New Solid Propellant for European Apogee Boost Motor

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Abstract

EUROPEAN Space Agency programs have generated a requirement for higher-performance propellant for their apogee boost motors. This paper describes the development and characterization of a highly solids-loaded, carboxy-terminated polybutadiene, composite solid propellant, delivering the required higher specific impulse and providing the mechanical properties essential for grain structural integrity, while retaining excellent processibility.

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Introduction

Planned efforts of the European Space Agency (ESA) have resulted in requirements for apogee boost motors of the MAGE type. These motors will be used to place satellites of varying weights in a geostationary orbit in the early 1980's. The design and development of such motors has a sound background in the experience of similar motors of GEOS (ESA) and SIRIO (Italian) already successfully launched, both based on highly solids-loaded, carboxy-terminated polybutadiene (CTPB), composite solid propellants.

The first model of the MAGE motor incorporated a propellant formulation, with 86% weight total solids (71% ammonium perchlorate and 15% aluminum powder), which delivered a specific impulse of 2396 N·s/kg at standard conditions and 2832 N·s/kg in vacuum. Later, the MAGE satellite mass was increased, requiring an increase not only of propellant mass, but also of propellant performance.

Propellant Development

A detailed research and development program was then planned, with the objective of developing and characterizing a formulation delivering the required specific impulse and providing the mechanical properties essential for grain structural integrity, while retaining excellent processibility. As is well known, the specific impulse of a propellant depends exclusively on its composition; 1) it increases as binder quantity decreases; and 2) it increases as aluminum percent increases (within certain limits).

Increasing aluminum content presents no problem in mechanical properties and in castability, if it is done at constant binder level. Nevertheless it was preferred to increase the aluminum content of the propellant only 1%, from 15% to 16%, in order to avoid too high a flame temperature. Reducing binder content gives a significant increase in specific impulse, if it is done at constant aluminum content, but this reduction might be critical to mechanical properties and castability unless a binder of excellent properties is utilized.

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CTPB propellant mechanical properties depend mostly on type and level of curing agents:

1) As polymer chains are practically linear and bifunctional, curing agents must be at least partially trifunctional; otherwise a cross-linked network, and consequently an elastomeric matrix, is not formed.

2) To obtain the best elastic properties, it is desirable that some bifunctional curing agent be present to provide for chain-extension. This philosophy led to the definition of: 1) the curing agents themselves, 2) the total quantity of curing agents, with respect to polymer quantity (total cure level), and 3) the quantity of each curing agent and consequently the ratio of trifunctional/difunctional curatives. Excellent mechanical properties in 87%-solids propellant were obtained utilizing such a cure system, and this encouraged further efforts to get similar results with only 12% binder, thereby further improving ballistic performance.

Many compositions (all with 88% total solids) were tested, making possible a comparison between mechanical properties obtained as a function of different ammonium perchlorate particle size distributions. Of course, only distributions almost equivalent in specific surface were chosen, in order to obtain burning rates in agreement with design requirements. The best solution, with regard to mechanical properties, castability, and burning rate, was found in a tetramodal distribution of ammonium perchlorate, with only a small quantity of ground material (6%).

Mechanical Characterization

Mechanical properties were measured in all cases at temperatures ranging from $-40°C$ to $76°C$; for the best compositions (among which was the one definitively chosen), a mechanical characterization was performed. It consisted of an experimental phase and a data evaluation phase. A number of tensile tests were made, using an Instron model TT-C-M1 dynamometer, on JANNAF specimens (class B) at three different crosshead speeds and eight testing temperatures, from $-57°C$ to $76°C$. Stress-strain diagrams were obtained presenting the three base mechanical parameters of: 1) tensile strength $\sigma_{max.}$, 2) elongation at maximum stress $\epsilon_{max.}$, and 3) modulus E.

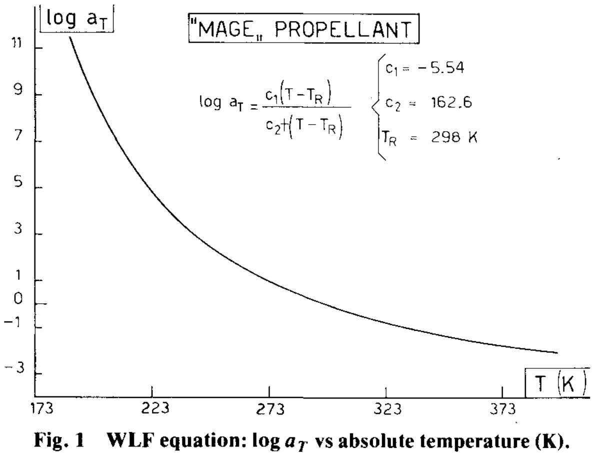

Fig. 1 WLF equation: log a_T vs absolute temperature (K).

