PART I: INTRODUCTION

1.1 Purpose and Scope

In response to veterans' concerns, the Department of Defense (DOD) established a task force in June 1995 to investigate all possible causes of physical symptoms being experienced by Gulf War veterans. The Investigation and Analysis Directorate of the Office of the Special Assistant for Gulf War Illnesses (OSAGWI), now known as the Office of the Special Assistant to the Secretary of Defense for Gulf War Illnesses, Medical Readiness and Military Deployments, assumed responsibility for these investigations on 12 November 1996 and has continued to investigate probable causes of Gulf War illnesses. In January 1998, OSAGWI directed the U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM) to conduct a human exposure assessment and health risk characterization for military personnel potentially exposed to depleted uranium (DU) during service in Southwest Asia (see Memorandum, OSAGWI, 30 January 1998, subject: *Request for Assistance with Depleted Uranium (DU) Risk Assessment*). Published DOD DU munitions test data were reviewed to determine adequacy for use to complete this human exposure assessment and health risk characterization for chemical and radiological exposures to DU. This review was also a preliminary assessment of future research needs and recommendations for future data collection studies.

The USACHPPM provided interim Level I human exposure assessments and health risk characterization that comprised one component of the OSAGWI Interim Environmental Exposure Report (4 August 1998)[1] which was prepared for review by veterans of the Gulf War

and Congressional personnel, as well as the general public. As part of the effort to keep the public aware of the progress of this effort, DOD published accounts related to possible causes of illnesses among Gulf War veterans, along with whatever documentary evidence or personal testimony was used in compiling the accounts.

1.2 Document Overview

Part I, Introduction, includes the Purpose and Scope of this report, the organization of this report, the data quality objectives (DQOs) for this report, the methods used in estimating DU intake, Levels of Exposure, background information on DU and the Army, and the Overall Conclusions. Part II, Human Exposure Assessment and Health Risk Characterization, includes a discussion of the assessment process and what methodology was used to conduct the human exposure assessments and health risk characterizations for military and civilian personnel potentially exposed to DU during their service in Southwest Asia. Part III, Technical Literature Review, provides a summary of the experimental data used to determine the human exposure assessments and health risk characterizations and the Data Gaps that exist in the current data and areas for data improvement. Part IV provides a detailed assessment of the OSAGWI Level I Scenarios. Part V provides a detailed assessment of the OSAGWI Levels II and III Scenarios. The Camp Doha report is included in Appendix C. This report concludes with a glossary containing technical terms, abbreviations, and acronyms, plus appendices, endnotes, and a list of references used in preparing this report.

The USACHPPM recognizes that reporting radiation quantities in International System of Units [grays (Gy), sieverts (Sv), and bequerels (Bq)] is currently the standard in the scientific community. However, we also understand that the lay reader or Gulf War veteran may be more familiar with the traditional units (rad, rem, and curies). Therefore, USACHPPM will use the traditional units when presenting the results in this assessment. Also, when small radiation doses are reported they will not be reported as exponential values for example, 0.000008 rem, not 8×10^{-6} rem).

1.3 Data Quality Objectives

Exposure Assessments and Health Risk Characterizations

Data Quality Objectives are qualitative and quantitative statements derived from the DQO process that:

- Establish and clarify the project's objectives.
- Define the appropriate type of data.
- Specify the tolerable levels of potential uncertainties.
- Provide an understanding of the limitations of data to be used as the basis for establishing the quality, quantity, and defensible data needed to support conclusions or decisions.

The first step in the DQO process is to state the problem. In this case, the question was, "Were the exposures and intakes of DU by veterans of the Gulf War the cause of their adverse health effects?"

The following are the DQOs used for this DU human exposure assessment, intake estimation, and health risk characterization:

- Review published munitions developers' test data on the behavior of DU during impacts and perforations of armor and during fires that involve DU munitions.
- Evaluate the usefulness and appropriateness of the munitions developers' test data in modeling the amount of DU a soldier might take in (internalize) through inhalation, ingestion (indirect, direct and secondary), or wound contamination.
- Peer review draft (unpublished) munitions developers' test data on the behavior of DU during impacts and perforations of armor and during fires that involve DU.
- Identify data gaps regarding data required for dose modeling and exposure assessment.
- Perform estimates of the radiological and chemical intake and dose ranges (lower and upper bounds) for each of the 13 OSAGWI scenarios involving DU exposure.
- Perform a human exposure and health risk characterization by estimating the range (lower and upper bounds) of DU intakes, which may have been internalized for each of the 13 OSAGWI scenarios.

The limitations of this DU human exposure assessment and health risk characterization are as follows:

- Used data not intended for estimating DU exposures.
- Did not address the human body's susceptibility to other kinds of potential toxic exposures on the battlefield or how DU may alter the metabolism of other compounds that may have been potentially internalized by the veterans.
- Cannot be used as a dose reconstruction.
- Did not address the issue of smoking and how it may have altered any potential uptake of DU and associated health effects.
- Did not address the direct ingestion of foodstuff, soil, or water that may have been contaminated, because data were not available to estimate the intake.
- Did not address multiple exposures (that is, repeated exposure and accumulation of other contaminants for any single individual), because data were not available to estimate the intakes.
- Lacked an actual database of potentially exposed personnel obtained at the time of the event.

There is a possibility that longer-term, lower level effects other than carcinogenicity and kidney toxicity from these DU exposures could occur; therefore, there is a medical follow-up program being conducted by the Department of Veterans Affairs (VA). Because there was no immediate medical evaluation after exposure on the battlefield, determination that acute temporary renal

tubular affects that occurred as a result of the internalization of DU by Gulf War personnel is not possible.

1.4 Methods

To perform the human exposure assessment and health risk characterization requested by OSAGWI, USACHPPM assembled a team of health physicists, toxicologists, industrial hygienists, occupational health physicians, health professionals, and other technical subject matter experts to review the technical and scientific documents concerning DU. The OSAGWI DU Level I, II, and III exposure scenarios were used as the basis for the assessments and characterizations. The potential source term of DU for internalization, the potential routes of exposure, the exposure duration, the frequency of exposure, and the individuals at risk were some factors considered. This information was used to characterize the potential for both the chemical and radiological effects associated with Gulf War exposure scenarios involving DU. Information presented is based on published DOD DU munitions test data reports. Some considerations in this analysis follow:

- DOD published test reports and other scientific literature related to the subject were reviewed and evaluated. Characteristics of DU oxides such as chemical composition, particle-size distributions, isotopic composition, equilibrium with progeny, and solubility of particles in lung fluid were extracted from the reviewed data. Test data were evaluated for usefulness in modeling of atmospheric transport, environmental dispersion, and the intake of DU by potentially exposed individuals.

- The quality of an exposure assessment depends upon the value of the input data and associated assumptions. Test data on the formation of DU oxides and resulting respiratory tract solubility characteristics documented that fires involving DU munitions produce DU oxides that are predominantly insoluble. DU perforations of armor increase the percentage of soluble oxide compounds. Computation of exposure was based on the source term being either entirely soluble or entirely insoluble (an extremely conservative estimation); however, the data from the munitions developers' reports indicated that this approach was not realistic. Also, the data from their field tests substituted for atmospheric modeling only under very similar exposure circumstances. Uncertainties with the data came from difficulties of sampling airborne particulate matter in an explosive environment. Uncertainties also exist in sampling airborne concentrations that are dispersed at distances from the source.

- Data from published reports were used to estimate potential exposure and intake of DU by personnel in, on, or near (within 50 meters) Abrams tanks or Bradley Fighting Vehicles (BFVs) from a single DU perforation into the Crew Compartment and to recovery personnel from residual DU aerosol concentrations and resuspension of settled DU particles. The radiation dose was calculated using estimated intakes of DU from airborne concentrations and surface DU contamination levels. The available data were then used in internationally and nationally recognized internal dosimetry modeling programs to calculate the radiation dose to organs and whole body and the chemical concentration in the kidney.

- Measurements of the percentage of the DU round aerosolized during perforation were collected but varied widely. Also, the measurements were collected outside the vehicle. To

calculate a DU intake, assumptions about the DU airborne concentrations inside the vehicle and exposure duration had to be made. The test data used as a basis for these assumptions were taken from Fliszar et al., (1989), and they provided estimated lower- and upper-bound airborne concentrations of DU. These data were not originally collected for the purpose of conducting human exposure assessment and health risk characterizations.

- The uncertainties associated with the chemical and physical form of the DU residue, DU particle-size distribution, its solubility in lung fluid, dissolution rate, and resuspension were increased due to sampling difficulties and site and target specific factors. In previously conducted tests, material could have dispersed before sample collection commenced, which could have resulted in dust loading and possible underestimation of the fine particle fraction [< 1-micrometer (μm) aerodynamic equivalent diameter (AED)]. Exposure and intake estimates could be affected if a large fraction of material aerosolizes but finer particles are not collected. Future efforts in measuring such parameters should be directed to reduce uncertainty in the above factors.

- The existing field measurement data could only provide estimates for exposure and dose assessments. More precise measurements of DU aerosol characteristics and aerosol resuspension data would lead to more robust values for use in human exposure assessments and health risk characterizations. DU penetrator impact/perforation data for aerosol concentration and subsequent resuspension inside the BFV are non-existent.

1.5 Characteristics of Uranium and DU

Uranium, a common radioactive element, is very dense in its metallic form. It occurs in nature in a wide variety of compounds. It readily combines with other elements to form uranium oxides, silicates, carbonates and hydroxides. These compounds range from being highly mobile to being relatively immobile in the environment and soluble to insoluble in the human body. Several conditions affect the formation of these compounds: the relative amounts of oxygen, moisture, and the hydrogen ion concentration (pH); the presence of other metals alloyed with uranium; and the temperature history of the uranium solid, Erikson et al., (1993). The resultant uranium compound also depends on the original form of the uranium (alloy and mineral phase) and its interaction with environmental media (soil, air, surface and ground water, and biota). Uranium compounds, much like other heavy metals, dissolve and migrate at different rates.

Uranium metal alloys are readily machinable and have metallurgical properties similar to those of many high strength steels, Magness, (1985). Small particles of uranium metal and some uranium alloys are pyrophoric – they can ignite spontaneously in air, as a function of surface to volume ratio, and they burn rapidly at very high temperatures, Stokinger, (1981)[2].

Natural uranium (U_{Nat}) contains a mixture of uranium isotopes, including U-234, U-235, and U-238. Naturally occurring uranium nominally contains 99.2830 percent by weight U-238, 0.7110 percent U-235, and 0.0054 percent U-234. Uranium ore is mined, milled, and refined for use in nuclear reactors and nuclear weapons. To enable use in reactors and weapons, uranium is enriched, a process that increases the weight percentage of the U-235 isotope from about the 0.7

percent found in nature to a content ranging from 2 percent to more than 90 percent. During the enrichment process, the weight percent of U-234 is also increased. Depleted uranium is a byproduct of the uranium enrichment process and is chemically identical to U_{Nat}. However, DU is about 40 percent less radioactive than naturally occurring uranium (for the same weight of material).

The isotope U-238, which makes up about 99.8 weight percent of DU, is an alpha and a weak gamma emitter. Uranium-238 has a T_p of 4.5×10^9 years. Uranium-238 decays into short-lived progeny: thorium (Th)-234, with a T_p of 24.1 days; protactinium (Pr)-234m, which has a T_p of 1.2 minutes; and Pr-234, which has a T_p of 6.7 hours. All three of these progeny are beta and weak gamma emitters. Protactinium-234m and Pr-234 both decay to U-234. The isotope U-234 makes up about 0.0006 weight percent of DU and has a T_p of 2.4×10^5 years. Uranium-234 is an alpha and a weak gamma emitter. Uranium-234 decays into Th-230 having a T_p of 7.7×10^4 years. Because of this long "in-growth" half-life, the build-up of alpha activity from Th-230 is negligible and therefore not present in DU munitions. The isotope U-235, which makes up about 0.2 weight percent of DU, has a T_p of 7.0×10^8 years. Uranium-235 is an alpha and a weak gamma emitter and decays into Th-231 with a T_p of 25.5 hours. Thorium-231 is a beta and a weak gamma emitter.

There may be impurities in DU that are the result of reprocessing nuclear fuel. The isotope U-236 is not a naturally occurring uranium isotope but is sometimes present as an "impurity" or byproduct from reprocessed nuclear fuel. It makes up about 0.0003 weight percent in DU and has a T_p of 2.3×10^7 years. Uranium-236 is an alpha emitter. Some other impurities may be

trace quantities of plutonium (Pu)-238, Pu-239, Pu-240, americium-241, neptunium-237, and technetium-99. It is estimated that these impurities add less than 1 percent to the dose and are, therefore, inconsequential from a radiological or chemical toxicity standpoint. (See Memorandum For Record, 7 August 2000.)

The radioactive decay chains of U-235 and U-238 are broken (that is, the progeny nuclides are removed as impurities) during the processing of DU metal. To determine the time required to reach equilibrium in the partial decay chains, the assumption is made that the DU metal contains only the parent, not the progeny. However, the progeny of U-235 and U-238 that reach secular equilibrium with their parent isotope in about six months are included in the dose estimates.

Depleted uranium cannot sustain a nuclear reaction or be used as the fuel for nuclear weapons, but its high density and metallurgical properties make it useful in kinetic energy weapons and armor systems. Table 1 provides an example of the uranium isotopic composition of DOD DU munitions. The activity listed does not include any activity from progeny of the uranium isotopes.

Table 1. Isotopic Composition of DOD DU Munitions

Isotope	Percentage By Weight	Isotopic Activity [microcuries per gram (μCi/g) of DU]
U-234	0.0006 %	3.7 E-2*
U-235	0.2 %	4.3 E-3
U-236	0.0003 %	2.0 E-4
U-238	99.8 %	3.4 E-1
Total DU Specific Activity: 3.8 E-1 μCi/g		

*Note: 3.7 E-2 μCi/g = 3.7×10^{-2} μCi/g

Table 2 provides a summary of the specific activities and densities for DOD DU and the oxides of DU.

Table 2. Specific Activity and Density for DU and DU Oxides[3]

Compound	Chemical Formula	Specific Activity (μCi/g)	Density [grams per cubic centimeter (g/cm^3)]
Depleted Uranium	DU	0.38	18.95
DU Dioxide	DUO_2	0.33	~ 10.97
DU Trioxide	DUO_3	0.31	~ 7.30
Tri DU Octaoxide	DU_3O_8	0.32	~ 8.30

Reference: Agency for Toxic Substances and Disease Registry, 1999, p. 237

1.6 Military Uses of DU

Depleted uranium has been used in armor to increase resistance to enemy projectiles and in munitions to increase penetrating power. The favorable characteristics of DU as a munition are its density, adiabatic shearing (self-sharpening), and pyrophoric nature. The density of DU is about 1.7 times the density of lead (18.95 g/cm^3 compared to 11.35 g/cm^3). Adiabatic shearing means that as the DU penetrator perforates a hard target, it self-sharpens flaking off particles that may burn (oxidize) if sufficient oxygen is present. Burning particles, as well as the heat generated upon perforation of a target, may ignite fuel, ammunition or other combustible material. Adiabatic shearing is less prevalent against lighter targets or more thinly armored vehicles such as BFVs.

For U.S. Army munitions, DU is alloyed with 0.75 percent by weight titanium. This allows for high acceleration of the penetrator without breaking up during flight. The Army DU munitions

are identified as Armor-Piercing Fin Stabilized Discarding Sabot with Tracer (APFSDS-T). Table 3 identifies Army munitions that contain DU[4]. The mass listed in Table 3 is the average value, in grams of DU.

Table 3. Army DU Munitions

Munition	Caliber	Type	Mass
Cartridge	25 millimeter (mm)	APFSDS-T	90 g
Cartridge	105mm	APFSDS-T	2,200 g
Cartridge	105mm	APFSDS-T	3,300 g
Cartridge	105mm	APFSDS-T	3,600 g
Cartridge	105mm	APFSDS-T	3,600 g
Cartridge	120mm	APFSDS-T	3,100 g
Cartridge	120mm	APFSDS-T	3,800 g
Cartridge	120mm	APFSDS-T	4,700 g

During the Gulf War, DU helped U.S. forces fight more effectively and defend themselves more confidently. American tankers and A-10 pilots destroyed thousands of Iraqi combat vehicles without the loss of a single U.S. tank to enemy fire.

During Operation Desert Storm, the U.S. Army fired the following DU tank rounds: M829, M829A1, and M900. The 120mm DU rounds were called "silver bullets" by tankers due to the tremendous lethal advantage these rounds provided against enemy tanks. The M919 round was not fielded until 1996. The U.S. Air Force used the GAU-8 (PGU-14) 30mm round, which contained approximately 300 g of DU. The GAU-8 is fired from the A-10 Thunderbolt II, ("Warthog" or "Tankbuster") aircraft. The U.S. Marine Corps used the GAU-12 (PGU-20), 25mm round, which contained approximately 150 g of DU. The PGU-20 is fired from AV-8B Harrier aircraft.

1.7 Potential Health Implications for the OSAGWI Exposure Levels and Scenarios

Depleted uranium's combat debut showed the metal's clear superiority for both armor penetration and armor protection. However, its chemical properties, common to all forms of DU, as well as many other heavy metals, and its low-level radiological properties give rise to consider possible combat and non-combat health risks associated with DU use.

Depleted uranium can enter the human body by inhalation, ingestion, fragment implantation, and wound contamination. Inhalation is one of the major routes of entry of material into the human body.

For DU to be inhaled, the particles must be airborne and of appropriate size. Once DU particles are deposited either in the vehicle or in the environment, they may become resuspended into the air and be inhaled and ingested. Resuspension may be caused by various mechanisms, some natural and some by human interaction.

The OSAGWI Interim Environmental Exposure Report, 4 August 1998[1], examined a variety of exposures that occurred during and after the Gulf War. The OSAGWI classified possible DU exposures into three levels, encompassing 13 separate scenarios. The three levels and 13 specific scenarios are summarized below in Table 4. These exposure levels are initial estimates about the extent of the exposures. Each level provides a description of the activity and the personal protective equipment (PPE) used, if any.

During the Gulf War, U.S. tanks mistakenly fired DU armor-piercing rounds into other U.S. combat vehicles, exposing surviving crewmen in those vehicles to wounds from DU fragments and/or inhalation and ingestion of DU particles. During these fratricide or "friendly fire" incidents, personnel rushing to evacuate and rescue soldiers from damaged vehicles may have also been exposed to DU. These types of exposures constitute the OSAGWI Level I scenarios.

A second category of exposure to DU occurred after combat during recovery and maintenance operations in, on, and near vehicles damaged from fratricide incidents and fires involving DU munitions. Also classified with this group were the personnel involved in cleanup and recovery operations in the North Compound of Camp Doha, Kuwait, following the motor pool fire in which DU munitions detonated and burned. Another group of personnel include intelligence investigators inspecting DU-damaged Iraqi vehicles. These types of exposures constitute the OSAGWI Level II scenarios.

A third category of DU exposure, OSAGWI Level III, defines personnel whose exposure to DU was short-term and generally very low. These exposures may have occurred as personnel passed through and inhaled smoke from burning DU, casually handled spent DU penetrators, or briefly entered DU-contaminated vehicles on the battlefield or in salvage yards.

Table 4. OSAGWI Incident Summary

Level I	
Soldiers in, on or near a vehicle at the time it was penetrated by a DU munition.	None
Soldiers who entered U.S. vehicles immediately after fratricide incidents to rescue occupants (First Responders).	None
Level II	
Explosive Ordnance Disposal (EOD) and unit maintenance personnel who downloaded equipment and munitions from DU-contaminated vehicles to remove munitions. Received DU training.	None
Unit maintenance, service, and supply (salvage) personnel who worked in and on damaged or destroyed vehicles being processed for repair or disposal.	None
Logistics Assistance Representatives (LARs) who inspected DU-contaminated systems to determine reparability. Received DU training.	Some wore PPE***
Battle Damage Assessment Team (BDAT) members who examined U.S. combat vehicles damaged and destroyed by DU penetrators. Received DU training.	Most wore PPE
144th Service and Supply Company personnel who processed damaged equipment, including some with DU contamination.	None
Radiation Control (RADCON) team members who worked in and on the damaged or destroyed vehicles. Received DU training.	PPE
Personnel exposed to DU contamination during cleanup operations at Camp Doha.	None
Level III	
Personnel exposed to smoke from burning DU rounds at Camp Doha.	None
Personnel exposed to smoke from burning Abrams Main Battle tanks.	None

Table 4. OSAGWI Incident Summary (con't.)

Personnel who entered DU-contaminated equipment.	None
Personnel exposed to airborne concentrations of DU downwind of a vehicle perforated by a DU round, which includes personnel exposed to smoke from DU-impacted Iraqi vehicles.	None
***PPE includes surgical masks, coveralls, boots, and gloves.	

*Reference : OSAGWI Interim Environmental Exposure Report, 1998.

1.8 Overall Conclusions

The estimated exposures and intakes of DU for individuals in Levels I, II, and III scenarios during and immediately following the 1991 Gulf War were below established Federal radiation safety standards; however, some of the exposures did exceed chemical guidelines that are intended to be protective. Because they are meant to be protective, if the guidelines are not exceeded, it can usually be stated with confidence that adverse health effects are not expected to occur. However, because safety factors are built into the guidelines to ensure protection of the most sensitive individuals, exceeding a guideline does not necessarily imply that adverse health effects will result nor can the degree of a potential effect be accurately predicted. When an exposure has occurred and a guideline has been exceeded, the health of the exposed individual is monitored, as is being done in the case of Gulf War veterans with the greatest potential for DU exposure (embedded DU fragment patients being followed by the VA).

