6. POTENTIAL FOR HUMAN EXPOSURE

6.1 OVERVIEW

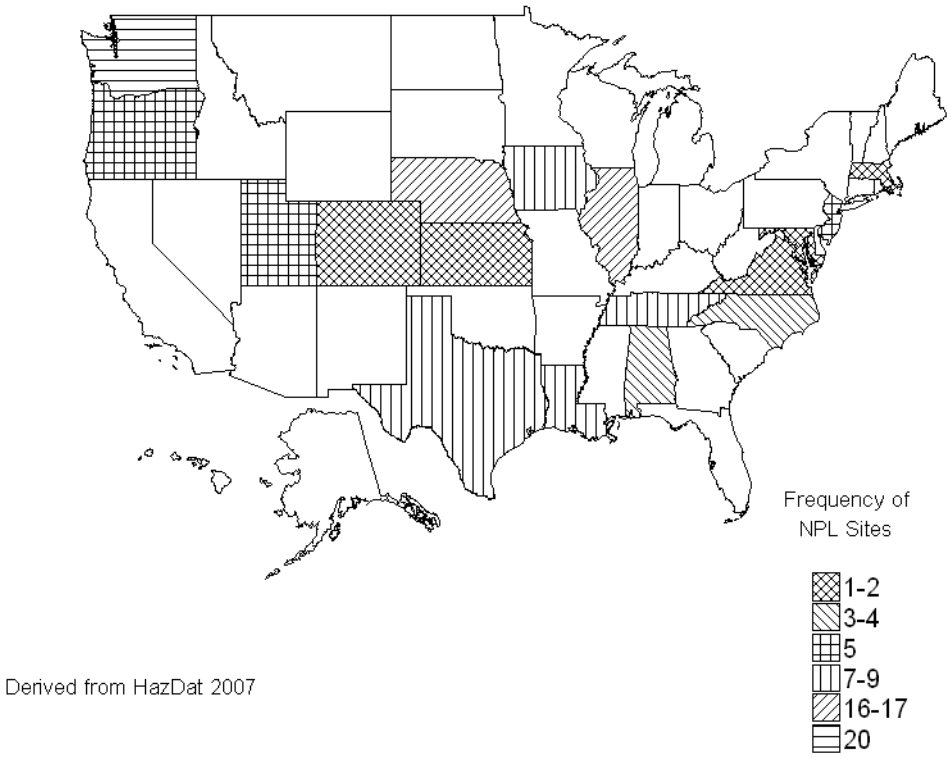
RDX has been identified at 31 out of the 1,699 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (HazDat 2007). However, the number of sites evaluated for RDX is not known. The frequency of these sites can be seen in Figure 6-1.

RDX is a military explosive produced by the nitrolysis of hexamine with nitric acid (Boileau et al. 2009). It is a synthetic compound and is not known to exist in nature. Effluents and emissions from ammunition plants are responsible for the release of RDX into the environment (Pennington and Brannon 2002; U.S. Army 1984a). RDX is expected to exist as a particulate in the atmosphere. When released to water, RDX is subject to photolysis (half-life of 9–13 hours). Photoproducts include formaldehyde and nitrosamines (U.S. Army 1980a). Alkaline hydrolysis can also occur (Balakrishnan et al. 2003; Heilmann et al. 1996). RDX undergoes biodegradation in water and soil under anaerobic conditions (Funk et al. 1993; Pennington and Brannon 2002; U.S. Army 1984f). Its biodegradation products include MNX; DNX; TNX; hydrazine; 1,1-dimethyl-hydrazine, 1,2-dimethyl-hydrazine; formaldehyde; and methanol (McCormick et al. 1981). RDX is mobile in soil, and can leach into groundwater (U.S. Army 1980c), and can be transported from soils or water to terrestrial and aquatic plants (Best et al. 1999; Harvey et al. 1991, 1997; Pennington and Brannon 2002; Simini and Checkai 1996).

RDX has been identified in environmental samples, primarily near army munition depots (Bishop et al. 1988; Dacre 1994). Indoor air samples collected at ammunition plants were found to contain RDX in concentrations ranging from 0.032 to 60 mg/m^3 (Bishop et al. 1988; U.S. Army 1975). In water, RDX has been identified in a variety of groundwater samples from ammunition plants in the United States (<1–14,100 μg/L) and Germany (21–3,800 μg/L) (Bart et al. 1997; Best et al. 1999; Godejohann et al. 1998; Steuckart et al. 1994; U.S. Army 1988). Sediment samples from Army depots have been found to contain RDX in concentrations ranging from <0.1 to 3,574 mg/kg (Simini et al. 1995; Sunahara et al. 1999; U.S. Army 1988) and in composts prepared from contaminated sediments (>2.9–896 mg/kg) (Griest et al. 1995; Gunderson et al. 1997). Additionally, RDX was indentified in plant species irrigated with or grown in contaminated water (<20–3,196 μg/L) (Best et al. 1999; Pennington and Brannon 2002).

For the general population, exposure to RDX is primarily limited to areas around ammunition plants and military installations where it is manufactured, converted to munitions, packed, loaded, or released

Figure 6-1. Frequency of NPL Sites with RDX Contamination



through the demilitarization of antiquated munitions (Hundal et al. 1997; Pennington and Brannon 2002; U.S. Army 1980a, 1984a, 1984f). The most likely route of exposure is ingestion of contaminated drinking water or agricultural crops irrigated with contaminated water (Harvey et al. 1991, 1997; Simini and Checkai 1996). Dermal contact with soil containing RDX or inhalation exposure of contaminated particulate matter produced during incineration of RDX-containing waste material are also possible routes of exposure. Occupational exposure to RDX can occur when workers handle RDX at Army ammunition plants (Hathaway and Buck 1977; Kaplan et al. 1965). According to the National Occupational Exposure Survey (NOES) of 1981–1983 conducted by NIOSH, the estimated number of workers potentially exposed to RDX in the United States was 488 (NIOSH 1990).

