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## Precise and Accurate Density Determination of Explosives Using Hydrostatic Weighing

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# **Precise and Accurate Density Determination of Explosives Using Hydrostatic Weighing**

by

**Bart Olinger**

## **Abstract**

**Precise and accurate density determination requires weight measurements in air and water using sufficiently precise analytical balances, knowledge of the densities of air and water, knowledge of thermal expansions, availability of a density standard, and a method to estimate the time to achieve thermal equilibrium with water. Density distributions in pressed explosives are inferred from the densities of elements from a central slice.**

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## **Introduction**

Engineering with high explosives requires thorough knowledge of their bulk density and internal density distribution. The density of an explosive is a measure of how much potential energy in the form of hot, high-pressure gas is in a given volume. The velocity of a detonation front in an explosive is dependent on density, and internal density variations effect the direction of the detonation wave. In addition, the compression strength of an explosive increases rapidly with density.

## **Basic Concept**

The density of an object is its average mass per unit volume. The object's weight is considered the force of its mass-caused gravitational acceleration. But the measured weight includes the forces from the hydrostatic pressure of the fluid the object is immersed in. The hydrostatic pressure is the weight of a column of fluid of unit area at a particular depth. For an immersed solid unit cube, the difference in pressure between that on top of the cube and that at the bottom is the weight of the fluid for the same volume. The measured weight would be the cube's mass times the gravitational acceleration minus the force of the pressure difference, which is the mass of fluid with the cube's volume times the gravitational acceleration. Since all shapes can be made from unit cubes, the end result is what was succinctly observed by Archimedes

thousands of years ago, that a body wholly or partially immersed in a fluid is buoyed up by a force equal in magnitude to the weight of the fluid displaced by the body. Archimedes was observing the effect of hydrostatic pressure of the fluid on the body's weight.

The measured weights of an explosive in air and then in water are

$$Wt_{air} = g \times V_x \times \rho_x - g \times V_x \times \rho_{air} \quad (1)$$

and

$$Wt_{water} = g \times V_x \times \rho_x - g \times V_x \times \rho_{water} \quad (2)$$

$Wt_{air}$  is the explosive's weight in air,  $Wt_{water}$  is the explosive's weight in water,  $g$  is the acceleration from gravity,  $V_x$  is the explosive's volume, and  $\rho_x$ ,  $\rho_{air}$ , and  $\rho_{water}$  are the densities of the explosive, air, and water. From Eqs. (1) and (2), an expression is derived for the density of the explosive in from terms of the two measured weights of the explosive and the densities of the air and water.

$$\rho_x = \frac{(Wt_{air} \times \rho_{water}) - (Wt_{water} \times \rho_{air})}{Wt_{air} - Wt_{water}} \quad (3)$$

### Details for Precise and Accurate Density Determination

Precision is achieved by using sufficiently sensitive analytic balances for weighing, and accuracy is achieved by simultaneously measuring the density of a standard to determine and correct systematic errors.

The weights of the explosive are normally measured with electronic analytical balances. The balances are equipped with weighing pans suspended in large water baths. The densities of explosives are in the range of 1 to 2 g/cm<sup>3</sup>, but their densities must be determined to a precision of less than 0.001 g/cm<sup>3</sup>. This requires the balance to provide 5 significant figures. For a 12,000-g explosive, the balance must measure to a precision of 1 g. For a 1.2-g explosive, it must measure to a precision of 0.0001 g.

The density of air is small,  $\rho_{air} = 0.00091$  g/cm<sup>3</sup> at Los Alamos' elevation. Variations around that value caused by atmospheric pressure or room temperature changes are smaller than what we need to be concerned with. To cause an error of 0.0001 g/cm<sup>3</sup> in the explosive density, the density of air would have to differ from this value by 13%; typical atmospheric variations are about 1/2%.

The other critical value is the density of water. Its value as a function of temperature is

$$\rho_{water} = \left( 1 - \left\{ \frac{[T - 3.9863]^2}{508929.2} \right\} \times \left\{ \frac{T + 288.9414}{T + 68.12963} \right\} \right) \times 0.999973 . \quad (4)$$

$T$  is the temperature of the water in °C. This is the Tilton-Taylor formula for the density of water with a conversion factor to g/cm<sup>3</sup> added at the end [L. W. Tilton, J. K. Taylor, *J. Res. NBS*, **18**, 205 (1937)]. It is still the best formula around. Other factors influence the density of water, such as the amount of dissolved air or minerals or the effect of hydrostatic pressure, but these unquantified effects are determined and corrected from the density standard measurements.

