Engineering Notes

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Scaling Law for Estimating Liquid Propellant Explosive Yields

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Introduction

WHEN rocket propellants are mixed together, an explosive release of energy, or detonation, can occur. To represent a significant hazard, at least three elements are required: 1) the quantity of propellant must be substantial; 2) the mixture ratio of fuel-to-oxidizer must fall within a certain restricted range; 3) there must be a source of ignition energy, unless the propellant mixture is hypergolic (i.e., self-igniting upon contact).

Until recently, it was common practice to express the explosion potential in terms of an equivalent weight of TNT, based on experimental data.[1-5] However, the current state-of-the-art now allows more accurate estimates to be made of the explosive yield for liquid propellants in terms of several factors including[6] the type and mass of propellants, the type of failure or accident which causes an explosive mixture to occur, and the time delay between initiation of mixing and detonation.

Nevertheless, considerable variability in explosive yield is observed for otherwise similar situations, and empirical rules may still be useful for preliminary facility planning purposes. For example, the TNT equivalent for liquid-oxygen/liquid-hydrogen propellants employed in a static engine test stand might be based on the following rules:

Propellants stored in tanks or unburned in a combustion chamber

equivalent TNT weight = 20% of total propellant weight

Propellants flowing in fuel lines between fuel storage, tankage, and combustor

equivalent TNT weight of propellant flowing in a period of, say, 2 seconds

The "2-second" rule for the quantity of propellant in flow lines potentially involved in an explosion is based on industry experience for the maximum time required to close a typical rocket propellant flow valve in a test stand.[7] In this case, the equivalent explosive yield might be assumed to be 60% of the propellant weight that is spilled by the 2-second flow of both propellants.

The choice of a 20% TNT equivalent yield for the stored propellant, the large quantity of propellant, and a 60% yield for the flow spill, the lesser quantity, appears inconsistent at first. However, a new evaluation of the available data on equivalent TNT yields from actual LOX/LH_2 explosions indicates that the use of lower percentage TNT equivalents for larger quantities of propellants is consistent with an average trend from propellant explosions, and with a simple scaling law for propellant TNT equivalents.

The purpose of this Note is to outline this simple law. It is presented as a possibly useful guide for rough initial estimates of the explosive yield of liquid propellants that may be applied only when the more accurate prediction methods in Ref. 6 are not required.

Analysis

Results of intentional LOX/LH_2 propellant explosions from 23 of the Project PYRO tests[2] and three real accidental explosions involving these propellants[1] are summarized in Fig. 1. The figure shows the estimated equivalent TNT weight (W_T), based on measured explosion parameters (i.e., overpressure versus distance) as a function of the actual propellant weight (W_p). Data were utilized from Project PYRO for nine tests of LOX/LH_2 with $W_p = 200$ lb, eight tests with $W_p = 1000$ lb, five tests with $W_p = 25{,}000$ lb, and one test with $W_p = 91{,}000$ lb of propellant.

Although there is a wide scatter in the results at the lowest propellant weights, *the average values of the equivalent TNT weight* (W_T) *fall surprisingly close to a simple two-thirds power scaling law.* Such a scaling law is, indeed, not unexpected on the basis of the following rationale.

1) The weight of propellants (W_p) in tanks (of similar shape) will tend to vary as the cube of a characteristic tank dimension (d) or $W_p \propto d^3$.

2) The equivalent TNT weight (W_T) of a propellant that participates in a denotation can be expected to vary in direct proportion to a mixing area, which in turn should tend to vary roughly as the square of a characteristic tank dimension (d) or $W_T \propto d^2$.

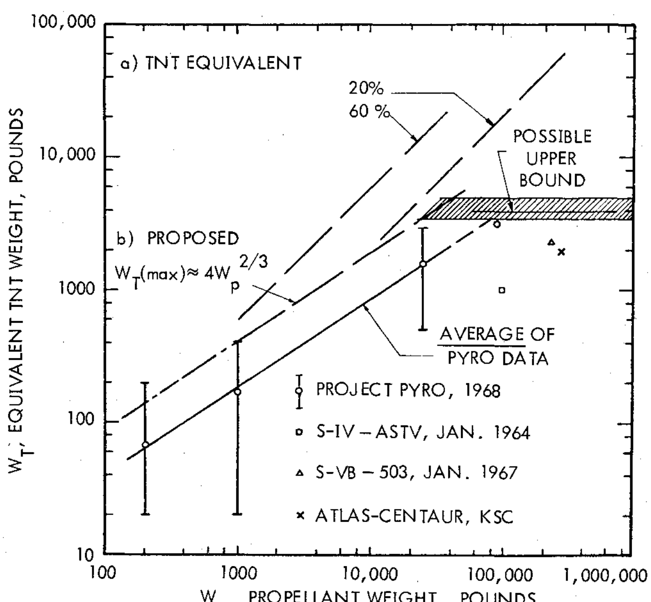

Fig. 1 Trend in measured equivalent TNT weight from propellant explosions compared to a) earlier TNT equivalent design rules, b) a proposed new scaling law, and c) a possible upper bound in TNT equivalents for LOX/LH_2 based on studies by Farber[5] (data from Refs. 1 and 2).

Received May 10, 1977; revision received Nov. 21, 1977.

Index categories: Fuels and Propellants, Properties of; Combustion Stability, Ignition, and Detonation; Safety.

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3) Combining these two highly simplified relationships leads to the scaling law suggested by the results in Fig. 1, namely that

$$W_T \propto W_p^{2/3}$$

4) Other effects, such as the method of propellant confinement, method of tank rupture, and ignition delay time, appear to be secondary to this basic scaling trend and are undoubtedly, the source of significant and, indeed, predictable[6] variation about the mean trend.

