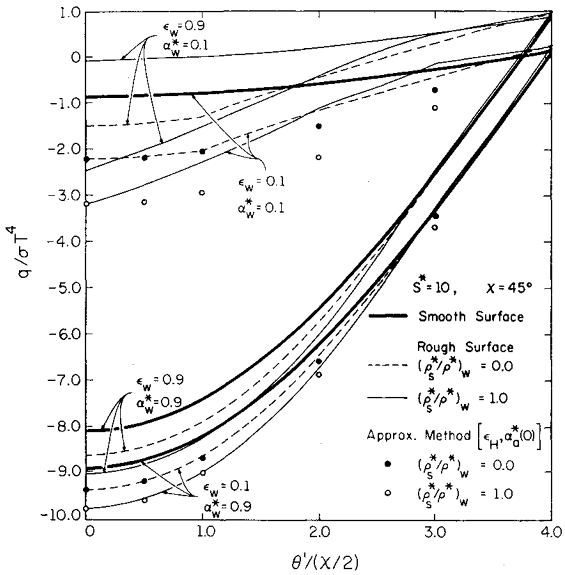

Fig. 3 Surface roughness effects on radiant heat transfer ($S^* = 10$).

rection of incident energy, although in the latter instance, the smooth surface flux generally exhibits a weaker directional dependence. For the emission-dominated situation illustrated in Fig. 1, radiant fluxes are positive and less than unity with the level of flux determined by wall emittance. The influence of the specularity parameter for solar energy $[(\rho_s^*/\rho^*)_w]$ is imperceptible in the figure. As interreflections within surface asperities vary from diffuse to specular, the rough surface flux increases by less than 4% for the high-emittance surface and 15% for the low-emittance surface. Heat transfer from the rough surface exceeds that from the smooth surface of identical material at all directions of incidence with the discrepancy at normal incidence less than 10% for the low-emittance surface and as large as a factor of 15 for the low-emittance, high-absorptance surface. The large discrepancies for the latter surface are attributed to the small smooth surface flux values and the large increase in apparent emittance caused by roughness on surfaces of low emittance. In the solar-flux-dominated situation shown in Fig. 3, the radiant flux varies from a large negative value at normal incidence to values lying between zero and unity at grazing incidence. Now the flux level is dictated by solar absorptance except at and near grazing incidence when the flux is governed by apparent emittance. The influence of wall specularity for emitted energy is imperceptible and as surface asperities vary from diffusely to specularly reflecting, the rough surface heat-transfer rate to the surface at normal incidence increases by less than 5% for the high-absorptance surface to a value 70% larger for the high-emittance, low-absorptance surface. At normal incidence, radiant flux to the rough surface exceeds that to the smooth surface by about 10% for the high-absorptance surface but this discrepancy increases to a factor of almost 25 for the high-emittance, low-absorptance surface for reasons similar to those cited earlier. For the situation in Fig. 2, where emission and solar flux are equally important ($S^* = 1.0$), the extent of the variation in flux with direction of incidence is intermediate to those already discussed. Except at large angles of incidence, the dominant wall property value now is the ratio of solar absorptance to emittance (α_w^*/ϵ_w). Both specularity parameters are important, although the S^* affects normal-incidence, rough-surface heat flux results for small and large values of α_w^*/ϵ_w by a factor of two to three times more than the 5% influence of $(\rho_s/\rho)_w$. Again, large discrepancies between smooth- and rough-surface heat transfer exists when small flux values are encountered.

At grazing incidence, rough-surface fluxes are determined by apparent emittance. Employing this apparent property with apparent solar absorptance at normal incidence yields the rough-surface results at normal incidence. Since measurements of these two properties are not uncommon, one may ask how accurately these two property values will predict heat flux rates for all directions of incidence. Calculations were performed and the results are shown in Figs. 1 and 3. It is apparent that in the emission-dominated situation, the approximation is excellent. Results derived on the same basis for $S^* = 10$ show good agreement for the high-solar-absorptance surface, but those for the low-absorptance surface depart significantly from the rough-surface results at intermediate directions of incidence particularly for surface asperities that are specularly reflecting. In the latter instance, the results are sometimes in poorer agreement with the rough-surface results than are the smooth-surface values. The large discrepancies at low α_w^* and large S^* are attributed to the strong dependence of the apparent directional absorptance on direction of incident energy for the surfaces considered here. The use of the aforementioned technique at $S^* = 1.0$ shows the same trends but to a lesser degree than those discussed for the emission-dominated and solar-flux-dominated situations.