The ionizing radiation (any mention of radiation risk will involve ionizing radiation risk) exposures and intakes of DU by veterans during the Gulf War are below the current Nuclear

Regulatory Commission (NRC) and the Occupational Safety and Health Administration (OSHA) radiation safety standard of 5 rem in any year, based on two DU munition perforations into the Crew Compartment. However, a potential exists for exceeding the safety standard for personnel in, on, or near (within 50 meters) a vehicle at the time of perforation depending on the number of large caliber DU munition penetrations and exposure durations. Since there are no test data for multiple penetrations, simply multiplying the single penetration data by the number of penetrations may not be appropriate. Many factors will influence the actual DU aerosol concentration including resuspension, the time between perforations, munition type, vehicle type, armor type, perforation angle, as well as perforation location. Since no appropriate test data are available, it has been assumed, based solely on professional judgment, that the intake via inhalation and indirect ingestion of DU for two penetrations may be a factor from 1.5 to 3 times greater than a single perforation. These factors need to be validated in future tests.

1.9 Specific Conclusions

Based on this assessment of the potential exposures and qualitative characterization of health risk to military personnel potentially exposed to DU during service in Southwest Asia, USACHPPM makes the following conclusions concerning the three exposure levels established by OSAGWI:

Level I. These personnel internalized DU through various potential routes of exposure: inhalation, ingestion, and wound contamination and embedded fragments. Some of these personnel may have internalized DU through multiple routes. The potential exists that they may have internalized DU in excess of the annual occupational radiation and chemical exposure

standards. Based upon medical evidence to date, the amounts internalized by these personnel were not sufficient to adversely affect their present health. However, the amounts estimated are high enough that continued medical follow-up of these individuals is warranted. The DOD originally partnered with the VA in establishing a voluntary, medical follow-up program for Gulf War veterans at the Baltimore VA Medical Center in 1993. This medical follow-up program continues to this day.

Levels II and III. Exposure estimates to Levels II and III personnel are at least an order of magnitude below the annual occupational radiation and chemical exposure standards. These personnel internalized DU primarily through inhalation and ingestion. Based upon medical evidence to date, the amounts internalized by these personnel were not sufficient to affect either their present or future health.

PART II: HUMAN EXPOSURE ASSESSMENT AND HEALTH RISK CHARACTERIZATION

2.1 Health Risk

A health risk is generally thought of as something that may endanger health. Scientists consider health risk to be the statistical probability or mathematical chance that personal injury, illness, or death may result from some action. Most people do not think about health risks in terms of mathematics. Instead, most people consider the health risk of a particular action in terms of whether they believe that particular action will, or will not, cause them some harm.

2.2 Health Risk Characterization

A health risk characterization can be quantitative or qualitative. A quantitative risk characterization is expressed either as the probability of a health effect per unit of dose received or as the ratio of the expected exposures to acceptable exposures. A qualitative risk characterization is defined in general rather than mathematical terms. This document contains a qualitative health risk characterization and is not a dose reconstruction.

In addition to being quantitative or qualitative, health risk characterizations can be retrospective or prospective. Retrospective analysis typically involves past exposures to individuals who were exposed to radionuclides, as in the case of the Chernobyl reactor incident, while prospective analysis involves scenarios that have not yet occurred.

When assessing chemical or radiological risk, prospective risk characterizations can be qualitative and/or quantitative. However, chemical risk is not generally quantitatively characterized retrospectively. This is because the necessary toxicity benchmark values and methodology do not exist to retrospectively quantify chemical risk following a battlefield exposure. Additionally, the methodology currently in place for quantitative risk characterization is not intended for retrospective studies following a chemical exposure. This is because the guidelines used for the process, as well as occupational exposure guidelines, are intended to be protective. Because they are meant to be protective, if the guidelines are not exceeded, it can usually be stated with confidence that adverse health effects are not expected to occur. However, exceeding a guideline does not necessarily imply that adverse health effects will result, nor can the degree of a potential effect be accurately predicted. When an exposure has occurred and a guideline has been exceeded, the health of the exposed individual should be monitored. The estimated chemical exposures and radiological doses may have exceeded peacetime guidelines (Appendix K) for some of the OSAGWI Level I individuals. Therefore, the health of the Gulf War veterans with the greatest potential for DU exposure is being monitored through the VA.

2.3 Human Exposure Assessment and Health Risk Characterization Process

The human exposure assessment and health risk characterization process involves evaluation, integration, and analysis of hazard identification data; estimation of the source term; estimation of exposure; and intake of a contaminant (upper and lower boundary). Then the upper-bound value is used to estimate the nature and likelihood of adverse human health effects as a result of exposure and intake of the contaminant. The degree of health risk due to inhalation, ingestion, or

injection (wound) of DU particles depends upon numerous and varying exposure factors. The amount of DU residue transported, transferred, or resuspended depends on several parameters including the amount of material deposited, the nature of the deposition surface, the time since deposition, the chemical properties of the deposited material, and the manner of the physical disturbance.

2.4 Methodology

Depleted uranium is a heavy metal that is slightly radioactive. Therefore, when DU is internalized, it is a potential chemical and radiological health hazard. The fate of internalized DU in the human body depends on the particle size, morphology, chemical form, physical form, and solubility in lung fluid.

Depleted uranium present in a battlefield situation is expected to primarily consist of DU metal and its oxides: DUO_2, DUO_3 and DU_3O_8 which will be discussed in this section.

All uranium isotopes of a particular chemical compound have identical chemical properties and will exert the same chemical effects on the human body. However, the solubility of the inhaled DU residue determines how rapidly it is cleared from the respiratory tract. The International Commission on Radiological Protection Publication No. 30 (ICRP-30) has established respiratory tract clearance classifications for inhaled material that are based on a contaminant's solubility in lung fluid and relates its clearance pathway from various compartments of the modeled respiratory tract (ICRP-30)[5]. Three solubility classes are used to describe the

respiratory tract clearance classification: Class Y (years), Class W (weeks), and Class D (days)[6]. (See Appendix J.)

In 1993, ICRP adopted the new respiratory tract model for radiological protection in ICRP-66[7]. In this publication, the term dissolution or absorption rate replaced the term respiratory tract clearance rate. The human body will absorb most soluble compounds from the respiratory tract within hours or days (Type F for fast absorption, formerly called Class D). The human body will solubilize and absorb moderately soluble compounds in weeks (Type M for moderate absorption, formerly called Class W). These compounds include non-oxide compounds as well as Uranium Trioxide (UO_3). The human body will solubilize and absorb relatively insoluble compounds in years (Type S for slow absorption, formerly called Class Y). These compounds include Uranium Dioxide (UO_2) and Tri-Uranium Octaoxide (U_3O_8) (ICRP-71)[8]. This assessment uses these solubility characteristics for the DU oxides that are formed during impact, perforations, or fires. The DUO_3 is formed after time and weathering in the environment. (See Appendix J.)

Information gathered during the process of identifying health hazards is used to estimate the exposure and intake for specific scenarios involving DU. The exposure rate from the source of DU, the potential routes of exposure, the exposure duration, the frequency of exposure, and the individuals at risk are all factors for consideration.

The technical aspects of a health risk characterization involve several steps[9]:

- Source term analysis
- Pathway analysis
- Exposure, intake, and dose assessment
- Human health risk characterization
- Uncertainty and sensitivity analysis

2.4.1 Source Term Analysis

Source term analysis consists of estimating the amount of material, for example, in grams or curies (Ci), released to the environment. The initial source term is the amount of material driven airborne at the incident source. The inhalable fraction of the source term is the amount of material driven airborne at the source that can reach the respiratory tract (see Appendix J).

The airborne pathways (inhalation and indirect ingestion) are of primary interest for scenarios involving DU exposures[10]. The main factors that influence the degree of the health hazard from airborne particles are: (1) the amount internalized, (2) the site of particle deposition in the respiratory tract, and (3) the fate of the particles in the respiratory tract and the human body.

- The deposition site within the respiratory tract depends on the particle size of the inhaled aerosol.

- The fate of the particles within the human body depends primarily on their physical and chemical properties and the physiological conditions of the lungs (for example, asthma or effects of smoking).

See Appendix D for a discussion on inhalability and respirability of airborne particles and adjusting the Annual Limit on Intake (ALI) for various particle-size distributions.

See Appendix F for a discussion of calculational methodologies.

See Appendix K for a discussion of the exposure limits for uranium.

See Appendix J for a discussion on the respiratory tract models, intakes, and DU transport through the kidney.

The ingestion of material is the next most important exposure pathway following inhalation.

The ingestion pathway is composed of indirect, direct, and secondary routes of entry. Indirect ingestion includes those particles that have been deposited in the respiratory tract and removed by mucoecilliary clearances and transported to the gastrointestinal (GI) tract. Direct ingestion is the consumption of contaminated water, soil, or foodstuffs. Data were not available pertaining to the potential contamination of water, soil, and foodstuffs. Therefore, the direct ingestion route of exposure is not considered in any portion of this exposure assessment/risk characterization. Secondary ingestion includes the hand-to-mouth transfer of a contaminant to the GI tract.

The ICRP has established GI tract transfer coefficients for many radionuclides based on their respiratory tract clearance classification. These transfer factors for uranium are published in ICRP-69 [11] and Appendix J. The material that is not transferred to the blood, about 82 percent to 99 percent, is excreted in the feces.

The DU oxides that are formed, DUO_2 and DU_3O_8, are considered insoluble or Class Y [or Type S (slow)]. However, DUO_3 is considered Class D [or Type F (fast)], since time and weathering may have occurred in the environment. The ICRP considers UO_3 to be Class W [or Type M (medium or moderate)]. In this report, the lung solubility of DUO_3 used is Classes D or W (or Type F and Type M, respectively), because data have been taken from published munitions developers test data. Because many of the targets (or target areas) were involved in several DU penetrator tests, over a period of time, it is possible that there was a mixing of different oxidation states of the DU residue. Therefore, the solubility studies or dissolution rate studies done for these tests may have a greater uncertainty associated with the measurement results than is normally expected.

The exposure from the inhalation pathway will dominate the intake or internalization of DU, excluding any exposure from embedded DU fragments. The airborne source term may be estimated by the following five-component linear equation[12] [see Appendix E and the Department of Energy (DOE) Handbook-3010-94]:

$$\text{Source Term} = \underbrace{\text{MAR} * \text{DR} * \text{ARF} * \text{RF}}_{\text{Initial Respirable Source Term}} * \underbrace{\text{LPF}}_{\text{Initial Source Term}}$$

Where:

MAR = Material-at-Risk (Ci or grams)

DR = Damage Ratio

ARF = Airborne Release Fraction (or Airborne Release Rate for continuous release)

RF = Respirable Fraction

LPF = Leakpath Factor

The initial source term and initial respirable source term are products of the first three factors and first four factors, respectively. A reduced source term after a subsequent stage of deposition or filtration is a product of the initial source term multiplied by the LPF of the specific stage. There can be several LPFs in an armored vehicle [for example, environmental control (EC)/nuclear, biological, and chemical (NBC) System in operation, some or all of the hatches open, or the vehicle being penetrated]. Where multiple leakpaths exist, their cumulative effect is often expressed as one value, that is the product of all leakpath multiples.

The ARF and RF values are assessed separately for sources of airborne material generated during perforation, fire or explosion of DU munitions, and surface contamination. All of the above factors may need to be determined for particulate releases. Furthermore, the solubility of the airborne material in the respiratory tract may be influenced by the particle-size distribution.

DU-Aerosol Characteristics. Depleted uranium metal does not readily produce particles in the size range that can be transported long distances and that can be inhaled into the respiratory tract. The predominant mechanism to form smaller particles from DU metal is oxidation**.**

For each oxide generated, the conditions of the oxidation process influence both the DU particle-size distribution and the potential solubility in the interstitial lung fluid of an exposed individual. Once DU particles are deposited either in the vehicle or in the environment, they may again become resuspended into the air and be inhaled and ingested. Resuspension may be caused by various mechanisms, both natural and man-made. The amount of DU that is resuspended will depend on several parameters, including the nature of the deposition surface, length of time after deposition, chemical and physical properties of the deposited material, and the manner of the physical disturbance.

A wide variety of deposition surfaces may be encountered when evaluating DU resuspension. For "interior" deposition such as inside a vehicle or building, the deposition surfaces tend to be smooth, and deposited particles are less likely to become firmly attached, except for oily and dirty surfaces. For "exterior" or environmental deposition, many types of surfaces such as grass, sand, open fields, and streambeds may be involved. Due to the variety of surfaces that may be encountered and the type of stresses that may be applied, estimating the resuspension factor is complex. Given the complexity of the interaction among the various factors influencing resuspension, there is a wide range of uncertainty in developmental test results for DU munitions. Therefore, the results of such previous studies should be considered qualitative, and the data must be used with discretion.

Military Scenarios Involving DU Aerosol Production. In a military action or maneuver, the following situations represent the most logical initiating circumstances in which DU could conceivably become aerosolized, Parkhurst et al., (1995b):

Fires

- In a tank containing DU munitions
- In a tank containing DU armor (this is unlikely given the design of the Abrams Tank)
- In a tank containing both DU armor and munitions
- In a vehicle or other structure hit by DU munitions
- In an ammunition storage area (that is, bunker, munitions trailer, or open pallet storage) involving DU munitions

Impact/Perforation by DU

- At an armored target
- Breaching a target containing DU munitions or armor
- At or otherwise disturbing with force a DU penetrator or armor on the ground (for example, driving a vehicle over a spent penetrator)

Explosions

- Perforations into a vehicle carrying DU munitions that explode and set off the propellant in the munitions, similar to a fire.

- Exploding munitions (DU or other type) in a disabled vehicle that has DU residue present.
- Explosion in an ammunition storage area (that is, bunker, munitions trailer, or open-pallet storage) involving DU munitions.

In any of these scenarios, the resulting DU components are likely to be in the form of DU metal or DU fragments, intact or fused with other metals, or DU oxide powder. The DU oxide (for example, DUO_2 or DU_3O_8) is the portion that may become aerosolized under certain conditions and is most likely to be formed when the metal is exposed to open flames and when impacted against hard targets. The DUO_3 will be formed if DU is allowed to corrode in the environment, Parkhurst et al., (1995b).

Environmental oxidation or corrosion of metallic fragments may contribute to DU-aerosol production. DU fragments solubilize at the rate of about 1 percent per year when exposed to environmental conditions[13]. The rate of solubilization is dependent upon climatic conditions. The potential DU inhalation hazard is from the DU residue (oxides) formed by the fire or impact or perforation. The amount of DU oxidized depends on the circumstances.

Factors that affect the DU-aerosol generation during a fire include the type of fuel, the number of rounds, the type of munitions, and the type of structure housing the munitions. Some of the factors that affect the aerosol generation during impact include type of munitions, velocity of the penetrator, hardness/thickness of the target, angle at which penetrator strikes target, and whether perforation of the target occurs.

Based on a review of field test data, only a small percentage of particles generated during a fire are small enough to be entrained in the plume by the convective flow induced by the heat of reaction in the metal. As a result, only a fraction of the generated-DU oxides can be suspended without violent explosions. The solubility in lung fluid of this fraction of DU oxide is usually low, which means that many of the particles remain in the respiratory tract for more than 100 days, Parkhurst et al., (1995b).

After DU oxide particles have been deposited on the interior surfaces of a vehicle, they could be resuspended and released from openings such as opened hatches. Resuspension of DU oxide particles could occur by the entry of personnel into the vehicle causing air displacement, by moving or lifting personnel or equipment, as well as by stepping in DU residue, Parkhurst et al., (1995b). Also, damaged vehicles recovered from the battlefield may undergo inspection or repair. Repair activities such as cleaning, welding, cutting, or grinding may generate or suspend DU oxide.

The data contained in Parkhurst et al., (1995b) reported that in a fire, the onset of oxidation is typically limited to areas with sustained fire temperatures. Once started, oxidation of the DU continues for some time even after the intensity of the heat source subsides, until the DU returns to ambient temperatures. However, as oxygen becomes deficient and temperatures fall, oxidation may cease on its own. DU oxides formed by fire are typically a dull, charcoal-colored powder. DU fragments embedded in a target or laying loose on other surfaces could be engulfed in a fire, producing black ash or powder. In theory, oxidation may also occur in a much shorter timeframe at the surface of the DU penetrator that becomes “scorched” by the fire. The resulting

surface scale-like oxide appears to be more firmly attached and less likely to be dispersed than the oxide powder, Parkhurst et al., (1995b). Oxide produced in a fire is more likely to be dispersed by explosions of undetonated ordnance rather than from fire. The plume may carry off some DU oxide if the fire lasts a long time and is sufficiently strong. Explosions from a fire may propel intact DU components away from the high temperatures, reducing the opportunity for oxidation, Parkhurst et al., (1995b).

In an impact and perforating event with a target dense enough to slow down or stop the projectile, DU metal alloy can fragment and produce spall that, if sufficiently heated, can oxidize quickly generating particulate matter. In certain instances, all of this material may remain "captive" within the target until dispersed by outside forces. In cases where the projectile penetrates the target partially or completely intact, spall and DU alloys are the most likely remnants left behind at the target's entrance and exit holes, Parkhurst et al., (1995b).

If DU oxide is dispersed outside vehicles in the open air of a battlefield from an assortment of circumstances, resuspension of deposited material is likely if there is vehicle and foot traffic in the area. Entering perforated or burned vehicles is a more direct way to encounter aerosolized DU. Personnel entering a vehicle or handling equipment with oxide residues may disturb particulate material thus causing resuspension.

Both specific incidents and general combat activities could generate conditions where DU could be internalized by inhalation and ingestion. For combat activities, DU oxides may be present in the form of residual aerosol or surface contamination in armored vehicles that have been

perforated by DU penetrators or DU-armored vehicles penetrated by other projectiles. Vehicles that have experienced fires that ignited DU munitions in the vehicle may have some residual DU-oxide airborne and as surface contamination. Personnel entering these vehicles for rescue or inspection activities could be subject to some level of airborne particles of DU oxide. The resuspension of surface contamination or powder residue could result from the entry activities alone. Inspection or repair activities such as cleaning, welding, cutting, or grinding may generate or suspend particles, Parkhurst et al., (1995b). The following specific scenarios (extracted from Parkhurst et al., 1995b) offer more detail on credible DU aerosol generation, dispersion, and resuspension making DU oxide available for inhalation and indirect ingestion.

Fires. Fires in vehicles uploaded with DU munitions (and within storage buildings) can oxidize the DU metal. The munitions will be "cooked-off", thus exposing the metal surface at high temperatures to the atmosphere in the interior of the vehicle. Burning of the propellant in the munitions does not consume atmospheric oxygen, since the propellant supplies its own oxygen, and combustion of the propellant occurs so rapidly that it results in little, if any, oxidation of the DU metal. If other combustible materials (for example, oils, grease, fuel, cloth, paper, cardboard, or wiring insulation) are ignited, the exposed-DU alloy may oxidize if adequate oxygen is available. The reactions (burning of combustible materials and oxidation of DU metal) compete for the available oxygen. Flaming combustion requires oxygen concentrations in excess of 15 percent, but smoldering combustion can continue at very low oxygen concentrations. Oxidation of DU metal can consume all the oxygen available, but the rate is greatly reduced as oxygen ions within close range of the DU metal are reduced.

The results of field tests show that few of the particles generated by fire are small enough to be entrained by the convective flow induced by the heat of reaction in the metal. As a result, only a limited fraction of the generated DU oxides can be suspended without violent explosions. The solubility of the oxide formed by fire is typically low, generally about 93 percent to 100 percent Class Y (or Type S) and 0 to 7 percent Class W (or Type M). Airborne particles would tend to be carried to the cooled surfaces, such as the sides of armored vehicles. These large metal surface areas lose heat to the atmosphere by convection and radiative transfer, by thermophoresis (heat flux to cooler surface), and by diffusiophoresis [mass flux of vapors (for example, water, unburned pyrolysates) to the cooler surfaces]. With the large surface-to-volume ratios in such vehicles, the heat loss to the atmosphere by these processes may be substantial during some phases of the fire. The deposition of fire combustion products (for example, soot, cracked but unburned organic materials, and water) will make deposited DU oxide particles adhere to surfaces by providing a "sticky" surface and by sealing the particles to the surface by subsequent deposition, Parkhurst et al., (1995b). After loss of particles to the interior surface of the vehicle, aerosols could be released from openings such as perforations and opened hatches. The plume would be buoyant but partially cooled by the heat transferred to the walls.

Without the driving force of a fire and fire products, agglomeration will occur at a slower rate, Parkhust et al., (1995b).

