Air Flames" by
   M. Slack, J. Cox, A. Grillo, R. Ryan, and O. Smith

9. "The Feasibility of a CARS Technique for the Study of Muzzle Flash" by
   J.A. Vanderhoff, R.B. Peterson, and A.J. Kotlar

10. "ARDEC Laboratory Flash Studies" by J. Salo and A. Bracuti

11. "An Overview of the RARDE Facilities for Gun Muzzle Flow and Flash
    Studies" by P.S. Henning

12. "Secondary Combustion Suppression in Rocket Exhausts" by G.A. Jones and
    A.C.H. Mace

13. "Suppression Mechanism of Rocket Afterburning" by N. Kubota

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