Formulating Propellants for Fully Case-Bonded End-Burning Motors

H. E. MARSH JR.* AND D. E. UDLOCK†
Jet Propulsion Laboratory, Pasadena, Calif.

Theme

A NEW family of solid propellants is developed which makes possible high performance, fully case-bonded end-burning motors (CBEB), resulting in an order-of-magnitude improvement in the thrust-to-mass capability of solid propellant rocket motors. This new capability is demanded of solid rocket motors by missions, such as planetary orbit insertion, requiring both low acceleration and large total impulse. Propellants having very high elongation and very low modulus are made by means of a new formulating concept without sacrifice in performance and with improved quality control. Structural integrity tests in flight-weight motors have demonstrated this new technology.

Contents

Heretofore unattainable, a high performance CBEB motor was demonstrated[1] using JPL 540J propellant, an established formulation which has been used in conventional motor configurations in previous flight programs.[2] The JPL 540J binder formulation is as follows: 0.83 equivalents of hydroxyl-terminated polypropylene oxide (Union Carbide Corp. PPG 2025, elastomer grade), 0.11 equivalents of Alrosperse 11P (Geigy Chemical Co.), 0.06 equivalents of 2,6-tolylene diisocyanate, 0.25% of ferric acetylacetonate, and 1.25% of phenyl-beta-naphthylamine. The limited success of this CBEB motor demonstration was possible because of the unusually high elongation of JPL 540J (Table 1).

Motor chambers from previous flight programs were reused for all motor tests reported here. The two types of motors cited in Tables 1 and 2 are scaled versions of the same design. The motor axial cross section is illustrated in Fig. 1. The determination of propellant properties required for CBEB construction has been based on engineering judgment and empirical testing; however, a limited structural analysis[3] was made after the new propellant, described below, had been developed and partially tested.

Two shortcomings in JPL 540J propellant for CBEB application were illuminated by the preliminary tests (Table 1). They are, marginally high modulus and very poor quality control. The buckling of flight-design chambers (see Table 1) was caused by excessive propellant modulus. The difficulty with control of mechanical properties is predictable on the basis of Flory's theory of polymer network formation[4,5]: Sensitivity of Flory's α (which is an index of gel fraction) to variations in ingredient weights, extent of cure, etc., is inversely proportional to the cross-linking agent concentration, which in JPL 540J is very low.

Presented as Paper 71-654 at the AIAA/SAE 7th Propulsion Joint Specialist Conference, Salt Lake City, Utah, June 14–18, 1971; submitted June 15, 1971; synoptic received November 19, 1971; revision received March 22, 1972. Full paper is available from AIAA. Price: AIAA members, $1.50; nonmembers, $2.00. Microfiche, $1.00. **Order must be accompanied by remittance.**

Index categories: Solid and Hybrid Rocket Engines; Properties of Fuels and Propellants; Properties of Materials.

* Group Supervisor. Member AIAA.

† Engineer.

Table 1 Preliminary CBEB demonstration motors, JPL 540J propellant

Batch size, kg	Elongation at maximum load, %	Secant[a] modulus N/cm²	Number or motors	Motor propellant weight, kg	Observations
115	139[b]	37[b]	1	27[c]	Fired successfully.
115	160	45	2	27	No failure in pressure and temperature cycling tests
545	129	67	1	360	Fired successfully.
227	145	87	3	27	Chamber walls buckled.
545	82	122	1	27	Nozzle end pull-away; repaired and fired successfully.

[a] Secant modulus is ratio of tensile strength and elongation at maximum load.
[b] Tensile test conditions; Standard ICRPG specimens, 5.08 cm (2 in) gage length, 6.86 cm (2.7 in) effective gage length; Instron tester, 22°C, 5.08 cm/min extension rate.
[c] Syncom apogee motor chambers were used for 27 kg CBEB. Applications Technology Satellite apogee motor chambers were used for 360 kg CBEB.

Reduction of modulus requires decreased cross-link density, whereas improvement in quality control calls for increased concentration of cross-linking agent. The development of a propellant meeting these two opposing requirements was achieved by increasing cross-linking agent concentration while at the same time frustrating actual cross-link production by causing an intentional increase in chain termination.

Two methods for introducing chain termination were experimentally screened; they were stoichiometric shift and monofunctional ingredient addition. The latter method readily produced promising results. An investigation of the effects on tensile properties produced by varying monool and triol concentration was carried out with the aim of producing

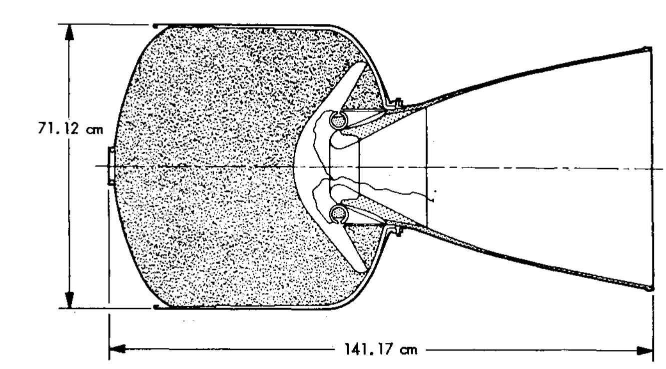

Fig. 1 Case-bonded end-burner motor design, 360 kg propellant charge.