Vehicles Perforated by Projectiles. Heavily armored vehicles, such as tanks perforated by DU munitions or vehicles containing DU armor, may generate aerosols by the oxidation of DU metal during or following passage of the penetrator through the armor. Because armor thickness and

design vary on the vehicle, the location of the impact will affect the amount of interaction between the penetrator, the armor, and the production of DU residue and aerosols. The more resistant the armor, the more aerosol is generated. This in-turn will affect the amount of DU deposited in the vehicle's interior provided perforation occurs. The solubility of the DU oxides formed by impact with a hard target is generally in the range of Class D/W (or Type F/M) (17 percent to 43 percent) and Class Y (or Type S) (57 percent to 83 percent). The highest radiological dose would be estimated based on 83 percent insoluble oxide (Class Y or slow absorption) and 17 percent soluble oxide (Class D/W or fast/moderate absorption), and the highest chemical exposure would be based on 43 percent soluble oxide and 57 percent insoluble oxide. However, the DOD DU munitions test data that produced the 43 percent soluble (Class D/W or fast/moderate absorption) and 57 percent insoluble oxide data (Class Y or slow absorption) are not believed to be representative of the OSAGWI Gulf War scenarios, since multiple DU penetrator tests over an unspecified time period were performed on the same target (or target area). The DU oxides formed during the earlier tests would continue to oxidize and become more soluble in addition to being co-mingled with the oxides formed during the latter tests. Therefore, the 43 percent soluble oxide value is not used in any DU exposure and intake estimates.

Unpublished data[14] were presented at a Depleted Uranium Working Group Meeting at the U.S. Army Armament Research, Development and Engineering Center (ARDEC) in July 1997 concerning solubility and particle-size distribution of DU. A study initiated by the U.S. Army Aberdeen Test Center generated these data. Studies of hard-target impacts indicated the percentages for the three solubility classes as being the following: Class D 17 percent, Class W

9 percent, and Class Y 74 percent. The chemical form and specific dissolution rates were not presented. The particle size range studied extended from < 1 μm to 10 μm AED.

Greater potential for aerosol resuspension will occur if the penetrator fragments and DU residue remain in the vehicle's interior. Generated aerosols could be released to the ambient atmosphere through openings such as hatches and perforations(s), thereby, reducing the airborne concentration within the vehicle. Deposition and surface adsorption will occur if the aerosol is not released. This will result in changes of the particle-size distribution and mass over time, Parkhurst et al., (1995b).

Lightly armored vehicles may not present a sufficiently hard target to result in a large amount of shearing of the penetrator's surface and the production of airborne particles. As a result, aerosol production with this type and softer targets would be limited, Parkhurst et al., (1995b).

Entry into Contaminated Vehicles. Personnel entering a vehicle involved in a fire or perforated by DU munitions for rescue operations, equipment recovery, and/or curiosity or souvenir collection could potentially resuspend DU particles from residue of oxide powder. These activities could cause air turbulence that could suspend powder deposited on surfaces, especially on the floor or horizontal surfaces. Examples of these activities may include the opening of hatches that may create positive or negative pressures within the vehicle, the entering of personnel resulting in air displacement, the moving or lifting of personnel or equipment, and the stepping into residue of powder resulting in mechanical entrainment, Parkhurst et al., (1995b).

Inspection and Repair Activities on Contaminated Vehicles. Damaged vehicles recovered from the battlefield may undergo inspection and/or repair. Cleaning techniques such as abrading, grinding, or simply dry wiping could suspend surface contamination on the area being cleaned. Suspension via dry wiping is relatively small compared to abrading or grinding. Repair techniques such as cutting and welding in which a torch is used to melt the materials may suspend surface contamination by entrainment in the fume flow (the melting temperature of DUO_2 is 1,132° Centigrade (C), Parkhurst et al., (1995b).

Routine Combat Activities. The DU penetrators that perforate an armored vehicle but do not penetrate the DU armor may be heated by friction as the metal is deformed by the perforation. If the temperature is adequate and the penetrator is quickly buried in soil, the DU metal may continue to oxidize for some period of time after burning due to the insulating effect of the soil. To date, no observations of this behavior on any Army test ranges have been made. Subsequent activities over the soil location such as movement of tracked and wheeled vehicles (for example, tanks, infantry fighting vehicles, and artillery) and digging may expose the oxide to the ambient atmosphere. Troops closely following or passengers in vehicles behind the initial vehicles could be exposed to resuspended oxide powder for varied time periods, Parkhurst et al., (1995b).

2.4.2 Pathway Analysis

Pathway analysis (or modes of human exposure) examines the method by which an individual is exposed to material. The individual can be exposed externally (to penetrating radiation) or

internally to DU or both. Inhalation of DU and embedded fragments in wounds are the most important modes of internal exposure. The principal routes of entry into the body are:

- Inhalation
- Indirect ingestion (swallowed sputum with inhaled, larger particles)
- Secondary ingestion (hand-to-mouth)
- Direct ingestion by consumption of contaminated foodstuffs, soil, and water
- Embedded DU-fragments (injections)
- Wound contamination

Depleted uranium is a heavy metal. Unlike the radiological characteristics of an element, the chemical characteristics of a heavy metal are independent of its isotopic form. All isotopes of a particular uranium compound exhibit the same chemical behavior and possess the same physical characteristics; however, the radiological properties are different. Both the impact of the DU penetrator on a hard target and the burning of DU produce DU dusts or aerosols. The DU metal oxidizes to a series of complex oxides. The uranium compounds present in a military environment include DU metal and its oxides: DU_3O_8, DUO_2 and DUO_3.

The solubility of DU in lung or body fluids depends on the chemical form. The inhaled DU oxides, DU_3O_8 and DUO_2, are typically classed as insoluble or respiratory tract clearance Class Y (or Type S). This means that the particles reside in the lungs for years. However, DOD studies suggest that DU_3O_8 and DUO_2 when formed during impact events and fires may be more soluble than reported in the technical literature. Inhaled DUO_3 is soluble or moderately soluble

and is clearance Class D/W (or Type F/M). Based on the differences of solubility, the chemical and radiological properties of DU have been considered during the health risk characterization.

2.4.3 Exposure and Intake Assessment

The exposure assessment and intake of DU and the resultant health risk characterization use available data on the perforation of hard targets and fires involving DU munitions; the concept of aerosol generation; and the knowledge of biological and pharmacokinetic behavior of DU in the body to determine the likelihood of adverse health effects in an exposed individual.

The exposure and intake of a radionuclide by inhalation and ingestion as well as the chemical intake are calculated in the same manner. The only difference is that the exposure and intake of a radionuclide is not divided by body weight or averaging time. For radionuclides, the dose conversion factors (DCFs) already have a reference body weight [70 kilograms (kg)] included allowing the dose to be expressed in energy deposited per gram of tissue.

The intake in milligrams (mg) or μCi of an airborne contaminant by inhalation and indirect ingestion is the product of the airborne concentration in milligrams per cubic meter (mg/m^3) or $\mu Ci/m^3$, breathing rate (or ventilation rate) (1.2 m^3/hr, 1.668 m^3/hr, or 3 m^3/hr), the exposure duration (hr), and exposure frequency. Multiply the intake (μCi or mg) by the DCF (rem/μCi or rem/mg) to calculate the internal dose from this intake. Because systemically incorporated radionuclides can remain within the body for long periods of time, the integrated internal dose is

best expressed in terms of the committed effective dose equivalent (CEDE) over the 50-year period following the intake of the contaminant. (See Appendix J.) The result of this calculation is the CEDE in units of rem. Appendix F provides a discussion of the dose calculational methodology.

The practical methods or models for calculating the intake of DU (resulting from inhalation and ingestion) are discussed in Appendix F. The four modes of intake considered (either alone or in combination) are—

- Intake of the material that is airborne in the vehicle at the time of tank compartment perforation.
- Intake from resuspension of surface contamination due to personnel movement and mechanical action within the vehicle.
- Intake from resuspension of surface contamination due to personnel or vehicular movements outside the vehicle.
- One or more intakes by the ingestion of DU particles from hand-to-mouth transfer and from contaminated foodstuffs, soil, and water (see Appendix F).

Appendix G provides the organ or tissue weighting factors. Appendix H provides the radiation Quality Factors (Q) and the radiation Weighting Factors (W_R). Appendix I discusses the resuspension calculational models. Appendix J discusses the respiratory tract models, computer dosimetry models, and transport of DU through the kidney.

PART III: TECHNICAL LITERATURE REVIEW

3.1 Summary of Reviewed Experimental Data

The aim in evaluating DOD published DU-aerosol test data was to determine if there were adequate data to estimate the exposure and intake of DU by soldiers in, on, or near vehicles that had been damaged by DU penetrators through fires or projectile impacts or perforations and for the First Responders to these vehicles. This section summarizes the reviewed experimental data of DU oxide particulate characteristics, especially those documented in reports prepared by the Pacific Northwest National Laboratory (PNNL) and Los Alamos National Laboratory in support of DOD initiatives. An emphasis is placed on defining a range based on experimental data gathered to date and factors that could cause a parameter to be outside this range. An evaluation was made of the quality of the data for modeling use and areas were identified in which more information is needed for each of the three main causes (fire, impact or perforation, and explosion) of DU aerosol production.

Data from the Fliszar et al., (1989) report form the basis for making assumptions and estimating the exposures and intakes of DU. These intakes were used to calculate radiation dose to the organs and whole body and chemical concentration in the kidney.

3.1.1 Variable Factors

Meteorology. The weather used for transport modeling may either be based on actual meteorological data, onsite observations, or default values. With the exception of an accident at a well-characterized testing facility, most accident situations will not occur where there are convenient meteorologic data for the time of the incident or for the time since the incident. Modelers may choose input parameters that best describe the general weather conditions as well as some weather extremes.

In many cases, the conservative estimate uses the diffusion Pasquill Stability Class F or G to simulate minimum dispersion and maximum deposition of material within 50 meters of the target. In other cases, the downwind dispersion is most critical to the analysis. An unstable or windy condition may be used instead to assess the possibility of offsite populations receiving substantial exposure to the aerosol plume. Surface terrain has an effect on meteorology, deposition, and resuspension and again may be modeled based on site knowledge using standard defaults or extremes. Selection of these factors is left up to the modelers and is not addressed further.

A munition impact on DU armor, a perforation by a DU penetrator, or an explosion involving oxidized DU will result in an instantaneous release in the form of a puff. The instantaneous puff release will result in a cloud of DU at an elevated temperature. Because of the formation of this cloud, the Gaussian puff trajectory model is more appropriate than the plume model to describe movement of DU and other material downwind as it spreads from the point of origin. The

instantaneous puff release will be followed by a much slower release rate, which will depend on the conditions of the debris following DU penetrator impact, Parkhurst et al., (1995b).

For the impact, perforation, or explosion scenarios, the transport model should be the Gaussian puff trajectory model. For fire scenarios, the transport model should be the Gaussian plume.

Airborne Release Fraction (ARF)

Fire ARF. Unless more realistic information is known from observations and measurements, the total quantity released, or source term, may be calculated as the total inventory involved in the incident multiplied by the probable fraction oxidized and suspended or by the fraction aerosolized.

The following studies, mostly involving palletized munitions, evaluated the generation of aerosols produced by fires:

- Gray (1978)
- Mishima et al., (1985)
- Haggard et al., (1986)
- Mishima et al., (1986)
- Fliszar et al., (1989)

- Parkhurst et al., (1990)
- Parkhurst et al., (1999)

In Parkhurst et al., (1999), a BFV uploaded with a complement of 25mm cartridges was set on fire to evaluate the consequences of DU oxidation and environmental dispersion during a catastrophic fire. This test provided information to better understand recovery procedures following such an incident. A non-functional and non-armored but structurally sound vehicle hull was used. No fire suppression equipment was used in this study. For safety reasons, training rounds were used instead of high explosive cartridges, and the missiles present were defused or inert. As a result of these actions, the test could not fully simulate an actual burn in a fully loaded condition. However, it did maximize the potential for DU oxidation and environmental dispersion of the oxide (Parkhurst et al., 1995b; Parkhurst et al., 1999). Air monitors and deposition trays were set up at various distances from the vehicle to intercept DU in the fire plume.

The fire fully engulfed the BFV and cooked off the cartridge propellant and rocket motors, which were responsible for some explosions. Trace amounts of DU (maximum of 5.5×10^{-15} µCi/cm^3 or 1.4×10^{-5} mg/m^3) were found in several of the air samplers most directly in the path of prevailing winds. The deposition trays [100 square centimeters (cm^2)] directly adjacent to the vehicle showed the most DU with a maximum of 1.65 mg. Other deposition trays in the path of the dominant wind direction also collected some DU with the largest amount, 0.0012 mg, collected at 100 meters. It appeared that the explosions, rather than the fire, were responsible for

suspending oxide in the wind plume and that the suspended material deposited rather quickly (within a short distance).

Table 5 summarizes data related to palletized fires involving DU munitions.

Table 5. Aerosols from Palletized Fire Tests

DU Oxide Composition	Solubility & Dissolution Half-Time ($T_{1/2}$) Class	Particle Size	Airborne Fraction	Sampling Methods	Analysis Methods	Reference
Mostly U_3O_8 Good*	96% - 98% Class Y, 2% – 4% Class D Good*	= 0.2% <20 μm AED; = 0.07% <10 μm AED Good*	Worst case: 0.6% not recovered and may have become airborne Somewhat uncertain*	Air samples, mass recovery; monitoring meteorological conditions	Gamma spectro-analysis, x-ray diffraction, solubility in interstitial lung fluid; sieves, liquid sedimentation, and particle morphology	PNL-5928; Haggard et al., (1986)
Not determined, but assumed to be U_3O_8	96% - 98% Class Y; 2% – 4% Class D Good*	= 0.2% <20 :m AED; = 0.07% <10 μm AED Good*	=0.2% small enough to be suspended Good*	Visual observation and repeat of conditions from 120mm tests	Deduction based on similarities to tests on 120mm	PNL-6084; Mishima et al., (1986)
35% DU oxidized, all oxide U_3O_8 Fair to Good*	93% Class Y : $T_{1/2}$ = 240 days 7% Class W Good*	0.1% - 0.2% oxide had an AED <10 μm, 5% < 20 μm; nonspherical and crystalline Good*	Not measured	Air sampling and deposition trays to collect airborne oxides from external ammunition fire	Mass balance, sonic sieve, x-ray diffraction, solubility in simulated lung fluid. Same as above.	PNL-7232; Parkhurst, et al., (1990)

*Represents subjective assessment by the authors of this report.

In the Parkhurst et al., (1999) BFV Burn study, more than half of the DU penetrator inventory was recovered fully or nearly intact. Some of the remaining penetrators were buried in the pools

of moltened aluminum. Instrument readings and visual observations clearly showed that oxide had also been formed. Some oxide even coated the aluminum-covered BFV treads. Most of the remaining oxide was probably mixed with the ash. One nearly pure pile of oxide was analyzed and found to be DU_3O_8. The particle size analysis determined that 6.5 percent of the DU was ≤ 3.3 μm AED and the RF was 33 percent (≤ 10 μm AED). The AED refers to an individual particle, and the activity median aerodynamic diameter (AMAD) refers to the entire particle distribution. The AMAD was 13.3 μm. The DU residue was entirely insoluble in Class Y (or Type S), with a dissolution half time greater than 100 days.

During the recovery portion of the test, explosive demolition of the hull was used to split it into smaller parts for disposal. Each explosion briefly suspended DU oxide/ash mixture. Air monitors and deposition trays set around the vehicle collected particulates during these events. Tables 6, 7, and 8 summarize test data from Parkhurst et al., (1999).

Table 6. BFV Burn Test

DU Oxide Composition	Solubility, $T_{1/2}$ Dissolution Rate	Particle Size	Sampling Methods	Analysis Methods
~35% DU oxidized, all oxide DU_3O_8	Class Y > 99% Class D < 1%; $T_{1/2}$ > 100 days	6.5% ≤ 3.3 μm AED; 33% ≤ 10 μm AED; AMAD = 13.3 μm	Air monitors, deposition trays	X-ray diffraction, scanning microscopy, solubility in simulated lung fluid

Air monitoring was conducted using stationary and portable high-volume air samplers and deposition trays.

Table 7. BFV Air Monitoring
Mass of DU Collected on Filters [Micrograms (μg)] at Various Distances

Collectors	≤ 100 m	100 m	200 m	300 m	400 m
Air monitors	34 to 50	0.76 to 13	0.35 to 2.4	0.23 to 0.95	0.10 to 0.32
Deposition trays	0.0001 to 0.36	0.002 to 1.2	0.001 to 0.04	NA	NA

NA: Not Available

Table 8. BFV Air Sampling Results
Mass (μg) and Airborne Concentration (μCi/cm^3) at Various Distances

Monitor	Location		Mass (μg) (as U_{nat})	Mass Concentration (mg/m^3)	Activity Concentration (μCi/cm^3)
	Meter	Degree			
AP-3	30	315	49.9	1.4 E-5	5.5 E-15
S-1-9	100	330	12.6	4.7 E-6	1.8 E-15
S-1-23	100	75	9.81	2.9 E-6	1.1 E-15
S-2-8	200	295	2.37	8.4 E-7	3.2 E-16
S-3-5	300	300	0.95	3.2 E-7	1.2 E-16

The above results (Tables 7 and 8) are uncorrected for uranium in the background, which averages about 1.6×10^{-16} μCi/cm^3 or 2.4×10^{-7} mg/m^3. Because of the long sampling time (29 hours), the sampling results probably underestimate the maximum airborne concentration which would have occurred at the time of greatest dispersion and probably overestimate the concentration for the rest of the time. These results are below the calculated occupational limit from the U-234, U-235, U-236, and U-238 NRC derived air concentrations for Class Y (Type S) (insoluble) airborne DU of 2.0×10^{-11} μCi/cm^3 or 5.3×10^{-2} mg/m^3. The above airborne concentrations are also less than 6×10^{-14} μCi/cm^3 or 1.6×10^{-4} mg/m^3, which if inhaled continuously over a year (365 days), would result in a CEDE of 0.05 rem. A DU airborne concentration of 1.2×10^{-15} μCi/cm^3 or 3.2×10^{-6} mg/m^3 will result in a CEDE of

0.001 rem for continuous inhalation of that airborne concentration for a year. Therefore, an exposure to the highest airborne concentration in Table 8 for a year would result in a total effective dose equivalent (TEDE) of 0.005 rem, Parkhurst et al., (1999). For perspective, this value of 0.005 rem for a year could be compared to the total average annual dose of 0.1 rem received by members of the U.S. population from naturally occurring radiation, excluding radon. The TEDE to individual members of the public is limited to not more than 0.1 rem per year excluding background and radiation from any medical administration[10].

In addition to NRC limits, workplace exposure limits (40 hours per week) have been established. The OSHA permissible exposure limits (PELs) for inhalation of insoluble Class Y (or Type S) uranium compounds are 0.25 mg/m^3 and soluble Class D (or Type F) are 0.05 mg/m^3. The American Conference of Governmental Industrial Hygienists Threshold Limit Values (TLVs®) Time-Weighted Average (TWA) airborne concentration of soluble uranium Class D (or Type F) and insoluble uranium Class Y (or Type S) is 0.2 mg/m^3. Therefore, the NRC DU mass concentration of 5.3×10^{-2} mg/m^3 is below the PEL of 0.25 mg/m^3 and TLV-TWA of 0.2 mg/m^3. (See Appendix K for a discussion of exposure limits for uranium and their relevance for a retrospective evaluation of exposures and intake of a contaminant for a battlefield situation).

Table 9 summarizes field results for DU munitions fire incidents.

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Table 9. Aerosols from DU Munition Fires

DU Source	Oxidized Fraction	Chemical Composition	Particle Size	Solubility & Dissolution $T_{1/2}$ Class	Reference
105mm	None	DU metal	Penetrators intact	--	PNL-2670; Gilchrest, et al., (1978)
120mm, wooden shipping case	About 84% Good*	DU oxide – form undetermined	No measurable levels of airborne DU	> 99% Class Y	PNL-4459; Hooker, et al., (1983a)
120mm, wood	About 85% Good*	Predominately U_3O_8 Good*	0.2 wt% to 0.65 wt% < 10 μm AED < 0.1 wt% respirable	$T_{1/2}$ > 100 days > 99% Class Y Good*	PNL-5415; Mishima, et al., (1985)
120mm, metal case 105mm, metal case	About 9.5% Good*	Predominately U_3O_8 Good*	0.2% < 20 μm AED; 0.07% < 10 μm AED Particles non-spherical and crystalline	96% – 98% Class Y; 2% – 4% Class D Good*	PNL-6084; Mishima et al., (1986) PNL-5928; Haggard et al., (1986)
25mm	About 35% Good*	100% U_3O_8 Good*	0.1% - 0.2% < 10 μm AED; 5% < 20 μm AED; ~ 17% in respirable range	> 99% Class Y ($T_{1/2}$ = 240 days) ; 7% Class W Good*	PNL-7232; Parkhurst et al., (1990)
25mm/BFV	< 35% oxide and penetrators buried in molten A1; oxide mixed with ash Good*	> half of inventory recovered intact; oxide sample collected was 100% U_3O_8 Good*	6.5% ≤ 3.3 μm AED; 33% ≤ 10 μm AED; 13.3 μm = AMAD Good*	100% Class Y Good*	PNNL-12079; Parkhurst et al., (1999)

*Represents the author's subjective assessment of the quality of data.

In the Parkhurst et al., (1995b) study, fires involved munitions only. In these fires, the oxidized percent ranged from 0 to 94 percent. The percentage depended on whether DU remained in the fire or was ejected by the propellant or other explosives. The quantity of oxidized DU, that was

suspendable for a significant period of time, was likely to be 5 percent or less, Parkhurst et al., (1995b). In one instance, where oxidizing material was trapped within a vehicle hull, the particle size of the oxide generated was finer than other examples and suggests the possibility in limited circumstances of generating well over 33 percent of potentially suspendable material, Parkhurst et al., (1999).

