1.0 Introduction

This report was prepared for the U.S. Army by PNNL to document a study of exposures of personnel to DU during and after the fire that occurred at Camp Doha, Kuwait on July 11 and 12, 1991.[(a)] The fire engulfed the 2nd Squadron motor pool at Camp Doha. Although fighting in the Gulf War had ceased several months before the accident, sudden aggression by the Iraqi military was considered a serious possibility, and the U.S. 11th Armored Cavalry Regiment at Camp Doha was poised to serve as a deterrent or rapid response force if needed. Thus military vehicles, including M1A1 tanks, BFV, and ammunition carriers, were combat-ready in the motor pool, uploaded with a full complement of ammunition. After the fire started in an ammunition carrier, it quickly became an extremely hazardous event with exploding ammunition. These explosions distributed ordnance over a wide area, leaving an extremely dangerous debris field containing a high concentration of UXO.

The recovery and cleanup work after the fire was performed with a sense of urgency due to the threat of an enemy nearby. The immense area to be recovered was scattered with UXOs, which were often concealed by other debris. In fact, unintentional UXO explosions caused serious injury and three deaths among recovery workers. In addition to the military threat and life-threatening danger of UXOs, environmental conditions made recovery work very difficult. Desert temperatures were typically above 100°F, a constant wind blew, smoke from burning oil wells was always present, and biting sand flies and other insects were a constant annoyance.

Approximately 660 120-mm series rounds, containing DU penetrators, were involved in the fire. The hazards of DU are of two types: chemical and radiological. The chemical toxicity of DU is similar to other heavy metals with storage in the skeleton and excretion via the urine accompanied by renal toxicity. The radiological toxicity of DU is derived from U-238, the major constituent of DU, which is radioactive, albeit with a low SpA (0.336 μCi/g). Consequently, DU presents potential chemical and radiological risks from repeatedly handling of the penetrators or from inhaling or ingesting DU oxides formed in the fire. At the time of the recovery work, the chemical and radiological risks were acknowledged, but generally considered insignificant in relation to other safety hazards, and for many recovery workers it was unknown. Thus, protective actions that are considered standard practice for routine industrial chemical and radiological work in more comfortable settings were not typically employed.

This report documents the assessment of chemical and radiation exposures received by personnel who may have been exposed to airborne releases and debris from the Camp Doha fire and to recovery personnel who worked in and near the contaminated areas in the months after the fire (see camp map in Figure 1.1). The data needed for the dose assessments were gathered by studying accounts of the accident and recovery work including the Environmental Exposure Report released by the OSAGWI, OSAGWI (1998).

(a) PNNL is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

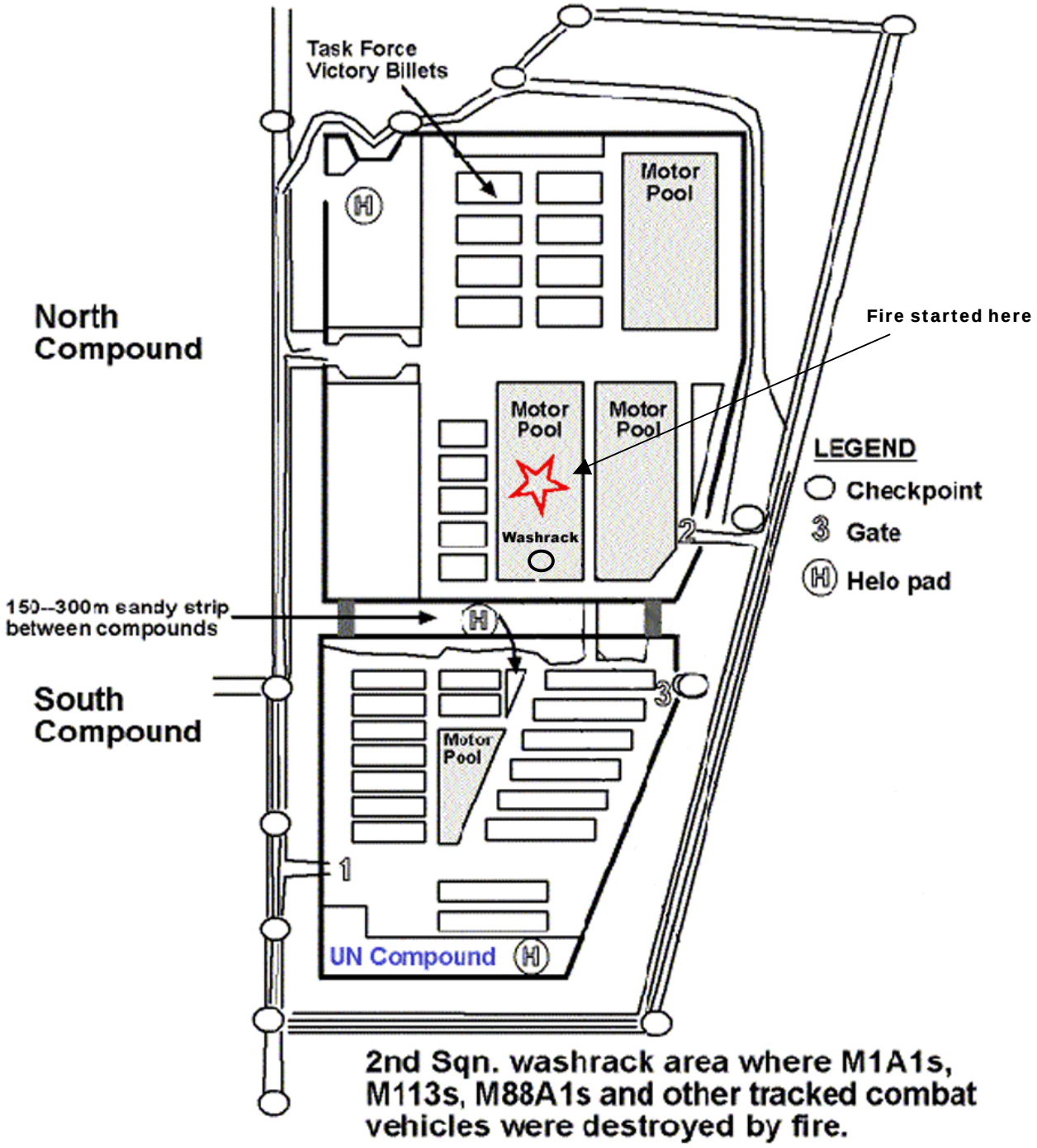

Figure 1.1. Camp Doha Map

Additionally, results of tests that have been performed to understand the physical behavior of DU during fires and airborne transport were reviewed for pertinent properties. Some of these were reviewed and summarized by Parkhurst et al. (1995).

These dose assessments are based on our best current understanding of post-fire conditions and personnel recovery activities. Limited quantitative information about DU oxides actually present means that large uncertainties exist in input parameters used in the analysis. In lieu of actual information, numerous assumptions were made concerning the existing conditions and personnel activities. These assumptions were always chosen to be as reasonable as possible but still conservative to avoid underestimating a dose. The bases for these assumptions are documented in this report.

The ensuing chapters describe the dose assessment approach, how the quantity and distribution of DU oxides were estimated, how the concentrations and transportation of DU in air were estimated, the activities of the recovery workers and their related chemical and radiological exposure to DU, the assessment of dose to recovery workers, and finally conclusions about the significance of DU exposures and modeling uncertainties.

2.0 General Approach to Dose Assessment

This chapter describes the approach taken to assess doses to recovery workers after the Camp Doha fire. In considering possible dose pathways, it was determined that recovery workers could have been exposed to the hazards of DU via the following dose pathways:

- external doses to the hands and whole body from handling DU penetrators
- inhalation of DU oxides entrained in smoke generated by the fire
- inhalation of DU oxides resuspended from surface contamination
- ingestion of DU oxides from contaminated surfaces.

Of these possible pathways, the most significant sources of exposure are the two inhalation and the incidental ingestion pathways. The external radiation dose rate from DU, including DU penetrators, is low and requires long exposure times to approach significant levels. The inhalation pathway is significant only when the DU is in the form of fine particles, which can happen only after the DU oxidizes. In military scenarios, DU can oxidize when a penetrator strikes an obstacle such as armor or becomes engulfed in a fire. Because there were no oxides caused by impact of armor, fire-generated oxides represent the primary chemical and radiological risk factors in the Doha event.

To assess the intake of DU oxides entrained in smoke, the following steps were taken:

1. The mass of DU oxides generated in the fire was estimated.
2. The fraction of the DU oxides entrained by the fire effluents was estimated.
3. The transport of airborne DU oxides to personnel downwind was calculated.
4. The amount of DU oxides inhaled by a person downwind was calculated.
5. The intake of DU oxides was converted to dose.

To assess the inhalation of DU oxides by recovery workers in contaminated areas and downwind of contaminated areas, the following steps were taken to estimate the source term:

1. The mass of DU oxides generated in the fire was estimated.
2. The distribution of DU oxides as surface contamination in Camp Doha was estimated.
3. The resuspension of DU oxides from contaminated surfaces was estimated.

4. The air concentrations from resuspended DU oxides were estimated.

Activities of recovery workers were reconstructed, including the following:

- the dates of activities during which exposure might have occurred
- the total number of hours spent in the recovery areas
- the types of recovery activities causing DU oxide resuspension.

Finally, the amount of DU oxides inhaled by a representative person in each worker category was calculated, and the DU oxide intake was converted to dose.

3.0 Estimate of the Quantity and Distribution of DU Oxides

This chapter discusses the source term used to assess potential personnel exposures and describes the steps involved to estimate 1) the mass of DU involved in the fire, 2) the amount of DU that was converted to DU oxides, and 3) the distribution of these DU oxides over the Camp Doha site. The source term is the quantity of the material in question that is available for personnel exposures. For this study, the source term is the mass of DU, in an oxide form, that could present chemical and radiological exposures.

3.1 Mass of DU Involved in the Fire

There were 660 120mm DU rounds reportedly involved in the Doha fire. This figure was derived from an accident report (U.S. Army Safety Center 1991) containing a list of ammunition destroyed in the fire. The 120mm DU round is an antitank round deployed by the M1A1 main battle tank during the Gulf War. The round includes a DU penetrator, which is a rod of DU metal that weighs approximately 4 to 5 kg. Two variations of the 120mm round were used in the Gulf War: one with an approximate mass of 4 kg and one with an approximate mass of 4.68 kg. No report exists that states how many of the two variations were involved in the Doha fire, but this study conservatively assumes that all rounds were of the 4.68 kg variation. Thus, the total mass of DU metal from the 660 rounds would be approximately 660 x 4.68 or 3,090 kg DU.

The 120mm DU rounds represent the only source of DU that could produce personnel exposure in the Doha incident. During the Gulf War, the military also employed two other types of munitions containing DU, the 105mm antitank round and 30mm rounds in the GAU-8 Gatling gun mounted on A-10 aircraft; neither of these rounds were present in Doha. Bradley Fighting Vehicles currently employ 25mm rounds, and some witnesses mistakenly recollect the presence of these rounds in Doha, but the military did not field this type of round until well after 1991. There was also concern about the DU that was part of the heavy armor of the M1A1. However, the BDAT that inspected the burned M1A1 tanks at Doha reported that the armor packages were undamaged, and there was no possibility that DU from the tank armor was available to add to the DU source term, OSAGWI (1998).

Thus, the source term for this study assumes an approximate 3,090-kg mass of DU, in the form of metal, available for oxidation and dispersion.

3.2 Mass of DU Oxides Created by the Fire

The only DU available for personnel exposure by the inhalation and ingestion pathways was DU oxides. The oxides of DU, in the form of UO_2 and U_3O_8, are formed when DU penetrators are subjected to high temperatures (above several hundred degrees Celsius) for several hours. Generally, when a round is exposed to high heat sufficient to ignite the propellant in the cartridge case, the resulting pressure ejects the projectile containing the penetrator some distance away. If there were no obstacles in the way, the penetrator could travel 20 ft or more before coming to rest (based on the results of tests performed using the 12mm DU round, Haggard et al., (1986). On the other hand, nearby obstacles could stop a penetrator

near its original position. In the Doha event, the resting location of the penetrator determined the degree of oxidation: if the penetrator landed in a portion of the fire where it would be exposed to high temperatures for a number of hours, the oxidation could be extensive, approaching 90 to 100 percent of the metal. If the penetrator landed in a location sheltered from high temperatures, no oxidation would occur (there may have been minute quantities of DU oxides clinging to the penetrator from previous corrosion, but these oxides would be insignificant contributors to the source term). Observers found examples of both extremes in the debris of the Doha North Compound, OSAGWI (1998).

Burn tests were performed on 120mm DU ammunition in 1982, 1983, and 1985 and provide insights into probable oxidation behavior. The results from these tests can give some information on the possible creation of DU oxides in the Doha fire, but care must be taken in applying the results of the burn tests because they did not simulate the conditions at Camp Doha.

The first and second burn tests were conducted with 12 120mm DU rounds in wooden shipping containers using wood and diesel oil to fuel the fire, Hooker et al., (1983). In this test, as each round's propellant burned off, there was no pressurization in either the cartridge case (which is combustible) or the shipping container, so the penetrators dropped into the fire, and the fire burned for approximately 2 days. Thus, the penetrators remained at high temperature for a long period of time, and oxidation was extensive. Many of the rounds oxidized completely, and a total of 84 percent of the DU metal was oxidized.

The 1985 test (Haggard et al. 1986) was conducted similarly with 12 120mm DU rounds except that the cartridges were packaged in metal shipping containers. The metal container provided pressurization when the propellant ignited for each round, and the penetrators were ejected to some degree. Eight of the rounds were ejected out of the fire area and experienced no oxidation. Three more landed 5 ft from the test stand, where they oxidized slightly (2, 10, and 12 percent of the metal was oxidized for these rounds). One round landed at the base of the stand and experienced 90 percent oxidation.

The 1983 test was performed with rounds in wooden shipping containers, which was unlike the configuration used in Doha. Thus, it did not include the effect of pressurization and subsequent ejection of a penetrator as occurred in Doha. However, it indicated that penetrators remaining in the fire for many hours would completely oxidize. This may have some applicability to cartridges loaded and trapped in the M1A1 tanks that caught fire.

The 1985 test used penetrators in metal containers, so the pressurization and ejection mechanisms were the same for this test and for the rounds stored in conexes that were involved in the Doha fire. However, the analogy is limited, because in the burn test an ejected penetrator was likely to land outside the fire, where no oxidation would occur. In the Doha fire, a round may have been ejected 20 ft or more from its original position but may still have been within the fire and subjected to temperatures that produce oxidation.

In addition to the intentional burn tests, rounds stowed in an Abrams tank were involved in a vehicle fire at the conclusion of a series of impact tests, Fliszar, Wilsey, and Bloore (1989). This vehicle had several holes from impact providing channels for the fire to vent. Seventeen penetrators were expelled

during the fire. One was caught on a tow hook and remained in the fire where it oxidized about 70 percent of the penetrator. Of those expelled, about 4.4 percent of their DU oxidized. Of those retained in the tank, about 15.5 percent of their DU oxidized.

Immediately before the Camp Doha fire started, there were two general locations for 120mm DU rounds: uploaded in M1A1 tanks and stored in conexes on the motor pool pad. Three M1A1 tanks burned; each held a full load of 37 120mm DU rounds, accounting for 111 of the 660 damaged rounds. The other 549 damaged rounds were stored in conexes in the motor pool area. The fate of rounds originating in the conexes is different than the fate of the rounds in the tank because of the differing fire conditions and, consequently, different oxidation conditions in the two locations.