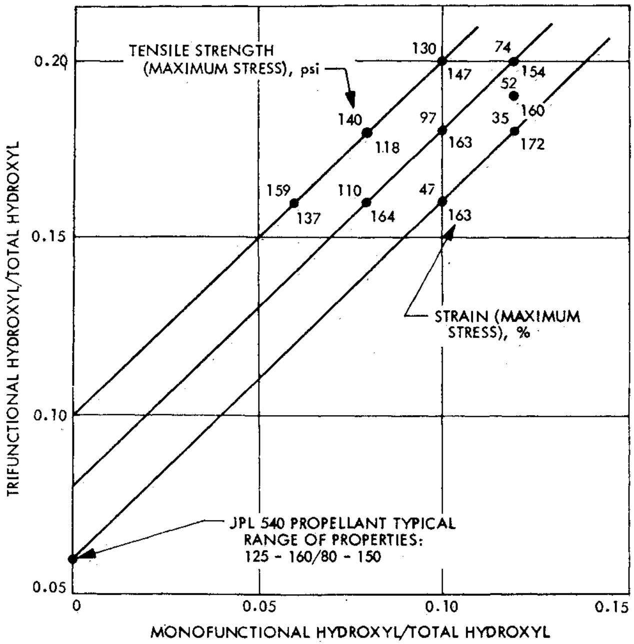

Fig. 2 Mechanical properties of propellants containing varying amounts of 1-decanol.

elongations and moduli in the adopted target ranges for subsequent CBEB development (which were: tensile strength, 28 to 70 N/cm² (40 to 100 psi); elongation, over 100%, secant modulus, 17 to 45 N/cm² (25 to 65 psi)). Results plotted in Fig. 2 show a systematic dependence of tensile properties on the two parameters. Only PPG and TMP equivalents were adjusted to accommodate the mono-alcohol.

All subsequent CBEB motor development and testing has been done with monool-modified JPL 540 propellant formulations having mechanical properties in the adopted target ranges cited above. Test results of five batches and three motors are presented in Table 2. No structural failures occurred, and quality control was improved, over a wide range of batch size.

Finite element analysis[3] of the motor configuration shown in Fig. 1, and based on stress relaxation measurements of the monool-modified JPL 540 propellant at two strains and four temperatures, showed no limitation in the propellant for withstanding all planned environmental conditions and duty cycles. The only critical stress found in the system was the buckling stress of the thin-walled chamber at −46°C (−50°F). The analysis showed further that this limitation may be lowered (by 20 to 40°C) with this motor system by the use of pressurization, to 120 N/cm³ (175 psi), during propellant curing. The results of the finite analysis and the tests cited in Table 2 were supplemented with two other tests for structural integrity. These are described below.

The monool-modified JPL 540 propellant is so soft that cantilevered beam samples begin to fall rapidly under their own weight. To find the limitations imposed by this property, a 360 kg propellant motor (Fig. 1 configuration) was loaded with a formulation having a secant modulus of only 21 N/cm² (30 psi) and subjected to a series of slump tests. At 22°C this motor was stored successively in three positions, nozzle end down, nozzle end up, and horizontal, 30 days or longer in each position. Periodic measurements of selected grain surface locations showed no significant deformation. The maximum displacement measured was 0.44 cm. Following this, the motor was subjected at 22°C to a launch simulation vibration test with accelerations of from 1 to 8 g over a range of frequencies of from 5 to 1500 Hz with no evidence of failure.

The thrust-to-mass level of CBEB solid propellant motors is inversely proportional to L/D. Increase in L/D over that of the design discussed above (a value of 1) imposes a more severe strain field on the propellant grain. To test one point on this spectrum, a 15.24 cm diam motor chamber (also flight weight) was loaded to an L/D of 6 with monool-modified JPL 540 propellant having a secant modulus of 30 N/cm². The motor was subjected to temperature cyclings between −23°C and +43°C and to a pressure equivalent to that of firing for that chamber (482 N/cm²). No failure was found, either visually or by means of radiographs recorded during stress.

Table 2 Tests with Monool-modified JPL 540 propellant

Batch size, kg	Elongation at maximum load, %	Secant modulus, N/cm²	Number of motors	Motor propellant weight, kg	Observations
545	157	33	1	360	Fired successfully
0.80	154	33	0		
100	148	30	1	27	Fired successfully
545	178	26	1	360	Fired successfully
115	156	26	0		

References

[1] Shafer, J. I., "Solid Propellant Spacecraft Motors," Space Programs Summary 37–63, Vol. III, Jet Propulsion Lab., Pasadena, Calif., April 1970, p. 188.

[2] Anderson, R. G., "The Applications Technology Satellite Apogee Rocket Motor: A Summary Report," TM 33-338, Feb. 1970, Jet Propulsion Lab., Pasadena, Calif.

[3] Holsapple, K. A. and Fourney, M. E., "Stress Analysis of JPL End Burning De-Orbit Solid Propellant Motor," Rept. 70-50-1, Aug. 1970, Mathematical Sciences Northwest, Seattle, Wash.

[4] Flory, P. J., "Molecular Size Distribution in Three Dimensional Polymers. I. Gelation," *Journal of the American Chemical Society*, Vol, 63, 1941, p. 3083.

[5] Marsh, P. E., Jr., "Formulations and Quality Control in Polyurethane Propellants," *Industrial and Engineering Chemistry*, Vol. 52, Sept. 1960, p. 768.