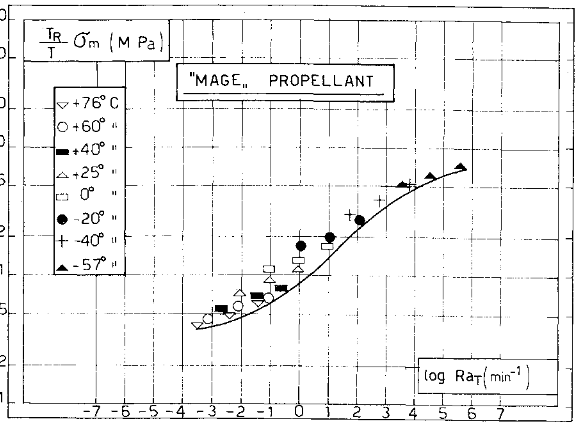

Fig. 2 $(T_R/T)\sigma_{max.}E$ vs $\log R \cdot a_T$.

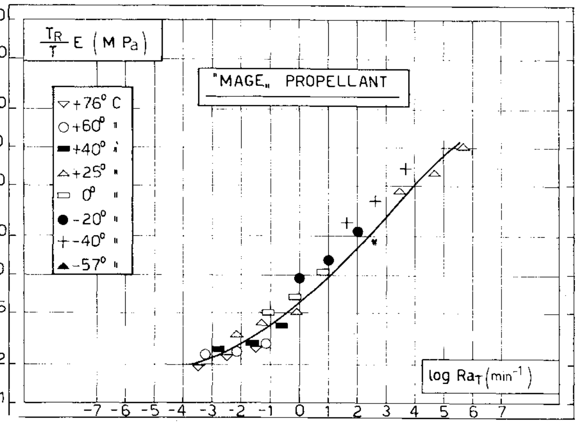

Fig. 3 $(T_R/T)E$ vs $\log R \cdot a_T$.

The data evaluation phase consisted of the development of "master curves" which depict tensile strength, modulus, and elongation as a function of $\log R \cdot a_T$, depending both on crosshead speed (through R) and testing temperature (through a_T). R is defined as crosshead speed divided by effective gauge length, and the dependence of $\log a_T$ on the temperature is expressed by the WLF equation plotted in Fig. 1:

$$\log a_T = \frac{C_1(T - T_R)}{C_2 + (T - T_R)}$$

where $C_1 = -5.54$, $C_2 = 162.6$, and T_R is the "reference temperature."

In design calculations it is preferred not to plot $\sigma_{max.}$ and E as functions of $\log R \cdot a_T$, but rather some derived quantities such as $(T_R/T)\sigma_{max.}$ and $(T_R/T)E$. The advantage of such "master curves" lies in the possibility of foreseeing propellant mechanical performance during short- and long-time stresses, in the light of equivalence of effects on propellant of deformation speed and testing temperature (Figs. 2-4).

Ballistic Characterization

The ballistic performance of the MAGE propellant (delivered specific impulse at standard conditions) can be easily calculated as a function of formulation, obtaining the figure of 2450 N·s/kg. The burning rate of the propellant at different pressures was determined by means of Crawford Bomb tests of solid strands, and by static firing tests of standard motors. The following burning-rate equation was obtained

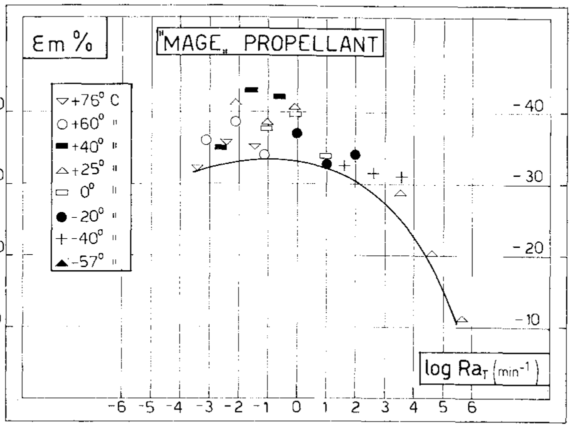

Fig. 4 Elongation at maximum stress $\epsilon_{max.}$ vs. $\log R \cdot a_T$.

$$b_r = 4.28\, p^{0.306} \quad \text{at} \quad 21°C$$

where b_r (burning rate) is in mm/s and p (pressure) is in MPa.

Finally, specific impulse in vacuum was measured by firing a 270-kg (propellant mass) motor in a high-altitude test facility. Obtaining 2861 N·s/kg confirmed the foreseen increase, compared with the value of 2832 N·s/kg obtained in the same conditions by the previously available propellant.

The first series of MAGE motors, 335 kg propellant mass, is now undergoing qualification testing. One motor has already been successfully fired in the high-altitude test facility with excellent results, indicating attainability of a specific impulse of 2891 N·s/kg.

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