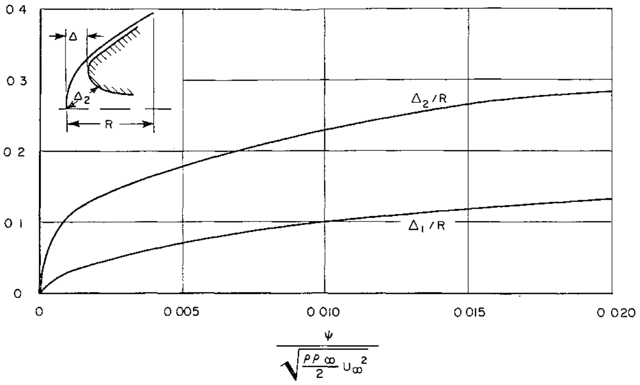

Fig 4 Effect of mass injected on buffer distances for paraboloidal contact surface with Newtonian pressure

Similarly, in the case of a paraboloidal contact surface ($B = 0$),

$$\psi = \left(\frac{\rho\rho_\infty V_\infty^2}{2}\right)^{1/2} \xi^2(1 - \eta^2) \qquad (8)$$

for Newtonian pressure resulting on the contact surface (see Fig 3)

Of course any stream surface ψ may be chosen as the body contour The corresponding mass flow rate required for injection is $2\pi\psi R^2$, where R is the nose radius Figure 4 shows, as an example, the relation between mass flow rate and "buffer" distances in the case of the paraboloidal contact surface with Newtonian pressure distribution

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Heterogeneous Reactions in Ignition and Combustion of Solid Propellants

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Of the many processes that are germane to the effective operation of a solid propellant motor, probably the most complex (and consequently least understood) have been the ignition and subsequent combustion processes As a result, development of operational solid-propellant systems have been largely empirical and have required costly and lengthy development effort With the advent of more sophisticated and advanced solid-propellant systems, the current empirical approach becomes economically unsound Thus, it has become increasingly important to understand the basic mechanisms controlling ignition and combustion

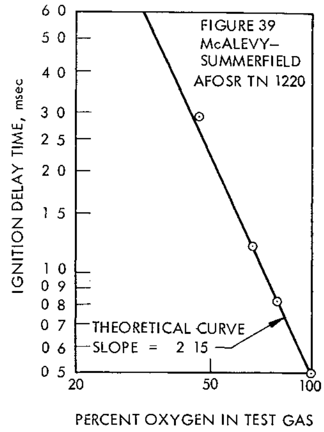

Fig 1 Comparison of heterogeneous reaction theory with experiment for oxygen-polystyrene propellant system

Many investigators have studied the basic processes that are generic to the over-all ignition and combustion process The results of these studies have provided valuable information but have not produced a unified theory that permits the quantitative prediction of the effects of the independent variables on ignition and burning-rate characteristics of solid propellants

Recent basic research studies on hypergolic ignition of solid propellants have significantly advanced the analytical understanding and description of both hypergolic and rocket-exhaust type ignition of solid propellants[1-4] The results of these studies have established that heterogeneous reactions between the oxidizing gases from solid oxidizer decomposition and the binder fuel constitute the rate-controlling mechanism in ignition response of the propellant regardless of the mode of external heat flux Furthermore, this same mechanism has been shown to play a dominant role in the deflagration characteristics of the propellant

Role of Heterogeneous Reactions in Solid Propellant Ignition

Basic ignition studies with reactive gases, such as fluorine and oxygen, and conventional propellants have shown that spontaneous exothermic, heterogeneous reactions occur at the interface between the reactive oxidizer and polymer fuel matrix These reactions release heat at the propellant surface and raise the surface temperature of the propellant very rapidly to a level where stable combustion proceeds without additional external heat A theoretical model based on this concept has been developed The resultant analytical model describes quantitatively the effects of environmental oxidizer concentration, temperature, and pressure on the ignition delay time of the solid propellant in both static and flow environments

The excellent agreement between the experimentally observed ignition delays[5] and the theoretically predicted values for the oxygen-polystyrene composite propellant is shown in Fig 1 Equally excellent agreement has been found between theory and experiment for a wide variety of typical composite propellant formulations with such gaseous oxidizers as oxygen,[5] fluorine,[1] and chlorine trifluoride[6] These results conclusively establish the validity of the spontaneous, heterogeneous reaction concept Details of the theoretical development, as well as additional experimental verification of the theory, will be published in a subsequent paper[7]