The densities  $Y$  of the explosive and standard are adjusted to 20°C by including a correction that is based on their volume thermal expansion coefficients,  $\beta$ .

$$Y = 1 - \beta \times (20^\circ\text{C} - T) . \quad (5)$$

$T$  is the temperature of the water and the explosive and standard after they have come into thermal equilibrium with the water. The volume thermal expansion coefficient for each of the common explosives, PBX 9501, PBX 9502, TNT, and Comp B, has a range of reported values. Usually a value of 0.000160 is sufficiently accurate for any of them.

The density standard used is silicon. The present value of its density at 20°C is 2.32908 g/cm<sup>3</sup>, and the volume thermal expansion coefficient is 0.0000077. High purity single crystals are inexpensive and readily available in any size from commercial suppliers for the semiconductor industry. When doing a series of density measurements of explosives, a density measurement of a similar mass of silicon is also made. A correction,  $Z$ , is determined for the weight measurement in water that yields the correct density for silicon (Eq. 6). Corrections are made on the weight in water because that is where most of the experimental unknowns reside.

$$\rho_x(20^\circ\text{C}) = \frac{(Wt_{air} \times \rho_{water}) - (Wt_{water} \times Z \times \rho_{air})}{Wt_{air} - Wt_{water} \times Z} \times Y . \quad (6)$$

After the correction is determined, it is then used for the explosives that are being measured at the same time with the same equipment.

If several measurements of  $Wt_{air}$  and  $Wt_{water}$  are made for each density determination, then from their standard deviations,  $\Delta Wt_{air}$  and  $\Delta Wt_{water}$ , the standard deviation of the measured density,  $\Delta\rho_x$ , can be determined;

$$\Delta\rho_x = \left( \frac{\rho_x - \rho_{air}}{Wt_{air} - Wt_{water}} \right) \times \Delta Wt_{water} + \left( \frac{\rho_x - \rho_{water}}{Wt_{air} - Wt_{water}} \right) \times \Delta Wt_{air} . \quad (7)$$

## Achieving Temperature Equilibrium with Water

The only temperature known accurately during an immersion density measurement is that of the water. If the explosive is given sufficient time to reach thermal equilibrium with the water, then its temperature is known accurately as well. We need to know the time required for the temperature of an explosive to be sufficiently close to the water's temperature to measure the density to within  $0.0001 \text{ g/cm}^3$  of its actual value.

An estimate of that time can be made by assuming that the explosive is an infinite slab with finite thickness,  $2L$ , that the water at temperature  $T_{water}$  is infinitely good at transferring the heat away from the explosive's surface, and that the explosive has a uniform temperature,  $T_x$ , throughout. Heat engineers have derived a formula to calculate the time required to reach a temperature,  $T_{center}$ , at the center of an infinite slab (M. P. Heisler, *Trans. ASME*, **69**, 227 [1947]).

$$t(\text{sec}) = -0.435 \times \ln \left( \frac{T_{center} - T_{water}}{T_x - T_{water}} \right) \times (\rho_x \times C_p \times L^2) / k \quad (8)$$

The time,  $t$ , is the length of time the explosive remains submerged. The constant,  $-0.435$ , increases in magnitude if heat-removing efficiency decreases. The explosive's density is  $\rho_x$ ,  $C_p$  is the explosive's heat capacity, and  $k$  is the thermal conductivity of the explosive.

## Determining Internal Density Distributions

Pressed explosives have regions of higher and lower densities. The variation is usually about  $0.005 \text{ g/cm}^3$ . The densities are lowest adjacent to the contracting or moving surface of the press and highest adjacent to the immobile surface. With the cylindrical steel-die presses, the walls cause additional complications; high densities occur adjacent to the walls at the end with the moving surface and low densities at the immobile end.

The density throughout the pressed explosive can be inferred from the density distribution in a slice of explosive cut from along the axis of compaction. For compacted explosives with hemispheric or cylindrical shapes, a slice is saw-cut along the axis of symmetry. A grid is marked on the slice's surface, each element of the grid is labeled, and then the elements are cut free. The density of each element is measured, and a composite diagram of the densities of the elements is assembled to represent the density distribution of the solid.

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