freestream particles m_P is plotted against incident particle mass flux for normal impact on flat Teflon targets. The data points, which are identified in the legend, were acquired from a cold-flow facility using helium carrier gas to accelerate the particles,[1] a rocket simulator facility,[2] and an aluminized solid-propellant rocket.[3] The volume mean diameter D_{30} of the particles used in the several facilities varied from 1 to 5μ, whereas the incident mean particle velocity ranged from approximately 1500 m/sec for the helium tests to 3000 m/sec for some of the simulator tests. For purposes of illustration, Fig. 1 also includes a plot of centerline particle mass flux vs axial distance from the nozzle exit plane for a typical solid-propellant rocket operating at high altitude. This curve was calculated for the following conditions: 4000 lb thrust, 500 psia chamber pressure, 25% alumina loading, and 30° nozzle with 40 to 1 expansion ratio. It was also assumed that at each axial station the particles uniformly fill the nozzle cone angle. For other engine sizes the particle flux can be scaled directly with the thrust level.

The scatter in the data of Fig. 1 can be attributed in part to differences in test conditions, including the shock layer gas density,§ target heating, particle size, and incident particle velocity. It is significant, however, that a consistent trend is observed which indicates that target shielding persists as the particle flux changes over four orders of magnitude. In addition, it is of interest to note that as the particle mass flux becomes smaller the major constituent of the debris layer changes from spent projectile material to ejected target material. With further decrease in particle flux, it is expected that the concentration of ejecta eventually will become sufficiently dilute so that the shielding affect will vanish and the particles will impact unaltered on the target. In this case, all other factors being equal, the relative target damage should become independent of particle mass flux. Finally, it should be pointed out that the recorded damage is due principally to mechanical erosion by the impacting particles. This is clearly evidenced by the fact that, while convective gas heat transfer dominated target heating in the solid rocket tests and contributed as much as 30% of the total energy flux in the simulator experiments, the surface regression during a gas-only flow was, respectively, at least 6 and 10 times less than that observed for a two-phase flow. Furthermore, analysis of the cold-flow tests[1] indicates that ablation can account for only a small fraction of the observed damage.

In view of these findings it is of interest to compare the target damage described in Fig. 1 to that expected for a single impact. Reinecke[4] used a light gas gun to determine the damage produced by a single SiO_2 particle impacting on a Teflon target initially at room temperature. For particle diameters ranging from 64 to 73μ and particle velocities of approximately 5000 m/sec, the observed mass loss ratio was 10 g of target per gram of projectile. Sorenson's[5] correlation of impact damage produced by metal projectiles impinging on metal targets shows that, for these projectile-target combinations, energy scaling is approximately valid for velocities as low as several km/sec. Consequently, neglecting the difference in particle size and assuming 1) that a similar relationship holds for oxide particles impacting Teflon targets and 2) that the shear strength of Teflon, which is known to be strain-rate-dependent, is roughly constant over the velocity range from 1500 to 5000 m/sec, Reinecke's data indicate a mass loss ratio of approximately

§ The shock layer gas density has an important effect on the development of the debris layer through its influence on the drag force exerted on debris particles. For the data points shown in Fig. 1, the stagnation-point gas density varied by a factor of ten while the mean value was approximately two orders of magnitude less than that of sea level air. A complete evaluation of the effects of particle drag, however, must also take into account the gas velocity and viscosity, which, in turn, depend on the composition of the gas.

1 and 3 at projectile velocities of 1500 and 3000 m/sec, respectively. These results, shown also in Fig. 1, demonstrate that the mass loss ratio for cloud impingement can be greater or less than that for single impact, by as much as several orders of magnitude. This fact serves to illustrate the consequences of two competing processes which characterize particle cloud impingement. On one hand, the shielding effect of the debris layer reduces the particle energy below its freestream value which, in turn, tends to decrease the impact damage. On the other hand, the target heating produced either by impinging particles or by heat transfer from the surrounding gases causes a significant increase in surface temperature.[1,3] At elevated temperatures, the shear strength of the target is reduced, leading to greater damage than that corresponding to cold targets. The two processes are related since particle heating is controlled by the degree of shielding, which itself is dependent, in part, on the amount of material ejected from the target. Although the degree of shielding and extent of heating were not resolved in the tests reported here, Fig. 1 indicates that the magnitude of the damage depends on which process is dominant.

On the basis of the preceding discussion, it is clear that particle cloud impingement introduces several significant processes which are not associated with single impact phenomena. As a result, multiple impact damage cannot be estimated by extension of single impact data. Although the experiments to date have identified the major problem areas, further investigation is necessary before reliable methods for predicting cloud impingement damage can be established.