Since RDX releases are not required to be reported under SARA Section 313, there are no data on RDX in the Toxics Release Inventory (TRI 1993).

6.2 RELEASES TO THE ENVIRONMENT

6.2.1 Air

There is no information on releases of RDX to the atmosphere from manufacturing and processing facilities because these releases are not required to be reported (EPA 1997). However, all emissions are evaluated under Title V of the 1990 federal Clean Air Act Amendments within each state's Title V programs. RDX emissions from the manufacturing process are considered insignificant under the Title V air pollution control permits for facilities because they are contained systems. Thus, emission quantities are such that dispersion from the facilities is unlikely to be detectable by ambient monitoring.

RDX can enter the air through the release of contaminated particulate matter formed during the incineration of RDX-containing mixtures (U.S. Army 1984a). RDX can also enter the air through evaporation from aquatic effluent streams or waste storage lagoons (U.S. Army 1984a).

6.2.2 Water

There is no information on releases of RDX to the water from manufacturing and processing facilities because these releases are not required to be reported (EPA 1997). Water discharges from RDX manufacturing and processing facilities are regulated by the National Pollutant Discharge Elimination System (NPDES) permit managed by each state's NPDES program. The monitoring methodology may vary from state to state.

RDX can be released to water in waste discharge effluents from ammunition production, formulation, manufacturing, loading, assembly, and packing, and through the demilitarization and disposal of antiquated munitions (Hundal et al. 1997; Pennington and Brannon 2002; U.S. Army 1980a, 1984a, 1984f).

6.2.3 Soil

There is no information on releases of RDX to the soil from manufacturing and processing facilities because these releases are not required to be reported (EPA 1997). Releases to soil are generally confined to manufacturing facilities and points of use such as firing ranges. These sites are monitored by the Department of the Army as well as state and federal environmental regulatory authorities under several environmental programs such as CERCLA, RCRA, Emergency Planning and Community Right-to-Know Act (EPCRA). Response activities include monitoring, cleanup, and land use controls as determined approporiate.

Manufacturing, packing, and use of RDX have often resulted in contamination of soil. RDX can enter soil by leaching from waste lagoons and from improper disposal of contaminated sludge (U.S. Army 1984a). RDX can also enter the soil from spills during manufacture, transportation, and storage. Releases can also occur from the settling of airborne particulates from manufacturing and demilitarization practices such as incineration onto soil surfaces (Hundal et al. 1997; Pennington and Brannon 2002; U.S. Army 1984a).

6.3 ENVIRONMENTAL FATE

6.3.1 Transport and Partitioning

RDX is expected to exist in the particulate phase in the atmosphere. The solubility of RDX in water is low to negligible (Budavari and O'Neil 1989). The following water solubility values have been reported: 21.8–21.9 mg/L at 10 °C, 38.4–38.9 mg/L at 20 °C, 59.7 mg/L at 25 °C, and 66.7–67 mg/L at 30 °C (U.S. Army 1983b; Yalkowsky and He 2003). RDX is slightly soluble in methanol, ether, ethyl acetate, and glacial acetic acid (Budavari and O'Neil 1989). The Henry's law constant for RDX is approximately $2x10^{-11}$ atm-m^3/mol (PHYSPROP 2009), indicating that volatilization from water or moist soil surfaces is expected to be a slow process.

The soil adsorption coefficients normalized to organic carbon content (K_{oc}) for RDX range from 42 to 167 (U.S. Army 1980c). These K_{oc} values are indicative of moderate-to-high mobility in soil (Swann et al. 1983); therefore, RDX can be expected to leach into groundwater. Experimental data have shown that RDX is not readily bound or retained in soil as evidenced by its early breakthrough in column leachates (U.S. Army 1985a). A lysimeter study of the migration of RDX in soil showed that RDX was found in leachate from the soil columns (U.S. Navy 1982). Based on these K_{oc} values and the experimental data, adsorption to sediment and particulate matter in the aquatic environment should not be significant (U.S. Army 1980a). Although RDX does not significantly adsorb to sediment, greater adsorption occurs with an increase in organic matter or clay content (U.S. Army 1980a). However, the clay content seems to be more important than organic matter content in influencing the amount of RDX adsorbed (U.S. Army 1980a). In a study sponsored by the U.S. Army Medical Research and Development Command (USAMRDC), the adsorption rate constant of RDX in soil was found to be low (K_d of <1 mg/g). The adsorption constant was linearly correlated with a combination of soil properties, such organic carbon and clay content, pH, and cation exchange capacity (U.S. Army 1993a). Adsorption to soil was measured using samples from the Louisiana Army Ammunition Plant. RDX was retained on a bentonite/sand column with a 90% recovery after 11 pore volumes. Retardation of RDX by fine-silty soils was limited (Selim et al. 1995). It appears that sorption of RDX in soils is not solely the result of hydrophobic partitioning of RDX to the organic carbon phase of the soils.