3.2.1 DU Oxides Produced from Rounds in Tanks

Each of the three burned tanks had 37 120mm DU rounds that were damaged by the fire. It is possible that some of these rounds were ejected from their storage locations or from the tank itself by ignition of the propellant, but BDAT and other observers stated that the blast control panels were extremely effective at confining the penetrators. These eyewitness accounts are believed to mean that the penetrators/projectiles remained within their storage racks. However, to be conservative, this study assumes that for each tank, no more than one penetrator was ejected and 36 penetrators, whether oxidized or not, remained inside the tank, OSAGWI (1998).

The degree of oxidation can be estimated based on several observations by eyewitnesses:

> "Most of the penetrators found in the tanks were scorched but intact. Others had melted, fragmented, or oxidized to some degree in the intense heat."
>
> "The heaviest concentration of DU contamination was found in the interiors of the burned tanks."

A possible scenario that would match these observations would have 26 rounds experiencing less than 10 percent oxidation (5 percent assumed) ("most … scorched but intact"); the others remaining in the tank would experience more. Nine rounds would experience 20 percent oxidation, and one round would experience 50 percent oxidation. This degree of oxidation could be experienced in an extended hot fire. This scenario produces an average oxidation of 10 percent; when applied to the 36 rounds remaining in each tank during the fire; it would produce 16.9 kg of DU in the form of oxide (roughly 40 lb of charcoal-colored powder). If the degree of oxidation had been substantially more than 10 percent, the quantity of DU oxide inside a tank should have drawn astonished remarks from observers, who would have found large piles of charcoal dust in the bustle or hull racks or found themselves ankle-deep in charcoal dust when they entered a burned tank. No such comments were mentioned so 10 percent oxidation inside the tanks seems reasonable.

For the estimated (hypothetical) three rounds (one from each burned tank) that might have landed outside the tanks, it is difficult to reconstruct the oxidation conditions—they may have landed in cool spots or hot spots. Observers mentioned that substantial DU oxides were found in the vicinity of the

burned tanks, so an estimate of 50 percent oxidation for these penetrators would be reasonable, leading to an estimate that about 7 kg of DU as oxides could be found on the surface near the tanks.

A summary of the DU oxides produced from rounds in the three burned tanks is presented in Table 3.1.

Table 3.1. DU Oxides Produced from Rounds in Burned M1A1 Tanks

Rounds in each M1A1 tank	37
Number of penetrators remaining in each tank	36
% Oxidation of DU remaining in tanks	10%
Mass of DU oxides inside each tank at end of fire	16.9 kg
Mass of DU oxides inside three tanks at end of fire	50.5 kg
Number of penetrators ejected from three tanks	3
% Oxidation of DU, ejected penetrators	50%
Mass of DU oxide outside tanks	7.0 kg

In the event that the eyewitness accounts or the interpretation of them underestimate the number of ejected penetrators, an alternative estimate for the number of rounds remaining inside the tank could be derived by analogy with the results of a test with an Abrams tank, Fliszar, Wilsey, and Bloore (1989). During this test, after a number of rounds had been fired at an uploaded tank, the tank caught fire, and 17 DU rounds out of 27 uploaded DU rounds were expelled. However, the assumption used in this assessment considers 37 uploaded DU rounds. If this observation were used as a basis for estimation, the values in Table 3.1 would be modified so that 19.7 kg (14 penetrators/tank x 4.68 kg/penetrator x 10% oxidation x 3 tanks) of DU oxides remained in the tank at the end of the fire and 161.5 kg (23 penetrators/tank x 4.68 kg/penetrator x 50% oxidation x 3 tanks) of DU oxides would have formed outside the tanks as a result of penetrator ejection. The values in Table 3.1 are used as this study's basis for dose assessment, because they are based on eyewitness expert observation, but the alternative values should be recognized as alternate upper-bound values.

3.2.2 DU Oxides Produced from Rounds in Conexes

For the 549 rounds that were stored in conexes, an estimate of the DU oxide produced can begin with some quotes from eyewitnesses and excerpts from Tab I of the OSAGWI (1998) report:

> "In addition to the estimated 111 sabot rounds uploaded on the burned tanks, several hundred other sabot rounds were stored in MILVANS trailers or conexes in the 2nd Squadron motor pool. Some of these had exploded in fires that were of such sustained intensity that steel howitzers and other equipment had melted, making it likely that many DU rounds had been damaged by oxidation in the fires."

> "Localized contamination was also found around three of the tanks and several of the burned conexes, however, reports and accounts by RADCON personnel indicated that the

levels of radiation here were below even the regulatory guidelines for donning respiratory protection."

"In addition, several hundred spent DU penetrators had been scattered and in some cases partially burned and oxidized in and around the MILVANS containers holding each platoon's ammunition resupply load."

"Upon entering the 2nd Squadron motor pool, the ECC team found large quantities of DU scattered around the vicinity of the MILVAN containers (used for ammo storage) that had detonated in the fire. Many of these DU penetrators were intact, but others had fragmented or burned down to varying degrees, with some almost completely reduced."

In addition to these reports, Tab I of the OSAGWI (1998) report contains a photograph of a collection of more than 40 penetrators that were gathered from the North Compound (see Figure 1.1). Inspection of this photo shows that 11 of the penetrators still had their nose cones and tail fins intact, which meant that the temperatures to which they were exposed were probably not high enough to produce oxidation. Another 14 had either tail fins or nose cones still intact, so if any oxidation occurred it was trivial: probably less than 5 percent of the metal oxidized. Another 14 exhibited some degree of oxidation, but not substantial: probably less than 10 percent of the metal oxidized. The three penetrators that showed the worst degree of oxidation probably did not suffer more than 20 percent oxidation. This collection was not a representative sampling of the 549 rounds from conexes (it did not include any that were almost completely reduced to powder, nor did it include any where the propellant failed to ignite), but it does give a general indication of the range of penetrator conditions that could be found after the fire.

Another photograph shows a conex containing DU rounds in essentially undamaged shipping packages. These rounds would have been designated as damaged, because they were in the fire area and their serviceability would be suspect for future use. Yet no oxidation of these penetrators should have occurred.

With these observations as a guide, a scenario for the fate of the 549-conex penetrators was developed is summarized in Table 3.2.

A summary of the estimate of the quantity of DU oxide generated in the Doha fire is presented in Table 3.3.

As shown in Table 3.3, this study assumes that the total amount of DU in the oxides produced by the Doha fire was 465 kg, which is 15 percent of the DU metal present in the 660 penetrators. The uncertainties involved in this estimation are large, because there were no careful measurements made at Doha that could guide the estimating process. However, it is extremely unlikely that the total oxidation was less than 5 percent or more than 20 percent, and in the judgment of the study authors, 15 percent is probably a conservative overestimation.

Table 3.2. Scenario for Fate of DU Rounds in Conexes

		Estimate
Total number of rounds		549
Rounds with 0% oxidation		300
0 – 10% oxidation	(assume 5%)	100
10 – 25% oxidation	(assume 17.5%)	50
25 – 50% oxidation	(assume 37.5%)	25
50 – 90% oxidation	(assume 70%)	25
> 90% oxidation	(assume 95%)	49
Overall oxidation		16%
Mass of DU oxide produced		408 kg
Note: The "assumed %" is used in calculating the overall oxidation percentage.		

Table 3.3. Summary of DU Oxide Produced in the Doha Fire

DU oxide produced in burned M1A1 tanks	50.5 kg
DU oxide produced by rounds ejected from tanks	7.0 kg
DU oxide produced from rounds stored in conexes	408.0 kg
Estimated Total	465.0 kg

If the number of ejected penetrators were assumed to be 17 per burned tank rather than 3, as discussed in Section 3.2.1, the value in Table 3.3 for DU oxide produced by rounds ejected from tanks would be 119.3 kg instead of 7.0. (The oxides produced inside the tanks would be 28.1 kg instead of 50.5 kg.) The estimated total would be 555 instead of 465 kg.

The oxides produced from DU penetrators in fires exist in a wide range of particle sizes. The results of the 1983 and 1985 burn tests with 120mm DU rounds indicated that only a small fraction, ranging from 0.08 to 0.6 percent (Mishima et al. 1985; Haggard et al. 1986), of the DU oxide formed in a fire was in the form of particles with an AED smaller than 10 μm, which is the generally accepted upper limit of particles that are respirable and may pose an inhalation risk. In Section 3.3, the total mass of DU oxides that were produced, including the complete array of particle sizes, is discussed. The impact of particle size on resuspension is discussed in Section 4.2, and its impact on dose assessment is discussed in Chapter 6.0.

3.3 Distribution of DU Oxide in the Doha North Compound

The recovery workers reported that no DU was found outside the North Compound, and the DU oxides were restricted to the concrete pad that served as the motor pool for the 2nd and 3rd Squadrons. This observation is consistent with data from the 1985 burn test, which showed that 120mm DU rounds were ejected no more than 24 ft from the fire. DU deposits found in the North Compound consisted of

intact penetrators, solid remnants of penetrators (those portions that did not oxidize), and piles of DU oxides.

After the fire, significant amounts of DU were found in two general locations: near the conexes in the general vicinity of the 2nd Squadron motor pool and near the burned tanks in the washrack area at the southern end of the North Compound. Because the distribution of DU oxides in the North Compound determined the exposures received by recovery workers, a conceptual model was developed to describe the location and quantity of DU oxide deposits. This model was developed based on eyewitness accounts, assumptions about the formation of DU oxides as described in the previous section, and knowledge of the behavior of DU oxides. The model illustrates the assumed DU oxide distribution and was used as a basis for estimating personnel exposures during the recovery effort (Figure 3.1). The map shows roughly the southern two-thirds of the North Compound. Dimensions on the map are approximate.

The northern area of contamination, in the central part of the motor pool pad, is the region where fire engulfed conexes containing stored ammunition. Here penetrators were ejected from conexes and oxidized in the intense part of the fire. The intense fire area is assumed to cover a 70-meter-by-30-meter area (based on photographs and the observation of videos); any oxidation of penetrators would be expected to occur in this area. The model assumes that there were 249 discrete deposits of DU oxides randomly distributed in this area, one for each penetrator that experienced some degree of oxidization. Each penetrator was assumed to produce a small pile of DU oxide that would have collected on the ground underneath it.

The data from Table 3.2 were used to determine the makeup of the individual DU oxide deposits distributed in the intense fire area in the 2nd Squadron motor pool area. The 249 penetrators with oxidation are assumed to be randomly distributed in the intense fire area. The model assumes that the DU oxides in the three highest oxidation categories fell off the penetrator and formed a pile of dust on the ground, where it could be exposed to resuspension effects. For the 17.5 percent oxidation category, some of the DU oxides fell to the ground to form a deposit, but some clung to the penetrator where it could not be resuspended. For the 5 percent deposits, it was assumed that the DU oxides clung tenaciously to the penetrator (matching the experience with oxidized penetrators in the laboratory, as reported in Haggard et al., 1986) and did not form loose powder deposits that could be resuspended. Table 3.4 gives a summary of the mass of DU oxides in each of the deposits. These deposits of DU oxides represent the source terms for exposure of recovery workers by resuspension.

In the southern contamination area, near the washrack, three penetrators are assumed to have been ejected from the three burned tanks; the other rounds uploaded in the tanks were assumed to stay inside the tank. This gives two sources of contamination in the southern contamination area: 17 kg of DU oxide inside each of the three tanks and 7.0 kg in three discrete piles (with 2.3 kg DU each) where the penetrators were oxidized.

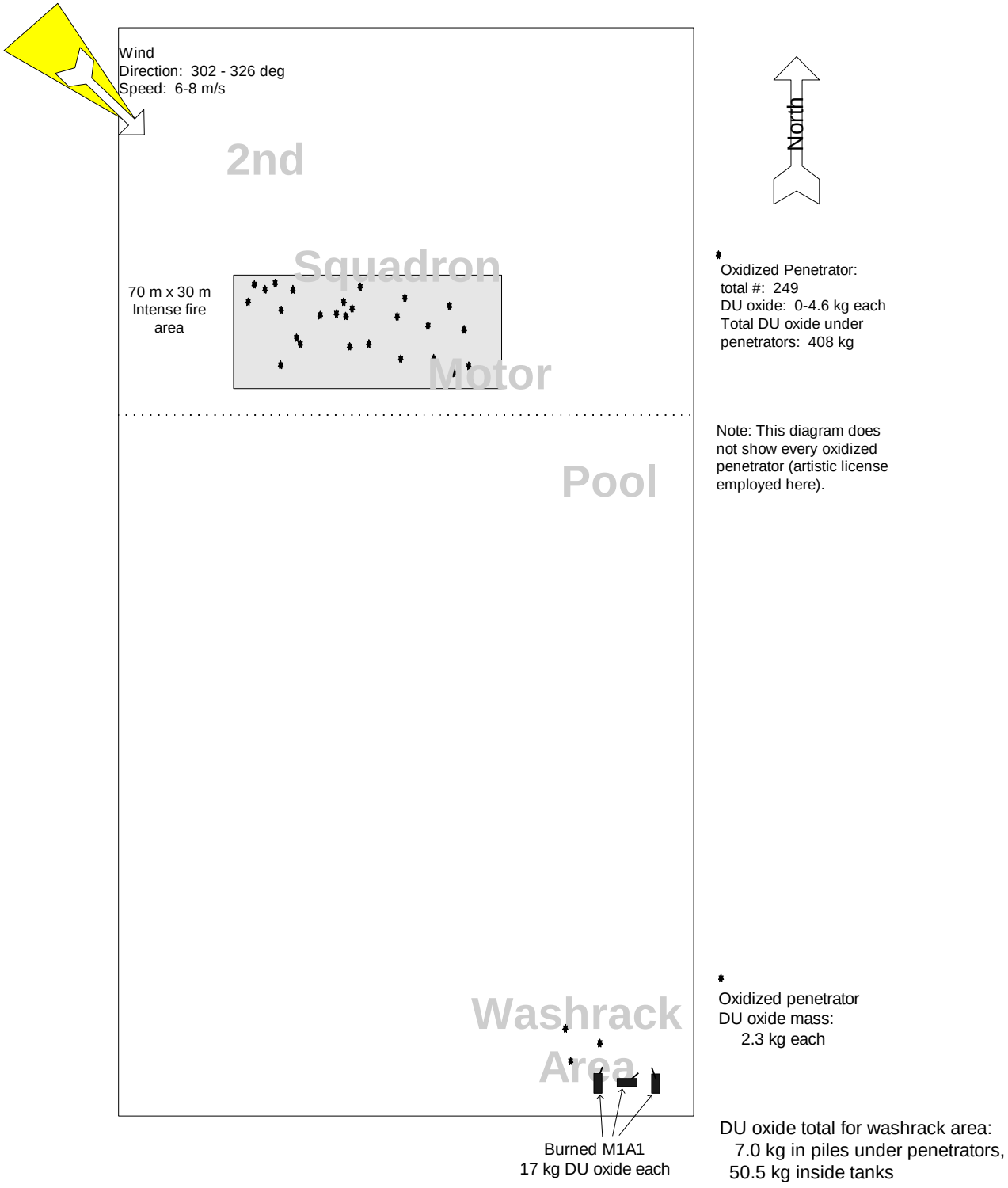

Figure 3.1. Conceptual Model of the Distribution of DU Oxides in the Camp Doha North Compound, July 12, 1991

Table 3.4. Deposits of DU Oxides in the North Compound Following the July 11-12 Fire

Number of Deposits	Average Amount of Oxidation	Mass of DU per deposit (kg)
49	95%	4.446
25	70%	3.276
25	37%	1.732
50	17.5%	0.819[(a)]
100	5%	0.234[(b)]
(a) Some of DU oxides cling to penetrator. (b) All of DU oxides cling to penetrator.		