In the Fliszar et al., (1989) study involving both DU munitions and armor, a fire ensued in an uploaded Abrams heavy tank during impact, Test 6B. Resultant downwind exposure data were collected. It was estimated that approximately 10 percent of the mass of the penetrators uploaded within the vehicle oxidized as a result of the fire. Six high-volume air samplers collected DU down range specifically from the fire at distances of 28 meters to 100 meters from the burning vehicle. The airborne concentrations measured at those distances range from 5×10^{-16} $\mu Ci/cm^3$ to 3.5×10^{-13} $\mu Ci/cm^3$ (1.3×10^{-6} mg/m^3 to 9.2×10^{-4} mg/m^3). The sampling took place approximately over a four-hour period after the fire started.

Based on field tests, the following input [Q_{MLV} is the most likely value of the source term (Q) and Q_{range} is the range of the source term] values are suggested by Parkhurst et al., (1995b) for fires involving DU:

- Q_{MLV}: 10 percent oxidized * 1 percent aerosolized = 0.1 percent of involved inventory.
- Q_{range}: 0 to (85 percent * 50 percent) = 0 to 43 percent of involved inventory.

Mishima et al., (1985) concluded that during a fire or burning about 0.6 percent by weight of the DU oxide had a respirable fraction that could become airborne. The percent of the DU oxide that was less than 10 μm AED was between 0.2 percent and 0.65 percent. According to Parkhurst et al., (1995b), the oxide formed from burning DU is only 2 percent to 4 percent soluble in lung fluid.

During the incidents that involved fires initiated by DU munitions perforation, it is believed that an undetermined quantity of DU may have been removed from the ambient air in the tank after the Halon fire suppression system activated. Data are insufficient to draw conclusions except that the DU airborne concentration would be reduced. The MLV for the percent of DU airborne concentration from fires was about 0.1 percent.

Table 10 summarizes the fire suppression equipment and method of activation. However, when activated, the effect of the fire suppression equipment on the airborne concentration of contaminants in the vehicle is not known.

Table 10. U.S. Armored Vehicle Organic Fire Suppression On-Board Equipment

Vehicle	Fire Suppression Equipment	Method of Activation	Remarks
M1 Abrams	1 ea. 7 lb. Halon Bottle	Automatic	Crew Compartment
	2 ea. 7 lb. Halon Bottles	Automatic	Engine Compartment
	2 ea. 2 ¾ lb. Hand-Held Halon Bottles	Manual	Crew Compartment
M2 BFV	1 ea. 5 lb. Halon Bottle	Automatic	Driver Compartment
	1 ea. 5 lb. Halon Bottle	Automatic	Troop Compartment
	1 ea. 7 lb. Halon Bottle	Automatic	Engine Compartment
	2 ea. 2 ¾ lb. Hand-Held Halon Bottles	Manual	Crew Compartment

Reference: ARDEC, May 1998, p 4-11.

***Hard-Target ARF*.** The following studies have evaluated the generation of aerosols produced by hard-target impact or perforation:

- Glissmeyer et al., (1979)
- Chambers et al., (1982)
- Wilsey and Bloore (1989); Fliszar et al., (1989)
- Parkhurst et al., (1990); Jette et al., (1990); Parkhurst et al., (1994b)
- Parkhurst et al., (1995b); Gilchrist et al., (1999)

In the Glissmeyer et al, (1979) study, one of the first impact tests was performed. They concluded that up to 70 percent of the DU penetrator's mass was aerosolized when it hit but did not penetrate a hard target. This value was back calculated from observed cloud data, and according to the authors, may be an overestimation due to the method used to estimate the aerosolized fraction. A number of other tests indicate that aerosol levels produced when perforation occurs are considerably lower. In a test conducted by Jette et al., (1990) and reported in Parkhurst et al., (1995b), it was postulated that less than 18 percent of the penetrator was aerosolized and that 24 percent to 43 percent of the respirable dust was soluble in lung fluid. This postulation was based on data from real-time continuous monitors. The percent aerosolized from hard-target impacts ranges from 10 percent to 37 percent. The MLV is 18 percent, which is the value used in this report for the OSAGWI Level I scenarios. For soft-target impacts, the percent aerosolized ranges from <1 percent to 10 percent.

In the Fliszar et al., (1989) study, hard impacts of DU armor in an Abrams heavy armor tank by various munitions were performed. Air samplers were used to measure the amount of airborne DU in the turret compartment and downwind. The personal air samplers in the tank automatically shut off anywhere from the time of impact up to a few minutes after perforation of the Crew Compartment in Test 5A, thus causing uncertainties in the data (see Part IV). Table 11 summarizes DU collected by air monitoring for all seven of the Fliszar et al., (1989) tests involving the same Abrams heavy tank. Test 5A involved a 120mm DU penetrator that penetrated the DU armor into the Crew Compartment. Test 5B involved a 120mm tungsten penetrator that penetrated the DU armor into the Crew Compartment. Test 6B involved a fire in the uploaded Abrams heavy tank following impact. All the tests involved the same Abrams tank.

Table 11. DU Collected by Air Monitors (µg)

		5-100 m (outside plume path)	5-100 m (inside plume path)				
1	1.1	2 – 21	950 (5 m)	0.6	0.4	-	81 – 100
2	6.3	0.2 – 45	23 – 320	1.3	0.2	1.8	ND* - 69
3	2.0	4 – 70	240 – 14,000	4.6	0.5	0.4	76 - 84
4	0.07	1.8 – 7	10 – 62	1.2	0.4	0.1	57 - 94
5A	3700	ND* – 10	77 – 3300	2.3	0.3	0.4	29 - 100
5B	4600	0.5 – 21	44 – 2000	27	4.3	1.4	76 - 100
6B	--	--	44 – 1400	2.4	2.8	0.6	88 - 89

*ND: None Detected

Reference: Fliszar et al., (1989) and Parkhurst et al., (1995b)

Munson et al., (1990) (draft)[15] summarized reported data from impact tests of a DU penetrator with a hard-target (plate). The tests would have resulted in aerosol production of 12 percent to

37 percent of the penetrator. There would have been oxidized DU and DU fragments both inside and outside the vehicle. This document also provided guidance for entry and cleanup operations.

When a DU munition impacts or perforates a hard target, it forms DU dust of which approximately 10 percent to 37 percent is suspended in air, and approximately 60 percent to 96 percent is respirable according to Parkhust et al., (1995). The DU dust formed on impact is 17 percent to 43 percent soluble Class D (or Type F) in lung fluid and 57 percent to 83 percent insoluble Class Y (or Type S) in lung fluid. Table 12 contains the estimated airborne fractions from impact or perforation tests conducted by Glissmeyer et al., (1979) and Wilsey and Bloore (1989). The results in Table 12 show an oxidized fraction range between negligible and 35 percent with the percent of suspendable oxide between 0.2 percent and 70 percent. Wilsey and Bloore (1989) estimated that 42 percent to 92 percent may be aerosolized. Tables 12 and 13 summarize aerosol data from hard-target DU impact tests.

With such variability, estimating a Q_{MLV} or providing a reasonable range is difficult.

Chemical Form. Uranium chemistry is complex and the exact composition of the oxide may be uncertain. Uranium and DU are reactive metals that will react with most of the nonmetallic elements and form inter-metallic compounds. DU metal will oxidize becoming UO_2 at 20° C to 25°C. Initially, the metal has a shiny platinum-like surface. After the metal has been exposed to 20° C to 25° C air for three or four days, the metal surface becomes black. Therefore, the metal

Table 12. Aerosols From Hard-Target Impact Tests and Analysis Methods

DU Oxide Composition	Solubility and Dissolution $T_{1/2}$ Distribution	Particle Size and Distribution	Airborne Fraction	Sampling Methods	Analysis Methods	References
= 75% U_3O_8= 25% UO_2 Good*	43% soluble in 7 days Class D 57% Class Y Good*	Geometric mean size: 2.5 to 3 μm AED; DU collection per firing: = 360 grams within 50 ft of targets Reasonable*	Respirable fractions = 50% (≤ 3.3 μm AED); did not consider particle size between 3.3 μm and 10 μm; airborne particulate = 70% of total back calculated from cloud Uncertain*	Total particulate air samplers, high-volume cascade impactor, Lundgren impactor, deposition trays	Gamma spectro-analysis; alpha counting, fluorometry, x-ray fluorescence, x-ray diffraction, and scanning electron microscope	PNL-2944; Glissmeyer et al., (1979)
Not determined in this study	24% - 43% Class D 57% – 76% Class Y Good*	61% - 96% of aerosol <10 μm AED; depending on cartridge type Reasonable*	Measured 0.2% – 0.5% of original mass, up to 18% Reasonable*	Sequential air samplers (stage sampling for 1 hour post shot), cascade impactor, and a cyclone	Chemical separation of uranium, Scintrex UA-3 Uranium Analyzer	PNL-7452; Jette et al., (1990)
Not determined in this study	Insufficient material collected for analysis	Avg. approx. 14 μg on impact coupons	Max: 0.0014 mg/m^3	Air samplers, impact coupons, deposition trays	Laser fluorometry	PNL-9741; Parkhurst et al., (1994b)

* Represents the author's subjective assessment of the quality of the data.

surface has oxidized and has become DUO_2. DUO_2 is hyperstoichiometric as a result of surface oxidation. Finely divided DU metal is reactive (sometimes called pyrophoric), oxidizing to DU_3O_8 in air. The chemical form of the pure uranium oxide is DUO_3 when formed at

1 atmosphere oxygen (O_2) pressure and below 500°C. DU_3O_8 is the stable phase when formed above 500°C. In limited oxygen environments or as an intermediate, DUO_2 is formed, Parkhurst et al., (1995b).

As weathering takes place, DUO_2 further oxidizes and hydrates, and nonstoichiometric combinations of uranium and oxygen are formed. In situations where cleanup is delayed long enough for severe environmental weathering to occur, vegetation may play a significant role in forming complexes to assist uptake of minerals. This environmental weathering depends on humidity, temperature, and soil chemistry. Knowledge of the chemical form is useful in estimating the weathering time (t_W). The chemical form is required to assess the chemical and the radiological dose and resulting health effects. The chemical form most likely to be encountered in battlefield situations is DU_3O_8, although oxides from DUO_2 and DUO_3 and related forms may also be present, Parkhurst et al., (1995b).

Depleted uranium penetrators or DU fragments that are not recovered from test ranges or the battlefield are subject to environmental oxidation and corrosion. The extent of this environmental oxidation and corrosion depends on a variety of factors, some of which include moisture, soil composition, length of time in the environment, the extent of damage to the penetrator, and whether the penetrator or fragment came to rest above or beneath the soil or plant surface.

Table 13. Aerosols from Hard-Target Impact Tests and Sampling Methods

				Solubility & Dissolution $T_{1/2}$ Class		
105mm	=75% U_3O_8 = 25% UO_2 Good*	Respirable fraction = 50% ≤ 3.3 μm AED, airborne particulate = 70% of each penetrator (calculated); DU collection per firing ~360 grams within 50 ft of target Good*	Geometric mean of 2.5 to 3 μm AED Good*	Respirable fractions from impact samplers: 43% soluble in 7 days; total particulates: 15% soluble in 7 days; remainder insoluble	Total particulate samplers; high-volume cascade impactors; Lundgren impactor, deposition trays	PNL-2944; Glissmeyer et al., (1979)
105mm	Not determined	17% - 28% Good*	2.1 μm AED using high-volume impactors; 5.8 μm using low-volume impactors Good*	Not determined	High- and low-volume total particulate samplers; high- and low- volume cascade impactors	PNL-2881; Gilchrist et al., (1999)
25mm	Assumed to be U_3O_8 Reasonable*	0.3% - 2.0% measured; recommends estimating <10% airborne Good*	Very fine, AMAD of 0.1-1.1 μm Good*	17% Class D; 83% Class Y using sample fraction <1 μm AED Good*	Total particulate samplers and high-volume cascade impactors	PNL-7232; Parkhurst et al., (1990)
120mm	Not identified Good*	0.02% - 0.04% of original mass; possibly up to 18% if real-time monitor ratio is used; 15% - 25% value recommended Good*	91% - 96% of aerosol <1 μm AED Good*	Respirable fraction: 24% - 43% Class D; Class Y 57% - 76% Good*	Sequential samplers for total particulates, cascade impactor, cyclone, building real-time aerosol monitor	PNL-7452; Jette et al., (1990)
105mm	Not identified Good*	0.2% - 0.5% of original mass; up to 18% if real-time monitor ratio is used; 15% - 25% value recommended Good*	61-89% of aerosol <10-μm AED Good*	Respirable fraction: 22% - 48% Class D; Class Y 52% - 78% Good*	Sequential samplers for total particulates, cascade impactor, cyclone, building real-time aerosol monitor	PNL-7452; Jette et al., (1990)
105mm experi-mental; field test	Not identified	14 μg collected on coupons	Not determined	Not determined	High-volume air samplers, impact coupons, deposition trays	PNL-9741; Parkhurst et al., (1994)

*Represents author's subjective assessment of the quality of the data.

Unpublished data[14] concerning solubility and particle-size distribution of DU were presented at a DU Working Group Meeting at the ARDEC in July 1997. A study initiated by the U.S. Army Aberdeen Test Center generated the data. Studies of DU collected from DU firing ranges indicate the solubility percentages for the three classes as being: Class D 64 percent, Class W 7 percent, and Class Y 29 percent. The chemical form and specific dissolution rates were not presented. The particle size ranges from < 1 μm to 10 μm AED.

Extreme environmental conditions could possibly promote coagulation or agglomeration of small particles by increasing the particle size. Environmental conditions might increase the AED with time as coagulation proceeds and might also decrease the median diameter of the particles remaining in the air after an additional time owing to the settling of the larger agglomerates that form continuously.

Parkhurst et al., (1995b) found that assuming a predominance of DU_3O_8 is reasonable for most battlefield situations when assessing short-term conditions.

Particle Size. Particle size will affect the initial suspendability of the oxidized material and the fraction deposited in the different regions of the respiratory tract. Immediately following an impact or perforation, the DU aerosol puff will be a mixture of dusts, fumes, and smokes. As the puff cools, DU will agglomerate into particles with sizes ranging from very small to very large.

Because of this evolution, particle sizes are difficult to predict. However, most of the data accumulated in field tests show that a portion of the oxide produced falls within the respirable size range (<10 μm AED).

Aerosols generated by mechanical processes (impacts or perforations) should be considered separately from those generated during combustion or fire. This has been proven to be very useful. In the Glissmeyer et al., (1979) study, the particle sizes that have been reported in one impact study are 2.5 μm to 3 μm AED, for aerosols generated from hard targets. In Jette et al., (1990) where hard targets were also used, the fraction of the aerosol with an AED less than 10 μm was between 21 percent and 96 percent. The residue generated from field tests has been collected from DU powder during test recovery. The various DU shots on targets were conducted in the DU containment facility "Superbox" at Aberdeen Proving Ground, MD. Uranium concentration over time using average sequential sampler data indicated a reduction in concentration of over two orders of magnitude within approximately 8 minutes after the peak uranium concentration at time 0 was measured. These data do not indicate to what extent the air handling/filtration system within the "Superbox" contributed to particle settling and removal. Although Jette et al., (1990) demonstrates a reduction in the uranium concentration over time, the data were not used in the OSAGWI exposure scenarios, because the "Superbox" ventilation system was on during this run and contributed to the reduction of the DU airborne concentration by some undetermined amount. Table 14 summarizes the particle-size distribution for respirable particles (< 10 μm AED) from hard-target impact and perforation studies. The particle-size distributions presented in Table 14 do not consider the mass percent of aerosolized DU above

10 μm AED. The denominator for these fractions was the total mass of particles with an AED less than 10 μm. The particle-size distribution appears to agree between the studies with respect to the mass percent below 10 μm AED. Because of the lack of particle size information above 10 μm AED and total DU airborne concentration in these studies, the weighted mass percent was not used in the OSAGWI exposure scenarios.

Of these nonaerosolized powder particles, 0.07 percent (Haggard et al., 1986; Mishima et al., 1986) to 33 percent of the total residual oxide sampled was ≤ 10 μm AED.

In an unpublished study conducted by ARDEC personnel, a BMP-2 was challenged with a 120mm DU munition (Test 5). Air sampling from resuspension was conducted on the BMP-2 hull well after the 120mm DU round impact. Particle-size distribution was determined only at a one-time interval for Test 5. Because of this, the particle-size distribution for the single-time interval was used in conjunction with a stirred settling model, which predicted the DU particle-size distribution over time in a closed chamber. Several limitations were identified with using a stirred settling model for Test 5:

Table 14. Mass Percentage of DU Aerosol Particles (< 10 μm AED) within Particle Diameter Ranges for Hard-Target perforations

Particle Size Range (μm)	Studies				Weighted Mass Percent (%) ± Standard Error of Mean
	BRL-TR-02435; Chambers et al., (1982)	BRL-TR-3068; Fliszar et al., (1989)	PNL-7232; Parkhurst et al., (1990)	PNL-7452; Jette et al., (1990)	
> 7.0	28.1 ± 1.9	8.6 ± 5.9	15.3 ± 11.7	18.3 ± 6.2	25.4 ± 1.7
3.3 to 7.0	11.3 ± 0.9	12.1 ± 13.9	9.3 ± 5.3	8.6 ± 1.8	10.8 ± 0.7
2.0 to 3.3	7.2 ± 0.5	13.2 ± 8.0	7.4 ± 4.3	8.8 ± 0.3	8.4 ± 0.3
1.0 to 2.0	9.3 ± 1.2	17.8 ± 17.5	6.5 ± 3.6	9.6 ± 0.4	9.6 ± 0.1
≤ 1.0	44.2 ± 1.9	52.5 ± 16.7	61.5 ± 21.1	54.8 ± 7.4	45.3 ± 1.7

- Particle-size distribution only determined at one-time interval.
- Particle-size distribution was determined in a BMP-2 hull as opposed to a BFV, a T-72, or an Abrams tank.
- Particle density may differ under other circumstances and would vary according to porosity, occlusions, or agglomerated structures.
- The chamber used to model particle settling and mixing was considered a closed system, whereby particles do not enter or exit.
- The BMP-2 hulk was in a severely compromised state (structural damage resulting in numerous holes in the hulk).
- Diffusion and resuspension of settled particles and particle deposition were considered in the particle-settling model but not included in the calculation.

Keeping in mind the limitations, the model predicted a reduction in the aerosol concentration by 50 percent after 10 minutes when using the particle-size distributions determined from Test 5.

The DU aerosol concentration in Test 5 appeared to change with respect to time after applying the stirred settling model. Data from the modeling indicate that the total DU airborne concentration drops to 50 percent of the original concentration within 10 minutes, 25 percent within 50 minutes, and 12.5 percent within 34 minutes. The overall DU airborne concentration drops very quickly in the time sequence due to gravitational settling of the larger particles but not as quickly as time goes on, since the smaller more respirable particles take much longer to settle out, Fliszar, R.W., personal communication, (2000).

In a more recent test involving DU munitions against an armored vehicle, unpublished data from sequential air sampling over a period of 35 minutes indicate a significant reduction in the initial mass of DU collected on filters. This indicates the DU-airborne concentration would have behaved similarly. Personal air samplers were positioned in the armored vehicle prior to a DU impact and turned on after impact. The samplers were programmed to collect DU on filters in an atmosphere with aerosolized DU by sampling in five-minute intervals. Only four sets of air samplers were used in this sequence, and the sampling time after impact was as follows:

- 0 to 5 minutes after impact: #1 air sampler ran
- 5-10 minutes after impact: time interval not sampled
- 10-15 minutes after impact: #2 air sampler ran
- 15-20 minutes after impact: time interval not sampled
- 20-25 minutes after impact: #3 air sampler ran
- 25-30 minutes after impact: time interval not sampled
- 30-35 minutes after impact: #4 air sampler ran

The unpublished data indicate that after the #2 set of air samplers ran (10-15 minutes after impact), the mass collected on the filter was nearly 10 times less than the mass collected on the #1 set of air samplers for the 0-5 minute sampling time. The DU-airborne concentration sampled in the armored vehicle was the result of a glancing blow, not a true perforation, Parkhurst, M.A., personal communication, (2000) and Fliszar, R.W., personal communication, (2000).

The unpublished data do, however, support the theory that the DU-airborne concentration decreases over time due to gravitational settling but to what extent for the OSAGWI exposure scenarios is not known. As part of the upcoming live-fire tests to simulate Gulf War fratricide incidents, time integrated DU-airborne concentrations and particle-size distributions will be included in the test development plan. Time integrated DU-airborne concentrations and particle-size distributions will better address Level I First Responder exposures, intakes, radiation doses, and kidney concentrations.

- Table 15 summarizes the particle-size distribution from fires that involve DU munitions as reported in Parkhurst et al., (1990).

Table 15. Mass Percentage of DU Aerosol Particles Within Particle Diameter Ranges for Fires

Particle Size Range (μm)	Mass Percent (%)
>210	29.7
210-105	21.5
105-37	31.4
37-20	12.5
20-10	4.4
<10	0.5

Due to its pyrophoric nature, many of the DU metal fragments and particles that are formed during and following impact or perforation will spontaneously ignite, resulting in a shift of particle size probability distribution function (PDF) to a smaller mean diameter. These shifts are

a result of physical differences between DU and its oxides. The oxide particles tend to crumble under relatively weak mechanical forces, further shifting the particle size to an even lower mean diameter.

The chemistry and, in particular, the solubility of the DU fragments and their oxides in the natural environment define, in part, the possibility of transport from the spent DU munition to soil, plants, water, animals, and eventually to the human.