The logarithm of the octanol/water partition coefficient (log K_{ow}) is a useful preliminary indicator of potential bioaccumulation of a compound. The log K_{ow} for RDX was estimated to be 0.87 (PHYSPROP 2009), indicating that RDX is not very lipid soluble and therefore has a low potential for bioaccumulation in aquatic species. Experimental bioconcentration factors in edible tissue for bluegill (*Lepomis macrochirus*), channel catfish (*Ictalurus punctatus*), and fathead minnow (*Pimephales promelas*) were 1.9–6.4, 1.2–5.5, and 1.4–5.9, respectively (U.S. Army 1984a). These factors indicate that bioaccumulation in aquatic organisms is not an important fate process.

Data indicate that RDX can be taken up by both terrestrial and aquatic plants (Best et al. 1999; Harvey et al. 1991, 1997; Pennington and Brannon 2002; Simini and Checkai 1996; U.S. Army 1990a). Studies of bean plants grown in 10 ppm RDX hydroponic solutions and exposed for 1 or 7 days indicated that uptake of RDX readily occurred. Following uptake, translocation of the compounds to the aerial tissue occurred, resulting in foliar concentrations of 20 and 97 ppm for the 1- and 7-day exposures, respectively. Metabolism of RDX to polar metabolites was observed in plants exposed for 7 days (Harvey et al. 1991). Additional studies of hydroponic plant-culture systems indicated that RDX (1–10 ppm) was also absorbed

by the roots of blando brome and wheat and that plant absorption was concentration-dependent (U.S. Army 1990a). In a simulation of field conditions, uptake of RDX to lettuce leaves, corn stover, and alfalfa shoots correlated to levels of RDX (2, 18, and 90 ppb) in the irrigation water (Simini and Checkai 1996). Submerged aquatic plants, including Elodea, pondweed, and water star-grass, grown using sediment and contaminated groundwater containing 1,529 µg/L from the Milan Ammunition Plant in Milan, Tennessee had RDX concentrations of 976, 42, and 1,496 µg/L, respectively, after 13 days. The emergent plant species, parrot-feather, sweet-flag, reed canary grass, and wool-grass contained RDX at 3,196, 1,156, 704, and <20 µg/L, respectively (Best et al. 1999). When grown in soil contaminated with 58 mg/kg RDX, lettuce was found to contain 1,200 mg/kg of RDX, while nutsedge, tomato fruit, corn kernels, and corn stover contained RDX at concentrations of 62, 7, 6, and 56 mg/kg, respectively (Pennington and Brannon 2002). For plants grown in soils containing 10 ppm RDX over a period of 60 days, the extent of plant uptake was found to be dependent both on soil type and plant species (Cataldo et al. 1993). RDX was transported unchanged from soils to plants and the plant uptake increased as the organic matter content of soil decreased. In bush bean plants, RDX was mostly concentrated in leaves and seed, with less found in roots, stems, and pods. In the case of wheat and blando brome, RDX mostly concentrated in leaves and roots, with very little or none in seeds (Cataldo et al. 1993). After plant uptake, RDX in storage tissues of plants (i.e., roots and stems) mostly metabolized to unidentified polar metabolites or nonextractable products, while RDX remained mostly unchanged (>50%) in leaves and seed tissues (Cataldo et al. 1993).

6.3.2 Transformation and Degradation

6.3.2.1 Air

RDX is expected to exist in the particulate form in the atmosphere, and may be subject to removal from air by dry deposition. No data were located on photolysis of RDX in the atmosphere. However, it is expected that photolysis of RDX is an important fate process in the atmosphere since RDX absorbs ultraviolet wavelengths between 240 and 350 nm (U.S. Army 1986e) and it undergoes rapid photolysis in water (U.S. Army 1980a).

6.3.2.2 Water

In a hydrolysis study of RDX in seawater (pH 8.1) at 25 °C, 11.6% of initial RDX hydrolyzed in 112 days (Hoffsommer and Rosen 1973). Other data found that RDX was stable to hydrolysis in an aqueous solution at a pH range normally found in natural waters (U.S. Army 1980a). Therefore, hydrolysis is not

expected to significantly influence the environmental fate of RDX. Hydrolysis can occur, however, under alkaline conditions. RDX underwent alkaline hydrolysis (pH 10) in the presence of water over 17 days. The approximate half-life for this reaction was about 7 days and was accompanied by the formation of the ring cleavage product 4-nitro-2,4-diazabutanal, as well as NO_2^-, N_2O, formaldehyde, and formic acid (Balakrishnan et al. 2003). Aqueous alkaline hydrolysis is thought to be a possible method of remediating RDX contaminated waste water (Heilmann et al. 1996).

The primary physical mechanism that degrades RDX in aqueous solutions is photolysis (U.S. Army 1986e). The range of ultraviolet wavelengths that produce photolytic reactions with RDX is generally between 240 and 350 nm (U.S. Army 1986e). RDX in waste water (23.9 mg/L) exposed to ultraviolet radiation decomposed with a half-life of 3.7 minutes (Burrows et al. 1984). Photolysis of an aqueous solution of RDX in natural sunlight is fairly rapid with an experimental half-life of 9–13 hours. Consequently, RDX is not expected to persist for a long period of time in clear, sunlit surface waters (U.S. Army 1980a). Formaldehyde and nitrosamines were identified as photoproducts. Nitrosamines may be of environmental importance because of their potential mutagenicity/carcinogenicity. Conversion to this product, however, occurs only to a limited extent since the product itself is photoreactive (U.S. Army 1980a). The rate of photodegradation under different environmental conditions is also dependent upon the nature of the water body itself. RDX was shown to degrade very slowly in dark, tea-colored lagoon waters at a Louisiana Army Ammunition Plant during a field study at this site (U.S. Army 1983b). The half-life for RDX was approximately 2,100 days in winter and 456 days in summer for a lagoon 50 cm deep (U.S. Army 1983b). The slow rate of degradation was attributed to the rapid attenuation of sunlight in the top layers of the water column, thereby preventing photons of radiation from reaching RDX, which was reported to be well mixed throughout the water column (U.S. Army 1983b).