In conclusion, it has been demonstrated that surface roughness can significantly influence radiant heat-transfer rates. When roughness is neglected and fluxes are evaluated using material property values, the discrepancy between values so calculated and those which fully account for roughness can be orders of magnitude when the dimensionless fluxes are less than unity. For dimensionless flux values greater in absolute value than unity, the difference exceeds 10%. Surface-roughness effects are particularly important for low-emittance surfaces when emission is dominant, low-solar-absorptance materials when incident flux is dominant, and for materials with α_w^*/ϵ_w near unity in situations where emission rate and incident flux are comparable. The use of apparent emittance and normal solar absorptance for all directions of incident energy yields results in excellent agreement with rough-surface fluxes except for materials of low α_w^* in solar-flux-dominated situations at intermediate directions of incidence.

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Exothermic Bimetallic Ignition System

P. N. Laufman*

Lockheed Propulsion Company, Redlands, Calif.

SOLID-PROPELLANT rocket-motor ignition systems are becoming more complex as the associated missile systems become more sophisticated. The acceptable bands of ignition transients (Fig. 1) become narrower and ignition spikes must

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* Engineering Supervisor, Lockheed Propulsion Company. Associate Fellow AIAA.

be progressively minimized. This Note describes exothermic bimetallic ignition systems (EBIS) to meet such requirements.

Of concern for tactical missiles are shock damage to the launcher assembly, carrier vehicle, and/or personnel and initial shock loading upon the warhead or guidance and control equipment. Shock loads imparted during the ignition phase are proportional to the pressure (or thrust) rise rate, dP/dt (or dF/dt). However, there is a minimum allowable dP/dt to achieve the minimum acceptable initial velocity for a successful ballistic trajectory. The ignition spike is the result of one or more of the following three events: 1) excessive duration of igniter burn, 2) excessive igniter mass discharge for the application, or 3) excessive igniter impingement concentration on the motor grain, causing local erosive burning. These events neglect instances in which the spike may be described by a purely ballistic phenomena.[1] Elimination of the spike by tailoring of the igniter may unacceptably lower dP/dt or severely limit fabrication capability (for example, an available, small pyrogen igniter† is likely to already have a propellant web approaching the minimum thickness processible). The ignition spike, then, is often limited to both magnitude and duration and frequently in the maximum integral enveloped on the pressure-time curve ($\int P dt$, represented by the shaded area under the curve in Fig. 1). The EBIS avoids these problems because it releases very little mass and ignites the rocket grain primarily by heat conduction. Of the available bimetals, the most well characterized is Pyrofuze,‡ an aluminum-cored, palladium-clad matrix that is available in solid and braided wire, sheet, granules, tubes, etc. (Other combinations, e.g., Mg-Pt and Pb-Li, are being further developed.) The exothermic reaction of the Al-Pd alloying function liberates 327 cal/g, very locally concentrated.

Use of EBIS in Pulse Char Motors

An EBIS is in use as a pulse char motor igniter at the Air Force Rocket Propulsion Laboratory (AFRPL), Edwards Air Force Base, Calif. It is fastened to the bottom of a rubber cup that forms the flame barrier of the preceding pulse (see inset, Fig. 2). The spiral of wire is held on the barrier by adhesive-backed rubber patches in a pattern that avoids significant slack, assuring that the bimetal will not enter the uncured propellant to an appreciable depth. In the pulse char motor, pulse 4 is cast first, an EBIS assembly is installed and bonded to the insulated case wall, and the wire leads are potted into the internal raceway. The remaining pulses are installed identically. The only unique concern is elimination of any air entrapped beneath each barrier before each bond cure thereby achieving intimate contact with the propellant. (Braid is especially attractive in use with uncured propellant because it performs as a screen-type structure, entrapping the viscous propellant within its matrix.) The EBIS will not deteriorate in presence of propellant before use, thereby providing infinite dwell time limits between pulses.

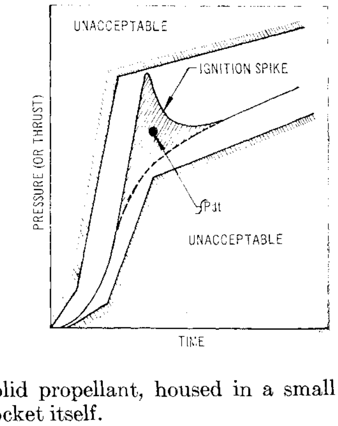

Fig. 1 Ignition transient conditions.