***Non-Radiological Contaminants*.** Patrick and Cornette, (1979) determined the elemental composition of individual DU particles from hard-target perforations. Depleted uranium particles frequently contained iron, aluminum, silicon, calcium, magnesium, potassium, titanium and tungsten as a result of contamination during impaction or perforation. These contaminants are inconsequential from a dose and chemical toxicity standpoint, but they may influence the solubility of the DU compounds.

Environmental Deposition.

Dry deposition of DU particles results from gravitational settling and impaction of surfaces exposed to turbulent atmospheric flow. The rate of dry deposition is dependent upon particle-size distribution, particle shape, particle density, chemical form, and degree of air turbulence.

Dry deposition of airborne contaminants may be calculated from the ratio of the deposition flux to the airborne concentration. The airborne concentration is calculated from the transport

models, and the deposition flux is estimated from the local weather conditions and the aerosol parameters. The aerosol parameters that are needed to estimate the deposition flux are size distribution and concentration. These are dependent upon the details of the DU incident and cannot be estimated reliably *a priori*. The review of deposition and resuspension data gives values of the deposition velocity as a function of particle size. It has a broad minimum around 10^{-6} meter/sec to 10^{-5} meter/sec for particles between 0.1 μm and 1.0 μm AED and a maximum above 0.1 meter/sec for sizes greater than 10 μm AED, Parkhurst et al., (1995b).

Generalizations for the deposition of DU particles in non-turbulent air with an AED of 10 μm is about 0.3 cm/sec for a friction velocity of 30 cm/sec to 100 cm/sec, and for particles of 1 μm, it is about 0.003 cm/sec. Particles ≤ 20 μm AED are generally small enough to remain suspended or to be carried downwind a significant distance, Parkhurst et al., (1995b). The larger DU particles settle according to Stokes' Law (see Appendix E). These larger particles settle rapidly and travel short distances through the air because of their higher density. The smaller particles deposit by impaction and diffusion, Parkhurst et al., (1995b).

The variation in deposition with time is large, and its estimation is based on measurements of long-term averages. The day-to-day variability could be as high as five orders of magnitude, Parkhurst et al., (1995b).

In wet deposition of airborne contaminants, rain, sleet, snow, and other forms of moisture wash DU from the atmosphere. The rate of wet deposition depends on particle-size distribution, particle shape, and solubility (chemical form).

Wet deposition of an airborne contaminant can be estimated within a factor of two if the droplet size and frequency are known but will vary by orders of magnitude during an incident. Washout of airborne particles only affects the downwind concentration if it is raining during the period of transport. With the complexity of the phenomenon, washout is generally ignored for a conservative estimate of the downwind hazard, Parkhurst et al., (1995b).

During the Gulf War, rain and thunderstorms occurred during the ground campaign, which affected the deposition of DU particles, the resuspension of deposited DU particles, and their penetration in the sand.[16]

Dry and wet deposition are "integrating pathways." Both dry and wet deposition depend on the physical and chemical form of the contaminant. The real amount of deposited material is proportional to the time integral of the airborne concentration of the contaminant. Such processes can lead to localized areas of elevated ground deposition or "hot spots" of the contaminant.

Resuspension. During battle and during cleanup following battle, vehicles damaged by DU fires and DU munitions, impacts, or perforations can be sources of DU particles that can be mechanically resuspended within vehicles or outside vehicles. Resuspension can be a concern to

responders entering poorly ventilated structures containing DU fragments or particulates that become resuspended during life saving, reconnaissance, or cleanup activities.

For any resuspension to occur, a threshold mechanical stress must be exceeded. This threshold stress is primarily a function of two parameters: Particle size and deposition surface properties. Particle size determines the quantity of material suspended for a given stress. Surface properties determine how firmly the DU particles are fixed in place following deposition; therefore, they also determine the magnitude of stress necessary to cause resuspension. Given the complexity of the interaction between the various factors influencing aerodynamic resuspension, a wide range of uncertainty in the results exists which should be considered qualitative in most cases. Resuspension is measured as a factor, K, which is the ratio of airborne concentration to surface contamination. Generalized values of resuspension due to wind range from 9×10^{-11}/meter to 3×10^{-4}/meter. Resuspension from mechanical disturbance usually ranges from 1×10^{-10}/meter to 4×10^{-2}/meter. Ranges for sandy soil are from 2×10^{-7}/meter to 5×10^{-5}/meter, with an average of 2.5×10^{-5}/meter. Resuspension from vehicular traffic ranges from 1×10^{-8}/meter to 1×10^{-2}/meter with an average of 5×10^{-3}/meter, Parkhurst et al., (1995b).

Oily surfaces will reduce the amount of DU residue that can be resuspended in a vehicle because of the adhesion of the DU particles with the oily surface, when compared to a clean surface.

Resuspension from the mechanical disturbance by light vehicles on an asphalt road has been measured (Sehmel, 1980)[17] with values ranging from 10^{-5}/meter up to 10^{-2}/meter per passage; the resuspension factor increased with vehicle speed. Resuspension is also measured as a rate of the

fraction suspended from the soil per second. In Parkhurst et al., (1995b), annual rates for soil resuspension due to aerodynamic forces were found to range from about 1×10^{-10}/sec to 1×10^{-8}/sec. For wind resuspension, the values range from 2×10^{-12}/sec to 1×10^{-8}/sec, and for mechanical disturbance, the values range from 3×10^{-9}/sec to 1×10^{-6}/sec.[18]

Variation in resuspension rates is a major uncertainty in modeling aerosol concentrations. Time since deposition is a major factor in resuspension, since resuspension drops off dramatically shortly after deposition. Several methods of quantifying this parameter exist. The initial factor, $K_{(0)}$, has a measured range of 10^{-7}/meter to 10^{-2}/meter for mechanically caused resuspension and 10^{-7}/meter to 10^{-3}/meter for wind-caused resuspension. Most measured values of mechanically caused resuspension are below 10^{-4}/meter. Parkhurst et al., (1995b) reported the weathering half time as being between 35 and 70 days for the first few weeks. A resuspension factor at longer times, up to 20 years after deposition, is usually underestimated[18].

Table 16 summarizes surface resuspension factors (K) determined under various conditions as compiled by Beyeler et al., (1998)[19].

Table 16. Resuspension Factors

No mechanical disturbance	3.3E-8
Light work activity	9.4E-6
Walking (14 steps/min)	9.1E-6
Walking (36 steps/min)	6.9E-6
Vigorous walking	3.9E-5
Vigorous work activity	1.9E-4

Reference: Beyeler et al., (1998).

A resuspension factor of 8.5 x 10^{-6}/meter represents an average of the experimental data for light activity from Table 16. Under conditions of moderate activity, the above factor should be increased tenfold to 1 x 10^{-5}/meter. For heavy activity, the value of 1 x 10^{-3}/meter is reasonable.

The DU particles that are resuspended in a vehicle are probably large particulates or agglomeration of particulates than that initially formed during perforation. The larger particles may be less soluble because of the surface-to-volume ratio of the particles, Parkhurst et al., (1995b).

Resuspension rates for respirable particles (<10 μm AED) vary from 2.2 x 10^{-10}/sec for the 1.3 meter/sec to 3.6 meter/sec surface wind-speed intervals to 2 x 10^{-8}/sec for the 5.8 meter/sec to 20.1 meter/sec surface wind-speed interval. This is an increase of two orders of magnitude. The overall increase in resuspension rates is a non-linear function of surface wind-speed. For surface wind-speeds greater than 3.6 meter/sec, resuspension rates increase with surface wind-speed to the 6.5 power[20].

Although there are some apparent relationships between resuspension rates and resuspension factors, insufficient data exist on DU resuspension to draw general conclusions. At most, the conclusion is that resuspension factors between 1 x 10^{-10}/meter and 1 x 10^{-9}/meter are comparable to resuspension rates between 1 x 10^{-10}/sec and 1 x 10^{-8}/sec.

The following are some of the variables that influence the resuspension of DU particles:

- Particle properties – size, shape, reactivity, density, and surface roughness.
- Soil properties – moisture content, soil size and distribution of soil particles, soil depth, specific gravity, and texture.
- Particle-soil interactions – attractive forces, molecular forces, electrostatic forces, and chemical forces.
- Surface properties – surface moisture, oily surfaces, binding action of materials, temperature, and cohesiveness of particles.
- Topography – crop fields or desert, valleys, or hills.
- Meteorological – humidity, air, density, air turbulence, temperature, stabilizing, and pressure.

Table 17 provides a summary of the resuspension rates compiled by Parkhurst et al., (1995b), from heterogeneous surfaces.

Table 17. Resuspension Rates from Heterogeneous Surfaces*

		Nominal velocity			
		miles per hour	meter/sec		
Stainless Steel	Wind tunnel	23.5	10.5	8E-7	Mishima and Schwendiman (1973)
Concrete	Wind tunnel	14.5	6.5	1E-6	Nicholson and Branson (1992)
Teflon® – coated A1	Wind tunnel	4.0 2.7	1.8 1.2	<1E-5	Wu et al., (1992)
Kraft Paper	Field/static	<0.9	<0.4	<1E-10	Pond and Jones (1967)
	Field/activity	--		<4E-9	
Polyvinyl Chloride (PVC)	Field/static	--	--	<2E-14	Pond and Jones (1967)
	Field/activity	--		<1E-8	
Waxed and polished linoleum	Field/static	--	--	<1E-12	Pond and Jones (1967)
	Field/activity	--		<1E-12	

Table 17. Resuspension Rates from Heterogeneous Surfaces* (con't)

		Nominal velocity			
		miles per hour	meter/sec		
Linoleum	Field/static	--	--	Not detectable	Pond and Jones (1967)
	Field/activity	--		<6E-8	
Concrete	Field/static	--	--	3E-7 to 2E-5	Glauberman et al., (1967)
Mown grass	Field/wind tunnel	4.5 to 17.9	2 to 8	1.3E-8	Shinn et al., (undated)
Silt, loam soil	Field/wind tunnel	4.5 to 17.9	2 to 8	2.3E-8	Shinn et al., (Undated)
Medium coarse gravel	Field/wind tunnel	4.5 to 17.9	2 to 8	5.6E–8	Shinn et al., (Undated)

*Reference: Parkhurst et al., (1995b), p. 4.51

Control of all the variables that influence the resuspension of DU particles is impossible. Therefore, uncertainty in the measurement may exist which results in a wide range of values for a given condition.

Studies by Milford and Davidson and other studies by Shinn[21] have found that resuspended particles were between 2 μm to 6 μm AED with a geometric standard deviation of about 5.

Particles of about 15 μm AED have been found when soil was disturbed or when strong winds, ~ 20 meter/sec occured[21].

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The use of resuspension factors or resuspension rates is of limited value in developing generalized resuspension models. Resuspension factors do not indicate how rapidly a contaminant is removed from the surface and transported to the receptor. When using the mass loading method to calculate resuspension for soil, the contaminant must be uniformly mixed within the top 1 cm or more of soil.

The surface wind speeds during the Gulf War Ground Campaign varied from 5 to 36 knots (2.6 meter/sec to 18.5 meter/sec)[16]. With these wind speeds dust and sandstorms occurred. This range would result in a two order of magnitude change in the resuspension rate or resuspension factor. Recent review of resuspension is given in Garland and Pomeroy (1994)[22], Gavrilov et al., (1995)[23], and Nair et al., (1997)[24].

When the airborne concentration of a contaminant has been measured for a given scenario, the use of the measured data is preferred for estimating the intake of the contaminant via inhalation and indirect ingestion.

Appendix I discusses the resuspension calculational models that can be used when measurement data are not available.

Possible Input Parameters. Most of the data clearly show that large variations exist for almost every factor. Meteorological data may have a large effect on the results, and this factor, in particular, may have been inadequately documented. However, standard defaults used by atmospheric transport modelers in scenario simulations in which relative

information is to be derived do exist. These may be sufficient for situations suggesting low risk. The amount of source-term material that becomes oxidized varies by circumstance and is highest with fires in which DU was heated for several hours or longer and for impacts or perforations of a thick armor. Explosive force may suspend any oxide particle size and small fragments of DU metal, but sustained aerosol production requires small particle sizes that are not quickly deposited. The quantity of the oxidized fraction that may be made airborne varies with type of incident and circumstances surrounding its oxidation and suspension. The chemistry of the oxide and how the oxide is formed (that is, hard impact or fire) may also vary but is most likely to be predominately a form that is very slow to dissolve in lung fluid. General input to the analysis for fire and impact or perforation incidents include the following:

Fire

- Chemical composition: Primarily DU_3O_8 and smaller amounts of DUO_2
- Oxidized fraction: 10 percent to 84 percent
- Particle size range: 0.1 percent to 33 percent ≤ 10 μm AED; usually relatively coarse
- Lung solubility: 0.0 percent to 7 percent Class D/W 93 percent to 100 percent Class Y
- Fraction airborne: 0.1 percent MLV with range of 0 to 43 percent with less than 1 percent respirable

Impact/Perforation

- Chemical composition: DU_3O_8 and DUO_2
- Oxidized fraction: 10 percent to 37 percent
- Particle size range: ≤ 1 μm to 10 μm AMAD; about 50 percent to 74 percent are ≤ 1 μm, relatively fine
- Lung solubility: 17 percent to 43 percent Class D/W; 57 percent to 83 percent Class Y
- Fraction airborne: 10 percent to 37 percent with 60 percent to 96 percent respirable

The deposition velocity depends largely on the particle-size distribution. Particles of 10 μm AED are deposited with a velocity of about 0.3 cm/sec depending on friction and other factors. Resuspension from surfaces within a vehicle will vary greatly from resuspension of surface particulates from soil and road surfaces due to foot or vehicle traffic. General ranges are provided, but the variability is very large and changes with time and depletion of the source.

Table 18 summarizes data compiled by Parkhurst et al., (1995b), as modified by USACHPPM, and provides the parameters to calculate DU intake. Suggested generalized factors are provided as possible but are not inclusive. When using these factors for transport analysis, consider site-specific caveats. An "x" in the "C" column means the parameter is a constant. An "x" in the V column means the parameter is a variable, and then an MLV and a range of values are given. Blanks in the MLV or Range columns indicate insufficient information.

Table 18. Parameters to Calculate DU Intake*

Parameter	C	V	MLV	Range	References and Notes
Source Term					
Airborne Release Fraction		X	18%	10% to 37%	Driven by type of munition and type of target (PNL-7452 and PNL-10903); Jette et al., (1990) and Parkhurst et al., (1995b)
Airborne Fraction					
Release height		X	zero	Specify	Depends on temperature and momentum
Chemical form		X	U_3O_8	U_3O_8, UO_2	Depends on temperature, initiating circumstances
Particle size		X	5 μm	0.1 μm-100 μm	Depends on initiating parameters
Air Dispersion (Gaussian)					
Wind speed		X	Minimize (1-2 meter/sec) or maximize	0-50 kilometer per hour as desired or as observed	Probability obtained from the site meteorology if available; from observations
Wind direction		X	Observation		Probability obtained from the site "windrose" or observations
Stability class		X	C	A-G	Probability of Pasqual's stability classes obtained from the site records or observations
Deposition					
X (dry)		X			Depends on atmospheric transport output
F_d(dry)		X	~ 0.3 cm/sec at 10 μm AED	~ 0.003 cm/sec at 1 μm AED; ~25 cm/sec at 100 μm AED	Deposition velocity is a function of particle size
X_o(wet)		X			Depends on atmospheric transport output
W (wet)		X			Can be calculated from the rainfall or derived from an experimentally determined rain spectra
Resuspension					
$K_{(o)}(m^{-1})$		X	1E-4	1E-7 to 1E-3	Time-independent factor activity and surface dependent
t_w(days)		X	50	35-70	Large variability; used in resuspension rates
Lung Deposition and Transport					
Age and sex	X		Adult Male	Specify	Reference Man values given in ICRP-23 and ICRP-66
Breathing (or ventilation) rate		X	3.0 m^3/hr	1.2 m^3/hr to 3.0 m^3/hr	Depends on activity; see Table 6 in ICRP-66
Respirable fraction		X	0.96	0.001-0.96	Strong dependence on particle size; see Table 28 and Figure 43 in ICRP-66
Solubility type(s)		X	Y (S) D (F)	D, W, Y (F, M, S)	Type W (M) recommended when uranium form not known (ICRP-66)

*Reference: Parkhurst et al., (1995b), as modified, p. 5.8.

3.1.2 Summary of Parameters Contributing to Dose Estimations

Table 19 summarizes the parameters considered to calculate DU doses for OSAGWI Level I scenarios within this report. The blanks in the reference column indicate that the source of the range of parameter is in Parts III and IV of this report.

3.2 Gaps in Existing Data and Knowledge

A preliminary assessment of additional data needs and recommendations for future data needs after reviewing DOD published data follows:

- Airborne Fraction or airborne concentration: DU airborne concentration within the vehicle immediately following a perforation as well as over a time period of at least 1 hour and the contribution of aerosol production of the DU armor to the airborne concentration. Resuspension of material by individuals entering vehicle (internal and external to the vehicle).
- Quantity, particle size variation, particle shape, chemical form, morphology, lung solubility of airborne DU inside vehicle, and surface contamination levels (internal and external to the vehicle).
- Effect of other metal contaminants from DU munitions and armor on DU oxide solubility.
- Adsorption of airborne particulate materials to oily surfaces.
- Adsorption of airborne particulate materials to combustion products from a fire.

- Characteristics of DU oxides generated by heated and buried DU penetrators (impact but no perforation).
- Secondary ingestion (hand-to-mouth) transfer of residual DU from damaged military vehicles.

Table 19. Parameters Considered to Calculate DU Doses for OSAGWI Level I Scenarios[1]

Parameter	Range of Parameter	References
Type of DU munitions	120mm (DU munition) and Abrams tank	BRL-TR-3068 Fliszar et al., (1989)
Air Volume, Abrams Tank	7.6 m^3 (air volume)	BRL-TR-3068
Air Volume, BFV	9.8 m^3 (air volume)	
Air Exchange Exhaust Velocity (Abrams Tank)	0.092 m^3/sec	BRL-TR-3068
Turret Blower Exhaust Velocity	0.014 m^3/sec	BRL-TR-3068
ARF At Hard-target impact	10% - 37% (70% worst case) 18%	PNL-7452; Jette et al., (1990) PNL-10903 Parkhurst et al., (1995b)
Exposure Duration	2 minutes	
Solubility of DU aerosolized (lung)	17% - 43% Class D; 57% - 83% Class Y	PNL-10903
Solubility of DU aerosolized (kidney)	17% Class W; 83% Class Y	
Respirable Fraction	60% - 96%	PNL-10903
Particle Size(s)	0.05 μm to 10 μm (5 μm nominal)	ICRP-66
Chemical Form	DUO_2, DU_3O_8	PNL-10903
Heavy Exercise	100%	ICRP-66
Individual (Mouth Breathers) Lung Deposition Rates	Use ICRP-66 particle deposition rates	ICRP-66
Heavy Breathing Rate (Mouth Breather)	3 m^3/hr	ICRP-66
Hand-to-Mouth (Secondary Ingestion) Rate	1E-5 m^2/hr to 1E-3 m^2/hr (Average 1E-4 m^2/hr)	NUREG/CR-5512 (1992)

Table 19. Parameters Considered to Calculate DU Doses for OSAGWI Level I Scenarios[1] (con't)

Parameter	Range of Parameter	References
Deposition Rate (for 0.01 μm to <1.0 μm AMAD) (for 1 μm AMAD) (for 10 μm AMAD) (for > 10 μm AMAD) (for 100 μm AMAD)	 1E-5 cm/sec to 1E-3 cm/sec 0.003 cm/sec 0.3 cm/sec 0.25 m/sec	PNL-10903
Resuspension Factor (sandy soil)	2E-7/meter to 5E-5/meter, (Average 2.5E-5/meter)	
Resuspension Factor (in vehicle)	1E-8 to 1E-2/meter, (Average 5E-3/meter)	
Resuspension Rate	6E-9/sec to 1E-8/sec (Average 8E-9/sec)	
Airborne Release Rate	4E-6/hr to 4E-5/hr (Average 2.2E/5 hr)	DOE HDBK-3010-94

- The DU particle-size distributions generated from fires (DU oxide contributions as a result of fire conditions).
- Effects of both the BFV fire suppression system and the Abrams environmental control/ nuclear biological control (EC/NBC) System and fire suppression system on the characteristics of DU airborne concentrations, including particle size fraction, elemental composition, solubility, and dissolution rates of DU oxides in simulated lung fluid.
- Human factors information (OSAGWI interview data obtained from Gulf War veterans).
- The contribution of the DU armor from perforation by a DU round (DU on DU) and a non-DU round to the airborne concentration of DU inside the vehicle.
- The airborne concentration of DU inside a BFV when penetrated by a DU round.

PART IV: OSAGWI LEVEL I EXPOSURE SCENARIOS

4.1 Overview

The objective of this analysis is to estimate the amount of DU internalized by OSAGWI Level I personnel. Level I were those personnel who were in, on or near (less than 50 meters) an armored vehicle at the time their vehicle was perforated by 120mm DU munitions and the First Responders who entered damaged vehicles after the DU perforation to evacuate personnel. This effort focuses on estimating the amount of DU internalized by inhalation and ingestion pathways for these personnel. The intake for all Level I personnel will be modeled as if in the perforated vehicle at the time of perforation. The intake for personnel on or near the vehicle will be less, because they were not in an enclosed space.