The biodegradation of RDX has been studied under aerobic and anaerobic conditions. RDX did not undergo aerobic biodegradation using a variety of inocula and nutrients (Osmon and Klausmeier 1973). However, microbial degradation studies were carried out using water and sediment samples collected from the Holston River and the waste-water effluents from the Holston Army Ammunition Plant showed some degradation (U.S. Army 1980a). Only the addition of river sediments appeared to stimulate the aerobic biodegradation of RDX in samples of river water containing either 5.5 or 11.5 ppm of RDX. The half-life for the disappearance of RDX in water samples supplemented with sediment was approximately 7 days. A lag period of 2–3 weeks was observed before a noticeable degradation of RDX occurred. The results showed that biodegradation of RDX leads to mineralization of the molecule (U.S. Army 1980a). No degradation of RDX was observed during a 90-day aerobic experiment with RDX in the lagoon water

alone, with added yeast extract, or with 1% of bottom sediment (U.S. Army 1983b). Concentrations of RDX remained unchanged when cultures were inoculated with aerobic activated sludge and incubated aerobically. No RDX disappeared in uninoculated controls (McCormick et al. 1981).

Data are available indicating that biodegradation of RDX occurs under anaerobic conditions (U.S. Army 1984f; Crocker et al. 2006; Funk et al. 1993; Hawari et al. 2000; McCormick et al. 1981; Pennington and Brannon 2002; Walker and Kaplan 1992). RDX (50 or 100 μg/mL) disappeared rapidly from nutrient broth cultures inoculated with anaerobic sewage sludge and incubated anaerobically. Biodegradation of RDX was complete after 4 days (McCormick et al. 1981). The disappearance of RDX was accompanied by the appearance of several products identified as the mono-, di-, and trinitroso derivatives of RDX formed by sequential reductions of the nitro groups to nitroso groups (Crocker et al. 2006; Hawari et al. 2000; McCormick et al. 1981; Walker and Kaplan 1992). Anaerobic biodegradation products included MNX; DNX; TNX; hydrazine; 1,1-dimethyl-hydrazine; 1,2-dimethyl-hydrazine; formaldehyde; and methanol. The nitroso intermediates are known to be hazardous. Both 1,1- and 1,2-dimethylhydrazine, as well as hydrazine, are known mutagens and/or carcinogens (McCormick et al. 1981), but may be found naturally in the environment (e.g., certain mushrooms).

After an incubation period of 5 days, 97% of RDX was anaerobically degraded by a mixed population of purple photosynthetic bacteria of the genera Chromatium, Rhodospirillum, and Rhodopseudomonas, and possibly others (U.S. Navy 1973). Sixty percent of RDX was anaerobically degraded by Chromatium alone (U.S. Navy 1973). These photosynthetically active cultures, which do not release oxygen, were supplemented with sodium acetate and ammonium chloride. It was hypothesized that RDX was not actually metabolized, but rather was being reduced and modified as a result of the active electron transfer brought about by the anaerobic photosynthetic activity of the organisms. Data indicate that hydrogen can be the sole electron donor in the anaerobic degradation of RDX (Beller 2002). A proposed pathway for the degradation of RDX involves reductions leading to destabilization, ring cleavage, and mineralization. Degradation intermediates are much more susceptible to degradation under anaerobic conditions than under aerobic conditions (Pennington and Brannon 2002).

RDX (13 ppm) in lagoon waste water at the Louisiana Army Ammunition Plant did not undergo anaerobic degradation for approximately 90 days with yeast extract repeatedly added as a nutrient (U.S. Army 1983b). The RDX concentration fell to 2.9 ppm at day 90 and to 1.4 ppm at day 92. The authors reported that the repeated addition of yeast extract acclimated RDX-utilizing organisms. The RDX-

acclimated organisms then degraded 9.1 ppm of RDX 93% after 5 days of anaerobic incubation (U.S. Army 1983b).

6.3.2.3 Sediment and Soil

Three soils containing 0.5–7.2% organic matter were amended with 60 ppm (mg/kg) RDX and incubated for 60 days under aerobic conditions (Cataldo et al. 1993). After 60 days, >95% were extractable and remained unchanged as parent RDX; only <2% remained nonextractable in the soils. No significant transformation products of RDX were observed in the soils. RDX was not biodegraded after 56 days following addition to three soil samples (Grant et al. 1995). RDX, present at 30 ppm in soil cultures containing added potato starch as an additional carbon source, was not degraded after 24 days (Funk et al. 1993). These results indicate that RDX may not be easily amenable to aerobic biodegradation in soils.

