A Model of the Hypergolic Propellant Pop Phenomena

B. R. Lawver*
Aerojet Liquid Rocket Company, Sacramento, Calif.

Theme

THIS paper describes a semiempirical model of the hypergolic propellant pop phenomena which was used to successfully eliminate the popping observed in an Apollo Service Module Engine advanced research injector. The pop model and the rationale behind it are briefly described. Pop data correlations and equations are presented for design guide use.

Contents

Random high amplitude short duration (less than a millisecond) pressure and accelerometer disturbances were observed with the hypergolically fueled Apollo Spacecraft engines during their development phase. These disturbances, called pops, were and are undesirable because they may trigger damaging combustion instability. In all instances the pops were either eliminated or reduced to acceptable levels through trial and error testing since there were no design criteria by which logical element or pattern changes could be made. Generally, the pops were attributed to random accumulation and mono-propellant explosion of fuel pockets or zones caused by such things as poor element or pattern design, orifice flow instabilities (hydraulic flip), plugged oxidizer orifices, or fuel leakage through weld cracks. Although these postulated causes are certainly possible, recent investigations (Refs. 1–5) suggest that most of the observed pops are related to combustion phenomena associated with unlike hypergolic propellant stream impingement. For instance it has been shown (Ref. 1) that small local explosions of mixed fuel and oxidizer, rather than monopropellant fuel explosions, are most likely the source of pop triggers. On the basis of these investigations a semiempirical model has been developed which relates these small local hypergolic stream explosions to the occurrence of pops. This model was used to correlate development testing pop data obtained from the Apollo Lunar Module (LEM) ascent engine injectors, the Apollo Service Module (SPS) engine injectors, an advanced research SPS injector (SPS-IOS), and a NASA Jet Propulsion Lab. combustion research engine injector. The resultant correlations were used to predict injector pattern changes which successfully eliminated the popping observed previously with the advanced research SPS-IOS injector.

The pop model is based on the supposition that the small local explosions which occur within the impingement region of unlike hypergolic propellant streams act to trigger unburned spray detonations which produce transient pressure and accelerometer spikes that are identified as pops. The basis for this hypothesis lies in two basic pieces of experimental work reported in Refs. 1 and 2.

The supposed relationship between the small local explosion and the observed pop is illustrated in Fig. 1. It is postulated that the small local explosion emits a spherical blastwave which can initiate detonation of the adjacent element sprays if it intersects them with some minimum energy level. The occurrence of the small local explosions has been found to depend upon the element orifice diameter, the injection velocity, the propellant temperature, and the element mixing efficiency. Although more recent studies (Ref. 3) indicate a pressure dependence which is not accounted for, the model is in no way invalidated as a design guide as evidenced by its successful application in eliminating popping in the SPS-IOS injection.

A stream impingement parameter I defines the interrelationship between the injection parameters which produce the small local explosions. I is defined as the ratio of the ignition delay (i.e., fuel temperature) required to produce stream separation (i.e., blow-apart) to the actual ignition delay as determined by the fuel temperature. I is calculated as follows for the N_2O_4/A-50 propellant combination

$$I = e^{\{\ln[D_f/(V_f \sin 1/2\theta_i)] + 46.8 - 21{,}800(1/T)\}} \qquad (1)$$

where D_f is the fuel orifice diameter, ft; V_f the fuel injection velocity, fps; θ_i the included impingement angle, degs; T the fuel injection temperature, °R.

Coupling of the small local explosion with the adjacent element spray is determined by a detonation parameter D. It is defined as the ratio of the critical blastwave radius to the minimum distance between element centerlines, $D = R/S$ where R is the radius at which the blastwave transitions from supersonic to subsonic velocity (i.e., Mach 1), in., and S is the minimum distance between element centerlines, in. The radius at which the blastwave velocity decays to Mach 1 was arbitrarily selected as the critical radius beyond which coupling can not occur. The critical radius is calculated using a velocity decay equation developed by Sedov. For N_2O_4/A-50 propellants, $R = 49.2\ (D_f/P_c^{1/3})$ (in.) where D_f is the fuel orifice diameter, in., and P_c the steady-state chamber pressure, psia.

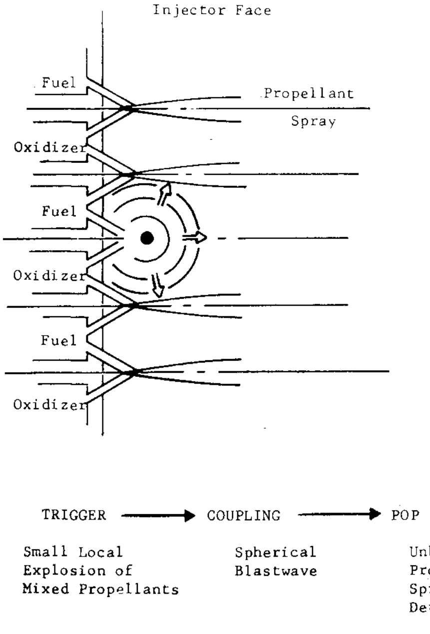

Fig. 1 Hypergolic propellant rocket engine pop model.

Received May 10, 1971; synoptic received November 22, 1971; revision received December 27, 1971. Full paper available from National Technical Information Service, Springfield, Va. 22151 as N72-13746 at the standard price (available upon request). This work supported under Contract NAS 9-8285.

Index category: Combustion Instability, Ignition, Detonation.