Although only a portion of the Project PYRO results were utilized for Fig. 1, they are considered representative of the general trend. This trend permits a reasonable and conservative estimate of the possible explosion magnitude. With this in mind, the following additional information is obtained from Fig. 1.

1) The maximum trend for the PYRO data, shown by the vertical bars through the data for $W_p = 200$, 1000, and 25,000 lb, lies roughly on a similar two-thirds power scaling trend line and indicates a maximum probable yield of about 2.2 times the average yield.

2) Based on the two-thirds scaling law, the data suggest that the maximum yields observed in the PYRO tests were about 7.3 times greater than the average (scaled) yield estimated for the three actual accidents.

For comparison, dashed lines corresponding to previous design rules of 20% and 60% TNT yield are shown on the figure. It is clear that the 20% or 60% TNT equivalent rules would lead to very conservative estimates of the TNT equivalency for large amounts of propellant. Clearly, these earlier constant percentage rules for TNT yield are not consistent with the experimental data cited in Fig. 1. The simple two-thirds power law shown appears to provide an improved empirical model for initial estimates of the TNT equivalence of LOX/LH_2 propellants over a wide range of propellant weights. The data suggest that a scaling law for the maximum TNT equivalent for these propellants can be given by $W_T \simeq 4W_p^{2/3}$. This is the principal result of this Note. The empirically determined scaling constant (4) may vary substantially for other types of propellants. However, it is estimated to be a reasonable maximum value for LOX/LH_2 propellant explosions from a variety of tank configurations and failure modes, which were demonstrated very well by the experimental studies considered here.[2,3]

Another scaling principle, based on thorough analytical and laboratory studies on propellant explosions by Farber,[5] is partly verified by the data in Fig. 1. This principle is based on the concept of self-ignition of LOX/LH_2 propellants by a "critical mass" equivalent to a TNT weight of about 4000 lb. This upper bound, indicated by the shaded bar in Fig. 1, appears to correspond approximately to the maximum yield observed in the data. Further investigation of these useful scaling principles seems warranted in order to expand the spectrum of prediction tools available for planning liquid propellant facilities—ranging from the type of simple empirical scaling law suggested herein to the more accurate methods reported by Baker et al.[6]

References

[1] Joint Army-Navy-NASA-Air Force (JANNAF) Hazards Working Group, "Chemical Rocket/Propellant Hazards—Volume I, General Safety Engineering Design Criteria," Chemical Propulsion Information Agency (CPIA) Publication 194, Oct. 1971.

[2] "Liquid Propellant Explosive Hazards—Project PYRO," Air Force Rocket Propulsion Lab., AFRPL-TR-68-92, Vols. I, II, and III, Dec. 1968.

[3] "Statistical Analysis of Project PYRO Liquid Propellant Explosion Data," Bellcomm, Inc., 1969.

[4] "Solid Propellant Explosive Test Program—Project SOPHY," Aerojet General Corp., AFRPL-TR-67-211, Vols. I and II, Aug. 1967.

[5] Farber, E.A., "Prediction of Explosive Yield and Other Characteristics of Liquid Propellant Rocket Explosions," NASA Contract NAS 10-1255, Final Report, University of Florida, Gainesville, Fla., Oct. 1968.

[6] Baker, W.E. et al, "Workshop for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels," NASA CR-134906, Southwest Research Institute, Nov. 1975.

[7] Weiss, H., personal communication, Rocketdyne Div., North American Rockwell Corp., Canoga Park, Calif., May 1971.

Radiative Heat Transfer within a Solid-Propellant Rocket Motor

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Introduction

THIS Note presents an approximate description of the radiative heat transfer between the two-phase combustion products and walls within a solid-propellant rocket motor. The study was motivated by the absence of a description that correctly accounts for scattering by the aluminum oxide (Al_2O_3) particles. Previous studies[1] and the model currently used within the industry are incorrect in this respect. The radiative transfer model proposed here correctly accounts for scattering but ignores the nonhomogeneous, nonisothermal structure of the two-phase flow. This simplification implies that the model is most accurate in the low subsonic Mach number region of the nozzle. In spite of its approximate nature, it is argued that the model is sufficiently accurate for its intended purpose; moreover, the accuracy is commensurate with our present knowledge of sizes and optical properties of actual particles in a rocket exhaust.

Radiative Transfer Solution

The axisymmetric flow of the two-phase exhaust products is modeled as a homogeneous and isothermal circular cylinder with a diameter equal to the local nozzle diameter and a temperature and particle density equal to the local average values. Particles in the flow absorb and are assumed to scatter radiation isotropically. A radiative transfer solution is constructed using the diffusion approximation for the mean (with respect to all directions) intensity. A general derivation of this approximation and a solution for plane layers are given by Edwards and Bobco.[2] Adzerikho and Nekrasov[3] have applied it to a cylinder and sphere.

The result of the radiative transfer solution which is applicable to heat-transfer predictions is the hemispherical emissivity E (τ_R,ω) of the cylinder with radius R, optical radius $\tau_R = \kappa^{(e)}R$, and albedo for single scattering $\omega = \kappa^{(s)}/\kappa^{(e)}$. The results of the calculation are summarized in Table 1 which gives the hemispherical emissivity for single-scattering albedos applicable to Al_2O_3 particles. Although the radiative transfer formulation is approximate, it is highly accurate, giving a hemispherical emissivity that underpredicts the exact value[4] (last row, Table 1) with an error less than 4% for

Received June 27, 1977; revision received Dec. 16, 1977.

Index categories: Radiation and Radiative Heat Transfer; Multiphase Flows.

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