Significant biotransformation, however, may occur under certain conditions. The degradation of pink water compounds in soil was studied (U.S. Army 1985a). Pink water is a generic term used for colored waters that may contain some explosive compounds, including RDX. A simulated pink water containing RDX (30 mg/L) was continuously applied to a series of soil columns at different flow rates, with and without carbon supplementation. The columns were inoculated with combined samples of micro-organisms from activated sludge, anaerobic sludge digest, and garden soil. Concentrations of RDX and biotransformation products were monitored on a weekly basis. There appeared to be a significant decrease in RDX recovery in the leachate of the column with slow and fast flow with carbon supplement, indicating microbial activity. The mononitroso derivative, MNX, and the dinitroso derivatives of RDX were identified in the leachate of the column with fast flow (100 mL/day) and carbon supplement (2.0 g/L glucose). MNX was also identified in the leachates from the columns with slow flow (40 mL/day) with and without carbon supplement (U.S. Army 1985a). Since the nitroso derivatives are intermediates in the anaerobic biodegradation of RDX in aqueous systems (Walker and Kaplan 1992), it is likely that the observed products resulted from anaerobic biodegradation of RDX. The authors reported that land treatment or land farming of pink water should not be considered as a treatment option for pink water. Hazardous biotransformation intermediates and unchanged concentrations of some of the pink water compounds would contaminate groundwater and soil. RDX, present at 30 ppm in anaerobic soil cultures containing added potato starch as an additional carbon source, were totally degraded after 24 days (Funk et al. 1993).

Douglas et al. (2009) added 20 mL of a solution containing 2.3 mg/L RDX to aqueous slurries containing pristine soils and soils fractured to simulate the effects of detonation. After 92 days, the measured concentration was approximately 1.3–2.2 mg/L in the slurries containing the fractured soils and virtually unchanged in the slurries containing the pristine soil. The authors suggested that the observed decrease in aqueous concentration in the fractured soil could be caused by enhanced adsorption to fractured soil particle surfaces or enhanced transformation in the presence of the fractured soil particles or a combination of both.

6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to RDX depends in part on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of RDX in unpolluted atmospheres and in pristine surface waters are often so low as to be near the limits of current analytical methods. In reviewing data on RDX levels monitored or estimated in the environment, it should also be noted that the amount of chemical identified analytically is not necessarily equivalent to the amount that is bioavailable. The analytical methods available for monitoring RDX in a variety of environmental media are detailed in Chapter 7.

6.4.1 Air

No data are available regarding levels of RDX in outdoor air. However, indoor air samples collected at Holston Army Ammunition Plant in Kingsport, Tennessee in 1974 contained RDX levels ranging from not detected (<0.5 mg/m^3 [4.5 ppm]) to 60 mg/m^3 (546 ppm) (U.S. Army 1975). A more recent study found that RDX was detected in only one of eight indoor air samples taken from the incorporation area of Holston Army Ammunition Plant in 1986; the concentration in this sample was 0.032 mg/m^3 (0.29 ppm) in the particulate fraction (Bishop et al. 1988).

6.4.2 Water

Seawater samples taken in 1971 from a munitions dumping area 85 miles west of Cape Flattery, Washington, and similar samples taken 172 miles south-southeast of Charleston, South Carolina, were analyzed for RDX (U.S. Navy 1972). No RDX was found in any of the samples examined (detection limit of 5 ppt). RDX was found on-site at the Savanna Army Depot in Illinois in surface water samples at a maximum reported concentration of 36.9 ppm (Agency for Toxic Substances and Disease Registry

1989c). The Savanna Army Depot is on the NPL. It was an Army munitions plant engaged in munitions renovation, loading, demolition, and burning, which was closed in 2000.

Onsite groundwater sampling at the Milan Army Ammunition Plant near Milan, Tennessee identified RDX at concentrations ranging from not detected to 11.24 ppm (detection limit not reported) (Agency for Toxic Substances and Disease Registry 1989b). Filtered groundwater samples from the Milan Army Ammunition Plant contained RDX at a concentration of 1,443 ppb. Filtration reduced RDX concentration in the water samples by 27% (Best et al. 1999). U.S. Army (2011) listed a range of detectable concentrations of 50–18,000 ppb in groundwater samples and 80–120 ppb in surface water samples taken from Milan Army Ammunition Plant. Groundwater samples from the Umatilla Army Depot Activity, a munitions storage and handling depot in Hermiston, Oregon and the Naval Submarine Base Bangor in Bangor, Washington contained RDX in concentrations ranging from <20 to 8,160 ppb (Bart et al. 1997).

Groundwater samples from monitoring and extraction wells at the Naval Base Kitsap at Bangor NPL site in Kitsap County, Washington, were collected from May 1994 to August 2004. Concentrations of RDX in the samples from a 12-acre Bangor Ordnance Disposal site (Site A) ranged from 0.19 to 1,000 ppb in perched zone monitoring wells, from 0.19 to 550 ppb in shallow aquifer monitoring wells, and from 0.4 to 660 µg/L in extraction wells (shallow aquifer). RDX concentrations at the site of a former waste water lagoon and overflow ditch (Site F) in groundwater from a shallow aquifer ranged from 0.95 to 3,800 ppb (U.S. Navy 2005).

RDX was identified in environmental samples at Cornhusker Army Ammunition Plant and Louisiana Army Ammunition Plant army bases (Dacre 1994). Maximum concentrations of RDX detected in water at the Cornhusker Army Ammunition Plant (Nebraska) were 307 and 371 ppb from on- and off-site wells, respectively (Agency for Toxic Substances and Disease Registry 1989a). A plume of RDX-contaminated groundwater, which stretched 6.5 km, was found near the Cornhusker Army Ammunition Plant. The concentrations ranged from 9 to >100 ppb (Spalding and Fulton 1988). A maximum concentration of 95 ppb in groundwater was reported by U.S. Army (2011) for the Cornhusker Army Ammunition Plant The Louisiana Army Ammunition Plant is a shell manufacturing and explosives load, assembly, and pack facility (U.S. Army 1988). From 1951 to 1980, waste waters were trucked to and discharged into a series of artificial leaching pits, which resulted in contamination of soil, sediments, and groundwater. Levels of RDX measured in groundwater at the Louisiana Army Ammunition Plant ranged from 1.3 to 14,100 ppb (U.S. Army 1988). U.S. Army (2011) reported a maximum groundwater concentration of 13,200 ppb at

this facility. U.S. Army (2011) also reported ranges of groundwater concentrations of 0.0087–86.4 ppb at Aberdeen Proving Ground and 3.3–13,000 ppb at Iowa Army Ammunition Plant. The surface water concentrations ranged from 0.73 to 7.6 ppb at Aberdeen Proving Ground and 4.4 to 249 ppb at Iowa Army Ammunition Plant.