† An igniter containing a solid propellant, housed in a small chamber; essentially a small rocket itself.

‡ Pyrofuze is a registered trademark of the Pyrofuze Corp., an affiliate of Sigmund Cohn Corp., Mt. Vernon, N.Y.

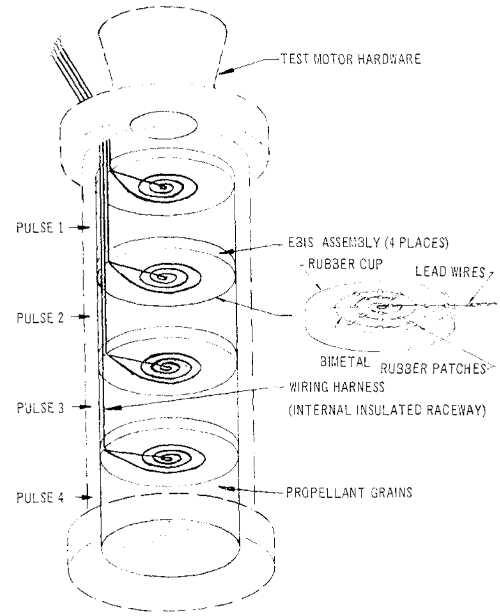

Fig. 2 Pulse char motor.

Use in Tactical Motors

Use of EBIS with tactical solid rockets requires the understanding of the phenomena in its use as a resistance wire. The bulk of experience in the past has relied upon the bimetal to provide specific delay times, achieved by its strand burn rate as a fuse. Peterson[2–4] initiated the bimetal with an explosive primer. However, Forbes[5] initiated burning by electrical means, using one end of the bimetal as a bridgewire. In doing so, he derived the relationship of ignition delay time t-(sec) to current applied I(amp), $tI^2 = K$, where t essentially equals the time to raise the bimetal to the alloying temperature (~1220°F, where the Al melts). Since t is inversely proportional to the power input W, where $W = I^2R$ and the average resistance $\bar{R}$ between ambient and the ignition temperature is a constant in any given system, $\bar{R}$ is accounted for in the complete system constant K. K describes all independent physical parameters of the system including the effects of adjacent heat sinks, electrical conductivity of the wire and of the propellant, bimetal style, environmental extremes, etc. As each system is unique, these system parameters must be experimentally determined within each configuration. The

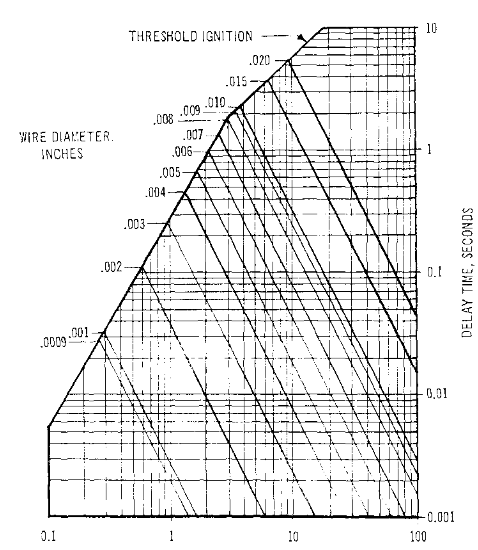

Fig. 3 Ignition delay time vs applied current (varying diameters at a 4-in. length).

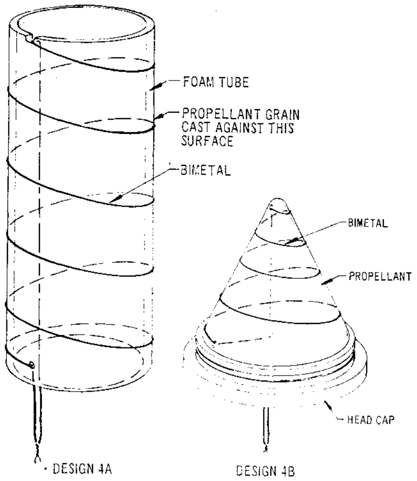

Fig. 4 Typical EBIS uses.

