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Solid-Propellant Scaleup Considerations

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The mixing of solid propellants for military and space applications remains largely an art rather than an exact science. Solid-propellant development requires a thorough understanding of process parameters. Scaleup bias is a critical consideration in the development, scaleup, and production of new solid-propellant formulations.

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Abstract

The mixing of solid propellants for military and space applications remains largely an art rather than an exact science. Solid-propellant development requires a thorough understanding of process parameters. Scaleup bias is a critical consideration in the development, scaleup, and production of new solid-propellant formulations.

Defense Systems Information Analysis Center

Contents

1.0 TI Request

1.1 Inquiry

At the conclusion of a development campaign for a new solid propellant, should rocket motors be loaded and tested from the first-production scale mix?

1.2 Description

In consideration of meeting aggressive solid-propulsion development program cost and schedule requirements, the inquirer would like to understand the risks of eliminating a full-scale process verification mix of a new propellant formulation, commonly called a "throwaway mix."

2.0 TI Response

This report is largely based on practical knowledge, experience, and lessons learned from the authors' decades of work as researchers, developers, and manufacturers of solid rocket motors and propellants for U.S. Department of Defense (DoD) system applications.

Beginning in 1994, the U.S. solid rocket industry rapidly consolidated and downsized from five distinct and capable second-tier propulsion suppliers to just two by 2003. More recently, emerging market demands for increased industrial capacity, capability, and competition from both the DoD and prime contractors have placed the solid rocket industrial base on the verge of its first significant expansion since the 1960s. Several companies and startups are poised to enter the solid rocket market. This market expansion has thinned the existing talent base and created a talent gap in the solid rocket industry. To successfully enter the market and become a reliable producer of solid propellants and rocket motors, the next generation of suppliers and talent must understand the inherent scaleup biases that exist in the development of solid propellants. Propellant properties at the 1-gal, 5-gal, and 30-gal scale are not the same as those produced in larger 150-gal, 300-gal, and 420-gal mixers.

Solid rocket propellants have been used by the United Stares for military and space applications for over 80 years. Over these many decades, process engineers have grappled with mix-to-mix and scaleup variability and biases inherent with the use of customary vertical-blade planetary mixers. One of the specific challenges has been the bias in propellant properties observed between mixers of various sizes and designs. In 1995, Richard Morgan published a seminal technical paper that describes many of these parameters and their effects on resultant propellant properties [1].

As propellant development progresses from small to large mixers, the blade-to-blade and blade-to-bowl clearances typically tend to increase, yielding poorer overall mixing. These attributes are exacerbated by the size of the mix, where heat flux and complete mixing can be a challenge as the batch size increases. Other process variables, such as manual ingredient feed vs. automated feed, between cycle bowl scrape downs, time for chemical reactions, and purge cycles based on propellant mass, can result in differences in mechanical properties, rheological properties, end-of-mix viscosity, and burning rates for typical hydroxyl-terminated polybutadiene/ammonium perchlorate (AP)/aluminum composite propellants. The properties are critical to system performance, particularly in the air-launched tactical missile regime.

It is customary to determine the bias between mixers by conducting standardized (or at least comparative) testing of propellant samples from different batch sizes. For example, a propellant mix would be prepared in a smaller mix size (e.g., 1 gal, 5 gal, or 30 gal) and understood before proceeding to larger mix size. A larger, production-scale propellant mix (e.g., 300 gal or 420 gal) would then be made to characterize processing characteristics (pot life, viscosity, rheology), mechanical properties (stress, strain, modulus), burning rate (strands, small ballistic test motors), and bond data (peel samples and conical bond-in-tension [known as CBIT] samples). The data would be collected and a scaleup bias factor determined using several mixes.

This bias factor then would guide the process engineer toward understanding the scaleup parameters. For example, a longer mix cycle, different orders of addition of ingredients, or differing blade speeds might be employed to achieve the desired properties.

Other factors to consider in the solid-propellant development process include:

- Cure ratio (may have to be adjusted)
- Presence of iron oxide or other burning-rate modifier
- Presence of cure catalyst(s)
- Presence of fine oxidizer, typically AP
- Presence of and identity of bonding agent(s)

Each of these factors may not only affect the properties obtained from different batch sizes but is also considered a variable that can be adjusted to meet system and program goals.

Due to the inherent scaleup bias historically experienced in the development of solid propellants, the authors strongly recommend that all programs conduct a process verification mix at production scale as the final step of the propellant development and scaleup process.

The process verification mix should not be used to load qualification or production motors but rather serve as final validation of the scaleup bias factor before commencing production.

Reference

[1] Morgan, R. E. “A Rheological Approach to Mixing.” JANNAF Propellant Development and Characterization Subcommittee Meeting, Chemical Propulsion Information Agency Publication No. 625, pp. 357–362, 1995.

Biographies

Dr. Jamie B. Neidert is a SPARC Research consultant and owner and principal of PropelTech Solutions, LLC, a technical consulting firm specializing in energetics technology, chemistry, and manufacturing. He retired as the chief scientist for energetics at the U.S. Army Combat Capabilities Development Command Aviation and Missile Center (AvMC), Redstone Arsenal, AL, in 2024. Prior to joining AvMC in a U.S. government civil-service role in 2003, he worked as a solid-propellant chemist at Thiokol Corporation and at Atlantic Research Corporation. Dr. Neidert holds a bachelor’s degree in chemistry and a Ph.D. in inorganic chemistry.

Dr. Gary T. Bowman is a senior scientist at Leidos and a technical consultant to SPARC Research, with over 40 years of experience in solid rocket propulsion. In previous positions with Atlantic Research Corporation and Aerojet Rocketdyne, he conducted and supervised the research and development of advanced ingredients/materials and energetic formulations (solid propellants, gas generator formulations, solid fuels for ramjet applications, and explosives). He is a subject matter expert for transitioning propellants from development to production. Dr. Bowman holds a B.A. in biology, with minor in chemistry, and a Ph.D. in organic chemistry.

Thomas L. Moore is vice president of programs and business development at SPARC Research, an engineering services small business dedicated to advancing the state of the art in missile propulsion. He has over 40 years of experience in solid-propellant rocket-motor research and development in prior positions with Northrop Grumman, Orbital ATK, ATK, the SURVICE Engineering Company, The Johns Hopkins University, and Hercules Aerospace. He also served as director of the Defense Systems Information Analysis Center from 2014 to 2016. Mr. Moore holds a B.S. in mechanical engineering and M.S. in technical management.