RDX was identified in a water sample obtained from a military training site in Germany at 21 ppb (Godejohann et al. 1998). Two contaminated water samples from the area of a former explosive production plant at Elsnig in Saxony, Germany contained RDX at concentrations of 2,380–3,800 and 310–400 ppb, with the exact concentrations dependent upon the method of detection (Steuckart et al. 1994).

6.4.3 Sediment and Soil

Ocean floor sediment samples taken in 1971 from a munitions dumping area 85 miles west of Cape Flattery, Washington, and similar samples taken 172 miles south-southeast of Charleston, South Carolina, were analyzed for RDX (U.S. Navy 1972). No RDX was found in any of the sediment samples analyzed. RDX was found onsite at the Savanna Army Depot in Illinois in soil samples at a maximum concentration of 12.3 ppm (Agency for Toxic Substances and Disease Registry 1989c). RDX was found at the Louisiana Army Ammunition Plant in soil and drainage sediments at concentrations ranging from <5 to 602 mg/kg (U.S. Army 1988). RDX was identified in a composite soil sample at a concentration of 130.5 mg/kg. The sample was composed of topsoil samples from the site of an explosives factory (Sunahara et al. 1999). Soils collected from the Joliet Army Ammunition Plant in Joliet, Illinois contained RDX in concentrations ranging from <0.1 to 3,574 mg/kg (Simini et al. 1995). RDX was identified in environmental samples at Cornhusker Army Ammunition Plant and Louisiana Army Ammunition Plant (Dacre 1994).

RDX was identified in compost at 884 mg/kg. The compost was prepared using contaminated sediments from the Umatilla Army Depot Activity in Hermiston, Oregon (Gunderson et al. 1997). Griest et al. (1995) identified RDX in dry compost prepared using soils from Umatilla in concentrations ranging from >2.9 to 896 mg/kg.

U.S. Army (2011) reported range of detectable soil concentrations of 5.45–890 mg/kg at Cornhusker Army Ammunition Plant, 0.587–3,300 mg/kg at Milan Army Ammunition Plant, 980 mg/kg at Aberdeen

Proving Ground, and 2.5–75,000 mg/kg at Iowa Army Ammunition Plant; sediment samples from Iowa Army Ammunition Plant contained 0.363–14,100 mg/kg RDX.

6.4.4 Other Environmental Media

Ocean floor fauna samples (rat tail fish and sea cucumbers) taken in 1971 from munitions dumping areas in the Atlantic and Pacific Oceans contained no apparent RDX residues (detection limit of 0.123 µg/kg) (U.S. Navy 1972).

Agricultural crops irrigated with contaminated water have been found to contain RDX. In a laboratory study simulating field conditions, uptake of RDX to lettuce leaves, corn stover, and alfalfa shoots correlated to levels of RDX in the irrigation water (2, 18, and 90 ppb). RDX did not significantly concentrate in tomatoes, bush bean seeds and pods, radish roots, and soybean seeds (Simini and Checkai 1996). Submerged aquatic plants, including Elodea, pondweed, and water star-grass, grown using sediment and contaminated groundwater containing 1,529 µg/L from the Milan Ammunition Plant in Milan, Tennessee had RDX concentrations of 976, 42, and 1,496 µg/L, respectively, after 13 days. The emergent plant species, parrot-feather, sweet-flag, reed canary grass, and wool-grass contained RDX at 3,196, 1,156, 704, and <20 µg/L, respectively (Best et al. 1999). When grown in soil contaminated with 58 mg/kg RDX, lettuce was found to contain 1,200 mg/kg of RDX, while nutsedge, tomato fruit, corn kernels, and corn stover contained RDX at concentrations of 62, 7, 6, and 56 mg/kg, respectively (Pennington and Brannon 2002).

6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

For the general population, exposure to RDX is most likely limited to areas around Army ammunition plants where RDX is manufactured, converted to munitions, or released through the demilitarization of antiquated munitions (Hundal et al. 1997; Pennington and Brannon 2002; U.S. Army 1980a, 1984a, 1984f). Two surveys of public places, including taxis, trains, and airplanes, hotels, and private homes, rarely detected RDX (Crowson et al. 1996; Cullum et al. 2004). The most likely route of exposure for populations living in the vicinity of Army ammunition plants is ingestion of contaminated drinking water or agricultural crops that have been irrigated with contaminated water (Harvey et al. 1991, 1997; Simini and Checkai 1996). Dermal contact with soil containing RDX and inhalation of contaminated particulate matter produced during incineration of RDX-containing waste material are also possible routes of exposure. However, since no monitoring data were located regarding levels of RDX in outdoor air, the extent of exposure by this route is not known. Dermal contact with contaminated soil is also a possible

route of exposure. However, since no absorption data following dermal exposure to RDX were located, the extent of exposure by this route is also not known.

