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# Dissolution kinetics of high explosives particles in a saturated sandy soil

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## Abstract

Solid phase high explosive (HE) residues from munitions detonation may be a persistent source of soil and groundwater contamination at military training ranges. Saturated soil column tests were conducted to observe the dissolution behavior of individual components (RDX, HMX, and TNT) from two HE formulations (Comp B and C4). HE particles dissolved readily, with higher velocities yielding higher dissolution rates, higher mass transfer coefficients, and lower effluent concentrations. Effluent concentrations were below solubility limits for all components at superficial velocities of 10–50 cm $\text{day}^{-1}$. Under continuous flow at 50 cm $\text{day}^{-1}$, RDX dissolution rates from Comp B and C4 were 34.6 and 97.6 $\mu g\ h^{-1}\ cm^{-2}$ (based on initial RDX surface area), respectively, significantly lower than previously reported dissolution rates. Cycling between flow and no-flow conditions had a small effect on the dissolution rates and effluent concentrations; however, TNT dissolution from Comp B was enhanced under intermittent-flow conditions. A model that includes advection, dispersion, and film transfer resistance was developed to estimate the steady-state effluent concentrations.

*Keywords:* Explosives; Dissolution; Kinetics; Composition B; C4; Contaminant flux; Mass transfer

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## 1. Introduction

Contamination of soil and groundwater with high explosive (HE) compounds has been observed at many military training ranges (Jenkins et al., 2001; Pennington et al., 2002; Clausen et al., 2004). The primary source of HE contamination at these sites is residues from detonation of military munitions including projectiles (e.g., mortar and artillery rounds), grenades, land mines, aerial bombs, and missiles, as well as ordnance demolition charges. At one military installation in the eastern US, surface and underlying soils have significant HE contamination as a result of more than 50 years of live-fire training. The main soil contaminants are the high explosives hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and 2,4,6-trinitrotoluene (TNT), although other contaminants such as 2,4-dinitrotolune (2,4-DNT), nitroglycerine (NG), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) have also been detected. RDX has been detected in soil at concentrations up to 16,000 mg $kg^{-1}$, although HE levels have generally been $<1$ mg $kg^{-1}$. Most HE contamination exists in near-surface soils and in the vicinity of firing range targets (Clausen et al., 2004). A primary concern is that soil contaminants may eventually migrate to groundwater and contaminate drinking water supplies of nearby communities. RDX is particularly worrisome because it is highly mobile in the subsurface and toxic to humans.

Military munitions typically utilize HE formulations such as Composition C4 (C4), composed of RDX and plasticizers, and Composition B (Comp B), a mixture of RDX and TNT, as their main charges (Jenkins et al., 2002). These formulations and many other organic chemicals are also used in munitions for primers, fuses, and ignition and propellant charges (Jenkins et al., 2002). The yield of a detonation is the fraction of HE that detonates. Types of detonations include dud (little or no explosion, resulting in unexploded ordnance), low order (a significant amount of HE does not detonate), or the desired high order, in which nearly 100% of the HE is detonated (Taylor et al., 2004). Depending on the munition type, up to 4.4% and 0.22% of all detonations may be duds and low-order detonations, respectively (Jenkins et al., 2001).

Any type of detonation deposits HE residues on the ground surface. Radtke et al. (2002) estimated that there were 19,900 TNT particles larger than 3 mm per cubic yard of surface soil from an explosives testing range, for a total mass of 1.7 kg of TNT. Taylor et al. (2004) measured residues from detonations of 155-mm howitzer rounds containing 6.76 kg of TNT. For low- and high-order detonations, an estimated 40–44% and 1–3% of the TNT charge was deposited on the ground surface, respectively, with many large TNT pieces observed for both. Jenkins et al. (2002) found 4430 μg RDX $m^{-2}$ and 40 μg TNT $m^{-2}$ deposited on a clean snow surface at after a high-order detonation of an 81-mm mortar round. Thus, even if only a small fraction of the total HE mass within a munition is not consumed during a detonation, repeated blasts at training ranges and impact areas will result in significant HE accumulation in surface soils, establishing a source of potentially leachable contaminants.

Although dissolution of HE particles and residues is the first and possibly rate-limiting step in the migration of HEs from firing ranges (Brannon et al., 1999), little is known about the rates or mechanisms that govern in-situ dissolution of HE residues prior to subsurface transport and transformation. Several previous studies (Lynch et al., 2002a,b; Pennington et al., 2002; Phelan et al., 2002) reported dissolution kinetics of HE compounds and formulations in batch reactors and found that dissolution rates generally increased with temperature and particle surface area. In single component dissolution tests with military-grade TNT, RDX, and HMX, TNT had the fastest dissolution rate (Lynch et al., 2002a). Dissolution rates of component HEs from Comp B were similar to the dissolution rates of pure HEs (Lynch et al., 2002b; Pennington et al., 2002),