To calculate intake, it is essential to have data on DU aerosolization. While there are a number of DOD reports that address aerosols generated after hard-target impacts, there is only one that provides data that may be used for Crew Compartment or enclosed space intake estimates, Fliszar et al., (1989). The other hard-target tests were not against enclosed targets. Testing reported in Fliszar et al., (1989) was performed in conjunction with a survivability test of the Abrams tank outfitted with armor containing DU. Several munitions types were used including DU and tungsten kinetic energy penetrators. Two shots in this test involved the purposeful overmatching of the DU armor to ensure that both the DU (Test 5A) and tungsten (Test 5B) munitions breached the Crew Compartment. Battery-operated personnel lapel air-sampling devices were placed in the Crew Compartment to measure the aerosols generated.

For this report, data from Test 5A were used. Test 5B data were considered but were not used because the test shot involved DU armor perforation by a tungsten munition. It was impossible to model the differences caused by the use of tungsten versus DU, because the penetration mechanisms of tungsten and DU are different.

It is important to understand the limitations of the data from Test 5A. The first limitation to using the data is that the test scenario does not match what occurred in the Gulf. In Test 5A, 120mm DU penetrator perforated the DU armor on an Abrams tank. There is no record of any incident of DU on DU during the Gulf War. The DU armor on the Abrams is heavier and harder to penetrate and could possibly provide additional aerosolized DU within the tank's interior. It can be assumed that the amount of aerosolized DU within an Abrams will be higher because of these characteristics. During the Gulf War, Abrams and BFVs were involved in fratricide incidents. The BFV does not contain DU armor, but the armor that the BFV has is much lighter and easier to penetrate than Abrams armor. These characteristics can lead to the assumption that the amount of aerosolized DU within the BFV will be lower than that within the Abrams. Because no known incidents of DU-on-DU occurred during the Gulf War, an over-estimation of the intakes by the crewmembers may have been made in this report. With further test data, the intake estimation can be better quantified.

The second limitation to using the data from Test 5A is the uncertainties in the air-sampler data inside the vehicle. There was uncertainty in the time the air samplers ran after perforation. In addition, the post-impact condition of the air samplers and damage to some of the filter paper

also contributed to additional uncertainty and probable reductions in collection efficiency. See Tables 20 and 21 of Section 4.3.2.1.

Other data collected during this performance test were used to estimate the time so that the condition of the air samplers (Crew Compartment and Driver's Compartment) and other uncertainties associated with the measured time were avoided. This approach uses Monte Carlo simulations and is described in Section 4.5. The inputs for this Monte Carlo analysis are estimated probability distributions for each input parameter. The end product of this analysis is probability distributions for DU airborne concentration, intake, radiation dose, and DU kidney concentrations. (See Appendix O for a discussion of the analysis of the end product.)

There are several points that need to be kept in mind while reading this report. First, the techniques used were designed to estimate the average airborne concentration of DU in the Crew Compartment. Films of hard target penetrations make it clear that in the first few milliseconds after penetration, the debris from the perforation is spraying into the Crew Compartment in a fan of a definite width. This fan contains remnants of the original penetrator behind armor debris and burning DU. Crewmembers whose breathing zones are in this initial fan will be subjected to much higher mass concentrations for a very brief period of time and, more than likely will be wounded and have both embedded fragments and wound contamination. Level I crewmembers are being followed medically in a voluntary program being conducted by the VA. The objective of this report is to estimate the intake for personnel who do not have contaminated wounds or embedded fragments.

The second point to remember is that this report provides an upper-bound estimate that is actually a range of upper-bound estimates. It does not provide a "best-estimate" of the intakes for OSAGWI Level I personnel. The development of a single "best-estimate" requires further testing. A test is already funded, and the test plan peer review is underway.

4.2 Summary of Methodology for Exposure and Intake Assessment

The following provides a quick overview of the equations used and which aspects come from literature, test data, or assumptions.

In order to assess human radiation risk, we must first define the CEDE (rem). The CEDE is the radiation dose received over 50 years following an intake of DU. The following equation was used to estimate the range of CEDEs.

$$\text{CEDE (rem)} = \text{I (mg)} * \text{DCF (rem/mg)}$$

Where:

- I = Intake which is calculated through the use of computer models and test data (mg).
- DCF = Dose conversion factor which is derived from technical literature data in rem/mg.

The committed dose equivalent (CDE) (rem) for the lung is defined by the following equation. The CEDE was previously defined. The organ or tissue weighting factor (W_T) is the fraction in the CEDE attributable to the lung.

$$CDE_{lung} = CEDE/W_T$$

The estimate of kidney concentration is required to characterize the chemical risk. The following equations were used to estimate the range of kidney concentrations.

$$K_y = I * \sum_{Class}^{D,W,Y} (f_b * f_k)$$

Where:

- K_y = Amount of DU reaching the kidneys (mg)
- I = Intake (mg)
- f_b = Fraction transferred to blood (see Appendix J)
- f_k = Fraction transferred to kidney (see Appendix J).

$$\text{Kidney Concentration (µg DU/g of kidney)} = \frac{mg\ to\ kidney \times (1000 mg / mg)}{M_{kidney}}$$

Where: M_{kidney} = Mass of kidneys (310 g)

The next equation describes how much of the DU airborne mass concentration was taken into the body or the intake (I).

$$I\ (mg) = C * BR * t_{exp} * RF$$

Where:

- C = Concentration which is obtained from test data in mg/m^3.
- BR = Breathing rate of the exposed personnel in m^3/hr (or liter per minute (L/min). It is obtained from the literature and a review of the accounts of what actually occurred in the Gulf War from Gulf War veterans.
- t_{exp} = Exposure time in minutes or hours based on the accounts of what actually occurred in the Gulf War from Gulf War veterans.
- RF = Respirable fraction which is obtained from test data.

The airborne mass concentrations of DU (C) were derived from air sampler data and calculations. These concentrations are in terms of a mass (mg) of DU per volume (m^3) of air.

$$C\ (mg/m^3) = M_{Col} / (FR * t) * 1/FCE$$

Where:

- M_{Col} = Mass collected by the air sampler obtained from test data.
- FR = Flow rate of air sampler obtained from test data.

- t = Air sampler run time obtained from test data and calculations.
- FCE = Filter collection efficiency obtained from manufacturer and test data.

4.3 Available Data for the OSAGWI Level I Scenarios

The review of test reports indicated no specific data on impact studies involving DU munitions and the BFV. The best data available to estimate the bounds of DU that may have been internalized by a soldier during the Gulf War was obtained from the Fliszar et al., (1989) report.

The following briefly describes tests reported in Fliszar et al., (1989), which included using a 120mm DU penetrator against a heavy armor Abrams Tank. The report states, "Test 5A was designed to have the DU penetrator (120mm) enter the Crew Compartment through the DU armor of the Abrams tank to radioactively contaminate the target interior." It should be noted that the DU penetrator was fired into a DU-armor plate, which had been hit but not perforated on two previous occasions in prior test shots (Tests 1 and 2). The cover plates for those previous impact holes had been removed for this test. For Test 5A, the NBC System was operating, and all hatches were closed prior to this test. The Loader's hatch opened slightly following impact. There was a 20-hour time period between the time of armor perforation in Test 5A and reentry into the vehicle because of safety reasons. The reason for such a long delay in entry was because the Abrams tank was uploaded with live munitions.

For Test 5A, there was an estimated change of about 70 percent of the air volume in the tank per minute due to the operation of the NBC System. The air volume of the Crew Compartment is

7.1 m^3 and the Driver compartment is 0.5 m^3 (total air volume of the tank is 7.6 m^3). When adjustments are made for the crewmembers and their personal equipment, the total air volume of the tank is about 7.2 m^3. The operation of the NBC System, along with the slight opening of the Loader's hatch with impact, may have contributed to the reduction in the airborne concentration of DU in the tank for the sampled time period. However, data are not available to estimate the magnitude or the rate of the reduction in the airborne concentration of DU in the tank due to these factors.

4.3.1 Air Inside a Tank

The air exchange velocity in an Abrams tank is 0.092 m^3/sec and in an M1 tank (with turret blower) is 0.014 m^3/sec. The M1A1 Abrams tank has an Environmental Control/Nuclear, Biological, Chemical (EC/NBC) System that filters external air through an EC and two High-Efficiency Particulate Air (HEPA) filters. The M1 Abrams tank does not have an EC/NBC System. The EC cools heated air, and the HEPA filters remove particles greater than 0.3 μm AED. The NBC System also has two activated charcoal membranes as part of the overall filtration system. The EC/NBC System serves two functions: the filtration of inlet air and the creation of an overpressure. This overpressure specifically serves to create a positive pressure inside the tank. This prevents unwanted NBC material from entering the tank. The driver and the four crewmembers in an M1A1 Abrams tank are supplied air that has passed through the EC/NBC System and is delivered via masks. In addition to providing filtered air to the individual occupants of the M1A1 Abrams, the EC/NBC System also delivers a bulk dump of filtered air creating an overpressure situation. Only personal respirators are available to filter

airborne contaminants from the interior of the tank. The M1 Abrams tank also has a blower in the turret to vent gases at a rate of 0.014 m^3/sec after firing. Because of these varying system designs, it is difficult to postulate how much greater the estimated DU intake would be for a situation similar to Test 5A but without the EC/NBC System (M1A1) or turret blower (M1) in operation.

4.3.2 Air Sampling

Personal air samplers, which sampled an average FR of 5 L/min, were placed inside the tank during all tests described in the Fliszar et al., (1989) report. The filter cassettes (Millipore AA™) used were made of cellulose ester with a pore size of 0.8 μm. The filter efficiency was 98 percent (or the correction factor was 1.02). The relatively low volume of air pulled through these filters prior to a test impact should not have significantly reduced the FR of these air samplers. One was placed at each of the four crewmember stations. Three samplers were placed in the Crew Compartment (air volume 7.1 m^3) and one in the Driver's Compartment (air volume 0.5 m^3). Each at the crew stations was affixed to mannequins with the sampler cassettes located at the appropriate breathing zone level. Four additional samplers were also placed in the Crew Compartment: one inside the ammunition-stowage ready-rack compartment; one connected to an inlet probe on the downstream side of the NBC System; one placed above the gun breech; and one located on the ledge behind the commander/loader position. Once the air samplers shut off,

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there would be some undefined additional amount of contaminant collected on the filter because of the residual vacuum on the filter at the time the vacuum pump shut off.

The accurate measurement of sampler FR and sampling time or sample volume is important, since aerosol mass concentration is determined by the ratio of sampled mass (or quantity) to the sampled volume and is corrected for dust loading and FCE. Most flow meters are calibrated at some atmospheric pressure, and many flow meters require pressure corrections when used at other pressures.

4.3.2.1 Air Sampling Inside the Tank

Air sampling results from inside the Abrams heavy armored tank Crew Compartment following an impact test were obtained from the Fliszar et al., (1989) report.

In a test when the round did not perforate the Crew Compartment, the highest estimated intake inside the turret Crew Compartment was 0.042 mg of DU (average of 0.021 mg of DU). This value is based on a BR (or ventilation rate) of 30 L/min or 1.8 m^3/hr (this BR is equivalent to 6.3 hours of light exercise and 1.7 hours of heavy exercise). This measurement was made with the turret hatches open and the EC/NBC System operating.

Test 5A was the first impact in which heavy armor was perforated (a DU on DU event). The amount or quantity of DU that was collected on the filter from the air samplers following Crew

Compartment perforation is presented in Table 20. Table 20 also summarizes personal air sampler data from Test 5A of Fliszar et al., (1989).

Table 20. Uranium Activity at the Target, Estimated from Personal Air Sampler Filters, Test 5A, 1334 Hours*

Location	Time Pump Was		Sampling Time	Flow Rate	Amount of DU on Filter	DU Intake
Inside[a]	On (hrs)	Off (hrs)	(min)	L/min	µg	µg
Commander	1005	b,c	210	4.98	3,000[d]	21,000
Wall behind Commander & Loader	1005	1338[c]	213	5.02	<11.7	---
Same, D + 1 days	1617	b	80	5.06	<11.7	---
Loader	1005	b,c	210	5.02	e	e
Above gun breech	1005	1742[c]	457	5.02	642	4,400
Same, D + 2 days	0855	1059				
	1220	1608	352[f]	5.06	642[g]	2,500[h]
Gunner	1005	b, c	b	5.00	3,700[d]	26,000
Driver	1007	1336[c]	209	5.02	2,673	19,000
Ammo. Compartment	1005	b, c	b	3.51	0.63[d]	---
Behind NBC filter	1007	b	1	5.02	<11.7	---
Background	0753	1005	132	5.02	<11.7	---
Outside						
Left front	1012	1408[c]	236	5.02	72.6	430
Left rear	1012	b, c	b	4.98	<11.7	---
Right front	1012	b, c	480	5.02	<11.7	---
Right rear	1012	b, c	b	5.03	<11.7	---
Background	0754	0904	70	5.02	<11.7	---
Initial entry	b	b	b	5.00	<11.7	---
Welder	b	b	20	5.00	<11.7	---

Notes:

a. All hatches were closed for this test; only the Loader's hatch opened slightly.

b. Not recorded.

c. The battery that powered the vacuum pump was discharged by reentry time.

d. Analyzed by fluorometry, with a detection limit of 0.03 µg of uranium. Other samples were analyzed by beta counting, with a detection limit of 11.7 µg.

e. Sample not analyzed.

f. Total of two sampling periods on D + 2 days.

g. This value is based on a moderate BR of 20 (not 30) L/min.

h. The equivalent airborne concentration: 360 $\mu g/m^3$ or 1.3×10^{-10} microcuries per milliliter (µCi/ml).

* Reference: Fliszar et al., (1989), p. 155 (as modified by the senior author).

The Fliszar et al., (1989) report does not document resuspension data for reentry following Test 5A which involved a 120mm DU penetrator. The DU deposited on the filters was from DU particles due solely to the perforation event. However, there are resuspension data available for reentry after Test 5B that involved a tungsten penetrator and Test 6B that involved an anti-tank guided missile (ATGM). Test 5B was conducted approximately 2 weeks after Test 5A. Test 6B resulted in a fire in the tank while uploaded with DU munitions. All three of these tests involved the same Abrams tank.

Table 21 summarizes the conditions of the personal air sampler equipment after Test 5A.

Table 21. Conditions of the Personal Air Sampler Equipment After Test 5A

Inside	
Commander	Charred flame damage over filter surface. Air enters at tube connection at cassette bottom.
Between Commander & Loader	Tube collapsed and burned.
Loader	Waxy coating on filter. Tube "kinked" near pump. Cassette damaged in back. Oil in vicinity.
Ammo. Door Behind Loader	Waxy coating and burned area on filter, heat and fragment damage to filter and cassette. Fragment in cassette.
Gunner	Heavy sample on filter. Perhaps minor heat damage.
Driver	Heavy, dark sample over entire filter.
Ammo. Compartment	(Timer had been set to run for 50 mins.)
Outside	
Left Front	Located 11 feet from front left corner of target. Slight deposit on filter.
Left Rear	Located 21 feet in front of left front edge of target. No visible sample on filter.
Right Front	Located 12 ½ feet in front of right front edge of target. No visible sample on filter.
Right Rear	Located 32 inches from target. Slight indication of sample on filter.

4.3.2.2 Air Sampling Outside the Tank

The primary task of Fliszar et al., (1989) was to obtain air-sampling results outside the Abrams tank. The air samples were obtained from an impact puff and from a plume of smoke from a tank fire. The highest estimated DU inhalation intake (0.079 mg) from Test 5A data, a perforation event, occurred at 22 meters from the tank. The intake of 0.079 mg would result in a 0.0016 rem dose (CEDE). At distances less than 100 meters, the average DU inhalation intake was 0.020 mg. This 0.020 mg intake would result in a CEDE of 0.0004 rem dose (CEDE). For 200 meter and 300-meter arcs, DU intakes were 0.0006 mg and 0.00003 mg, respectively. Studies have shown that up to 90 percent of the DU that was aerosolized remains within 50 meters of the hard target[25].

4.3.3 Surface Contamination Inside the Tank

In the DU used in military applications, there are approximately 1.79 beta particles emitted for every alpha particle (see Table 27, Section 4.5.4, for derivation). The beta activity reported in Fliszar et al., (1989) was adjusted to give total DU activity per unit area. Radioactive contamination levels in and on the tank obtained from the Fliszar et al., (1989) Test 5A are provided in Table 22.

Table 22. Smear Survey of Target Contamination, Test 5A, 21 May 1987*

Location	Total DU activity disintegrations per minute (dpm)/100 cm^2)	Area (cm^2)
Loader's hatch cover, outside	53	4,098
Loader's hatch cover, inside	263	2,640
Loader's hatch, outside	50	3,081
Side of hatch opening, loader	525	557
Side of hatch opening, commander	978	2,710
Commander's hatch, outside	30	10,685
Commander's hatch cover, outside	45	1,920
Commander's hatch cover, inside	414	14,155
Machine gun ring mount	129	-
Machine gun mount	23	-
Vents	-	-
Turret front	-	1,830
Turret back	18	1,830
Turret right front	-	-
Turret right top	-	-
Turret right side	-	-
Turret left side	179	7,050
Turret left top	240	4,000
Hull front	13	73,800
Hull back	-	89,600
Hull right side	17	48,500
Hull left side	27	48,500
Hull left side, 1/3 back	112	15,587
Hull top	-	-
Hull top below perforation	106	-
Hull top by left fuel cap	42	-
Fuel cap	-	-
Fuel cover, left front	26	-
Fuel handles	-	-
Air pre-cleaner exhaust	26	-
Air cleaner intake	-	-
Crankcase oil vent intake	-	-
Seat, driver	56	2,265
Seat, commander	1,543	696
Seat, loader	436	862
Seat, gunner	922	2,529
Headrest, commander	1,096	840
Headrest, loader	492	990
Headrest, gunner	827	990
Control handles, commander	615	250
Control handles, gunner	571	541

Table 22. Smear Survey of Target Contamination,
Test 5A, 21 May 1987* (con't)

Crew Compartment, gun breech	827	4,213
Crew Compartment, box area of perforation	503	-
Front wall inside by point of perforation	917	-
Driver's hatch	-	3,846
Outside of Driver's hatch	32	7,045
Driver's floor	34	1,944
Dummy driver	47	-
Dummy commander	755	-
Dummy gunner	352	-
Dummy loader	307	-
Floor of turret	1,817	13,548
Inside of breech	201	-
Inside front end of barrel	-	-
Gun tube by impact, left side	-	-
Old perforation	50	-
Outside of ammo door	1,588	-
Sides of ammo on impact side	92	-
Round 14	52	5,120
Round 24	56	5,120
Round 25	56	5,120
Round 29	42	5,120
Round 29, after wipe down	29	5,120
Round 32 (Position 6)	37	5,120
Round 33 (Position 7)	48	5,120
Round 34 (Position 16)	32	5,120
Round 35 (Position 17)	48	5,120
Round 36 (Position 5)	45	5,120
Round 37 (Position 4)	92	5,120
Round 37, after wipe down	43	5,120
Round 39, (Position 2)	46	5,120
Round 39, after wipe down	44	5,120
40 rounds, average of swipes	37	204,620
16 ammo. sleeves, average	41	-
Ready rack, left side	112	4,697
Ready rack, floor	111	1,859
Ready rack, right side	41	4,697
Ready rack, back	41.93	-
Ammo box 2	59	-
Ammo box 4	61.5	-
Inlet to cascade impactor on pad	ND	-
Pad – 15 feet from impact	ND	-
Northwest corner of pad	30	-
Southeast corner of pad	ND	-

Table 22. Smear Survey of Target Contamination,
Test 5A, 21 May 1987* (con't)

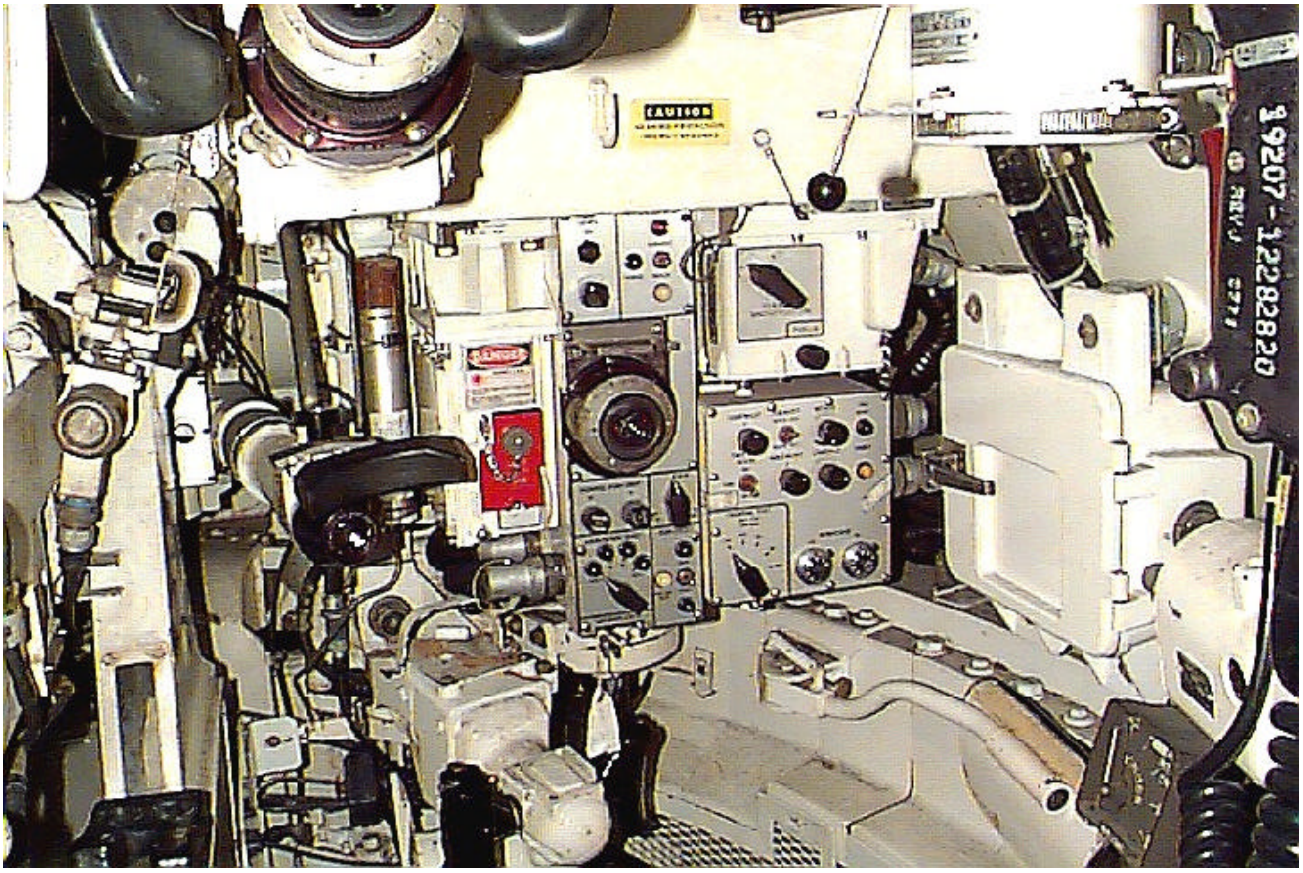
Southwest corner of pad	ND	-
Driver's floor	1,813	1,944
Breech	200	-
Ready compartment door	588	4,697
Ready compartment wall	-	-
Ammunition rack	-	-
Commander's area	492	4,800
Commander's floor	-	~4,000
Commander's hatch	-	-
Loader's area	4,815	5,550
Wall near loader	-	-
Gunner's area	3,026	13,520
Gunner's area floor	-	5,828
Bilge pump outlet	-	-

* Swipes were counted on an Eberline™ gas flow proportional counter at the Reynolds Electrical and Engineering Compand Rad Safe Trailer. ND – Non-detectable; NT – Sample not taken
Reference: Fliszar et al., (1989), pp. 197-200.