* Technical Specialist, Engine Components Department.

The various engine pop data were correlated using this model. A computer program was written to calculate the impingement parameter, the detonation parameter, and the normalized mixing efficiency for each injector at each test condition. The impingement parameter was calculated using Eq. (1). The fuel temperature, velocity, and orifice diameter was used to make the calculation for both doublet and triplet elements. The impingement point fuel temperature was calculated from the inlet temperature data taking into account manifold heating and convective heating of the

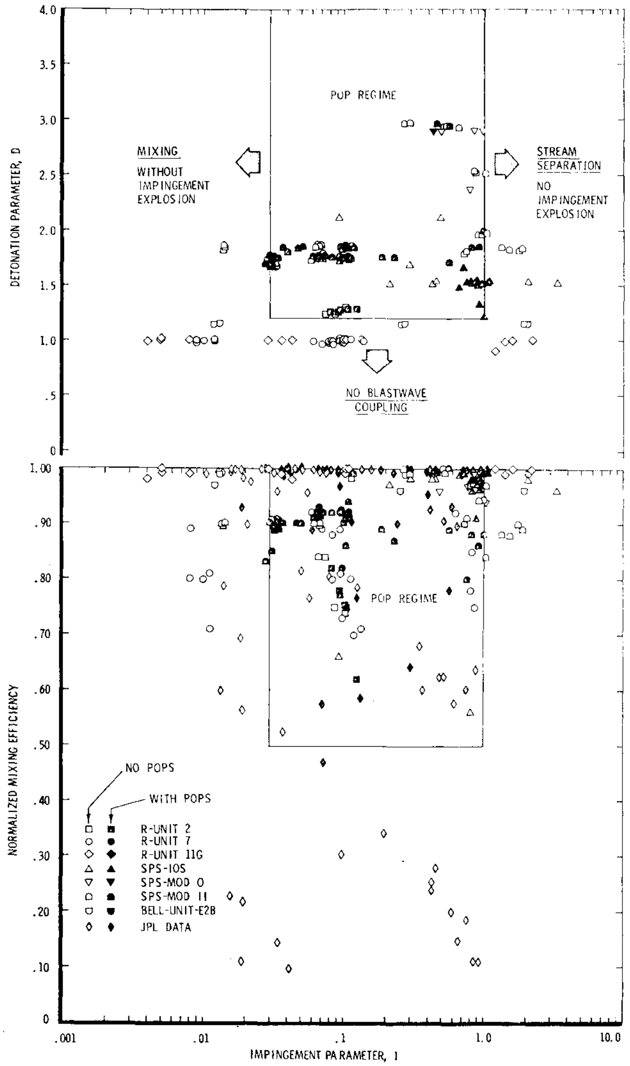

Fig. 2 *I* vs *D* and *I* vs η **for various engine injectors.**

Table 1 Pop criteria

Pop	No Pop
$0.03 < I < 1.0$	$1.0 < I < 0.03$
$1.2 < D$	$D < 1.2$
$0.5 < \eta$	$\eta < 0.5$

freestream ahead of impingement. The detonation parameter was calculated using $D = R/S$. The minimum spacing between elements, whether between adjacent element rows or adjacent elements was used to calculate D. In cases where elements were placed close to chamber or baffle walls, the distance from the element centerline to the wall was used. The element normalized mixing efficiency was calculated using the following equation:

$$\eta = [1 - (1 - 2R_N)^2]^2$$

where: η = element normalized mixing efficiency and

$$R_N = \{1/[K + (\rho_{ox} V_{ox}^2 D_{ox}/\rho_f V_f^2 D_f)]\}$$

where $K = 1$ for a doublet element and 1.5 for a triplet element, ρ_{ox} is oxidizer density, lb/ft^3; V_{ox} is oxidizer injection velocity, fps; D_{ox} is oxidizer orifice diameter, in.; ρ_f is fuel density, lb/ft^3; V_f is fuel velocity, fps; D_f is fuel orifice diameter, in.

Data plots of I vs D and I vs η for the various engine injectors are shown in Fig. 2. The data correlations indicate that the occurrence of popping with hypergolic unlike impinging element injectors is defined by the conditions listed in Table 1. All three pop conditions must be met to produce engine popping; however, only one of the three no-pop conditions are required to prevent it.

References

[1] Mills, T. R. et al., "Transients Influencing Rocket Engine Ignition and Popping," Monthly Report Contract NAS 7-467, Sept. 1968, Dynamic Science, Monrovia, Calif.

[2] Clayton R. M., "The Influence of Several Near-Wall Injection Conditions on Combustion Performance of a Liquid Rocket Engine," TR-32-1283, Sept. 1968, Jet Propulsion Lab., Pasedena, Calif.

[3] Zung, L. B. and White, J. R., "Combustion Process of Impinging Hypergolic Propellants," CR-1704, May 1971, NASA.

[4] Lawver, B. R. and Breen, B. P., "Hypergolic Impingement—Phenomena Nitrogen Tetroxide/Hydrazine," CR-72444, Oct. 1968, NASA.

[5] Clayton, R. M., "Experimental Observations Relating the Inception of Liquid Rocket Engine Popping and Resonant Combustion to the Stagnation Dynamics of Injection Impingement," TR 32-1479, Dec. 1970, Jet Propulsion Lab., Pasedena, Calif.

[6] Sedov, L. I., "Similarity and Dimensional Methods in Mechanics," Academic Press, New York, 1959.