The DU oxide piles created under the oxidized penetrators were disturbed by the following activities:

- wind erosion—the steady wind would resuspend some of the DU oxide particles and transport some particles downwind
- human and mechanical activity—recovery workers walking in the area or vehicles moving through the area would stir up the DU oxide particles
- decontamination work—recovery workers would clean up the DU oxide piles, removing the DU from the site and preventing it from causing personnel exposure
- sweeping—after the penetrators and piles of DU oxides were removed by recovery workers, the pavement was swept. Residual DU oxides remaining on the pavement would have become airborne.

The calculations performed in this study assumed that over time, the decontamination work decreased the quantity of DU oxides available for resuspension, and thus there was an air concentration that varied with time affecting the recovery workers. Figure 3.2 presents the assumed mass of DU in the form of oxides present in the 2nd Squadron motor pool area of the North Compound as a function of time following the fire. This graph is based on a set of simplified but conservative assumptions about the activities in the area that affected the DU:

- From July 11 until September 15, wind resuspension and light activity were the only major activities affecting the DU oxide mass.
- Following this time period, there was a 1-week decontamination effort where the bulk of the DU oxide piles were carefully removed.
- Following the decontamination effort, there was a 2-week period of sweeping the North Compound. This period was assumed to consist of a first sweeping, cleaning the entire intense fire area in 7 days. Then there was a second sweeping, again cleaning the same area in 7 days.

- At the conclusion of the cleanup effort, the North Compound was clean, with no DU oxides remaining on the surface.

The assumptions listed above differed in minor aspects from the reports of the activities, but the simplifications were made to allow for a reasonable modeling effort. As an example, some of the DU oxide was probably removed by EOD personnel in mid-July and by AMCOM and U.S. Army Communications-Electronics Command (CECOM) personnel in later July, whereas the model assumes that all oxide removal occurred in September. The simplified model, however, used conservative assumptions, and if the assumptions had been more realistic, it would have produced lower exposure estimates to the recovery workers.

The mass assumptions illustrated in Figure 3.2 are used in Section 4.2 of this study for the calculation of DU air concentrations.

One effect is intentionally ignored in this conceptual model: the quantity of DU oxide that was made airborne during the fire and transported offsite. An estimate of this quantity is used in Chapter 4.0, where doses are calculated for people situated downwind of the fire. However, this quantity is small in relation to the total mass of DU oxide generated, and uncertainties in the estimation of oxide generated are large enough that ignoring the quantity removed during the fire does not affect the analysis appreciably.

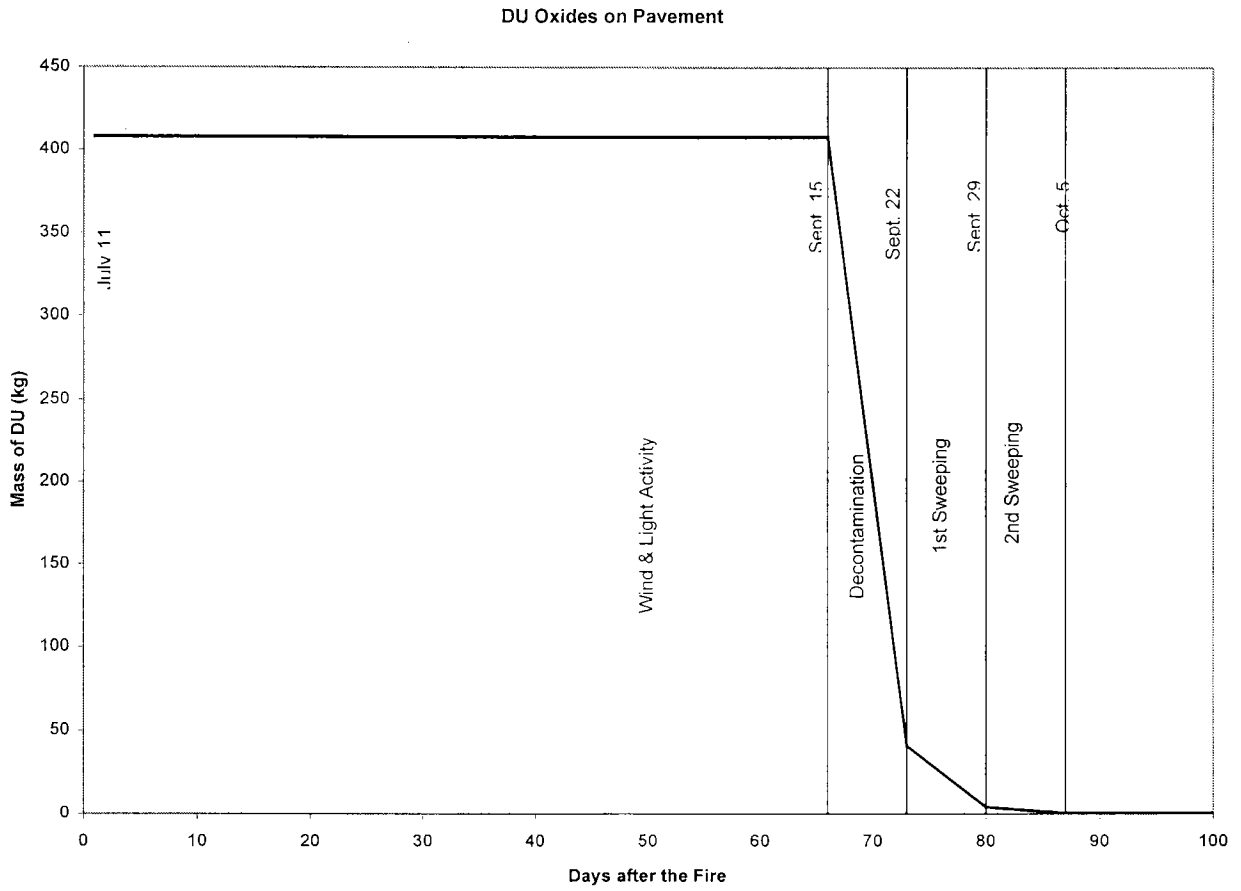

Figure 3.2. Modeling Assumptions for the Mass of DU Oxides Present in the Camp Doha North Compound from July 11, 1991 through November 15, 1991

4.0 Estimate of DU-In-Air Concentrations and Transport

This chapter discusses the estimations of air concentrations that were used to calculate exposure to the Camp Doha residents and recovery workers. Airborne exposure of DU occurred by transport of DU generated in the fire and entrained in the fire effluents and by resuspension of DU oxides loosely deposited on the ground.

4.1 DU-In-Air Concentrations Accompanying the Fire

During the fire, which began on July 11 and continued through July 12, DU oxides that were formed in the fire and were not contained by structures or debris could have become airborne and been transported downwind, exposing soldiers or other people in the area. This section describes how the study evaluated the degree of exposure that could have occurred from this source.

4.1.1 Mass of DU Released During the Fire

Analogies from previous burn tests provide a useful resource for determining the amount of DU that could have become airborne during the Doha fire. As part of the hazard classification test, in which 12 120mm DU rounds in metal shipping containers were burned (Haggard et al., 1986), a mass balance study was conducted of all DU involved in the fire. After the penetrators were burned, the researchers collected intact penetrators, partially oxidized penetrators, a large DU oxide pile that surrounded one penetrator, and DU-contaminated soil and ash debris. The mass of this metal and oxide was weighed or calculated from activity readings and compared with the pre-test DU inventory. The difference between the original and the post-test mass corresponded to the quantity of DU oxides that were unrecovered and represented the maximum amount of the DU oxides that could have become airborne during the fire. This unrecovered mass was found to be 0.1 percent of the total DU oxides formed.

The 0.1 percent value is used by the current study to estimate the ARF for the fires at Doha. This ARF is believed to be conservative, because the burn test was performed under ideal conditions, with no surfaces above the fire to prevent the DU oxides from being transported into the air. In the Doha fire, the internal structures of the tank would have inhibited, to some degree, DU oxides that were created in the tanks from becoming airborne where they could be transported downwind.

Using the ARF of 0.1 percent, the total calculated mass of DU oxides that became airborne during the fire would be 0.408 kg DU from the conexes (0.001 x 408 kg), and 0.0575 kg DU from the tanks (0.001 x 57.5 kg).

4.1.2 Relative Air Concentrations

The effect of the downwind transport of the airborne DU can be evaluated by atmospheric dispersion modeling. The computer code RATCHET-PC, a simplified version of the RATCHET software package (Ramsdell, Simonen, and Burk 1994) was used to perform the simulations. The transport calculations

were performed for a 24-hour time period to cover the duration of the fire. Actual Camp Doha meteorological data for July 11 and 12, 1991 were used in the model for the transport calculations. Atmospheric stability classes were chosen to match the existing conditions considering the time of day, temperature, and wind speed. The atmospheric mixing layer was chosen to be a constant 1500 meters. These conditions are summarized in Table 4.1.

Table 4.1. Meteorological Data for Time of Emissions

Time (hours elapsed)	Wind Direction (Degrees)	Windspeed (m/sec)	Temperature, ºC	Stability Class
0 - 2	310	7	43	2
2 - 8	310	7	44	2
8 - 12	310	7	41	2
12 - 14	320	6	38	4
14 - 20	330	6	36	5
20 - 24	320	7	39	4

The fire started at about 10:20 am, but no oxides were formed for several hours. Thus, the model assumed that airborne emissions began at 1:00 pm. The delay was to allow the fire to elevate the penetrators to their ignition temperatures. Most of the DU oxide emission was assumed to occur in the 12 hours following 1:00 pm; during this time period a release rate of 8 percent of the material per hour was used, for a total of 96 percent of the material emitted from the fire during the first 12 hours. The remaining 4 percent was assumed to have been made airborne during the remaining hours of the scenario.

Many atmospheric dispersion models use a uniform set of meteorological conditions for the duration of plume passage, but RATCHET-PC models the plume movement using meteorological conditions that vary with time. Thus, the output of the model shows a two-dimensional pattern of downwind air concentrations that would result from the changing wind conditions and stability classes as they actually occurred.

Two different scenarios were used for the release of the material: one with plume rise and one without. The heat generated by the fire causes the plume rise, giving the fire effluents buoyancy and driving the effluents high above the ground before transporting them downwind. Plume rise typically has the effect of making air concentrations lower within the first kilometer or so downwind. Ignoring plume rise, or modeling it as a ground-level release, would be conservative, so the ground-level release scenario was also modeled as an upper bound. The plume rise calculation was performed by assuming that releases occurred from four elevations: 10, 25, 50, and 100 meters above the ground. One-fourth of the material was released from each height. The ground-level release assumed that all material was released from only one elevation: 10 meters.

RATCHET-PC was used to calculate relative time-integrated air concentrations, in units of sec/m^3, for a grid of locations downwind of the release point (Table 4.2). These values represent time-integrated air concentrations for a hypothetical person located in the receptor position for the duration of plume

Table 4.2. Time-Integrated Relative Concentrations ("Chi/Q") as a Function of Distance from the Origin, Based on Elevated- and Ground-Level Release Heights

Distance from Origin	Time-Integrated Concentration Based on Unit Release Elevated Release			Time-Integrated Concentration Based on Unit Release Ground-Level Release		
	Coordinates		Plume Max Chi/Q	Coordinates		Plume Max Chi/Q
km	**km East**	**km South**	**(sec/m^3)**	**km East**	**km South**	**(sec/m^3)**
0.5	0.3	0.4	2.7×10^{-9}	0.4	0.3	9.7×10^{-9}
1.0	0.5	0.9	**7.8×10^{-7}**(a)	0.5	0.9	2.0×10^{-7}
1.2	0.6	1.1	2.1×10^{-7}	0.9	0.8	3.2×10^{-7}
1.5	1.0	1.1	3.0×10^{-7}	1.1	1.0	5.5×10^{-7}
1.7	1.1	1.3	4.0×10^{-7}	1.3	1.1	**6.0×10^{-7}**(b)
2.0	1.5	1.3	3.9×10^{-7}	1.5	1.3	4.4×10^{-7}
2.2	1.7	1.4	3.3×10^{-7}	1.7	1.4	2.6×10^{-7}
2.5	1.9	1.6	2.0×10^{-7}	1.9	1.6	1.2×10^{-7}
2.7	2.0	1.9	9.2×10^{-8}	2.0	1.9	7.6×10^{-8}

(a) Maxima in bold type; overall maximum for elevated release, 7.8×10^{-7}, is at 1.0 km.
(b) Maximum for ground-level release is 6.0×10^{-7} at 1.70 km.

passage. The values were calculated for nodal points of a grid that had 41 nodes in the East-West direction and 51 nodes in the North-South direction, with the nodes spaced 100 meters apart. The calculated relative air concentrations for the grid locations, assuming the elevated release, are presented diagrammatically as Figure 4.1, and the calculated air concentrations for the ground-level release are shown in Figure 4.2. Table 4.2 presents the maximum air concentrations for selected distances for both types of release.

