Conclusions

This study presents experimental results, which are in substantial agreement with results obtained by other investigators for similar materials. One possible explanation for the character of the conductance curves may be due to the sequence of achieving the surface areas contacting each other. Initially, only one or more discrete areas are in contact. As load is applied and the surfaces deform, the contact areas increase, and new regions make contacts. Since this is not a rigorously predictable or controllable process for engineering-type surfaces, as opposed, for example, to the sphericity of the contact surfaces of Clausing,[2] the prediction of the contact conductances becomes difficult. Although several investigators have developed theoretical analyses of this problem, they have been able to predict the thermal contact conductance for specialized conditions and surfaces only. At this time, there are no suitable theoretical analyses available which apply to the general case, although a need exists for such analyses and prediction methods.

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Need for a Variable Burning-Rate Solid Propellant

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At the present time, a large amount of work is being done to increase the specific impulse of solid propellants. However, some of these higher-specific-impulse propellants (e.g., recently developed composite propellants utilizing nitronium or hydrazine perchlorate) are ruled out for many applications because of their handling and storage properties.

Table 1 Typical solid-propellant applications

Application	Burning rate,[4] in./sec
Booster	1–10
Sustainer	0.2–1.0
Gas generator	0.01–0.2
Sounding	0.05–0.5
Ejection	1–10
Vernier	0.5–5.0
Separation	1–10
Retro-units	1–10
Spin	1–10
Space applications	0.05–5.0

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Table 2 Binder materials for solid propellants

Polyurethane	Nitrocellulose—nitroglycerin
Polybutadiene-acrylic acid	Styrene
Polysulfide	Alkyd resin
Cellulose acetate	Carbonyl polyester
Butadiene	Petrin acrylate
Methyl vinylpyridine	Acrylonitrile
Polyisobutylene	Polyvinyl chloride
Isoprene	Polyepoxide
Methoxyethyl acrylate	Polyacrylamide
Methyl acrylate	Asphalt

In other cases, the specific-impulse gain is sacrificed when the propellant burning rate is altered to suit the particular engine application; such changes usually require a propellant development program. This situation is expensive in time and money and reduces the flexibility of the over-all system.

The propellant application survey shown in Table 1 indicates that burning rates ranging from 0.01 to 10 in./sec are required. This requirement should be met with several rather than the hundreds of formulations of fuels, oxidizers, and binders now being used. Among these three propellant components, the most variable is the binder (Table 2). Each propellant company appears to prefer certain binders and to protect its knowledge with respect to them. As the propellant industry becomes more mature, this large number of candidate systems will be reduced.

Table 3 shows present and desirable ranges of solid-propellant properties. There appear to be two classes of propellants; one has a high flame temperature to get high specific impulse and has a burning-rate requirement between 0.1 and 10 in./sec; the other has a burning-rate requirement in the range of 0.01 to 0.2 in./sec.

The more common techniques for controlling the burning rate are 1) altering the burning surface,[1–3] 2) changing the combustion chamber pressure, 3) adding burning-rate catalysts to the formulations, and 4) changing the particle size of solid ingredients, but these techniques often reduce the performance of the solid-propellant motor. Burning rate can be increased without loss in performance by using metal fuels in various forms: hollow or filled spheres, wires of various diameters, foils of various thicknesses, staples of various lengths, or various mixtures of exothermic metal alloys (Table 4). Table 5 shows increases in burning rate (r) obtained by embedding 5-mil wires of various metals in an end-burning propellant grain[4] in the longitudinal (flame propagation) direction. The thermal diffusivities (α) and melting points (m.p.) of the metals also are given in Table 5. There appears to be some correlation between r and α but no clear trend with melting point; however, other data have shown that plating a low-melting-point metal, such as silver or copper, with 1 mil of a high-melting-point metal, such as platinum, increased the propellant burning rate. Unfortunately, there is no comparably simple way to reduce burning rate without penalty. Use of encapsulated endothermic or exothermic reacting material may offer a method of varying burning rate in either direction. When burning rate is varied, the effects on formu-

Table 3 Present and desirable ranges for solid-propellant properties

Parameter	Present range	Desired range
Burning rate, in./sec at 100 psi	0.05–2.0	0.01–10
Burning time of motors 50–60 in. in diameter, sec	2.5–80	0.5–100
Density, lb/in.[3]	0.052–0.0715	0.06–0.08
Flame temperature, °K	1200–4400	1000–5000
Number of propellant ingredients	4–15	1–3