typical ignition delay time vs applied current relationship is illustrated by Fig. 3. Using a constant length of solid wire, the figure provides a family of current vs delay-time curves, varying wire diameter, in an ambient air environment. Based on the linear relationship between resistance and wire diameter and utilizing Fig. 3, it is determined that any wire 0.003 in. diam and above will meet the commonly required 1-w/1-amp/5-min no-fire criteria. In addition, higher no-fire energies may be achieved; e.g., the 0.010 in. diam will withstand a 3-w/4-amp energy source and the 0.020 in. diam, a 2-w/9-amp source indefinitely. Variations in length will provide infinite combinations for choice, such that complete electrical safety may be achieved. Reliability, on the other hand, is also greatly enhanced by this concept (usually added safety occurs at the expense of reliability). Integrity of the system is monitored by a simple circuit continuity check, allowable monitoring current is substantially higher than that of normal electro-explosive devices (EED's), susceptibility to electromagnetic radiation sources on aircraft, shipboard and test sites is less than that of common EED's, and its strength is comparable to that of aluminum.

Selection of the EBIS Assembly

Although complete optimization can be attained only through testing, there are a number of basic rules of thumb that will initially aid the designer:

1) Positive attachment of the bimetal to the propellant is necessary because of negligible brisance; placing the bimetal in tension to maintain that condition is suggested.

2) A large number of small diameter wires (as in a braid) will require a longer function time than one wire of equal volume; therefore where available voltage is limited, a single strand of minimal length is suggested.

3) Every advantage of geometry should be used; placing the igniter at the forward-most position in the motor, for example, will necessitate only a minimum area to be directly ignited by EBIS, the remainder being progressively ignited as the hot gases sweep the motor grain on the path to the nozzle.

4) Avoid overlaying the wire upon itself without an intermediate electrical insulator because the unit to unit reproducibility of the system will degrade due to inconsistent electrical characteristics.

5) In choosing a system for which minimal support data exists, added data may be acquired by varying only wire length, since resistance is directly a function of wire length in like environments.

Fabricability must also be considered. The system shown in Fig. 2 may be used for a cured motor of an end burning configuration by casting the propellant upon the EBIS assembly. Figure 4 depicts means to achieve an EBIS in center-perforated (radial burning) grain designs. Design 4A consists of a mandrel-inserted foam tube around which is helically wound a length of bimetal wire; the tube acting as an electrical insulator and EBIS support. A star-grain or a slotted-tube configuration may be processed similarly, however, with the wire wound longitudinally in each star valley or slot. In addition, a center-perforated design may be achieved by placing a bimetal wire coincident on the centerline of the motor and casting propellant directly on it. The degree of resulting progressivity may be regulated by longitudinal placement of a number of EBIS, wired in parallel, within the grain such that the progressive burning pattern of each into one another will produce a neutral gross effect. The aforementioned systems achieve elimination of an igniter-caused ignition spike and minimize the thrust rise rate. These are accomplished as a result of elimination of igniter augmentation to the mass discharge of the motor. However, augmentation is also available with EBIS. Consider design 4B in which a conical mass of propellant is directly attached to the motor case. A length of bimetal wire is wrapped around the propellant cone and exits the motor through the propellant and case to the power source. Initiation will result in external burning of the propellant cone, producing hot gases which in turn ignite the motor. This is significantly less complex than a classic pyrogen igniter, requiring no independent chamber, insulation, nozzle, or EED and leaving no remnant mass. It may, however, be easily configured to achieve mass discharge rates comparable to most pyrogen designs of today's large solid rocket motors. Familiarity with the complex ignition systems on Minuteman, Polaris/Poseidon, and the 120-in., 156-in., and 260-in. series of large solid rocket motors provides appreciation of the design efficiency obtainable by this system.

Future Activity

We have established the EBIS concept, explored the potential for this method of rocket motor ignition and, indeed, even glimpsed into regulation of a complete motor burning pattern with the bimetal wire. It remains for the industry to develop its sophistication by utilization on experimental and test motors as opportunities arise. These may include research motors for such varied uses as radar attenuation studies, smokeless propellant development, materials evaluation, etc., or for quality assurance reasons such as propellant batch check motors or propellant aging surveillance.

Lockheed Propulsion Company is continuing a company sponsored program to further evaluate the concept. Some work has already been accomplished in the area of a.c. voltage sources and use is being made of some recent work by the British § in the area of capacitor discharge power sources. Remaining effort involving susceptibility to inadvertent electrical currents is planned. Assimilation of all data generated on the subject by the industry as a whole will result in a timely incorporation of the concept as a simple, practical, and highly efficient major assembly of increasingly more complex solid rocket motors.

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§ Royal Armament Research and Development Establishment, Fort Halstead, Seven Oaks, Kent, England.