4.1.3 Time-Integrated DU-in-Air Concentrations at Exposure Locations

The most significant location for troops who may have been exposed to airborne DU during the fire would be the United Nations (UN) Compound at the southern end of Camp Doha. Many soldiers assembled there during the fire and reported seeing smoke from the fire pass over them. This study calculated air concentration to soldiers located in the UN Compound by assuming that there were two sources of DU emitted by the fire, one in the region of the conexes and one in the area of the washrack, where the burning tanks were located. A point located on the Eastern edge of the UN Compound (which would get the highest exposure from the plume) is located about 980 meters South and 150 meters East of the part of the North Compound where the conexes were located. For the elevated release, RATCHET-PC calculated an integrated relative air concentration of 5.36×10^{-9} sec/m^3 for this location. Because the

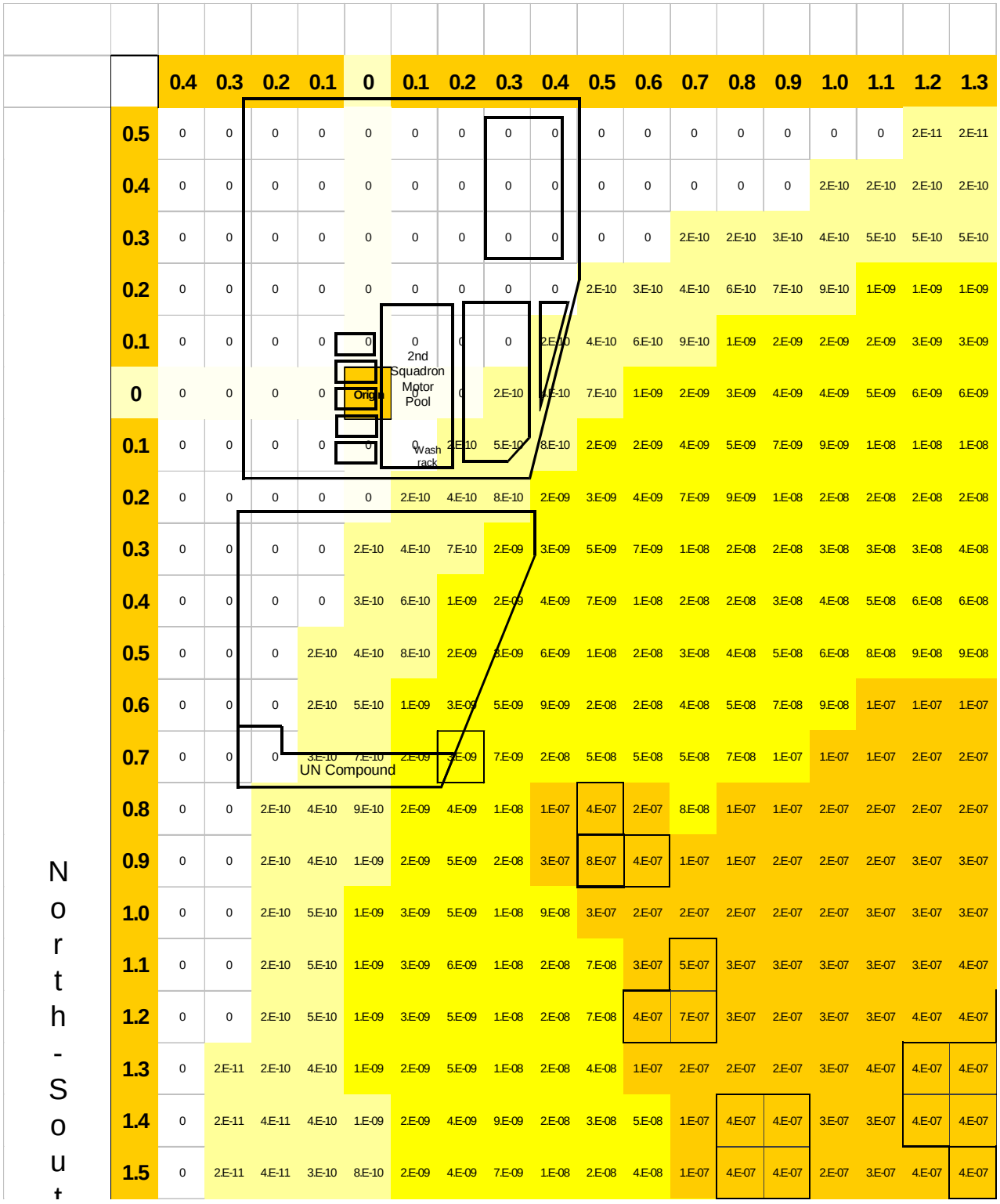

Figure 4.1. Calculated Relative Air Concentrations for the Elevated Release

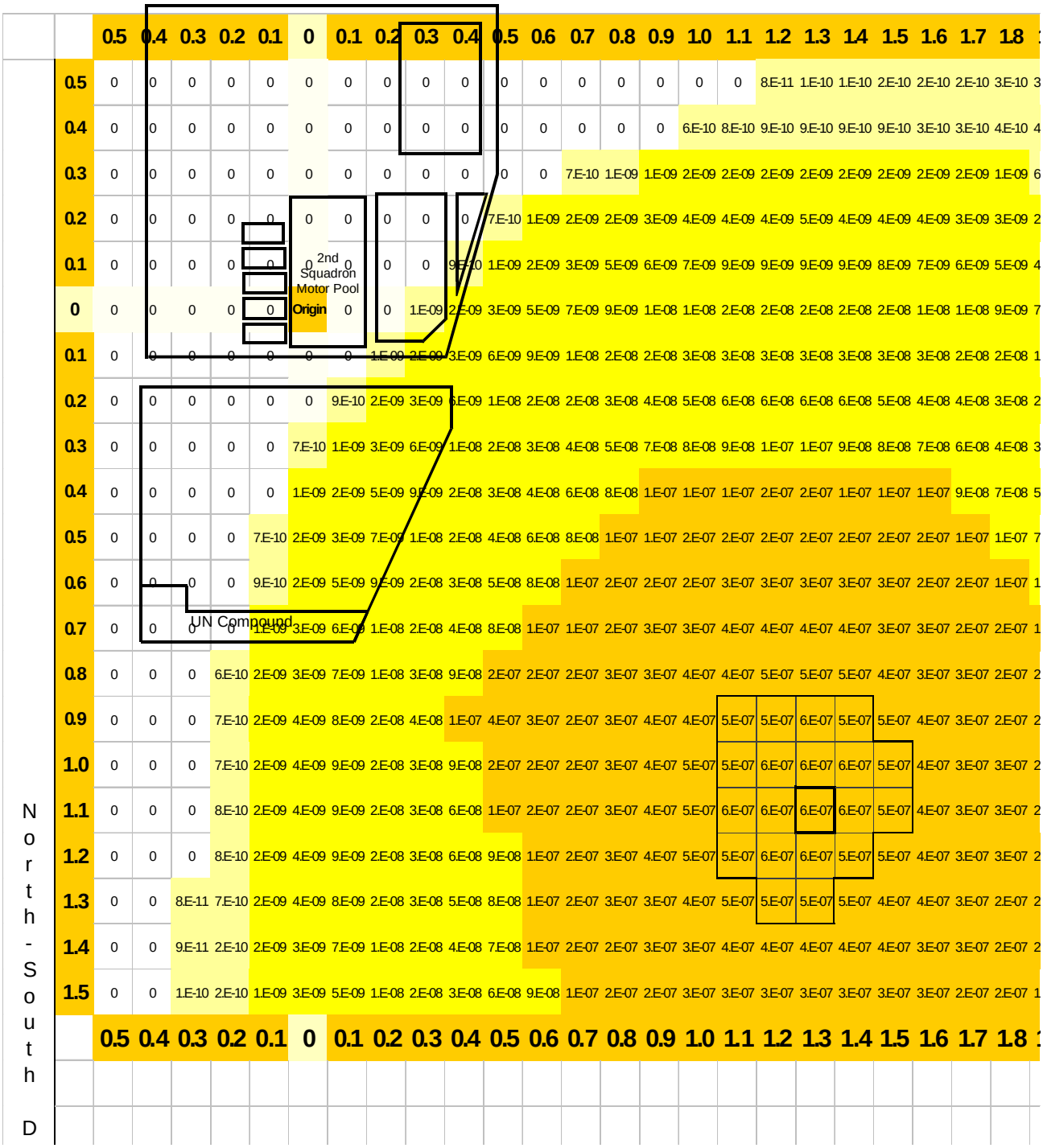

Figure 4.2. Calculated Relative Air Concentrations for the Ground-Level Release

quantity of DU released near the conexes was estimated to be 0.408 kg (as discussed in Section 4.1.1); the time-integrated air concentration from this source would be—

$$(0.408 \text{ kg}) \times (10^6 \text{ mg/kg}) \times (5.36 \times 10^{-9} \text{ sec/m}^3) = 0.0022 \text{ mg·sec/m}^3$$

For the source of DU in the burning tanks, the receptor point in the UN Compound is 750 meters South and 75 meters East, which would have a relative air concentration for the elevated release of 2.04×10^{-9} sec/m^3. Because the DU released from this point would be 0.0575 kg, the time-integrated air concentration would be—

$$(0.0575 \text{ kg}) \times (10^6 \text{ mg/kg}) \times (2.04 \times 10^{-9} \text{ sec/m}^3) = 0.00012 \text{ mg·sec/m}^3$$

The total time-integrated air concentration for this point, assuming an elevated plume, would be the sum of these two values, or—

$$0.0022 + 0.0001 = 0.0023 \text{ mg·sec/m}^3$$

This value represents the total airborne quantity of DU that a person would have been exposed to if he/she resided in the UN Compound for the entire duration of the fire. In Chapter 6.0, this value is converted to a dose by applying the correct BR and dose factor.

The time-integrated air concentration for this location would be different if a ground-level release were assumed. The RATCHET-PC calculations gave relative air concentrations of 1.77×10^{-8} sec/m^3 for the DU source near the conexes, and 7.25×10^{-9} sec/m^3 for the DU source in the burning tanks. When these values are used in place of the elevated concentrations, the total exposure is 0.0076 mg·sec/m^3.

The maximum value that a person could have been exposed to can be calculated using the maximum air concentration supplied by RATCHET-PC (7.80×10^{-7} sec/m^3) along with an elevated plume at a location 1 km directly downwind from the release point. To be conservative, this relative air concentration could be used with both DU sources to give a time-integrated air concentration of—

$$(0.408 + 0.0575) \text{ kg} \times (10^6 \text{ mg/kg}) \times (7.80 \times 10^{-7} \text{ sec/m}^3) = 0.363 \text{ mg·sec/m}^3$$

4.2 DU-In-Air Concentrations Resulting from Resuspension

Recovery workers in the contaminated area of the North Compound and those working downwind of the contaminated area may have been exposed to DU aerosols suspended in the air. This airborne DU would have been resuspended from deposits on the concrete surface by mechanisms such as wind, human activities, or the movement of vehicles. This section describes the calculation of the air concentrations from resuspended DU.

The resuspension analysis was conducted using the following sequence of events:

- From the time of the fire, July 11, until the start of final cleanup, September 15, it was assumed that only wind and light activity would have produced any DU resuspension or removal of DU oxides from the contaminated area. This conservative modeling simplification ignores DU removal that probably occurred during this time period, and results in a uniform DU-in-air concentration for this time period.

- For the 7 days following September 15, cleanup and decontamination of the piles is assumed to occur. We assumed that 90 percent of each pile of DU oxides was removed, leaving only a thin (possibly invisible) layer on the pavement. This action removed most of the mass of DU oxides from the contaminated area.

- For the 7-day period between September 22 and 28, it is assumed that the contaminated area was swept. Resuspension of DU oxides would have been high during this period because of the sweeping action, but a large amount of DU oxides would have been removed.

- For the 7-day period between September 29 and October 5, the contaminated area was swept for a second time. This produced a high airborne concentration as the residual DU oxides remaining after the first sweeping were resuspended. It also resulted in removing the remaining DU oxides from the contaminated area.

Air concentrations were estimated for each of the time periods of the recovery effort described above. Based on the observations that the winds were relatively steady in the time period following the fire, the winds are modeled as always being in one direction at a speed of 7 meter/sec. This assumption is good for short-term exposures. For periods of a day or longer, the actual concentration at a point will be lower because of the area's natural variability of wind direction.

Onsite air concentrations were computed using literature values of resuspension factors, Sehmel (1980). An upper limit resuspension factor for wind erosion/light activity of 1×10^{-4} m^{-1} was used to compute concentrations under pre-cleanup conditions. A resuspension factor typical of active onsite activities of 1×10^{-3} m^{-1} was used for the decontamination and sweeping activities. Assuming that the cleanup had helped stabilize the surfaces, a resuspension factor of 1×10^{-5} m^{-1} was used for the time period after the cleanup activity.

The emission rates for activities and wind erosion were based on estimates of the potential for suspension of DU oxide material. A bulk density of 4.5 g/cm^3 was assumed for the mixture of oxides. That material was assumed to be in individual piles distributed within the rectangular area where the penetrators oxidized (30 meters by 70 meters).

Before the first sweeping, the DU oxide particles that were susceptible to resuspension by wind or other activity were in a thin layer on the surface of a DU oxide pile. A 20-μm thickness was assumed for this surface layer. The average surface area for a pile was assumed to be 600 cm^2, based on photographs of DU oxide piles that formed under penetrators. This surface area was independent of the degree of oxidation of the penetrator, because it was assumed that oxides falling from a penetrator would land in roughly the same "footprint"; different degrees of oxidation would result in a difference in the thickness

of the piles, but not the exposed surface area. The average exposed DU surface concentration was found by summing the amounts of DU in this surface layer on each of the 149 piles of DU oxides, then dividing by the total area in which the piles resided. The average surface concentration was found to be 0.3831 g/m^2 over the 2100 m^2 area of intense burning, as shown in Table 4.3.

Table 4.3. Average DU Surface Concentrations for DU Oxide Piles in the North Compound Following the July 11-12 Fire

Average Amount of Oxidation	Number of Oxide Piles	Mass of DU per Oxide Pile (kg)	Average DU Surface Concentration (g/m^2)
95%	49	4.446	0.1260
70%	25	3.276	0.0643
37%	25	1.732	0.0643
17.5%	50	0.819	0.1286
Total			**0.3831**

This average surface concentration was assumed to stay constant during the initial period of wind and light-activity resuspension, because the wind gradually decreased the thickness of a pile but left the footprint of the pile undisturbed. It was assumed that the decontamination effort removed the bulk powder of a pile, thus dramatically decreasing the amount of DU oxides in the area, but left a faint footprint of the pile, which still left the same average surface contamination. When sweeping started, the discrete piles were smeared into a uniform distribution over the large area, and the two sweepings effectively removed the DU from the surface.

Air concentrations for areas downwind of the contaminated area were estimated using a standard Gaussian dispersion model. An emission rate equivalent to the assumed resuspension rates was estimated using the following process: first the dispersion model was run for a unit release rate of 1 g/sec from a 2100 m^2 area, then the emission rate required to simulate the onsite air concentrations (computed using resuspension factors) was back calculated. This emission rate could then be used to simulate downwind DU air concentrations that were consistent with the values for the contaminated areas. The estimates of DU air concentrations and equivalent emission rates for the contaminated area are given in Table 4.4.

Lacking specific details, arbitrary assumptions were made to allow for emulation of a time series of DU-in-air concentrations during the cleanup activities. The decontamination activity was assumed to occur over a 7-day period, so the surface DU was removed with 90 percent efficiency from 1/7 of the total area each day. The initial sweeping activity was assumed to occur over the 7 days following decontamination, and then a second complete sweeping was performed over the next 7 days. For each sweeping period, it was assumed that 90 percent of contaminated material was removed and that 1/7 of the area was swept each day. With the resuspension-factor-based approach, assuming shorter or longer

Table 4.4. Parameters Used for Resuspension

	Resuspension Factor (1/meter)	Onsite Air Concentration (g/m^3)	Equivalent Emission Rate (g/sec)
Before Cleanup Wind Erosion	1×10^{-4}	3.83×10^{-5}	1.41×10^{-6}
During Decon Activities	1×10^{-3}	4.21×10^{-4}	1.41×10^{-5}
During First Sweeping	1×10^{-3}	3.85×10^{-4}	1.41×10^{-5}
During Second Sweeping	1×10^{-3}	1.96×10^{-4}	1.41×10^{-5}
After Cleanup Wind Erosion	1×10^{-5}	1.94×10^{-7}	1.41×10^{-6}

time periods for these activities would correspondingly reduce or extend the exposure times but would not change the estimated concentrations. The assumptions of efficiency and number of sweeps directly impact the estimation of the effectiveness of the cleanup but do not impact the estimated concentration values.

The air modeling was performed using a standard sector-average Gaussian formulation and rural atmospheric dispersion values recommended by Briggs, Gifford (1976). The implementation of this atmospheric model in the Multimedia Environmental Pollutant Assessment System (MEPAS; Whelan et al., 1989; Droppo and Buck 1996) includes an algorithm to account for the spread of the release over the area. Deposition computations were based on a combination of atmospheric boundary layer similarity theory and empirical deposition rate curves, Sehmel and Hodgson (1978).

These computations were made for 10 particulate size groups to estimate the shift of particle size distribution that occurs as a function of travel distance. Reported size fractions were used to characterize the initial size distribution of airborne material.

