Theoretical research on this phenomenon in Russia are reflected in the review by Novozhilov.[19]

Conclusion

This note describes some of the early combustion studies in Russia on high-frequency unsteady propellant burning. Actually, they began in 1938 when peaks in the pressure of a rocket combustion chamber were detected: a short time later, the limits for their existence depending on propellant parameters and burning conditions were investigated. It was also shown that thermostable particles eliminated these peaks. However, at that period, the reasons for these phenomena were not established. Acoustic character of this combustion instability was described by American scientists.

During 1958–1962 at the Moscow Institute of Chemical Physics, experimental and theoretical investigations were performed on various aspects of high-frequency (acoustic) combustion instability. In particular, the theory of interaction of acoustic waves with the propellant combustion surface was developed, and the coefficient of the sound reflection from a burning surface was measured experimentally.

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Underwater Incineration of Heterogeneous Propellants

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Introduction

DISPOSAL methods for processing demilitarization of ammunition are being addressed in many countries throughout the world. Processes for recycling certain materials, such as brass from cartridges, are technically simple, well developed, and financially very attractive. Processing other components, such as rocket propellants, however, remains an unsolved problem. Initial studies in developing an ecological and economically friendly method for processing heterogeneous solid rocket propellants are described. The basic approach is to incinerate the propellant in a neutralizing solution that transforms the ecologically undesirable combustion products into substances that commonly appear in nature. This approach offers the potential advantage of simultaneously eliminating gaseous hydrogen chloride and trapping the aerosols of aluminum oxide.

Method Selection and Description

A number of possible methods for destroying common explosives exist. Selecting the most effective method for a particular explosive depends on many factors. These factors include the quantity of propellant to be processed or recycled; the original production price of ingredients, such as ammonium perchlorate; the obtained price for products of the recycling process; the cost of facilities for the disintegration and extraction process or burning and fume-scrubbing process and so on. Some possible methods are outlined below.

1) *Direct combustion or detonation:* This method is very simple, but because of the production of harmful substances, it is unacceptable for ecological reasons.

2) *Physical–chemical processing:* Mechanical grinding of the propellant followed by solvent separation of AP and subsequent recycling for reuse. The major concern with this method is the processing of the insoluble remnants consisting of binding agent, additives (primarily aluminum), and nonextractable oxidant. Disposing of these materials presents the same problems and hazards as disposing of the original propellant. For example, experiments conducted in the Czech Republic show that the reaction of aluminum with cutting water can be very dangerous and can cause a disaster.

3) *Recycling materials as explosives:* Reuse of the original substances or their components in production of explosives for industrial purposes. This method does not eliminate collection of the poisonous substances and is therefore unacceptable.

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4) *Destructive disposal by incineration:* Several studies using different thermal disposal methods are in progress in different countries. Explosives are burned in rotary kilns or in fluidized-bed incinerators. The gaseous products then are recovered in rather complicated systems consisting of filters, scrubbers, afterburners, etc. This approach requires construction of a small chemicals factory and the high cost of investment capital.

The method presented in this paper is a variant of the incineration approach that offers enhanced environmental safety, technical simplicity, and low costs. This method is adapted particularly to disposing of hetergeneous propellants. These solid propellants contain ammonium perchlorate (AP) a binding agent, and often contain additional high-energy additives, such as cyclotrimethylenetrinitramine (RDX), cyclotetramethylenetetranitramine (HMX), aluminum powder or metal hybrides. The combustion products of these propellants are characterized by a high hydrogen chloride content (around 20%). Carbon monoxide, hydrogen, and, in the most common propellent compositions, finely dispersed aluminum oxide are also present.

Specifically, this method is based on incinerating the propellants under the surface of an appropriate neutralizing solution. As the gaseous products of combustion rise through the solution, they are cooled simultaneously, their volume is reduced by a factor of 10, and then they are reacted with a neutralization solution. Ecologically undesirable materials are transformed into substances that commonly appear in nature. For example, hydrogen chloride is transformed into sodium chloride (common table salt). If the propellant contains metal, such as aluminum, the solid combustion products also are cooled and condensed into a fine dispersion of insoluble metal oxides. The mixture of the other escaping gaseous products can be burned over the solution surface, converting carbon monoxide to carbon dioxide, and hydrogen to water. The final waste products of this process are then a solution of sodium chloride with a suspension of aluminum oxide, and a mixture of gases containing primarily carbon dioxide, nitrogen, and water.