Verification of the theory that rapid, exothermic, heterogeneous reactions occur between gaseous oxidizing species and the fuel-binder matrix clearly indicates that a heterogeneous reaction controls the ignition response of the propellant to external heat flux, regardless of whether the heating is hypergolic, radiative, or convective As a typical example, consider ammonium perchlorate-based composite propellants When external heat is supplied to the propellant surface, the temperature of the surface rises and a

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Received November 1, 1963

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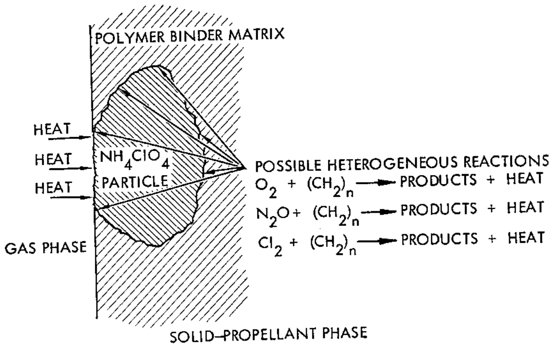

Fig 2 Schematic of heterogeneous reactions occurring at oxidizer particle-polymeric binder interface

steep temperature gradient is established in the solid This gradient extends to a depth of several microns, depending upon the external heat-flux rate As the propellant surface layers approach 150°C, the intermosaic blocks of the oxidizer particles[8] decompose, and gaseous products diffuse to the oxidizer particle-fuel interface From ammonium perchlorate decomposition studies, the over-all reaction for the low-temperature decomposition has been shown to be[9]

$$NH_4ClO_4 \rightarrow \rightarrow \tfrac{1}{2}Cl_2 + \tfrac{3}{4}O_2 + 2H_2O + \tfrac{1}{2}N_2O$$

Thus, oxidizing gases are generated at the propellant surface and in the surface layers from decomposition of the solid oxidizer, as shown schematically in Fig 2 Under these conditions, oxidizing species react heterogeneously with the adjacent fuel to generate a source of heat Once these reactions reach runaway conditions, ignition has been achieved Hence, the heterogeneous reactions between the oxidizer decomposition products and the fuel control the internal response of the propellant to the external heat flux

The model explains the observed effects on the ignition delay time of heat flux, pressure, initial temperature, and catalyst content Although the description herein has been made for composite propellants that contain ammonium perchlorate, it is completely general and applies to all composite and double-base propellants Details of the theory and confirming experimental evidence will be presented in a subsequent publication [10]

Role of Heterogeneous Reactions in Solid Propellant Combustion

The temperature and pressure during steady-state combustion are significantly higher than required for these heterogeneous reactions to reach runaway conditions Consequently, these reactions can play a dominant role in the over-all deflagration process and have been shown to explain a number of observed effects not incorporated in gas-phase combustion theories For example, the diffusion flame theory does not predict the high burning rate nor large pressure exponents of burning rate that are observed with composite propellants containing potassium and lithium perchlorate When these metal salts are used instead of ammonium perchlorate, the heterogeneous reaction is greatly enhanced by an increase of reactive oxidizer species from oxidizer decomposition The $KClO_4$ and $LiClO_4$ decomposition generates a much higher concentration of oxidizer gases than for NH_4ClO_4, since NH_3, H_2O, and other fuel-based species are absent For these oxidizers, the heterogeneous reactions have been observed to exhibit a more dominant role, which explains the apparently anomalous pressure and burning-rate behavior Experimental and theoretical evidence in support of the theory will be presented in a subsequent publication [11]

Therefore, heterogeneous reactions coupled with gas-phase reactions provide clear insight into the several unit processes that control the burning rate of solid propellants and related phenomena, such as combustion termination In addition, this model provides a possible means of coupling the over-all combustion process with oscillatory acoustical phenomena

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Effect of the Boundary Layer upon the Flow in a Conical Hypersonic Nozzle

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Nomenclature

Re_x = Reynolds number based on nozzle length
x = distance from throat to nozzle exit
R, r_t = nozzle and throat radius
M = Mach number
ρ_R = reference density at standard conditions = $8\,042 \times 10^{-2}$ lb/ft^3
θ_w = nozzle half angle
A_{geom}, A_t = geometric and throat area of the nozzle

In hypersonic wind-tunnel nozzles the boundary layer may occupy as much as 50% of the test section area[1] and so exerts a major influence upon the flow An application of a method developed by Burke and Bird[2] to the calculation of the combined core/boundary-layer flow in a conical hypersonic nozzle over a broad range of stagnation conditions has brought to light some surprising results, which are reported below

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Received November 4, 1963 The work reported here was sponsored by the Office of Naval Research under Contract Nonr-1224(31), NR 061-108

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