Concentrations as a function of particle size were computed for several locations in the area and downwind of the area. The maximum computed air concentrations occurred at the downwind edge of the area containing the piles of DU. Figure 4.3 shows the air concentration as a function of time after the fire. The air concentration values in this graph were used to calculate worker exposures.

The calculations of air concentrations described in this section were performed for assumed conditions in the 2nd Squadron Motor Pool area, but the general analysis can be extended to the washrack area. The DU concentrations in air were based upon the distribution of DU oxide piles in an area: for the 2100 m^2 area, there were 149 piles, or one for every 14.1 m^2. The sources of DU contamination on the surface of the washrack area were the three penetrators ejected from a tank. If they had been distributed in an area of 42 m^2, which is a realistic possibility, the airborne concentrations would have been the same as shown in Figure 4.3. If they had been spread out over a larger area, the concentrations would have

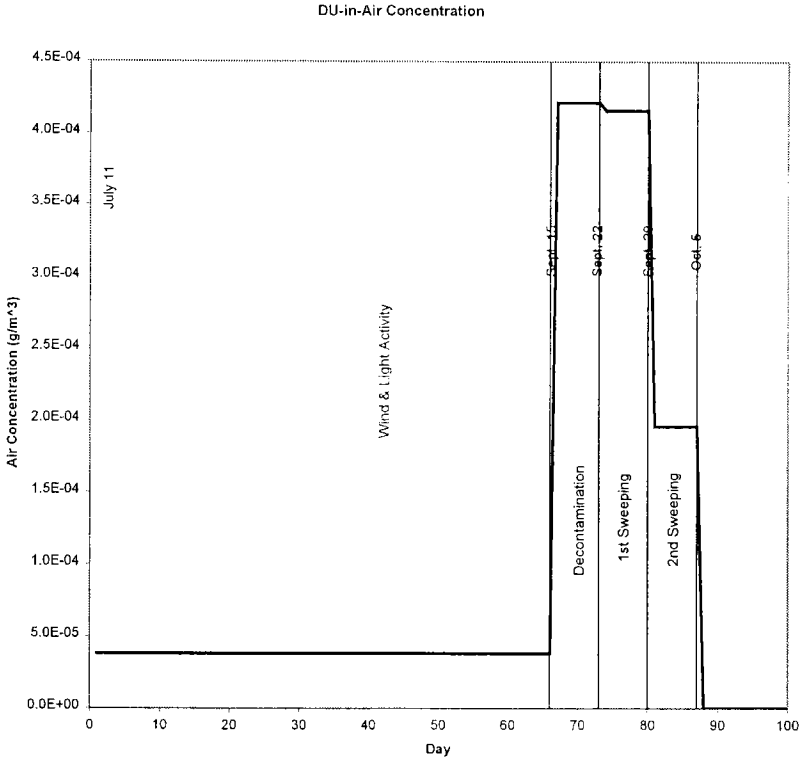

Figure 4.3. Air Concentrations of DU Over the Doha North Compound Following the July 11-12, 1991 Fire

been lower. If the three rounds landed close together, the surface concentrations would be higher, therefore, the air concentrations would be higher. However, if the three piles had been closer together, the area where workers could have been exposed to airborne DU would have been smaller, and the amount of time spent in the exposure area would have been low for any recovery worker, so the total dose would not have been larger.

5.0 Recovery Worker Activities and DU Exposure

Approximately 600 personnel were potentially exposed to DU during the Doha fire and during the 4-month recovery and cleanup period that followed. An estimate of the severity of their exposures must consider the following:

- their location in relation to source material
- the time period of their exposure
- the duration of their exposure
- the quantity of source material available for exposure.

For the reconstruction of the exposures received by Doha personnel, very few of these factors are known with much certainty. The necessary modeling input information was determined by studying the narratives in the OSAGWI (1998) report and the interviews conducted with workers.

This section presents the methodology for categorizing recovery workers, discusses the activities of recovery workers in the North Compound of Camp Doha, and describes the factors listed above that could affect the severity of worker exposure to DU.

5.1 Methodology

Eight job categories were chosen to represent the types of workers who were exposed to DU during the recovery work. For each job category, the approximate number of people in that category was estimated, and the approximate dates for their exposures were determined. The total number of hours of recovery work in the North Compound was estimated for a typical person in each job category, based on the OSAGWI (1998) report and worker interviews. The total number of hours of recovery work was broken down into two categories: hours spent upwind of the DU contamination, where there would be no inhalation of airborne DU, and hours spent either in the area of DU contamination or downwind of it, where inhalation of DU would occur.

Several general assumptions were made about work habits that affect the estimated exposures:

- Several reports indicate that workers spent long hours at their tasks, due to the urgency of cleaning up the base under the threat of a possible hostile enemy. This study assumes that a typical recovery worker worked 12 hours per day, 6 days per week. Of the 12 hours worked each day, 10 hours were assumed to be in the North Compound (the other 2 hours would cover mealtimes, errand running, administrative work, etc.).

- A simplifying assumption was used for this model that time spent in the North Compound was either upwind of the contamination or in an airborne contamination area (corresponding to the surface contamination area and the areas downwind from it). A uniform air concentration was used for the airborne contamination area, corresponding to the maximum concentration that would be expected. The air concentration was assumed to vary day-by-day, according to the type of resuspension activity occurring (as described in Section 4.2), but no attempt at calculating a variation by position was attempted. This uniform concentration assumption was necessary, because there are no data available to support a location-specific calculation, and the assumption is conservative.

- Work in the North Compound was assumed vigorous, given the hot temperatures and the difficult tasks performed. Thus BRs for inhalation would correspond to "heavy work" for estimating inhalation.

- It was assumed that recovery workers did not use PPE, so the usual effectiveness of PPE at reducing inhalation exposures was not accounted for in this study. In reality, a few of the workers wore protective masks, but most did not, so assuming no credit for PPE is a reasonable and conservative assumption.

5.2 Worker Activity

Table 5.1 summarizes the breakdown of hours in exposure conditions for the job categories. The following sections describe each job category, relating what is known from the OSAGWI (1998) report and eyewitness accounts of probable exposure conditions.

Table 5.1. Exposed Troops During July 1991 Doha Accident (recovery workers only – not counting troops downwind of the fire)

Job Category	Number of Personnel	Approximate Dates of Exposure	Number of Days Exposed	Total Hours of Recovery Work	Number of Hours Upwind (no exposure)	Per-Day Exposure Time (hours)
EOD Personnel – 146th Ord. Det.	10	7/14 to 7/23	10	100	25	7.5
Engineers - 58th Combat Engr Co. (CEC)	200 - 300	7/14 to 7/23, 9/15 to 11/15	72	58	15	0.6
				116	29	1.2
54th Chemical Troop	6	7/12 and 7/18	2	20	5	7.5
Regimental NBC staff	6	7/12 to 7/23	12	50	12	3.2
2nd Squadron Troops	100 - 200	7/14 to 7/23, 9/15 to 11/15	72	20	5	0.2
AMCCOM	3	7/19 to 8/2	15	120	40	5.3
CECOM	4	7/24 to 8/2	10	90	23	6.7
Env. Chem. Corp. (ECC) Contractors	15	9/15 to 11/15	62	480	120	5.8

5.2.1 EOD Personnel (146th Ordnance Detachment)

The 146th EOD Detachment had 10 to 12 personnel working in the North Compound from about July 14 to July 23. These troops were primarily occupied with remediating the hazard of UXO in the North Compound, but they also helped with identifying DU penetrators found in the rubble. Their activities primarily included disarming and removing UXOs. Because UXO removal had to be complete before heavy cleanup work commenced, there was very little sweeping or operation of heavy equipment while the EOD troops were in the North Compound.

Number of EOD Personnel: 10 to 12 (two died in a UXO accident on July 23).

Total Hours of Recovery Work: The typical EOD worker spent 100 hours in the North Compound (10 working days from July 14 to July 23; 10 hours per day).

Distribution of Recovery Hours: This study assumes that 25 percent of EOD personnel time (25 hours) in the North Compound was spent upwind of the DU contamination. Thus, each person would have spent 75 hours in an airborne contamination area (either in the area with burned penetrators or downwind of it).

5.2.2 Engineers 58th CEC

The combat engineers in the 58th CEC performed a variety of activities during the Doha recovery and cleanup. Engineers assisted the EOD troops during the first 2 weeks after the fire, picking up small pieces of debris including DU penetrators. They also worked to clear large debris and burned vehicles, and they operated heavy equipment such as scrapers and bulldozers. The 58th CEC troops worked during nearly all phases of the recovery work, including the final cleanup during the September to November time frame.

Number of 58th CEC Personnel: The OSAGWI (1998) report states that this unit represented the largest contingent of personnel working in the North Compound cleanup and recovery. While the number was not explicitly stated, it is estimated to be in the range of 200 to 300 personnel.

Total Hours of Recovery Work: Because engineers worked with EOD troops in the first weeks after the fire, an average engineer working in the compound would have worked 100 hours in July, similar to the EOD troops. In the September to November time frame, engineers would have worked for 8 weeks, so an average worker would spend 480 hours (8 weeks x 6 days/week x 10 hours/day) in this time frame. However, not all members of the Company were in the North Compound at any one time. If we assume that, on average, 20 workers were in the compound at any one time, then a total of 11,600 person-hours (20 workers x [100 hours + 480 hours]) were spent by engineers in the North Compound. If this time were spread over 200 people, an average of 58 hours per person would be spent in the North Compound. However, it is possible that a few engineers with special skills (for example, bulldozer drivers) may have spent twice as much time in the recovery work. Thus, Table 5.1 includes two entries for engineers: 58 hours for an average worker and 116 hours for a maximally exposed worker.

Distribution of Recovery Hours: This study assumes that 25 percent of personnel time (15 hours for the average worker, 29 for the maximum) in the North Compound was spent upwind of the DU contamination.

5.2.3 54th Chemical Troop

Soldiers from the 54th Chemical Troop operated the M-93 Fox NBC vehicle to monitor for radiation after the fire. This work, however, would not have resulted in measurable exposure to DU, because they operated on the periphery of the compound and the air inside the vehicle was well filtered. A few troops from this unit also did some radiation monitoring with hand-held instruments, but the OSAGWI (1998) report says that these troops spent very little time inside the North Compound.

Number of 54th Chemical Troop Personnel: There may have been several dozen soldiers in the unit, but only a few were in the North Compound and exposed to DU. This study assumes that 6 soldiers were possibly exposed.

Total Hours of Recovery Work: For the 6 exposed personnel, an average of 20 hours (2 days) may have been spent in the North Compound.

Distribution of Recovery Hours: About 25 percent of their time was spent upwind; the rest of their time in the North Compound occurred very soon after the fire, before any substantial cleanup activity occurred, so there would have been no sweeping or heavy equipment operation during this time.

5.2.4 Regimental NBC Officers

Several NBC staff worked in mid-July, monitoring for radiation and picking up a few DU penetrators.

Number of Regimental NBC Officers: 6

Total Hours of Recovery Work: Because they sometimes worked with the 146th EOD soldiers, this study assumes that they worked half of the number of hours of the EOD personnel that is, 50 hours.

Distribution of Recovery Hours: NBC staff work was similar to the EOD staff work, so the same proportional distribution for hours in the North Compound is used.

5.2.5 Armament Munitions and Chemical Command

Three radiological control staff members of AMCCOM worked at Doha from about July 19 until August 2. Their primary mission was to assess the levels of radioactive contamination of the burned tanks and sufficiently decontaminate them to allow them to be shipped back to the U.S. They also did limited radiation monitoring of contaminated areas.

Number of AMCCOM staff: 3

Total Hours of Recovery Work: The study assumed 12 working days, 10 hours per day in the North Compound, which totals 120 hours per person.

Distribution of Recovery Hours: The AMCCOM staff worked in the North Compound during a time when general cleanup was at a lull. Except for dragging incapacitated M1A1 tanks to a clean area, no sweeping or heavy equipment operation occurred to cause DU oxide resuspension to add to their exposures.

5.2.6 U.S. Army Communications-Electronics Command

Four RADCON staff members from CECOM were at Doha from about July 24 until August 2. Their primary mission was site characterization, including monitoring of general area surfaces for DU contamination.

Number of CECOM staff: 4

Total Hours of Recovery Work: The study assumed 9 working days, 10 hours per day in the North Compound, which totals 90 hours per person.

Distribution of Recovery Hours: The CECOM staff worked in the North Compound during a time when general cleanup was at a lull. Thus, no sweeping or heavy equipment operation was occurring to cause DU oxide resuspension to add to their exposures.

5.2.7 2nd Squadron Soldiers

Soldiers from the 2nd Squadron did much of the routine cleanup work in the area where their vehicles were parked in the North Compound. Troops from this unit picked up small debris and did most of the sweeping after UXOs and heavy debris had been cleared, which would have been a prime pathway for exposure to DU oxides in the air.

Number of 2nd Squadron Troops: 100 to 200.

Total Recovery Hours: The typical soldier from this unit spent 1 or 2 days in the North Compound, so 20 hours is assumed for the average time per person.

Distribution of Recovery Hours: This study assumes that 25 percent of 2nd Squadron personnel time was spent upwind of the contamination in the North Compound, and the rest of their time was assumed to have been spent sweeping contaminated areas. This assumption is conservative, because these troops performed activities other than sweeping, which would have resulted in lower air concentrations of resuspended uranium.

5.2.8 ECC Contractors

The EOD technicians from ECC worked in the North Compound from mid-September until mid-November. Their primary responsibility was clearing UXOs, but they also recovered half of the DU penetrators found at Doha and they cleaned up some of the DU oxide powder. Upon completion of their work in mid-November, the compound was completely cleared of UXOs and the DU contamination was cleaned up.

Number of ECC Contractors: 15, including 14 civilian contractors and an Army Sergeant First Class who provided onsite oversight and support.

Total Recovery Hours: Assuming 8 weeks of work at 60 hours per week, 480 hours would have been spent in the North Compound.

Distribution of Recovery Hours: This study assumes that 25 percent of ECC personnel time was spent upwind of contamination.

6.0 Dose Assessment

During and following the fire at Camp Doha, DU oxides could have been taken into the body by two routes: inhalation and ingestion. Inhalation exposure could have occurred as a result of personnel breathing powdered DU oxides that were entrained in air. Ingestion could have occurred as a result of touching contaminated objects such as machinery and soil that could contaminate an individual's hands. Following contact there may have been incidental hand-to-mouth transfer of the DU. It is also possible that DU oxides could have entered through open cuts on ungloved hands. However, this occurrence was not described in the reports reviewed and could not be modeled without additional information.

Chemical and radiation doses to workers from ingestion and inhalation intakes of uranium oxides were calculated in this study. Chemical doses calculated for this study were intended to be the maximum concentration of uranium in kidney tissues. Because the maximum concentration of uranium in the kidney might have occurred after the exposure ended, the calculations tracked the concentration of uranium in the kidney for a full year following the intake. Radiation doses were calculated as the cumulative doses that the individual would receive in the 50 years following the intakes. The radiation doses calculated for this report are formally called the CEDEs. A CEDE is the sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the CDE to these organs or tissues. Tissue-weighting factors are the proportion of the risk of stochastic effects resulting from irradiation of individual organs or tissues to the total risk of stochastic effects when the whole body is irradiated uniformly. The tissue-weighting factors used in the calculations are described in Section 6.4.1.

