# Nanoaluminum for Solid Rocket Propulsion: Illusions and Reality

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In a lecture at the California Institute of Technology, on 29 December 1959, Richard P. Feynman drew the attention to the "bottom scale". That year, studies of nanosized metal (nMe) particles had started for the initiation of nuclear reactions in USA and for material science in the then-USSR. Nanosized energetic ingredients were first prepared at the Semenov Institute of Chemical Physics, Moscow, when Gen et al. produced nMe particles by vaporization and consequent condensation of metal vapors in argon. In rocket propulsion, because of its high combustion enthalpy and easy availability, Al is widely used to improve performance mainly of composite AP/HTPB formulations, the workhorse of space launcher solid motors.

The first propellant samples loaded with nanosized Al (nAl) were burned in 1970. Remarkable increases in burning rates and decreases in condensed combustion product sizes prompted great expectations in the propulsion community. Higher energy densities, faster energy release rates, and mitigation of two-phase flow losses compared to conventional ingredients were anticipated. Intense research and development programs started worldwide.

Unfortunately, after about 60 years, pristine nano-sized energetic materials (nEM) ingredients still do not fit any propulsive system at industrial level. A number of issues prevent large-scale applications: active Al content ($C_{Al}$), inert particle coating, dispersion, nAl load (% vol), slurry propellant viscosity, mechanical properties, process scalability, aging, safety (production, storage, handling, transportation, etc.), and so on. To overcome these difficulties, several approaches were tested including particle modification by coating and other techniques. Stabilization through passivation helps to avoid spontaneous ignition in air, mitigate clustering and viscosity, control reactivity and hazards, and extend the shelf life. But it was not enough to transform promises into reality. What is the status today?

After recalling the unique applications for steady and unsteady burning made possible by nAl, this paper intends to discuss the basic technical challenges hindering its large-scale use and possible fixes. Regarding $C_{Al}$, the target is to approach the typical µAl level, ranging 97.5% to 99.5%. Among the current production methods, only Electrical Explosion of Wire (EEW) and Thermal Plasma (TP) are suitable for nAl bulk production. For BET particle size above 50 nm, the commercial EEW features $C_{Al}$ typically ranging 70% to 90%, but values up to 96% - 98% are also possible. The less common TP technique offers the advantages of high production rate and particle size control. According to a Russian patent, electric arc plasma recondensation can exceed 98.5% $C_{Al}$, while the maximum value reported in the open literature by several variants of plasma techniques is 94%.

Regarding loading, refined binder systems enable to manufacture metallized AP/HTPB grains up to 18% nAl mass fraction. Mechanical properties can also be improved by fine tailoring the binder microstructure. Incidentally, nAl up to 50% vol is ordinarily added to castable munitions formulations by implementing casting with a vaporizable diluent.

Hazards remain ubiquitous: nAl particles are overly sensitive to the risk of ignition by electrostatic charges (ESD) or friction even if partially passivated. Regarding ESD, nAl particles are much more sensitive than conventional µAl and sensitize AP, although this can be mitigated by suitable coatings. Regarding explosivity and flammability, nAl presents risks significantly higher than conventional µAl, although the explosion violence decreases for increasing specific surface area. DOD Hazard Division classification of 1.3 is imperative for propellants intended for space exploration missions which currently precludes the use of nAl. Overall, nAl-based formulations satisfactory for industrial use can be prepared, but large-scale operations have yet to be implemented, while delivered performance and ecological risks have to be assessed. Work is still needed for nAl scalability and commercialization in high-performance propulsive systems.