All Abrams series tanks have the same internal dimensions. Figures 1 through 4 identify major areas within the tanks and the estimated surface areas.

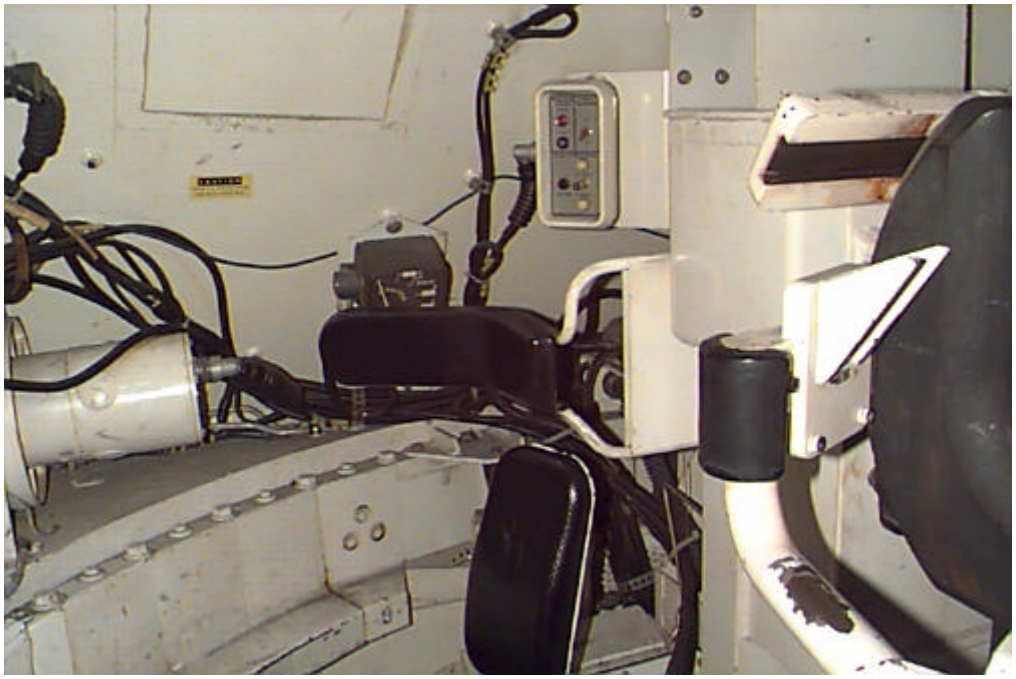
™Eberline is a registered trademark of Eberline Instrument Corporation, 5-4 Airport Road, Santa Fe, NM 87505.

Figure 1. Gunner's Area Within the Abrams Tank



Gunner's seat:	2,529 cm^2
Gunner's floor space:	5,828 cm^2
Gunner's left (includes the right side of the breech and gun area):	1,620 cm^2
Gunner's right [includes lower wire mesh panel (visible in the picture) and upper wall panel]:	11,900 cm^2
Control handles:	541 cm^2
Headrest:	990 cm^2

Figure 2. Loader's Area Within the Abrams Tank



Loader's floor space:	5,550 cm^2
Loader's hatch (outside):	3,081 cm^2
Loader's hatch cover (outside):	4,098 cm^2
Loader's hatch (inside):	2,640 cm^2
Side of hatch opening:	557 cm^2
Seat:	862 cm^2
Headrest:	990 cm^2

Figure 3. Driver's Area Within the Abrams Tank

Driver's floor space:	1,944 cm^2
Seat:	2,265 cm^2
Headrest:	750 cm^2
Hatch:	3,847 cm^2
Driver's hatch (outside):	7,045 cm^2

Figure 4. Miscellaneous Measurements of the Abrams Tank

Turret, floor:	13,548 cm^2
Turret, front:	1,830 cm^2
Turret, front (right or left side):	7,050 cm^2
Turret, back:	1,830 cm^2
Turret, left, top:	4,000 cm^2
Ready rack, left side:	4,697 cm^2
Ready rack, right side:	4,697 cm^2
Ready rack, floor:	1,859 cm^2
Ready compartment door:	4,697 cm^2
Hull, front:	73,800 cm^2
Hull, back:	89,600 cm^2
Hull, left side, 1/3 back:	15,587 cm^2
Hull (left or right side):	48,500 cm^2
Crew Compartment gun breech:	4,213 cm^2

4.4 Air Sampler Run-Time Controversy

The personal air samplers used to measure DU airborne concentrations inside the vehicle had an elapsed-time feature that recorded the amount of time (in whole minutes) the air sampler was on. This run-time is used in the calculation of the concentration the air-sampler was measuring. Under normal conditions, the air-sampler is turned on at the beginning of the sampling period of interest and turned off at the end. For this test shot (Test 5A), the time period of interest started at the moment of perforation and ended when the air samplers shut off some time after the perforation. However, the air samplers had to be turned on before perforation, because remote activation was not possible. This meant that the time recorded on the air sampler timer would be the total run-time, while the time required for estimating intake was the actual time the air-sampler ran after perforation.

Estimating the run-time after perforation was done by recording the time the air sampler was started and then by recording the time of the shot. (The time of perforation was assumed to be the time of the shot.) The time interval between air-sampler start-up and perforation was the time interval the air sampler ran prior to perforation. This interval could then be subtracted from the time recorded by the air sampler to yield the time the air sampler was on after perforation until the sampler shut off. Discussions with the senior author of Fliszar et al., (1989) indicated that the sampler on time and the time of the shot were recorded using the same digital watch.

The General Accounting Office (GAO) review of the 3 August 1998 version of USACHPPM's Interim report found that "the dose estimates for servicemembers in, on, or near vehicles when

struck by DU munitions are unreliable because of questionable assumptions used in the analysis. USACHPPM relied extensively on a single test conducted in 1987, which involved DU munitions striking an Abrams M1A1 tank equipped with DU armor. The conditions present during the 1987 test and those present during the Gulf War for the friendly-fire incidents differed significantly, which could result in higher or lower dose estimates than the center's 1998 dose assessment." (GAO, 2000). During a review of Test 5A data, it was determined that some of the sample times and air-sampler run-times may have been incorrectly recorded in the Fliszar et al., (1989) report. The senior author of Fliszar et al., (1989) reviewed the original datasheets to find the actual recorded times and run-times. The Gunner's position sampler did not have a sampler run-time recorded. The air sampler run-time data for the Crew and Driver's Compartments are listed in Table 23.

Table 23. Sampler Run-Time Data as Recorded on the Test Data Sheets for all Air Samplers in the Crew and Driver's Compartments[a]

Sampler Position	Sampler Start Time	Shot Time	Elapsed Time Between Starting the Sampler and Shot (mins)	Total Sampler Run Time	Elapsed Time between Shot and Sampler Stop Time (mins)
Commander[b]	1005	1334	209	210[c]	1
Driver[b]	1007	1334	207	209	2
Loader	1005	1334	209	210	1
Wall Behind Commander and Loader	1005	1334	209	213	4
Above Gun Breech	1005	1334	209	457	248

[a]Times were verified by the senior author's review of the datasheets.
[b]Indicates air samplers used in the dose evaluation. The remainder was not used for reasons discussed below.
[c]In Fliszar et al., (1989), this time was incorrectly reported as 212 minutes. The senior author provided the corrected value.

Although the GAO has raised questions about USACHPPM's 3 August 1998 Interim Report, the best indicator of the medical significance of the Gulf War DU exposures is the actual health of the individual soldiers. To date, the Baltimore VA medical follow-up program has demonstrated that those individuals in vehicles perforated by DU munitions during the Gulf War have experienced no detectable clinical kidney outcomes since their initial traumatic injuries (McDiarmid et al., 1999 and McDiarmid et al., 2000).

4.4.1. Discussion of the Controversy

The GAO review of USACHPPM's August 1998 Interim report brought to the surface a controversy over the interpretation of the air-sampler run-time data. The primary question was why, with the exception of the air-sampler above the breech of the gun, did all of the air samplers shut off so soon after perforation. This issue was not resolved at the time of the test. Two explanations surfaced that resulted in two distinct air-sampler run-time estimates. When this controversy first arose, all of the Crew Compartment air samplers, with the exception of the sampler above the breech and the Driver's Compartment, had calculated post-perforation run times of zero minutes (less than a minute). Since the air-sampler timer measured only whole minutes, it was initially thought that the run time for these samplers was a time period less than 59 seconds but greater than 0 seconds. The post-perforation run-time was greater than zero, because each sampler had measurable amounts of DU. The controversy was generated by two different but legitimate approaches for estimating the run-time for these air samplers.

The first approach assumed that the perforation event itself caused the air-samplers to stop either through the generation of an "Electromagnetic Pulse (EMP)-like" pulse at some point in the perforation or some other "immediate" phenomenon such as, ballistic shock. Past testing experience indicated that these events would occur on the order of 1 to 2 seconds. However, this approach could not explain why the breech air sampler continued to run for so long after the perforation event. It did, however, provide an explanation for why the air samplers that shut off stopped so quickly. The batteries were charged and designed to run for 480 minutes (8 hours).

The second approach for estimating run-time assumed that these samplers were not damaged by an immediate "EMP-like" pulse and shut off in time periods closer to 59 seconds. This was supported by the consistency of the total amount of DU collected on each of the filters and the long run-time for the air sampler on the breech. In this approach, the Driver's Compartment air-sampler time was used to estimate intake. This approach was further bolstered when the senior author of the Fliszar et al., (1989) report reviewed the data sheets and found a transcription error with the Commander's air-sampler time that resulted in a post-perforation run-time of one minute; which because the timer measured only in minutes, could be anywhere from 1 minute and 00 seconds to 1 minute and 59 seconds or almost 2 minutes. However, this approach still did not provide an explanation for the rapid shut off.

4.4.2 Detailed Analysis of Air-Sampler Post-Perforation Run-Time Uncertainties

The underlying assumption in both approaches is that the arithmetically derived post-perforation run-times were, in fact, exact. An uncertainty analysis of the procedures used to derive post-

perforation run times showed that this assumption was not true. In fact, the actual post-perforation run-times could be the same in both the Crew and Driver's Compartments.

As already mentioned, the time resolution on the air-sampler timer was whole minutes. The samplers would have registered a 1-minute run time for actual run times ranging from 1 minute and 00 seconds to a run time of 1 minute and 59 seconds. Using a digital watch to record the time an event occurred has the same uncertainty. Recording the time of an event as 1500 hours could represent an actual time that ranges from 1500 hours and 00 seconds to 1500 hours and 59 seconds. Discussions with the senior author of Fliszar et al., (1989) indicated that he recorded event times (the time of day the sampler was turned on, the time of day the shot was fired) using the hour and minute shown on the digital watch. The seconds were not recorded nor was the time rounded to the nearest minute. A time of 1500 hours 20 seconds was recorded as 1500 hours. A time of 1500 hours 45 seconds was also recorded as 1500 hours.

An uncertainty analysis of the impact of this measurement procedure on the shot time and actual run times for these air samplers is as follows.

4.4.2.1 Shot Time

The shot time recorded, using the digital watch that recorded all other run times, was 1334 hours. Therefore, this could have been as early as 1334:00 or as late as 1334:59.

4.4.2.2 Commander's Position Air Sampler

The Commander's position air sampler's on time was recorded as 1005. Therefore, this could have been as early as 1005:00 or as late as 1005:59. The sampler's run-time was initially reported as 212 minutes and then corrected to 210 minutes (see Table 23). Therefore, the sampler could have run from 210 minutes and 0 seconds (3 hours 30 minutes and 0 seconds) to 210 minutes and 59 seconds (3 hours 30 minutes and 59 seconds). Therefore, the earliest time the sampler could have shut off was 1335:00. This is the minimum sampler run-time (3 hours 30 minutes 0 seconds) added to the earliest sampler on time (1005:00). If this occurred, then the minimum sampler run-time is 1 second after perforation [1335:00 (earliest sampler off time) – 1334:59 (latest shot time)]. The latest time the sampler could have shut off is 1336:58. This is the maximum sampler run-time (3 hours 30 minutes and 59 seconds) added to the latest sampler start time (1005:59). Comparing the latest sampler off time (1336:58) to the earliest shot time (1334:00) results in the maximum sampler run-time of 2 minutes and 58 seconds.

4.4.2.3 Driver's Position Air Sampler

The Driver's position air sampler's on time was reported as 1007. Therefore, this could have been as early as 1007:00 or as late as 1007:59. The sampler's run-time was reported as 209 minutes. Therefore, the sampler could have run from 209 minutes and 0 seconds (3 hours 29 minutes and 0 seconds) to 209 minutes and 59 seconds (3 hours 29 minutes and 59 seconds). Therefore, the earliest time the sampler could have shut off is 1336:00. This is the minimum sampler run-time (3 hours 29 minutes 0 seconds) added to the earliest sampler on time (1007:00).

If this occurred, then the minimum sampler run-time is 1 minute and 1 second after perforation [1336:00 (earliest sampler off time) – 1334:59 (latest shot time)]. The latest time the sampler could have shut off is 1338:58. This is the maximum sampler run-time (3 hours 29 minutes and 59 seconds) added to the last sampler start time (1007:59). Comparing the latest sampler off time (1338:58) to the earliest shot time (1334:00) results in the maximum sampler run-time of 4 minutes and 58 seconds.

As shown in Table 24, each of these assumptions is supported by the calculated post-perforation run-times. This analysis also highlights that the potential exists that all of these samplers ran for the same time period post-perforation.

Table 24. Maximum and Minimum Possible Post-Perforation Run-Times

Air Sampler	Minimum	Maximun
Commander's Position	1 sec	2 min, 58 secs
Driver's Position	1 min, 1 sec	4 min, 58 sec

The uncertainties associated with time-keeping and air-sampler timer recording are important for several reasons. First, all of the air samplers did not run after the perforation for time periods that were tens of minutes long. As a result, it can no longer be assumed that the mass of DU collected by the air-sampler was representative of what crewmembers would internalize. Consequently, the actual airborne concentration needs to be estimated. Second, the estimated run-times are short enough that the difference engendered by the time recording methods will have a substantial impact on the estimated DU airborne concentrations.

4.5 Method for Time Resolution

4.5.1 Discussion of Basic Assumptions

As stated earlier, no clear rationale exists for a selection of a single run-time estimate (GAO, 2000). The approach taken to resolve this disparity consists of the following:

- Conduct a detailed review of all of the original data from the data sheets for Test 5A with particular emphasis on the data used to estimate how long the air-samplers ran after perforation.
- Conduct an uncertainty analysis of air-sampler run-time after perforation. The short duration of the run-times coupled with their relative importance in calculating intake made an uncertainty analysis critical. Up to this point, air sampler run times for this test were considered exact.
- Use the Monte Carlo simulation technique to establish a probability distribution of values rather than singular values for the upper and lower bounds.

As a result of this methodology, two separate and distinct methods were used to estimate sampler run-time. We refer to these as Assumption 1 and Assumption 2.

4.5.2 Discussion of Probabilistic Method for Dealing with Uncertainty

The above sections highlight the uncertainties associated with interior airborne data from Test 5A from Fliszar et al., (1989). It was necessary to decide upon a means of systematically dealing with these uncertainties. Two techniques were considered for dealing with the uncertainties in

the data and the uncertainties for the key parameters required to estimate intake. The first technique considered, the best-estimate technique, was to develop a best estimate for each parameter and data point. This technique was used in the August 1998 Interim report. (See Appendix F for a discussion.) These best estimates are used to calculate a single estimate of intake. Estimating uncertainty is relatively simple as long as the data are robust and the numbers of parameters are small. When uncertainties exist in the data and a large number of parameters exist, estimating total uncertainty is difficult. Justification of the values selected becomes impossible if a key parameter may have two discrete, very different, and equally justifiable values. This technique becomes particularly problematic when attempting to establish upper and lower bounds for the estimated parameters, because there is no method for excluding estimates based upon an unrealistic set of parameters. Given this dilemma, the best-estimate technique was not used in this report.

The second technique considered was to use a Monte Carlo simulation program that will generate a probabilistic distribution of intakes based upon a defined probability distribution of potential parameter values. (See Appendix O for a discussion.) One such computer software program is Crystal Ball®. The advantage of this technique is it provides a scientifically defensible method for dealing with the uncertainty generated by each parameter. It also provides a justifiable method for establishing reasonable upper and lower bounds for intake. This is especially important when there is uncertainty in the actual value of the data-point but relative

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certainty in the range of values that contain the actual value. This is the case for the data from Fliszar et al., (1989) Test 5A; therefore, the Crystal Ball Monte Carlo simulation program was used in this analysis.

A second issue remains. Estimates of intake are dependent upon the time the air samplers ran after perforation. There are two estimates of air-sampler run-times for Test 5A that are equally defendable. One estimate was based upon two underlying assumptions. First, the air samplers in the Crew Compartment stopped "moments" after the round impacted. Based upon testing experience, this typically occurs "seconds" after impact. Second, the air sampler result in the Driver's Compartment may have run for the reported time. However, the Driver's Compartment result still could not be used to estimate Crew Compartment exposures, because there may have been insufficient mixing between these two compartments.

The second estimate had one primary assumption: the mixing of the airborne concentrations between the Driver's Compartment and the Crew Compartment was sufficient to allow the use of the Driver's Compartment data to estimate the intake in the Crew Compartment. The only data used was actual run-time of the air sampler in the Driver's Compartment as captured in Fliszar et al., (1989) of 2 minutes.

The run-time-after-perforation analysis was important. It showed that the uncertainties associated with the technique used to determine air-sampler run-time were significant, because the reported run-times were so short. This analysis showed that while the Commander's Compartment air-sampler run-time had a reported run-time of 1 minute after perforation, it could

have run anywhere from 1 second after perforation to 2 minutes 58 seconds. Similarly, while the Driver's Compartment air sampler had a reported run-time of 2 minutes after perforation, it could have actually run anywhere from 1 minute 1 second to 4 minutes 58 seconds. The uncertainty analysis showed that both time estimates are valid, because they fall within the range of possible run-times.

The basic problem with the "moments" assumption is the need to come up with an independent estimate or distribution of estimates of the time that could be used to quantify a "moment." The approach chosen in this assessment was to use the removable surface contamination measurements in the Abrams tank to estimate the internal airborne concentration after perforation. A limitation to these measurements was the amount of aerosolized DU within the tank, because two activities occurred during the tests: the EC/NBC System was in operation and a hatch opened. Both of these pathways allowed airborne DU to escape; the exact amount is not quantifiable. Once the airborne concentration distribution was estimated, the distribution of air-sampler run-times could be calculated by estimating the time required for the air sampler to collect the measured mass of DU on the filter paper. As with the other techniques, rather than using single values for each of the parameters required for this calculation, a distribution of values was used.