The calculation of chemical and radiation doses received by personnel following the Camp Doha fire depended on the chemical and physical properties of the DU oxides, the site-specific conditions, and the characteristics of the personnel. This chapter describes the assumptions that were made to compute the doses. These assumptions are summarized in Table 6.1. In the final sections of this chapter, radiation dose factors are used to calculate the internal doses that may have been received by personnel during the fire at Camp Doha and during recovery work after the fire.

6.1 Physical Properties of DU Oxides

Two oxides of uranium, UO_2 and U_3O_8, are typically formed during fires and were presumed to have been formed during the fire at Camp Doha. These compounds are quite insoluble, but characterization of burn test oxides have shown that there is often a small percentage of the total mass that is considerably more soluble. A third oxide, UO_3, was included in the calculations as a surrogate to account for the possibility that a more soluble uranium oxide fraction was also present. Two physical properties of DU oxide—the density of the material and the particle size distribution—particularly influence the calculation of radiation dose received by personnel following exposures to airborne dusts.

6.1.1 Density of Uranium Oxides

The density of the uranium oxides influences the deposition pattern of the oxide in the lung. This occurs because the AED varies with density, relative to the physical size of the particle, and deposition of particles in the lung will generally increase as the AEDs decrease. The densities of the uranium oxides are shown in Table 6.1.

Table 6.1. Summary of Assumptions Employed in the Calculation of Inhalation and Ingestion Dose Factors

Personnel Information				
BR[a]	1.688 m^3/hr (Heavy Work)			
Breathing Habit[a]	Mouth Breather			
Soil Ingestion Rate[b]	100 mg/d			
Isotopic Composition of DU				
Isotope	Weight Fraction[c]			
U-234	6.00×10^{-06}			
U-235	2.00×10^{-03}			
U-236	3.00×10^{-06}			
U-238	9.98×10^{-01}			
Characteristics of Uranium Oxides				
Oxide	Weight Fraction[c]	Density[d]	Lung Solubility Class/Type[e]	GI Tract f_1 Value[e]
UO_2	0.465	10.96	Y/S	2×10^{-3}
UO_3	0.07	7.29	W/M	2×10^{-2}[f]
U_3O_8	0.465	8.3	Y/S	2×10^{-3}
Aerosol Size Distribution				
Exposure Condition	Size Distribution			
Fire	5 μm AMAD, gsd = 2.5			
Recovery Work	60 μm AMAD, gsd = 2.8[g]			

(a) Data from ICRP (1994)
(b) Data from NCRP (1999)
(c) Data from OSAGWI (1998)
(d) Data from Lide (1994)
(e) Data from ICRP (1979)
(f) Data from ICRP (1995)
(g) Based on data from Haggard et al. (1986) and Resuspension Calculations

6.1.2 Particle Size Distribution of Uranium Oxides

The fraction of an intake that is deposited in the respiratory tract is greatly influenced by the particle size distribution of the inhaled material. Large particles might not be inhaled or will be preferentially deposited in the anterior nasal or naso-oropharynx/larynx regions and, consequently, never reach the lung during inspiration of air. Extremely fine powders, on the other hand, may remain entrained in the expired air and may not be deposited in the lung. For other sizes, the fraction deposited in the lung and the fraction deposited in the various regions of the lung depends on the particle size and density in a complicated manner that was described by the ICRP in their Publication 66 (1994).

Two particle size distributions were used to provide dose factors for this study. The first size distribution corresponds to the aerosols generated during the fire, and the second distribution corresponds to the aerosols generated by resuspension of DU oxide during recovery work.

Burn tests conducted with 120mm DU rounds did not produce sufficient airborne DU aerosols to be collected and analyzed for particle size distribution. Therefore, following the ICRP (1994) recommendations when no other information is available, DU aerosols in a plume emitted from a fire are assumed to have a particle size distribution of 5-μm AMAD and a σ_g of 2.5.

The DU aerosols resuspended by recovery work were assumed to have a particle size distribution similar to those described by Haggard et al., (1986). They described the particle size distribution of uranium oxides that remained at the site of three burn tests. Their analyses showed that, of the samples that were analyzed, the minimum AMAD was about 550 μm; the σ_g was not stated. The particle size distribution given by Haggard et al., (1986) was used as input to the MEPAS code, as described in Section 4.2. The particle size distribution of the DU oxide suspended by the recovery work activities was determined to be 60-μm AMAD with a σ_g of 2.8. This σ_g is larger than the default σ_g of 2.5 recommended by the ICRP (1994). It was necessary, however, to increase the σ_g to account for the fraction of the particles having AEDs less than 3 μm. The DU oxide powders analyzed by Haggard et al., (1986) apparently did not contain particles smaller than about 0.5 μm; therefore, the particle size distribution chosen for this analysis will tend to overemphasize the small diameter particles. The effect of overemphasizing small particles is to overestimate the deposition of DU particles in the lung and the consequent dose.

6.2 Biokinetic Properties of Uranium Oxides

The solubility of uranium oxides varies according to the specific oxide. The ICRP lists UO_3 as exhibiting Class W (Type M) solubility and the solubility of UO_2 and U_3O_8 as Class Y (Type S) (ICRP 1979; 1995). Note that UO_3 was included in this study solely because of its solubility characteristics.

The relative amount of Classes W- or Y-soluble oxides depends on the manner in which the oxide was formed. Following burn tests of the 120mm DU rounds in metal shipping containers, Haggard et al., (1986) found that 4 percent of the total DU oxide was fairly soluble and was classified as Class D

(Type F) material, while the remaining 96 percent was highly insoluble and classified as Class Y (Type S) material. Other field measurements indicate that, following a fire, 0 to 8 percent of the oxides are determined to be Class W and 92 to 100 percent are determined to be Class Y, OSWAGI (1998). For purposes of these calculations, the total uranium oxide was assumed to be 7 percent soluble and 93 percent insoluble. The soluble oxide was assumed to be UO_3, and, following the ICRP recommendations, was modeled as Class W (Type M) material. The insoluble oxide was assumed to be 46.5 percent by weight UO_2 and 46.5 percent U_3O_8, based on the metal content, and, following the ICRP recommendations, was modeled as Class Y (Type S) material. Although the kinetics of UO_3 was modeled for this study, it should be noted that UO_3 has not been observed following any test burn of penetrators. The modeling included UO_3 only to account for the solubility characteristics that have been observed.

6.3 Personnel Characteristics

The personal characteristics of the exposed individuals influence the magnitude of the internal dose factors. For inhalation, the pertinent characteristics include the breathing habit and rate of the individuals. For ingestion, the quantity of soil and dust consumed by personnel influences the dose factors.

6.3.1 Inhalation

The personal characteristics that most greatly influence the quantity of DU oxide inhaled are the BR and the breathing habits of the individual. The BR, along with the air concentration of the DU oxide, determines the magnitude of the intake. The BR also influences the distribution of the aerosol within the lung. The breathing habit of the individual indicates the extent to which he/she breathes through his/her mouth.

The BR assumed for this dose assessment was 1.688 m^3/hr. This BR has been associated with "heavy work" by the ICRP (1994). This level of activity presumes that the individuals spend 12.5 percent of their workday at about two-thirds of their maximal workload and the remaining 87.5 percent, at one-third of their maximal workload, ICRP (1994). This level of work corresponds to heavy construction type work and is appropriate for the activities performed during the fire and recovery work.

For this dose assessment, it was assumed that the personnel were "mouth breathers," which means that they breathed through the mouth more than do individuals who are normal nasal augmentors. The impact of this assumption is to maximize the deposition of the DU oxide into the deep lung where it is available for absorption into the blood.

6.3.2 Ingestion Characteristics

Ingestion of uranium oxides was assumed to be due to incidental hand-to-mouth transfers of the uranium oxides after contact with contaminated soil or equipment. The total soil ingestion rate was assumed to be equal to that which would occur in a construction site, recommended by the NCRP as 100 mg/d, NCRP (1999). This study is based on the assumption that all soil ingested while working in the general area of DU contamination was uranium-contaminated soil, that the DU concentration in the

soil was 10 percent by weight, and that the entire ingestion occurred during the workday. The working day for the recovery work activities was assumed to average 10 hr/d. The resultant ingestion rate was 1 mg DU (normalized as the metal) per hour of recovery work.

6.4 Biokinetic Models

Biokinetic models are mathematical descriptions of the absorption, distribution, metabolism, and excretion processes within the body. In the case of uranium, the metabolism is limited to the transfer of uranium between the organs and tissues of the body. The biokinetic model employed for these calculations consisted of three submodels: respiratory tract, GI tract, and the systemic or other organs. The respiratory tract and GI tract models simulate the processes by which DU is absorbed into the body. The systemic model simulates the distribution of uranium within, and excretion from, the body. All biokinetic models used for this study are current or past recommendations of the ICRP.

6.4.1 Respiratory Tract Model

The ICRP 66 (1994) respiratory tract model was used. This model was chosen, because it provides a mechanism to compute the deposition in the lung of aerosols that have arbitrary particle size distributions. This model also accounts for the influence of the density and shape factors of the aerosol particles on the distribution of material in the lung. Earlier ICRP respiratory tract models could be used for only a limited range of aerosol size distributions. Also, with this respiratory tract model, it is possible to account for an individual's characteristics such as size, BR, and extent of breathing through the mouth.

6.4.2 GI Tract Model

The biokinetic model for the GI tract is described in ICRP 30 (1979). This model consists of four compartments that represent the stomach, the small intestine, the upper large intestine, and the lower large intestine. The fraction of the material entering the GI tract that is absorbed into the body is defined by the f_1 value, the larger the f_1 value the greater the absorption into the body. The f_1 values used in this study are shown in Table 6.1.

6.4.3 Systemic Models

Two different systemic models were used for this study. The systemic model used to compute the radiation dose factors is described in ICRP 30 (1979). This model assumes that the uranium entering the transfer compartment (that is, blood) is distributed to the mineral bone, kidney, and other, unspecified tissues. The biokinetic model also assumes that the uranium deposited in the mineral bone is uniformly distributed throughout the volume of the mineral bone.

The systemic model used to compute the concentration of uranium in the kidney was described in ICRP 69 (1995). This model explicitly models the blood and provides for cycling among the compartments of the body. In this model, the kidney is divided into two compartments, one that loses uranium to the urine and another that returns uranium to blood. The compartment that loses uranium to the urine is roughly equivalent to the renal tubules, ICRP (1995). In the model, uranium is removed from

the renal tubules to the urinary bladder with a half time of 7 days, ICRP (1995). The second kidney compartment represents the remaining tissues of the kidney and retains uranium with a half time of 5 years. For this report, the quantity of uranium in the kidney is the sum of both kidney compartments. To compute the concentration of uranium in the kidney, a kidney mass of 310 grams (ICRP 1975) was used.

6.4.4 Computer Implementations of the Biokinetic Models

The radiological dose calculations were performed using the LUDEP Version 2.06 computer code, Jarvis et al., (1996). This computer code has implemented the ICRP 66 respiratory tract model, the ICRP 30 systemic model, and the ICRP 30 GI tract model. The ICRP 69 systemic model was not implemented in the LUDEP code when these calculations were performed.

The concentrations of uranium in the kidney during and following exposures were calculated using the ICRP 66 respiratory tract model, the ICRP 69 systemic model for uranium, and the ICRP 30 GI tract models. The models were implemented in the Matlab®/Simulink® programming environment. This implementation was used, because the computer code used for radiation dosimetry (LUDEP) does not report instantaneous quantities of material in the model compartments that were necessary to determine the maximal concentration of uranium in the kidney. The ICRP 69 systemic model for uranium was used for these calculations to reflect the current recommendations of the ICRP.

6.5 Internal Dose Factors

Internal dose factors provide a simple means to convert exposure conditions to radiation dose. As discussed in the introduction to this chapter, the radiation dose factors provide for calculation of the CEDE. The dose factors were normalized to intakes of DU metal rather than uranium oxides. This normalization was chosen to be consistent with the calculations of previous chapters.

6.5.1 Tissue-Weighting Factors

Tissue-weighting factors are employed during the calculation of the CEDE to account for the varying sensitivities of tissues to the stochastic effects of radiation. The tissue weighting factors used for dose factors described in this chapter were published in ICRP 26 (1977). These tissue-weighting factors were also published in the Radiation Protection Guidance to Federal Agencies (54 FR 2822) and form the basis for regulations in the U.S. (for example, see 10 CFR 20.1003).

6.5.2 Inhalation Dose Factors

Inhalation dose factors were calculated using the LUDEP Version 2.06 computer code, Jarvis et al., (1996). This computer code has implemented the biokinetic models described in the preceding section. The dose factor for inhalation of the 5-μm AMAD aerosol was 1.74×10^{-4} Seivert (Sv)/mg (0.0174 rem/mg) of DU metal in the oxides. The dose factor for inhalation of the 60-μm-AMAD aerosol was estimated to be 8.43×10^{-6} Sv/mg (0.000843 rem/mg) of DU metal in the oxides.

6.5.3 Ingestion Dose Factor

A dose factor for incidental ingestion of DU oxide was calculated using data published by Eckerman, Wolbarst, and Richardson (1988). The GI tract and systemic biokinetic models used for this data tabulation are those described above. The dose factor for ingestion was estimated to be 1.52×10^{-7} Sv/mg (0.0000152 rem/mg) of DU metal in the oxides.

6.6 Doses Received by Personnel Exposed to DU During the Fire

The DU oxide particles that become airborne from fire were assumed to have a particle size distribution of 5 µm AMAD, based on ICRP recommendations for use when the exact particle size distribution is unknown. As described in Section 6.3.1, it is assumed that persons exposed during the fire had a BR of 1.688 m^3/hr, the same rate assumed for recovery workers.

The doses described in this section are based on the estimated quantity of oxides formed, based on the ejection of one penetrator from each tank, as described in Chapter 3.0. The alternate estimate of oxides formed, based on the ejection of 17 penetrators from each tank, also described in Chapter 3.0, would increase the estimated doses by 27 percent.

6.6.1 Chemical Doses

Because uranium is a nephrotoxin, it was necessary to compute the concentration of uranium in the kidney following exposure to uranium. For this study, the calculated kidney dose was the maximum concentration of uranium in the kidney that would occur over a 1-year period following the start of the exposure to uranium. The concentration of uranium in the kidney is dependent on the concentration of uranium in the air but the plume calculations given in Section 4.1.2 give a time-integrated air concentration, not a time-dependent air concentration. To calculate an average air concentration from the Chi/Q, it was first necessary to estimate for how long the uranium was actually suspended in the air. Consistent with Section 4.1.2, the chemical dose calculations were based on the assumption that 96 percent of the integral air concentration occurred in the first 12 hours (after oxidation was initiated) and the remaining 4 percent occurred in the final 12 hours. Using these assumptions, average air concentration during the first 12 hours was 5.1×10^{-8}, 1.7×10^{-7}, and 8.1×10^{-6} mg/m^3 at the UN Compound for an elevated release, at the UN Compound for a ground-level release, and at the maximum exposure location, respectively. The maximum concentrations of uranium in the kidney following these exposures are shown in Table 6.2.