Occupational exposure to RDX can occur when workers handle RDX in explosive plants (Hathaway and Buck 1977; Kaplan et al. 1965; Testud et al. 1996b). Inhalation exposure of workers to RDX has occurred as a result of release of dust into the workroom air, principally during dumping of dried RDX powder, screening and blending, and clean-up of spilled material (Kaplan et al. 1965; Testud et al. 1996b). Exposure to RDX can also occur through dermal contact during manufacture, handling, and clean-up of RDX (Kaplan et al. 1965). RDX was detected at a concentration of 0.052 mg/m^3 (0.47 ppm) in the particulate fraction of one indoor air sample taken from the incorporation area of Holston Army Ammunition Plants in Tennessee in 1986 (Bishop et al. 1988). Based on the observed concentration, the potential for exposure to RDX is considered to be very low.

According to the NOES (1981–1983), the estimated number of workers potentially exposed to RDX in the United States was 488 (NIOSH 1990).

6.6 EXPOSURES OF CHILDREN

This section focuses on exposures from conception to maturity at 18 years in humans. Differences from adults in susceptibility to hazardous substances are discussed in Section 3.7, Children's Susceptibility.

Children are not small adults. A child's exposure may differ from an adult's exposure in many ways. Children drink more fluids, eat more food, breathe more air per kilogram of body weight, and have a larger skin surface in proportion to their body volume. A child's diet often differs from that of adults. The developing human's source of nutrition changes with age: from placental nourishment to breast milk or formula to the diet of older children who eat more of certain types of foods than adults. A child's behavior and lifestyle also influence exposure. Children crawl on the floor, put things in their mouths, sometimes eat inappropriate things (such as dirt or paint chips), and spend more time outdoors. Children also are closer to the ground, and they do not use the judgment of adults to avoid hazards (NRC 1993).

Children can be exposed to RDX by inhalation, oral, or dermal contact with the chemical or by any combination of these routes. Children residing in areas around Army ammunition plants where RDX is manufactured, converted to munitions, or released through the demilitarization of antiquated munitions may be exposed to RDX (Hundal et al. 1997; Pennington and Brannon 2002; U.S. Army 1980a, 1984a,

1984f). The primary route of exposure is ingestion of contaminated drinking water. Inhalation exposure may result from breathing contaminated particulate matter produced during incineration of RDX-containing waste material. Dermal contact with contaminated soil is also a possible route of exposure. Children playing in contaminated water or soil may also be exposed via ingestion.

6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Exposure of workers can occur via the inhalation, oral, or dermal routes, or by any combination of these routes. Workers involved in the production and use of RDX at Army ammunition plants constitute a group at risk because of the potential for occupational exposure. Persons living near Army ammunition plants or hazardous waste sites may have a higher risk of exposure to RDX resulting from inhalation of dusts or fumes, ingestion of contaminated drinking water, or contact with contaminated soil (Hundal et al. 1997; Pennington and Brannon 2002; Testud et al. 1996b). Military personnel may also be exposed to high levels from the use of explosives that contain RDX. Individuals employed in demilitarization of nuclear, biological, and chemical weapons as per international treaty agreements may be exposed to high levels of RDX, as disassembly of these missiles involves disassembly of RDX-containing bursters and detonators.

6.8 ADEQUACY OF THE DATABASE

Section 104(i)(5) of CERCLA, as amended, directs the Administrator of ATSDR (in consultation with the Administrator of EPA and agencies and programs of the Public Health Service) to assess whether adequate information on the health effects of RDX is available. Where adequate information is not available, ATSDR, in conjunction with NTP, is required to ensure the initiation of a program of research designed to determine the health effects (and techniques for developing methods to determine such health effects) of RDX.

The following categories of possible data needs have been identified by a joint team of scientists from ATSDR, NTP, and EPA. They are defined as substance-specific informational needs that if met would reduce the uncertainties of human health assessment. This definition should not be interpreted to mean that all data needs discussed in this section must be filled. In the future, the identified data needs will be evaluated and prioritized, and a substance-specific research agenda will be proposed.

6.8.1 Identification of Data Needs

Physical and Chemical Properties. The physical and chemical properties of RDX are sufficiently characterized to permit estimation of its environmental fate (Akhavan 2004; Budavari and O'Neil 1989; McKone and Layton 1986; U.S. Army 1986e, 1987a).

Production, Import/Export, Use, Release, and Disposal. According to the Emergency Planning and Community Right-to-Know Act of 1986, 42 U.S.C. Section 11023, industries are required to submit substance release and off-site transfer information to the EPA. The TRI, which contains this information for 2006, became available in February of 2008. This database is updated yearly and should provide a list of industrial production facilities and emissions.

RDX is not produced commercially in the United States. Production in the United States is limited to Holston Army Ammunition Plants in Kingsport, Tennessee (SRI 2009),. Current import/export data for RDX are not available. RDX is primarily used as a high explosive (Boileau et al. 2009; HSDB 2009; Lewis 2007; Budavari and O'Neil 1989; Turley and Brewster 1987). RDX is primarily found in water, groundwater, and soil around Army ammunition plants (Agency for Toxic Substances and Disease Registry 1989a, 1989b, 1989c; Bart et al. 1997; Bishop et al. 1988; Dacre 1994; Simini et al. 1995; Spalding and Fulton 1988; U.S. Army 1988). Data on the most commonly used disposal methods are sufficient (Hoffsommer and Rosen 1972; U.S. Army 1986a, 1986c); however, additional data on the amounts of RDX being disposed of and on alternative disposal methods would be useful. RDX wastes produced in manufacturing and processing are classified as hazardous wastes and are subject to EPA regulations (EPA 1990a).