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Ignition of Metals with ClF_3 and ClF_5 for Use as Spacecraft Chemical Heaters

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Introduction

ONE of the many problems confronting a design of an unmanned spacecraft for landing on the surface of Mars is that, during the very cold Martian evenings, some

Table 1 Heat of combustion and ignition properties of metals with ClF_3 and ClF_5

Metal, state, supplier	Heat of combustion, kcal/g	Performance with ClF_3		Heat of combustion, kcal/g	Performance with ClF_5	
		Hypergolic with gaseous ClF_3	Hypergolic with liquid ClF_3		Hypergolic with gaseous ClF_5	Hypergolic with liquid ClF_5
Li, 100 μm size, Foote Mineral Co.	4.156	X	X (2)[a]	4.469	X	X (1)
Be, 325 mesh powder, Brush Beryllium Co.	3.493			3.835		
Mg, 325 mesh powder, Reade Mfg. Co., Inc.	3.083		X (5)	3.320		
Ca, 325 mesh powder, Research Chemicals Div. of Nuclear Corp. of America	2.859	X	X (4)[b]	3.035	X	X (3)[b]
Al, 325 mesh powder, Reynolds Aluminum Co.	2.565	X	X	2.786		
Na, 0.0625-in.-diam wire, City Chemical Co.	2.544	c	c	2.676	X	X (6)
44 NaK,[d] liquid, MSA Research Inc.	2.293	c	X (8)	2.400	X	X (7)
56 NaK, liquid, MSA Research Inc.	2.216	X	X (10)	2.316	X	X (9)
78 NaK, liquid, MSA Research Inc.	2.062	c	X (12)	2.149	X	X (11)
K, Small chunks, J. T. Baker Chemical Co.	1.891	X	X (14)	1.963	X	X (13)

[a] Numbers in parentheses indicate the recommended fuel/oxidizer combinations in order of declining preference.
[b] Selected because this reactant combination was extremely hypergolic.
[c] An oxide coating may have prevented ignition.
[d] An alloy of Na and K, containing 44% K by weight.

of the components may fail. Consequently, a heat source should be provided for the spacecraft to protect these components. The heat source may be based on nuclear reactors (or isotope disintegration) or chemical phase changes, or chemical reactions.

Systems analyses have indicated that when the unmanned spacecraft lander is designed to operate on the Martian surface for durations of several terrestrial days or less, then the optimum source of heat is a chemical reaction.[1] The selection of reactants for a chemical spacecraft heater is subject to the following requirements: 1) the reaction should produce the highest possible combustion energy per unit mass of the reactants, 2) the reactants must be hypergolic, 3) the reaction products should be solid, to avoid venting problems, and 4) the reactants should be heat-sterilizable.

The purpose of this Note is to propose reactant combinations that conform to the foregoing requirements. The oxidizers selected were ClF_3 and ClF_5, and the fuels were various metals. Table 1 presents the metals selected, the computed heats of combustion per unit mass of reactants (metal and liquid oxidizer in stoichiometric proportions), and experimental findings as to whether these metals ignited on contact with either gaseous or liquid ClF_3 or ClF_5 at ambient temperatures and pressure.

Experimental Procedure

To determine whether the metals ignited in gaseous or liquid ClF_3 or ClF_5, a stream of the oxidizer was directed at the metal (0.1–0.9 g), contained in a size 000000 Coors crucible. The experiments were performed in the open; the gaseous oxidizer was directed through a $\frac{1}{8}$-in. tubing, with the tip approximately $\frac{1}{2}$ in. above the crucible. The liquid ClF_3(ClF_3 was obtained from the Matheson Company and used without further purification) was also directed through the $\frac{1}{8}$-in. line, whereas the liquid ClF_5(ClF_5 was obtained from the Allied Chemical Company and used without further purification) was first condensed into a cooled test tube and then carefully poured onto the metal.

The Na, K, and NaK alloys reacted very quickly with air, forming protective oxide coatings prior to exposure to the oxidizers. Nevertheless, these substances inflamed upon contact with the gaseous oxidizers, as will be shown in the following section.

The computations for the heat of combustion per unit mass of reactants were based on thermodynamic data.[2] The ΔH_f

of ClF_5 is not available in the literature, but its value was assumed to be -60 kcal/mole.

Results and Discussion

In considering the results (Table 1) on the basis of the design criteria, it is seen that all of the reactants are heat sterilizable. Nearly all of the reactant combinations are hypergolic. Therefore, the recommended fuel oxidizer combinations, in order of declining preference, are indicated by the numbers in parentheses in Table 1, number 1 being best. Thus, the preferred fuel to be used with either ClF_3 and ClF_5 as the oxidizer for a chemical spacecraft heater would be either Li or Ca. A prototype of a spacecraft chemical heater should be built, and the performance of the proposed reactants should be determined in test runs.

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Approximate Analysis of Nonisentropic Flow in Conical Nozzles

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Nomenclature

a = speed of sound, $(\gamma R t)^{1/2}$
A_p, A_s = planar and spherical exit areas, respectively
A_t = geometric throat area, πy_t^2
A_* = minimum flow area (effective throat area)
b = $(n - 1)/(\gamma - 1)$