Table 6.2. Inhalation Doses Received by People Downwind of the Doha Fire

Exposure Condition	Time-Integrated Air Concentration	Chemical Dose (mg-uranium per gram of kidney)	Radiation Dose Sv (rem), CEDE
Elevated release, UN Compound	0.0023 mg·sec/m^3	1.8×10^{-9}	1.9×10^{-10} Sv (0.000000019 rem)
Ground-level release, UN Compound	0.0076 mg·sec/m^3	5.9×10^{-9}	6.2×10^{-10} Sv (0.000000062 rem)
Maximum exposure: 1 km downwind of elevated release	0.363 mg·sec/m^3	2.8×10^{-7}	3.0×10^{-8} Sv (0.0000030 rem)

6.6.2 Radiation Doses

Persons exposed to airborne DU would have received an inhalation dose that can be calculated using the following formula:

$$D = DF \times BR \times C / 3600 \qquad (6.1)$$

where

D = inhalation dose (Sv)
DF = dose factor (Sv/mg)
BR = breathing rate (m^3/hr)
C = time-integrated air concentration (mg·sec/m^3)
3600 = conversion factor (sec/hr)

Thus a sample calculation of an inhalation dose to a person in the UN Compound during an elevated release would be as follows:

$$D = (1.74 \times 10^{-4} \text{ Sv/mg})\ (1.688 \text{ m}^3\text{/hr})\ (0.0023 \text{ mg·sec/m}^3)\ /\ (3600 \text{ sec/hr})$$
$$= 1.9 \times 10^{-10} \text{ Sv } (0.000000019 \text{ rem})$$

Table 6.2 presents the calculated inhalation doses for three types of exposures.

The results of the downwind transport analysis (Table 6.2) show that the maximum chemical dose that may have been received by a person downwind of the fire would have been about 2.8×10^{-7} µg of uranium per gram of kidney tissue. For this dose to be received, the person would have had to remain in the location of the highest air concentration for the entire duration of the fire. For a person who was located in the UN Compound, the inhalation chemical dose was estimated to range from 1.8×10^{-9} to 5.9×10^{-9} µg of uranium per gram of kidney tissue, depending upon whether the plume was best described as an elevated release or a ground-level release.

The results of the downwind transport analysis (Table 6.2) show that the maximum radiation dose that may have been received by a person downwind of the fire would have been about 0.0000030 rem. This radiation dose would have been received by a person located in the area of highest concentration, and in order to receive this radiation dose, the person would have needed to be located in that position for the entire 24-hour period of the fire. For a person located in the UN Compound, the inhalation radiation dose would have been about 0.000000019 rem; with even more conservative assumptions, this estimate could be as high as 0.000000062 rem.

6.7 Doses Received by Personnel Exposed to DU During Recovery Work

Personnel who participated in recovery work at Camp Doha could have received doses from two pathways:

- inhaled DU that had been suspended in air during the various recovery work activities
- ingested DU from contamination on their hands that was incidentally transferred to their mouths

Workers in the North Compound could have received DU exposure in the form of DU oxide particles inhaled while working in areas of contamination or downwind of those areas. As described in Chapter 5.0, individual workers performed a variety of activities in the contaminated area or at some distance downwind from the actual contaminated area. Because the resuspension factors for the different work locations are similar, the maximum resuspension factor (as a function of distance) for each type of recovery work was used for the dose calculations.

The individuals who performed the Camp Doha recovery work activities were likely to have ingested incidental quantities of contaminated soil and ash while carrying out their activities. The concentration of DU in soils and ash on the motor pool pavement surface was not known. It was assumed that 10 percent of the ingested soil was DU in the form of oxides. A further assumption was made that all the soil ingested was ingested during a 10-hour working day. The DU ingestion rate was therefore estimated to be 1 mg DU per hour at work.

The doses described in this section are based on the estimated quantity of oxides formed, based on the ejection of one penetrator from each tank, as described in Chapter 3.0. The alternate estimate of oxides formed, based on the ejection of 17 penetrators from each tank, also described in Chapter 3.0, would increase the estimated doses by 27 percent.

6.7.1 Chemical Doses

To assess the concentration of uranium in the kidney for each job category described in Section 5.2 it was necessary to simulate the exposure and working conditions of the persons who were involved in the recovery work. The workers were assumed to work 6 days per week during their presence at Camp Doha. The daily exposure durations of the workers were obtained from Table 5.1, and the air concentrations in

the work area were obtained from Table 4.4. The calculations accounted for the intermittent nature of the exposures and the changes in the air concentrations to which the workers were exposed. The workers were assumed to ingest uranium-contaminated soil at the rate of 1 mg uranium per hour of exposure time.

The results of the calculations listed in Table 6.3 show the maximal concentration of uranium in the kidney due to inhalation and ingestion. The data in the columns labeled "Inhalation" and "Ingestion" show the maximal kidney concentrations when each intake route is considered separately. The data in the column labeled "Total" show the maximal kidney concentrations for the combined inhalation and ingestion routes of intake.

Table 6.3. Chemical Doses Received by Personnel During Recovery Work Activities at Camp Doha

		Maximum Concentration of Uranium in the Kidney mg-uranium per gram of Kidney		
		Inhalation	**Ingestion**	**Total[(a)]**
EOD Personnel 146th Ord. Det.		3.8×10^{-03}	5.9×10^{-02}	6.3×10^{-02}
Engineers 58th CEC	Average	3.1×10^{-04}	4.7×10^{-03}	5.0×10^{-03}
	High	7.3×10^{-03}	1.3×10^{-02}	2.0×10^{-02}
54th Chemical Troop		9.3×10^{-04}	1.4×10^{-02}	1.5×10^{-02}
Regimental NBC staff		1.9×10^{-03}	2.9×10^{-02}	3.0×10^{-02}
2nd Squadron Troops		1.2×10^{-03}	2.2×10^{-03}	3.3×10^{-03}
AMCCOM		3.2×10^{-03}	4.9×10^{-02}	5.2×10^{-02}
CECOM		3.0×10^{-03}	4.7×10^{-02}	5.0×10^{-02}
ECC Contractors		3.5×10^{-02}	6.3×10^{-02}	9.5×10^{-02}
(a) Totals may not sum because of rounding and because the time of maximal kidney concentration due to inhalation and ingestion may not coincide.				

The inhaled fraction calculated from the data presented in Table 6.3 ($\cong$ 36 percent) to the total concentration of DU in the kidneys will be greater for the 58th Combat Engineers (High), the 2nd Squadron Troops, and the ECC Contractors because of their exposure to higher airborne concentration of DU due to resuspension of DU from their decontamination activities and exposure durations during the Camp Doha cleanup.

6.7.2 Radiation Doses to Recovery Workers

The inhalation doses to persons exposed to airborne DU during recovery work are calculated using the following formula:

$$D = DF \times BR \times C \times ET \qquad (6.2)$$

where

D = inhalation dose (Sv)
DF = dose factor (Sv/mg)
BR = breathing rate (m^3/hr)
C = air concentration of DU (mg/m^3)
ET = total exposure time (hr)

A sample calculation for a person who was performing decontamination work for 15 hours would be as follows:

$$D = (8.43 \times 10^{-6}\ Sv/mg)(1.688\ m^3/hr)(3.83 \times 10^{-2}\ mg/m^3)(15\ hr)$$
$$= 8.2 \times 10^{-6}\ Sv\ (0.00082\ rem)$$

The air concentration recovery workers were exposed to varied day-by-day, depending on the quantity of DU oxides present in the North Compound and the types of activities occurring that created DU resuspension, as discussed in Section 4.2. To assess the inhalation dose for each worker category, an incremental dose for each day worked in the recovery area was calculated, and the daily incremental doses were summed. The day-by-day air concentration values are presented in Figure 4.4, and the dates of activity and number of hours worked per day in the contamination area, or downwind of it, are presented in Table 5.1 for each job category.

Inhalation doses for all activities are shown in Table 6.4.

The radiation dose due to ingestion of contaminated soil can be computed from the following equation:

$$D = DF \times SC \times SIR \times ET \qquad (6.3)$$

where

D = ingestion dose (Sv)
DF = ingestion dose factor (Sv/mg DU)
SC = soil concentration of DU (mg DU/mg soil)
SIR = soil ingestion rate (mg soil/hr)
ET =exposure time (hr)

The exposure time for each job category was taken from Table 5.1 and includes the total hours in recovery work minus the total hours upwind from the contaminated area. As discussed in Chapter 5.0, the exposure time is the sum of the time that the workers were estimated to spend in the contamination area, plus the time that the workers were estimated to spend downwind from the contamination area.

A sample calculation for a person who worked in a contaminated area for 360 hours would be as follows:

D = (1.52 x 10^{-7} Sv/mg DU)(0.1 mg DU/ mg soil)(10 mg/hr)(360 hr)
= 5.5 x 10^{-5} Sv (0.0055 rem).

Ingestion doses for persons who performed recovery work are shown in Table 6.4.

Table 6.4. Internal Doses Received by Personnel During Recovery Work Activities at Camp Doha

		Internal Doses Received, Sv (rem), CEDE		
		Inhalation	**Ingestion**	**Total[(a)]**
EOD Personnel 146th Ord. Det.		4.1×10^{-5} Sv (0.0041 rem)	1.1×10^{-5} Sv (0.0011 rem)	5.2×10^{-5} Sv (0.0052 rem)
Engineers 58th CEC	Average	6.5×10^{-5} Sv (0.0065 rem)	6.6×10^{-6} Sv (0.00066 rem)	7.2×10^{-5} Sv (0.0072 rem)
	High	1.3×10^{-4} Sv (0.013 rem)	1.3×10^{-5} Sv (0.0013 rem)	1.4×10^{-4} Sv (0.014 rem)
54th Chemical Troop		8.2×10^{-6} Sv (0.00082 rem)	2.3×10^{-6} Sv (0.00023 rem)	1.0×10^{-5} Sv (0.0010 rem)
Regimental NBC staff		2.1×10^{-5} Sv (0.0021 rem)	5.8×10^{-6} Sv (0.00058 rem)	2.7×10^{-5} Sv (0.0027 rem)
2nd Squadron Troops		2.2×10^{-5} Sv (0.0022 rem)	2.2×10^{-6} Sv (0.00022 rem)	2.4×10^{-5} Sv (0.0024 rem)
AMCCOM		4.3×10^{-5} Sv (0.0043 rem)	1.2×10^{-5} Sv (0.0012 rem)	5.5×10^{-5} Sv (0.0055 rem)
CECOM		3.7×10^{-5} Sv (0.0037 rem)	1.0×10^{-5} Sv (0.0010 rem)	4.7×10^{-5} Sv (0.0047 rem)
ECC Contractors		6.0×10^{-4} Sv (0.060 rem)	5.5×10^{-5} Sv (0.0055 rem)	6.5×10^{-4} Sv (0.065 rem)
(a) Totals may not sum because of rounding.				

7.0 Conclusions

This study estimated the exposures and intakes of DU for residents and recovery workers at Camp Doha, Kuwait, following the July 1991 fire. People who were exposed to airborne effluents from the fire were estimated to have received very small chemical doses: the maximum concentration in the kidney was estimated to be about 1.8×10^{-8} μg-U/g of kidney for people assembled in the UN Compound at the base and about 2.8×10^{-7} μg-U/g of kidney for a person who was located in the area of highest air concentration. Estimated chemical doses for recovery workers who spent extensive time in the contaminated areas of the North Compound after the fire range from 3.3×10^{-3} μg-U/g of kidney to 9.5×10^{-2} μg-U/g of kidney, depending on which type of activity they were involved in. People exposed to airborne effluents from the fire were estimated to have received very small radiation doses: about 0.000000062 rem for people assembled in the UN Compound at the base and about 0.000003 rem for a person who may have been located in the area of highest air concentration. Estimated doses for recovery workers who spent time in the contaminated areas of the North Compound after the fire, range from 0.001 rem to 0.065 rem depending on the recovery worker's type of activity.

7.1 Significance of DU Exposures

7.1.1 Chemical Doses

The OSHA PELs and ACGIH TLVs are standards that limit the exposure of workers to hazardous chemicals. For uranium, a major difference between the two standards is that the ACGIH TLVs are the same for soluble and insoluble compounds whereas the OSHA standard distinguishes between soluble and insoluble compounds. The ACGIH TLV-TWA is 0.2 mg/m^3 and the TLV-STEL is 0.6 mg/m^3, ACGIH (1999). The OSHA PEL is 0.05 mg/m^3 for soluble forms of uranium and 0.25 mg/m^3 for insoluble forms of uranium, 29 CFR 1910.1000 Table Z-1. These values may be compared with the air concentrations calculated for this study which were 0.038 mg/m^3, 0.42 mg/m^3, 0.385 mg/m^3, 0.196 mg/m^3, and 0.000194 mg/m^3 total uranium for initial wind erosion, decontamination, the first sweeping, the second sweeping, and final wind erosion, respectively. Based on these data, the TLV-TWA and PEL values may have been exceeded during the decontamination and sweeping activities.

The air concentrations of this study were calculated, not measured, however, and both the TLVs and PELs are intended to be compared with measurements made in the workplace. In particular, the ACGIH (1999) states that the term "total particulate" refers to airborne material sampled with a 37-mm closed-face cassette. No guidance is given concerning how to compare calculated air concentrations of aerosols that have arbitrary particle size distributions, such as those presented in this study, to either the TLVs or PELs, which are intended to be compared with measured air concentrations. For this study, the collection efficiency of the sampling cassette was assumed to be unity for all particle sizes. If the collection efficiency of an actual sampler is less than unity, then the calculated air concentrations might not have exceeded the air concentrations that would be measured by a sampler.

Because uranium is a renal toxin, studies have been conducted to determine a maximum permissible concentration of uranium in the kidney. A frequently quoted value is 3 μg-U/g of kidney—a value that was determined in 1949 to cause kidney damage, Spoor and Hursch (1973). There have been suggestions to lower this value to 0.6 (Kathren and Weber 1988) or 0.3 μg-U/g of kidney (Leggett 1989) based on the results of animal studies. The calculations of this study indicate that the kidney concentrations of workers did not exceed the historic value of 3 μg-U/g of kidney nor did they meet or exceed either of the proposed lower levels.

The reason that the kidney concentrations do not exceed even the lowest of the proposed maximum permissible concentrations of uranium in the kidney while at the same time the calculated air concentrations apparently do exceed published limits on air concentration is due to the short exposure durations and the particle size distribution of the uranium dust. The uranium dust generated during the decontamination activities was estimated to be 60-μm AMAD with a σ_g of 2.8. Calculations using the ICRP 66 (1994) respiratory tract model show that for this aerosol only about 1.9 percent of an intake is actually deposited in the thoracic regions of the lung. Thus very little of the uranium in the air actually enters the body.

7.1.2 Radiation Doses

To prevent radiation-induced injury to workers, ALIs and derived air concentrations (DACs) are used. An ALI is that annual intake of a radionuclide that would result in a radiation dose to Reference Man (ICRP 1975) equal to the relevant primary guide (that is, to the limiting value of committed dose, which is 5 rem). A DAC is that concentration of a radionuclide in air, which if breathed for a work-year, would result in an intake corresponding to its ALI.

The EPA has prepared tables of ALIs and DACs (Eckerman, Wolbarst, and Richarson 1988) for use by U.S. regulatory agencies such as the NRC (for example, 10 CFR 20 Appendix B, "Annual Limits on Intake (ALIs) and Derived Air Concentrations (DACs) of Radionuclides for Occupational Exposure; Effluent Concentrations; Concentrations for Release to Sewerage"). The published occupational DACs, based on U-238, are 0.9 mg/m^3 and 0.06 mg/m^3, for Class W and Class Y uranium, respectively. Because the ALIs and DACs are based on a particle size distribution of 1 μm AMAD, it is necessary to adjust the DACs for the actual particle size distribution, which was 60 μm AMAD. The adjustment for particle size distribution was based on the ratio of inhalation dose factors. The adjusted DACs are, for occupational exposures, 20 mg/m^3 and 1 mg/m^3, for Class W and Y uranium, respectively. For exposures of the general public, the adjusted DACs are 8 x 10^{-2} mg/m^3 and 6 x 10^{-2} mg/m^3 for Class W and Y uranium, respectively. The calculations of this report indicate that the adjusted occupational DACs were not exceeded during the decontamination and recovery activities.