Environmental Fate. RDX released to the environment partitions into air, water, and soil (Eisenreich et al. 1981; Lyman et al. 1982; U.S. Army 1980a, 1983b, 1987a). RDX is transported in soil, surface water, and groundwater (Swann et al. 1983; U.S. Army 1980c, 1983b, 1985a, 1986e, 1987a). Volatilization is expected to be a slow transport process (Lyman et al. 1982). RDX is expected to exist as a particulate in the atmosphere. No data were located in the literature regarding atmospheric transport of RDX. Experimental data are needed regarding photolysis of RDX in the atmosphere. Photolysis is the primary mechanism of RDX degradation in water (half-life of 9–13 hours) (U.S. Army 1980a, 1986e). Biodegradation of RDX occurs in water and soil, principally under anaerobic conditions (Funk et al. 1993; McCormick et al. 1981; Osmon and Klausmeier 1973; Pennington and Brannon 2002; U.S. Army 1984f, 1985a). Biodegradation half-life data for RDX and its breakdown products in water and soil are

needed. This information will be helpful in better identifying the most important pathways of human exposure to RDX.

Bioavailability from Environmental Media. Absorption data regarding dermal exposure in humans are not available. Very limited data indicate that RDX is absorbed following inhalation exposure (Kaplan et al. 1965; Testud et al. 1996b). RDX is absorbed through the gastrointestinal system following ingestion of the compound (Hollander and Colbach 1969; Ketel and Hughes 1972; Merrill 1968; Stone et al. 1969). The oral and dermal routes of exposure may be of concern to humans because of the potential for RDX to contaminate drinking water and soil. More information regarding all absorption routes, particularly on the absorption of RDX following ingestion of contaminated drinking water and soil or plants grown in contaminated environments, is needed to better characterize the bioavailability of RDX.

Food Chain Bioaccumulation. Based on a low log K_{ow} and low experimental BCF values of 1.2–5.9, RDX has a low bioconcentration potential in aquatic organisms (PHYSPROP 2009; U.S. Army 1984a). No data were located regarding bioconcentration potential in animals. Data are needed regarding bioconcentration/biomagnification potential in terrestrial food chains.

Exposure Levels in Environmental Media. Reliable monitoring data for the levels of RDX in contaminated media at hazardous waste sites are needed so that the information obtained on levels of RDX in the environment can be used in combination with data on potential pathways of exposure and the known body burden of RDX to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

RDX has been detected in surface water, groundwater, and soil at Army ammunition plants and current and former military installations (Agency for Toxic Substances and Disease Registry 1989a, 1989b, 1989c; Bart et al. 1997; Simini et al. 1995; Spalding and Fulton 1988). Data are needed regarding levels of RDX in ambient air and occupational air. No data were located regarding human intake estimates for each media. Reliable monitoring data are needed for levels of RDX in contaminated media at hazardous waste sites. The information on RDX levels in the environment and the resulting body burden of RDX can be used to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

Exposure Levels in Humans. RDX has been detected in surface water, groundwater, and soil at Army ammunition plants (Agency for Toxic Substances and Disease Registry 1989a, 1989b, 1989c; Bart

et al. 1997; Simini et al. 1995; Spalding and Fulton 1988). Data are needed regarding levels of RDX in ambient air and occupational air. No data were located regarding human intake estimates for each media. Reliable monitoring data are needed for levels of RDX in contaminated media at hazardous waste sites. The information on RDX levels in the environment and the resulting body burden of RDX can be used to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

This information is necessary for assessing the need to conduct health studies on these populations.

Exposures of Children. RDX has been detected in surface water, groundwater, and soil at Army ammunition plants (Agency for Toxic Substances and Disease Registry 1989a, 1989b, 1989c; Bart et al. 1997; Simini et al. 1995; Spalding and Fulton 1988). Data are needed regarding levels of RDX in ambient air. No data were located regarding human intake estimates for each media. Reliable monitoring data are needed for levels of RDX in contaminated media at hazardous waste sites as well as potential uptake by children through ingestion of drinking water and contaminated crops, and accidental ingestion of contaminated soils. Dermal contact is also a concern for children playing in or near contaminated areas. The information on RDX levels in the environment and the resulting body burden of RDX can be used to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

Child health data needs relating to susceptibility are discussed in Section 3.12.2, Identification of Data Needs: Children's Susceptibility.

Exposure Registries. No exposure registries for RDX were located. This substance is not currently one of the compounds for which a sub-registry has been established in the National Exposure Registry. The substance will be considered in the future when chemical selection is made for sub-registries to be established. The information that is amassed in the National Exposure Registry facilitates the epidemiological research needed to assess adverse health outcomes that may be related to exposure to this substance.

6.8.2 Ongoing Studies

The Federal Research in Progress (FEDRIP 2009) database provides additional information obtainable from a few ongoing studies that may fill in some of the data needs identified in Section 6.8.1. These studies are summarized in Table 6-1.

Table 6-1. Ongoing Studies on RDX

Investigator	Affiliation	Research description	Sponsor
Chu, K	Texas Engineering Experiment Station	Molecular probing and identification of active RDX-utilizing microorganisms	NSF
Schnoor, JL	University of Iowa	Involvement of an endosymbiotic *Methylobacterium sp.* in the biodegradation of explosive RDX and HMX inside poplar tree (*Populus deltoids x Populus nigra*)	NSF

NSF = National Science Foundation

Source: FEDRIP 2009