Description of Exploratory Experiments

Exploratory experiments were conducted using a propellent having the following approximate properties: AP, 65%; synthetic rubber, 13%; powdered aluminum, 19%; additives, 3%; material density, 1797 kg/cbm; and heat of explosion, 6563 kJ/kg.

The typical products of combustion are aluminum oxide, 37%; hydrochloric acid, 20%; carbon oxides, 31%; nitrogen, 8%; hydrogen, 4%; and volume of gaseous products, 934 l/kg.

Three sets of propellant samples were tested. Initially, samples having prismatic shapes and a mass of 30–50 g were burned under the surface of a neutralization solution in a glass vessel with a volume of about 50 liters. The samples burned at a depth of about 20 cm under the surface for approximately 20–40 s. Later, larger samples of a mass of approximately 1 kg were burned at a depth of 1.2–1.5 m under the surface in a concrete basin having an overall volume of about 500 cbm. These samples burned for 50–60 s. Finally, a complete charge of propellent with a mass of 10 kg was drawn from the rocket antiaircraft system and was tested. For comparison, a 10-g sample also was burned in the open air. Chemical analyses of the escaping gaseous products were tested in a special environmental laboratory. The result are presented in Table 1.

These analyses indicate that our simple method is effective. It was determined further that combustion of the unit underwater supports water circulation, which encourages absorption and neutralization reactions. These analyses also indicated that no hydrogen chloride or other harmful gases were present in the gases leaving the neutralizing solution. These results also suggest that the residual concentration of ammonia and chlorine can be reduced by changing the ratio of solution mass to propellant mass or by changing the concentration of neutralizing agent in solution.

Table 1 Comparison of open-air and underwater burning

	Burned, mg/m^3 of fume	
Agent	Open air burning	Underwater burning
Ammonia	16	<2
Chlorine	30,200	1,880

Conclusions

The results of these simple tests show that disposing of heterogeneous propellants by incineration under a neutralizing solution is technically very simple and potentially financially cost-effective. The data indicate that this method fulfills ecological criteria for propellant disposal. Finally, it appears possible to apply this method to decommissioned rocket motors of certain weapons systems provided with ignition equipment, with no additional preparations being needed.

It is recognized that significant further development of this method is needed. Later development studies must address quantitative analytical control of the distribution of all waste products in the neutralization solution and further define the species and their gas concentrations above its surface. The ultimate goal is the technical control of burning units with masses of several tens or hundreds of kilograms.

Approximate Solution Method for the Hyperbolic Heat Equation

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Introduction

MCALEVY and Summerfield[1] introduced the gas-phase ignition theory for composite solid propellants to explain the results of a set of ignition studies wherein a shock wave was reflected off the end wall of a shock tube using a tailored interface condition. The test gas, doubly shocked and stagnant, was of a controlled composition and its pressure was controlled by the initial, unshocked pressure. The end wall contained a planar mounted sample of propellant. The ignition delay, sensed with a filtered photoelectric tube, decreased as either the gaseous oxygen content or the pressure of the test gas increased. The investigators hypothesized that the propellant sample was heated by conduction from the stagnant test gas. The pyrolysis of the products of the polymeric fuel of the propellant then diffuse into the adjacent gas phase and react with the oxidizing gases, which lead to ignition of the propellant.

The thermal interaction of the propellant and the test sample was modeled by the classical heat conduction solution for the sudden contact of two semi-infinite bodies initially at different temperatures. The solution indicates that, instantly upon contact, the temperature at the interface jumps to a constant value that depends upon the ratio of thermal properties of the two bodies. This interface temperature depends upon the ratio of the quantity $R^2 = (\varrho c_p k)_{\text{solid}}/(\varrho c_p k)_{\text{gas}}$ such that

$$T_{\text{interface}} = \frac{T_{\text{gas}} - T_{\text{solid}}}{1 + R} + T_{\text{solid}}$$

When evaluated for the experimental conditions, the predicted interface temperature was approximately 400°C. This value seemed a little low, but it was adjudged that the model was highly approximate considering the assumption of constant density in the gas. In "reality," it was thought likely that high-temperature gases flow toward the surface because of the local cooling of the gas at the interface, which would further increase in temperature. Subsequent

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