All of the radiation doses reported in this study are lower than the annual radiation exposure that every person can expect to receive from natural background. The estimated radiation doses are 3 or more orders of magnitude lower than the thresholds for immediately observable physical effects in the body, so there is no possibility of acute health effects (that is, health effects observable soon after exposure) resulting from this exposure. Long-term health effects, such as cancer that may be caused by radiation exposure are theoretically possible with any non-zero exposure, but the probability of cancer resulting

from a 0.065 rem exposure is trivial compared to the naturally occurring cancer incidence in the general population. The increased probability of fatal cancer induction can be estimated by using the risk factors published in ICRP 60 (1991). The risk of fatal cancer induction from uniform whole body irradiation has been estimated to be 4×10^{-4} rem^{-1}, ICRP (1991). The risk of fatal cancer induction from the 0.065 rem dose is then $(4 \times 10^{-4}\ rem^{-1})(0.065\ rem) = 3 \times 10^{-5}$. This risk of fatal cancer can be compared to the natural incidence of cancer. Cancer is the second leading cause of death in the U.S., exceeded only by heart disease. In the U.S., one of every four deaths is from cancer, for a natural risk of 0.25, American Cancer Society (2000).

7.2 Modeling Uncertainty

The analyses in this study depended heavily on the interpretation of comments and reports to arrive at quantitative values that were used in the dose assessments. This type of dose assessment typically depends upon careful measurements and scientific observations to have a high degree of confidence in the analysis, but no such data were available for this study. Thus, there is a high degree of uncertainty associated with the results of this analysis. The study authors tried to ensure that the assumptions would be conservative, resulting in a dose assessment that probably overestimated the actual exposures rather than possibly underestimating them.

7.2.1 Sensitivity of Results to Assumptions

The North Compound surface contamination estimate depended heavily on the study's assumptions about the number, distribution, and characteristics of piles of DU oxides. Actual observations gave minimal guidance in making these assumptions.

A conservative assumption concerns the changes in contamination level with time: this analysis assumed that the contamination levels remained uniform over the first 2 months after the fire, ignoring the action of wind and cleanup personnel in removing the contamination from the surface of the motor pool during this time period. The study then assumed nearly complete removal of the DU oxides over a period of 3 weeks starting in mid-September. This assumption was made because there were no reliable data upon which to base a more realistic schedule for the removal of DU oxides. The highest dose estimates calculated in this study were for the ECC contractors, who spent the most time in the North Compound. However, they did not start their work until 2 months after the fire, and 2 months of a steady wind plus the action of recovery crews before them would have removed a substantial amount of contamination. Thus, the dose estimate for these workers is believed to be very conservative.

One assumption used in this study that was not the most conservative assumption possible was the fraction of DU in soil used for the ingestion dose calculation. Available data indicated the amount of soil that could be incidentally ingested by a worker, but the study had to make an assumption about how much of that soil would have consisted of DU. Possible choices ranged from 0 to 100 percent, and a value less than 100 percent was chosen because it seemed reasonable that a limitless supply of sand would have been blowing across the motor pool with some settling onto the surface and mixing with the DU. A value of 10 percent seemed reasonable to the authors, so it was used in the ingestion calculation. If this assumption was a significant underestimation, however, the highest possible ingestion dose,

corresponding to a soil composition, that is 100 percent DU, would be 0.055 rem (rather than 0.0055 rem) to an ECC contractor, for a total dose of 0.120 rem (rather than 0.065 rem presented in Table 6.3). This higher dose estimate, while much less realistic in the judgment of the study authors, would still be low enough to ensure that health effects from the radiation dose would be very unlikely.

Resuspension is a very difficult effect to model precisely, even when based on carefully measured input values. Resuspension factors from the literature can easily vary by a factor of 10 with only slightly varying assumptions. As an example, a value of 0.01 can be used for sweeping indoors, compared to the value of 0.001 used for sweeping in this study. The values chosen for this study were judged by the authors to be the most appropriate for the conditions, but the resuspension calculation should be thought of as an "order-of-magnitude" estimate.

7.2.2 Data Limitations

This study's modeling effort was limited by the quality of the data available. Most of these shortcomings included details of the conditions during the accident. Some of the more important data limitations include:

- DU oxides available for exposure
  - The quantity of DU oxides produced by the fire: there were no measurement data that could provide accurate input to this fundamental piece of data, so the study had to base the estimate on assumptions about the fire conditions.
  - Detailed fire conditions: little is known about the fire temperatures and duration of fire temperatures for various regions of the fire, at which DU rounds were stored, which would determine the degree of oxidation for the penetrators.
  - The distribution of penetrators in the fire: the distribution of penetrators in the North Compound was not documented, so the study relied on conservative but reasonable assumptions about where penetrators might have landed and how many could have been oxidized by fire.
  - The initial distribution of DU oxides in the North Compound (number and sizes of oxide piles, smeared-out surface contamination): the distribution and behavior of DU oxides that fell from burning penetrators in the North Compound was not observed and documented, so the study's analysis was based on conservative but reasonable assumptions rather than actual data.
  - The day-by-day change in distribution of DU oxides as recovery progressed: this was not systematically measured, and the monitoring that did occur was not documented in a way that could help this study, so assumptions were made about this behavior.

- Recovery worker activities

  - The day-by-day location of each recovery worker: the hours each recovery worker spent in contamination areas on each day of the recovery effort would have allowed for a more accurate dose assessment for the workers. The reports provide general descriptions of job categories, but it is impossible to reconstruct the location of each worker as a function of time, so the study made a number of assumptions based on these narratives in order to estimate exposures.

  - The day-by-day activities occurring in contamination areas: these activities caused resuspension and consequent changes in air concentrations. These activities were only generally outlined in the reports; a more detailed description of the activities would have provided a more detailed basis for the modeling.

- Physical behavior of DU oxides (a detailed discussion of this data limitation is discussed by Parkhurst et al., [1999])

  - Resuspension factors for DU: no resuspension factors have been measured specifically for DU, so the values used were derived from data for other material. These factors are not derived as a function of particle size. Confidence in the model would be vastly improved if more appropriate resuspension factors could be identified and applied.

  - Particle size distribution of DU oxides that remain close to a burned penetrator: this distribution was used for the estimation of resuspension and for the conversion of DU intake to dose. The distribution used by the study was based on limited data from burn tests; there were only two data sets from which to choose.

  - The ARF for 120mm DU rounds in fire: the ARF used in this study was derived from 120mm DU round burn tests, but no airborne DU has been directly detected in a 120mm DU round burn test, and the quantity released during the 1987 accidental Abrams fire was inconsequential. The ARF was assumed to be equal to the unrecovered fraction of a mass-balance study, an assumption that is definitely conservative.

  - Particle size distribution of DU oxide in a fire plume: this study used a value of 5 μm AMAD, based on an ICRP default recommendation, not based on an analysis of an actual airborne sample.

  - A mechanism to relate calculated air concentrations to the air concentrations that would be measured by a sampler: regulations for worker exposure are written in terms of what is collected by a particular type and size of air sampler but not necessarily in terms of a calculated air concentration. This study based the comparison to regulatory values solely on calculated air concentrations.

8.0 References

10 CFR Part 20. 2000. U.S. Nuclear Regulatory Commission, "Standards for Protection Against Radiation." U.S. Code of Federal Regulations.

29 CFR Part 1910.1000. 2000. Occupational Safety and Health Administration, Department of Labor, "Air Contaminants." U.S. Code of Federal Regulations.

52 FR 2822-2834. January 27, 1987. U.S. Environmental Protection Agency, "Radiation Protection Guidance to Federal Agencies for Occupational Exposure: Recommendations Approved by the President." *Federal Register*.

American Cancer Society (ACS). April 9, 2000. Available to downloaded from the World Wide Web: http://www.cancer.org/statistics/cff2000/basicfacts.html#expecteddie

American Conference of Governmental Industrial Hygienists (ACGIH). 1999. *TLV and BEIs: Threshold Limit Values for Chemical Substances and Physical Agents.* Cincinnati, Ohio.

Clayton, G. D. and F. E. Clayton, eds. 1994. *Patty's Industrial Hygiene and Toxicology: Fourth Edition, Volume II, Part C Toxicology.* John Wiley & Sons, Inc., New York.

Droppo, J. G. and J. W. Buck. 1996. *The Multimedia Environmental Pollutant Assessment System (MEPAS): Atmospheric Pathway Formulation*. PNNL-11080, Pacific Northwest National Laboratory, Richland, Washington.

Eckerman, K. F., A. B. Wolbarst, and A. C. B. Richardson. 1988. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion.* (Federal Guidance Report No. 11). EPA-520/1-88-020. United States Environmental Protection Agency, Washington, D.C.

Fliszar, R. W., E. W. Wilsey, and E. W. Bloore. 1989. *Radiological Contamination from Impacted Abrams Heavy Armor*. BRL-TR-3068, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland.

Gifford, F. A. 1976. "Turbulent Diffusion Typing Schemes: A Review," *Nucl. Saf*. 17(1):74.

Haggard, D. L., W. M. Herrington, C. D. Hooker, J. Mishima, M. A. Parkhurst, R. I. Scherpelz, L. A. Sigalla, and D. E. Hadlock. 1986. *Hazard Classification Test of the 120-mm, APFSDS-T, M829 Cartridge: Metal Shipping Container*. PNL-5928, Pacific Northwest Laboratory, Richland, Washington.

Harley, N. H., E. C. Foulkes, L. H. Hilborne, A. Hudson, and C. R. Anthony. 1999. *A Review of the Scientific Literature As It Pertains to Golf War Illnesses: Volume 7 Depleted Uranium.* Rand, Santa Monica, California.

Hooker, C. D., D. E. Hadlock, J. Mishima, and R. L. Gilchrist. 1983. *Hazard Classification Test of the Cartridge, 120 mm, APFSDS-T, XM829*. PNL-4459, Pacific Northwest Laboratory, Richland, Washington.

International Commission on Radiological Protection (ICRP). 1975. *Report on the Task Group on Reference Manual*. ICRP publication 23, Pergamon Press, New York.

International Commission on Radiological Protection (ICRP). 1977. *Recommendations of the ICRP*. ICRP publication 26, Pergamon Press, New York.

International Commission on Radiological Protection (ICRP). 1979. "Limits for intakes of radionuclides by workers." (ICRP publication 30, part 1). *Annals of the ICRP* Vol. 2, No. 3-4, Pergamon Press, New York.

International Commission on Radiological Protection (ICRP). 1991. "1990 Recommendations of the International Commission on Radiological Protection." (ICRP publication 60). *Annals of the ICRP* Vol. 21, No. 1-3, Pergamon Press, New York.

International Commission on Radiological Protection (ICRP). 1994. "Human Respiratory Tract Model for Radiological Protection." (ICRP publication 66). *Annals of the ICRP* Vol. 24, No. 1-3, Pergamon Press, New York.

International Commission on Radiological Protection (ICRP). 1995. "Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 4, Inhalation Dose Coefficients." (ICRP publication 71). *Annals of the ICRP* Vol. 25 No. 3-4, Pergamon Press, New York.

Jarvis, N. S., A. Birchall, A. C. James, M. R. Baily, and M. -D. Dorrian. 1996. "Ludep 2.0: Personal Computer Program for Calculating Internal Doses Using the ICRP Publication 66 Respiratory Tract Model." NRBP-SR287, National Radiological Protection Board, Chilton, Didcot, Oxon OX11 0RQ.

Kathren R. L. and J. R. Weber. 1988. "Ultrasensitive Techniques for Measurement of Uranium in Biological Samples and The Nephrotoxicity of Uranium." NUREG/CR-5125, U.S. Nuclear Regulatory Commission, Washington, DC.

Leggett, R. W. 1989. The Behavior and Chemical Toxicity of U in the Kidney: A Reassessment. *Health Phys.* 57(3):365-383.

Lide, David R., Ed. 1994. *CRC Handbook of Chemistry and Physics*, 75th Edition. CRC Press, Boca Raton, Florida.

Mishima, J., M. A. Parkhurst, R. I. Scherpelz, and D. E. Hadlock. 1985. *Potential Behavior of Depleted Uranium Penetrators under Shipping and Bulk Storage Accident Conditions*. PNL-5415, Pacific Northwest Laboratory, Richland, Washington.

National Council on Radiation Protection and Measurements (NCRP). 1989. *Comparative Carcinogenicity of Ionizing Radiation and Chemicals.* NCRP Report 96, National Council on Radiation Protection and Measurements, Bethesda, Maryland.

National Council on Radiation Protection and Measurements (NCRP). 1999. *Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies*. NCRP Report No. 129, Bethesda, Maryland.

Office of the Special Assistant on Gulf War Illnesses (OSAGWI). 1998. *Environmental Exposures Report: Depleted Uranium in the Gulf.*

Parkhurst, M. A., J. R. Johnson, J. Mishima, and J. L. Pierce. 1995. *Evaluation of DU Aerosol Data: Its Adequacy for Inhalation Modeling*. PNL-10903, Pacific Northwest National Laboratory, Richland, Washington.

Parkhurst, M. A., K. M. Krupka, A. D. Maughan, J. A. Glissmeyer, S. P. Shelton and J. G. Droppo. 1999. *Evaluation of DU Soil Contamination and Resuspension Data: Its Adequacy for Dose Modeling of Inhalation and Ingestion.* Pacific Northwest National Laboratory, Richland, Washington, in press.

Ramsdell, J. V. Jr., C. A. Simonen, and K. W. Burk. 1994. *Regional Atmospheric Transport Code for Hanford Emission Tracking*. PNWD-2224 HEDR. Prepared for the Technical Steering Panel and the Centers for Disease Control and Prevention by Battelle, Pacific Northwest Laboratories, Richland, Washington.

Russell, J. J., R. L. Kathren and S. E. Dietert. 1996. A Histological Kidney Study of Uranium and Non-Uranium Workers. *Health Phys*. 70(4):466-472.

Sehmel, G. A. and F. D. Hodgson. 1978. *A Model for Predicting Dry Deposition of Particles and Gases to Environmental Surfaces.* PNL-SA-6721, Pacific Northwest National Laboratory, Richland, Washington.

Sehmel, G. A. 1980. "Particle Resuspension: A Review." *Environment International*, 4:107-127.

Spoor, N. L. and J. B. Hursch. "Protection Criteria" pp 241-270, in Hodge, H. C., J. N. Stannard and J. B. Hursh. 1973. Uranium, Plutonium, Transplutonic Elements. *Handbook of Experimental Pharmacology*, XXXVI. Springer-Verlag, New York.

U.S. Army Safety Center. 1991. *Estimated Cost of Destroyed Ammunition*, Army Accident Report 910711001, Fort Rucker, Alabama.

Whelan G., J. Buck, D. Strenge, et al. 1989. "Overview of the multimedia environmental pollutant assessment system (MEPAS)." *Hazardous Waste & Hazardous Materials* (9):191-207.