Table 4 Effect of specific form of aluminum fuel on the propellant burning rate

Aluminum form	Range of burning-rate increase, %
Hollow sphere	50–100
Hollow tubes	10–200
Staple	20–300
Wire	50–400
Foil	50–450
Reactive metal coating	100–1100

Table 5 Effect of metal wire on burning rate (reference rate is 0.50 in./sec)

	Wire used		
Metal	α^a, cm²/sec	m.p., °C	r, along wire in./sec
Ag	1.23	960	2.65
Cu	0.90	1083	2.32
W	0.67	3370	1.82
Pt	0.35	1755	1.46
Al	0.94	660	1.16
Mg[b]	0.66	651	0.96
Steel[c]	0.064	1460 est.	0.80

[a] Thermal diffusivity at 650 C.
[b] Square filament cut from 0.005-in. Mg sheet.
[c] Music wire.

Table 6 Typical propellant development cycle

Cycle step	Time period, month
Establish propellant ballistic requirements	1–2
Analytical studies to define propellant formulation	1–2
Laboratory formulation	2–6
Small motor testing	3–6
Intermediate-scale motor testing	3–8
Full-size motor testing	6–8
Total months (does not include the time necessary to synthesize any of the ingredients)	16–42

lation and curing techniques, physical properties, and handling, storage, and safety properties of the propellants must be carefully evaluated, of course.

It is estimated (Table 6) that if a variable-burning-rate propellant were available, a typical propellant development cycle would be reduced by 16 to 42 months, depending upon the amount of motor testing required for acceptance. The monetary savings might be on the order of 1–3 million dollars. Furthermore, special facilities are often required for the production of the necessary raw materials for new multiple-ingredient propellants, and these facilities are often shut down at the end of the program. If the large effort now being expended on the development of a multitude of propellants could be transferred to the cause of increasing the knowledge about a few variable-burning-rate systems, a great savings in future program times and costs should result.

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Influences of Small Differences in Ballistic Coefficient on Satellite Station Keeping

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Nomenclature

g_E = earth's gravity
h = altitude
h_0 = satellite initial altitude at $t = 0$
h_1 = $R_1 - R_E$ = satellite altitude at the end of time t
n = integer
R = radius
R_0 = $R_E + h_0$
R_E = earth's radius
t = elapsed time
β = ballistic coefficient
γ = reciprocal of scale height
θ = anomaly angle
ρ = atmospheric density
ρ_0 = initial atmospheric density at $R = R_0$
ρ_1 = final atmospheric density at $R = R_1$
$\bar{\rho}$ = density coefficient

Introduction

THERE are applications where it is desirable to place a group of satellites in prescribed low circular orbits. Orbit decay of such satellites is influenced primarily by atmospheric drag (Refs. 1, 2, and their references). However, when it is desired to maintain the group of satellites at fixed relative distances, the effects of small differences in ballistic coefficient also become a problem of interest. This note presents the results of an investigation on the drift distance between two satellites caused by a small difference in ballistic coefficient which might be due to differences in weight, frontal area, geometry, and surface roughness. Other perturbing mechanisms, such as the earth's oblateness, variation of earth's gravity field, the gravity effects of the sun and moon, and magnetic field have secondary effects which apply almost equally to each satellite and will, therefore, be neglected. The present analysis is also limited to circular orbits at altitudes less than 400 miles where atmospheric drag has the dominating effect on orbit decay, and where the effects of solar radiation pressure are also negligible.

Using high-speed computers to solve this long-term decay problem from the equations of motion is costly. A numerical solution could accumulate, after a few orbits of calculation, errors of the same magnitude as the drift distance. Therefore, a closed-form solution is desirable. Billik,[1] Parsons,[2] Henry,[3] and Perkins[4] have obtained closed-form solutions for satellite lifetimes. Recently, Zee[5] has analyzed satellite trajectories under the influence of air drag and has obtained an approximate solution for anomaly angle. He obtained u, the ratio of perigee focal radius of original elliptical orbit to radial distance from the center of attraction to the satellite by assuming constant h, ratio of the angular momentum. He then substituted these results in a nondimensional equation of motion and expanded it into a series. Neglecting

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