4.5.3 Methods for Estimating Time for Assumption 1

Estimates of the sampler run-times were generated using the following model under the basic assumption that the removable contamination on the interior of the tank came primarily from the

settling of the DU aerosols in the tank. The contamination measurements from the wipe tests were used to estimate the total DU in the interior of the tank. The measurements of interior contamination were used to estimate the range of times the air samplers ran using the following model or equations.

$$(M_{Interior}/V_{Tank})*FC = M_{Col}/(FR*t) \quad \text{(Equation 1)}$$

$$M_{Interior} = AM_{Avg}*SA/(CE*DF) \quad \text{(Equation 2)}$$

To determine time, the first equation was solved for time.

$$t = M_{Col}/FR*V_{Tank}/(M_{Interior}*FC) \quad \text{(Equation 3)}$$

Substituting equation 2 into equation 3 results in the equation for the time estimate:

$$t = M_{Col}/FR*V_{Tank}/(AM_{Avg}*SA*FC)*(CE*DF) \quad \text{(Equation 4)}$$

Where:

- $M_{Interior}$ is the total mass of DU in the interior of the tank and is estimated by equation 2.
- V is the total volume of the tank.
- FC is the fraction of aerosol mass concentration generated in the vehicle that would be collected by the sampler.
- M_{Col} is the mass collected by the air samplers in the compartment under consideration.

- FR is the air sampler average flow rate.
- t is the time the air sampler ran to collect the M_{Col}.
- AM_{Avg} is the weighted areal mass average of DU per unit surface area in the tank.
- SA is the estimated total surface area in the tank.
- CE is the wipe test collection efficiency and is the ratio of the activity collected on the wipe versus the removable activity present in the area.
- DF is the deposition fraction of the DU mass that was available on the surface at the time the wipe was taken. The DF was modeled as a triangular distribution for input into the Crystal Ball. The upper-bound value is 100 percent (1.0) or no DU was resuspended from the surface at the time of the wipe test sample collection. The lower-bound and MLV was estimated by professional judgment to be 90 percent (0.9) or 10 percent of the DU had been resuspended and would not have been collected on the wipe test sample.

4.5.4 Discussion of Input Parameter Ranges and Modeled Distributions

Equation 2 Parameters. The DU mass deposited to the interior of the tank was estimated from the following parameters using equation 2.

$$M_{Interior} = AM_{Avg} * SA/(CE*DF)$$

Where: AM_{Avg} or weighted areal mass average in the vehicle.

The following spreadsheet, as shown in Table 25, was used to calculate the AM_{Avg}. The activities in Column 3 are taken from Fliszar et al., (1989), pp. 197-200. The USACHPPM employees measured the wipe test "local areas" (Column 4). The DU activity (Column 5) was estimated from the beta particle activity reported. Approximately 1.79 beta particles per minute

are emitted for each dpm of DU (dpm DU). Therefore, the DU activity in dpm/100 cm^2 was estimated by dividing the reported beta activity (dpm/100 cm^2) (Column 3) by 1.79. The calculation of the military DU specific activity (SpA) and the betas per minute per dpm DU are presented in Tables 25 and 26. Column 6 of Table 25, Normalized DU activity (dpm/cm^2), was calculated by dividing the estimated DU activity (dpm/100 cm^2) by 100. An assumption was made that the DU activity measured on the wipe test was representative of the areal activity in the "local area" as measured. Therefore, the weighted area DU activity in dpm (Column 8) was calculated by multiplying the Normalized DU activity (dpm/cm^2) by the "Local Area" measurement (cm^2). The weighted average DU activity (dpm/cm^2) was then calculated by summing the weighted area DU activities and dividing by the total "Local Area". The minimum, maximum, average and standard deviation of the Normalized DU activity was also determined and is listed in Table 25. *Note: The record numbers in Table 25 are not consecutive since wipe tests were performed outside the vehicle. Therefore, these exterior wipe tests were not included in the estimation of the DU mass deposited in the Crew Compartment.*

Table 25. Weighted Areal Mass Average

Record #	Location	Reported Activity (beta activity) dpm/100 cm^2	Wipe Test Local Area cm^2	DU activity dpm/100 cm^2	Normalized DU activity dpm/cm^2		Weighted area DU activity dpm
2	Loader's hatch cover, inside	470	2640	262.73	2.63		6936.11
4	Side of hatch opening, loader	940	557	525.46	5.25		2926.83
5	Side of hatch opening, commander	1750	2710	978.26	9.78		26510.73
8	Commander's hatch cover, inside	740	14155	413.66	4.14		58553.93
33	Seat, driver	100	2265	55.90	0.56		1266.14
34	Seat, commander	2760	696	1542.85	15.43		10738.23
35	Seat, loader	780	862	436.02	4.36		3758.52
36	Seat, gunner	1650	2529	922.36	9.22		23326.37
38	Headrest, commander	1960	840	1095.65	10.96		9203.43
39	Headrest, loader	880	990	491.92	4.92		4870.04
40	Headrest, gunner	1480	990	827.32	8.27		8190.52
41	Control handles-commander	1100	250	614.90	6.15		1537.26
42	Control handles-gunner	1020	541	570.18	5.70		3084.69
43	Crew Compartment, gun breech	1480	4213	827.32	8.27		34855.20

Table 25. Weighted Areal Mass Average

Record #	Location	Reported Activity (beta activity) dpm/100 cm^2	Wipe Test Local Area cm^2	DU activity dpm/100 cm^2	Normalized DU activity dpm/cm^2		Weighted area DU activity dpm
44	Crew Compartment, box area of perforation	900	100	503.10	5.03		503.10
45	Front wall inside by point of perforation	1640	100	916.77	9.17		916.77
48	Driver's floor	60	648	33.54	0.34		217.34
49	Dummy driver	84	100	46.96	0.47		46.96
50	Dummy commander	1350	100	754.65	7.55		754.65
51	Dummy gunner	630	100	352.17	3.52		352.17
52	Dummy loader	550	100	307.45	3.07		307.45
53	Floor of turret	3250	13548	1816.76	18.17		246134.77
54	Inside of breech	360	100	201.24	2.01		201.24
60	Outside of ammo door	2840	100	1587.57	15.88		1587.57
61	Sides of ammo on impact side	164	100	91.68	0.92		91.68
90	Driver's floor - 340 to 3244	3244	648	1813.41	18.13		11750.88
90.5	Driver's floor - 340 to 3244	340	648	190.06	1.90		1231.60
91	Breech	358	100	200.12	2.00		200.12
92	Ready compartment door	1051	4697	587.51	5.88		27595.46
95	Commander's area	880	4800	491.92	4.92		23612.30
98	Loader's area	8613	5550	4814.70	48.15		267215.63

Table 25. Weighted Areal Mass Average

Record #	Location	Reported Activity (beta activity) dpm/100 cm^2	Wipe Test Local Area cm^2	DU activity dpm/100 cm^2	Normalized DU activity dpm/cm^2		Weighted area DU activity dpm
101	Gunner's area	5413	13520	3025.89	30.26		409099.68
	Area (cm^2) =		79297	Avg (dpm/cm^2) =	8.53	Sum =	1187577.37
					Avg (dpm/cm^2) =		14.98
			Min (dpm/cm^2) =	0.34			
			Max (dpm/cm^2) =	48.15			
			Std dev (dpm/cm^2)=	9.70			
					SpA DU =	0.837924	dpm/µg
					dpm/cm^2	µg/cm^2	mg/cm^2
			Min =		0.34	0.40	0.0004
			Avg =		8.53	10.18	0.0102
			Avg +2s =		27.93	33.33	0.0333
			WT Avg =		14.98	17.87	0.0179
			WT Avg +2s =		34.38	41.02	0.0410
			Max =		48.15	57.46	0.0575

Reference: Fliszar et al., (1989), pp. 197-200

Table 26. Specific Activity of DU Calculation

Constants	Avogadro's # =	6.0221367E+23	Atoms/mole****						
	sec/yr =	31557600	= (365.25 * 24 * 3600)						
	1 Ci =	3.7E+10	Bq						
				DU					
Isotope	$t_{1/2}$ (yrs) *	g/mole**	Ci/g	picocuries (pCi)/µg	% by wt ***	Isotopic Activity		Molecular Weight fraction	
U-234	2.4450E+05	234.040945	6.247E-03	6.247E+03	0.0006%	0.037484		0.0014	
U-235	7.0380E+08	235.043922	2.161E-06	2.161E+00	0.2000%	0.004322		0.4701	
U-236	2.3415E+07	236.045561	6.468E-05	6.468E+01	0.0003%	0.000194		0.0007	
U-238	4.4680E+09	238.050785	3.361E-07	3.361E-01	99.8000%	0.335443		237.5747	
					100.0009%	**0.377443**	**pCi/µg**	238.0469	g/mole

*Half-lives from Kocher, (1981).
**Gram atomic weights of U-234, U-235, & U-238 from Nuclides and Isotopes – Chart of the Nuclides, 15th Edition, 1996.
***Percentages of U-234 & U-235 in Barg, (1997). U-236 & U-238 from Shelton et al., (1995).
****From Mohr, P.J. and B.N. Taylor, (1999).

Table 27. Alphas per Minute and Betas per Minute per dpm of DU

SpA DU = 0.3774431885 pCi/µg = 0.837924 dpm/µg											
		Isotope	Mass Abundance	Isotopic mass (µg)	Isotopic SpA(pCi/µg)	Isotopic pCi	Isotopic dpm	alphas/ trans	betas/ trans	alphas/ min	betas/ min
1 dpm DU = 1.19342583 µg		U-234	6.00E-06	7.16E-06	6247.4052	0.044735	0.099311	1	0	0.099311	0.000000
		U-235	2.00E-03	2.39E-03	2.1610862	0.005158	0.011451	1	1	0.011451	0.011451
		U-236	3.00E-06	3.58E-06	64.681544	0.000232	0.000514	1	0	0.000514	0.000000
		U-238	9.98E-01	1.19E+00	0.3361148	0.400326	0.888723	1	2	0.888723	1.777447
			1.000009				1.000000			**1.000000**	**1.788898**

The distribution of the AM_{Avg} was modeled as a triangular distribution for input into the Crystal Ball program. Since the weighted average (14.98 dpm/cm^2) was greater than the simple average (8.53 dpm/cm^2), the weighted average was selected as the MLV. The larger average was selected in order for the estimate to remain conservative. Two values were considered for the upper-bound of the triangular distribution – the Maximum DU activity (48.15 dpm/cm^2) and the value plus 2 standard deviations from the weighted average (34.38 dpm/cm^2). The plus 2 standard deviations from the weighted mean value was selected, since all measurements, except for 1, the maximum, are less than this value. Two values were considered for the lower bound of the triangular distribution – the Minimum DU activity (0.34 dpm/cm^2) and the value minus 2 standard deviations from the weighted average (14.98 – 2 * 9.70 = -4.42 dpm/cm^2). Since the minus 2 standard deviations from the mean value are negative, the minimum value (0.34 dpm/cm^2) was selected.

Wipe-Test Collection Efficiency (CE). The wipe-test CE was modeled as a triangular distribution for input into the Crystal Ball program. Since wipe tests were collected from different types of surfaces inside the vehicle, a range of wipe CEs would be expected. For smooth surfaces, such as handles, the moderate pressure applied in collecting the wipe test may remove 100 percent of the activity. Therefore, the upper bound for the triangular distribution was selected as 1.00. However, from rougher surfaces, such as floor areas in the tank, the moderate pressure applied in collecting the wipe test would remove less than 100 percent of the activity. Professional judgment was used to select the lower bound and MLV for the wipe CE. The lower bound was selected as 10 percent

(0.10) and is the "conservative" value provided in International Organization for Standardization-7503-1 (1980). The MLV was selected as 25 percent (0.25).

Tank Interior SA. The interior SA of the tank was modeled as a triangular distribution for input into the Crystal Ball program. The volume of the Crew Compartment (7.1 m^3) and the volume of the Driver's Compartment (0.5 m^3) as determined by Program Manager (PM)-Abrams had previously been provided. A rectangular box 1.83 meters by 1.83 meters by 2.13 meters has a volume of approximately 7.1 m^3. The interior SA of this box is approximately 22.3 m^2 [2 * (1.83 * 1.83) + 4 * (1.83 * 2.13) = 22.29m^2]. A rectangular box 1.52 meters by 0.914 meters by 0.366 meters has a volume of approximately 0.5 m^3. The interior SA of this box is approximately 4.6 m^2 [2 * (1.52 * 0.914) + 2 * (1.52 * 0.366) + 2 * (0.914 * 0.366) = 4.56m^2]. Therefore, the interior SA of two boxes that approximate the volume of the Crew and Driver's Compartment of the Abrams tank is 26.85 m^2 (22.29 m^2 + 4.56 m^2). From the interior and exterior measurements of Abrams SAs measured by USACHPPM, the interior SA was estimated to be 32 m^2. The actual interior SA of the Abrams Crew and Driver's Compartment would be greater than the interior SA estimated by the two boxes of equivalent volume, since items and equipment inside the vehicle increase the interior SA. Therefore, the lower bound of the triangular distribution was selected as 32 m^2. The upper bound was selected as two times this value or 64 m^2. This upper-bound value assumed there was a 100 percent uncertainty in the estimate from the measured areas. The MLV was selected as the midpoint between 32 m^2 and 64 m^2 or 48 m^2.

Deposition Fraction (DF). This is the fraction of the DU mass that was available on the surface at the time the wipe was taken. The DF was modeled as a triangular distribution for input into the Crystal Ball program. The upper-bound value is 100 percent (1.0), or no DU was resuspended from the surface at the time of the wipe test sample collection. The lower-bound and MLV were estimated by professional judgment to be 90 percent (0.9), or 10 percent of the DU had been resuspended and would not have been collected on the wipe test sample.

Equation 4 Parameters. The time (t) that the air samplers in the Crew Compartment ran was estimated from the following parameters using equation 4.

$$t= M_{Col}/FR*V_{Tank}/(AM_{Avg}*SA*FC)*(CE*DF)$$

- M_{Col} or the DU mass collected by the air samplers in the Crew Compartment. The mass collected was modeled as a uniform distribution for input into the Crystal Ball program. The DU mass values reported for the air samplers in the Commander's position (3.0 mg DU) and Gunner's position (3.7 mg DU) were used as the lower bound and upper bound values, respectively.

- FR or the air sampler average flow rate. The average FR was modeled as a triangular distribution for input into the Crystal Ball program. The initial sampler FRs for the Commander's and Gunner's position samplers were recorded as 4.98 L/min and 5.00 L/min in Fliszar et al., (1989), respectively. Post-sampling FRs were not determined. Summaries of pre-and post-

sampling FRs provided by the senior author of Fliszar et al., (1989) ranged from 3 L/min to 5 L/min. Therefore, the lower-bound value for the triangular distribution was selected to be 3 L/min (5×10^{-5} m^3/sec); the MLV was selected to be 4 L/min (6.67×10^{-5} m^3/sec); and the upper-bound value was selected to be 5 L/min (8.3×10^{-5} m^3/sec).

- V_{Tank} or the Crew-Compartment and Driver-Compartment volume. The tank volume was modeled as a triangular distribution for input into the Crystal Ball program. The volume of the Crew Compartment (7.1 m^3) and volume of the Driver's Compartment (0.5 m^3) as determined by PM-Abrams had previously been provided. When adjustments are made for the crewmembers and their personal equipment, the total air volume of the tank is about 7.2 m^3. Therefore, the MLV was selected to be 7.2 m^3. A 10 percent measurement uncertainty was assumed on this value to determine the lower-bound and upper-bound values. Therefore, the lower-bound value was selected to be 6.48 m^3, and the upper-bound value was selected to be 7.92 m^3.

- AM_{Avg} or weighted areal mass average in the vehicle is described with equation 2 parameters. (See page 112.)

- SA or tank interior surface area is described with equation 2 parameters.

- FC or the fraction of aerosol mass concentration collected by the air samplers. The fraction collected was modeled as a triangular distribution for input into the Crystal Ball program. The

upper bound of the DU aerosol mass concentration that could be collected by a filter is 100 percent (1.0). However, all particle sizes (AED) would not enter the sampler. This factor estimates many unknown factors that would reduce the concentration measured by the sampler when compared to the actual concentration in the Crew Compartment. Some of these factors include sampler CE, incomplete aerosol mixing, and venting of the aerosol from the interior of the tank. Professional judgment was used to estimate the lower-bound value of 50 percent (0.5). This assumes that the DU aerosol mass concentration calculated by the air sampler data is only 50 percent of the actual DU aerosol mass concentration in the Crew Compartment. It is believed that this is a conservative assumption. The MLV was assumed to be the midpoint between 50 percent and 100 percent or 75 percent (0.75).

- CE is described with equation 2 parameters.
- DF is described with equation 2 parameters.

Crystal Ball Estimates of Sampler Run-Time. The range of probabilistic run-times for 10,000 trials was from 2.25 seconds to 1,170 seconds with a mean of 30 seconds, a standard deviation of 37 seconds, a median of 21 seconds, and a σ_g of 1.9 seconds. (See Cell D15, Appendix O.) The Crystal Ball Report, to include a statistical description of the results forecast and a probability distribution, is included in Appendix O.

Assumption 1 input parameters are summarized in Table 28.

Table 28. Assumption 1 Input Parameters Summary

Parameter	Distribution Type	Lower Bound	MLV	Upper Bound
M_{Col} (mg)	Uniform	3.0	NA	3.7
FR (m^3/sec)	Triangular	5E-5	6.67E-5	8.3E-7
V_{Tank} (m^3)	*Triangular*	6.48	7.2	7.92
AM_{Avg} (mg/cm^2)	Triangular	0.0004	0.01787	0.0410
SA (m^2)	Triangular	32	48	64
FC (fraction)	Triangular	0.50	0.75	1.0
CE (fraction)	Triangular	0.10	0.25	1.0
DF (fraction)	Triangular	0.90	0.90	1.0

4.5.5 Methodology for Determining Sampler Run-Time for Assumption 2

The sampler run-time was modeled from the time analysis performed on the Driver's position air sampler. The time distribution was modeled as a triangular distribution with an MLV of 120 sec (2 minutes), a lower-bound of 61 sec (1 minute 1 sec) and an upper-bound of 298 sec (4 minutes 58 sec).

4.6 Methodology for Estimating DU Concentration in the Tank

The two sampler run-time estimates (Assumptions 1 and 2) were used to estimate DU aerosol mass concentrations (mg/m^3). The DU aerosol mass concentrations were assumed to be constant over an exposure time and intakes of DU (mg) were estimated. From the estimated intakes, the ranges of CEDE (rem), lung CDEs (rem), and DU kidney concentrations (µg of DU/g of kidney) were estimated.

The following equation was used to estimate the range of DU aerosol mass concentrations (C).

$$C\ (mg/m^3) = M_{Col}/(FR * t) * 1/FCE \qquad \text{(Equation 5)}$$

Where:

- M_{Col} is the mass collected by the air samplers in the compartment under consideration. For Assumption 1, a uniform distribution was used for input into Crystal Ball. The lower-bound value was 3.0 mg (Commander's position air filter result), and the upper-bound value was 3.7 mg (Gunner's position air filter result). For Assumption 2, a triangular distribution was used for input. The MLV was 2.67 mg (Driver's position air filter result). The lower bound selected was 2.40 mg (-10 percent of the MLV), and the upper bound selected was 2.94 mg (+10 percent of the MLV).

- FR is the air sampler average flow rate. For Assumptions 1 and 2, the FR parameter was modeled as a triangular distribution with an MLV of 6.67×10^{-5} m^3/sec, a lower-bound of 5.0×10^{-5} m^3/sec, and an upper bound of 8.3×10^{-5} m^3/sec.

- t is the time the air sampler ran to collect the M_{Col}. The parameter, t, was estimated by Assumption 1 and was used as input into the concentration forecast. For Assumption 2, t was modeled as a triangular distribution with an MLV of 120 sec (2 minutes), a lower-bound of 61 sec (1 minute 1 sec), and an upper bound of 298 sec (4 minutes 58 sec).

- FCE and was modeled as a constant of 0.98 for input into the Crystal Ball program.

4.7 Methodology for Assessing Intake

The following equation was used to estimate the range of DU intakes (I) in mg.

$$I\ (mg\ DU) = C * BR * RF * t_{exp} \qquad \text{(Equation 6)}$$

Where:

- C is the DU aerosol mass concentration in mg/m^3 as estimated from equation 5. The concentrations calculated from Assumptions 1 and 2 were used as input to determine Intake Distributions 1 and 2.

- BR is an individual's breathing rate in m^3/sec. The distribution for Assumptions 1 and 2 was modeled as a triangular distribution with an MLV and upper bound of 8.33×10^{-4} m^3/sec (3 m^3/hr). The lower bound was selected as 3.33×10^{-4} m^3/sec (1.2 m^3/hr).

- RF is the respirable fraction and was modeled as a triangular distribution with an MLV and upper bound of 0.96. The lower bound was selected as 0.60. These values for the RF were based on the technical literature review.

- t_{exp} is an individual's exposure time in seconds. The distribution for Assumptions 1 and 2 was modeled as a triangular distribution with an MLV of 60 sec. The lower bound was 10 sec, and the upper bound was 120 sec. These values were provided by OSAGWI personnel.

4.8 Methodology for Estimating CEDE for Inhalation

The CEDE is the dose received over 50 years following an intake of DU. The following equation was used to estimate the range of CEDEs.

CEDE (rem) = I (mg) * DCF (rem/mg) (Equation 7)

Where:

The DCFs for different lung clearance classes were developed by using the Lung Dose Evaluation Program (LUDEP) (NRPB-SR-287, 1996) based on the fractional mass amount of DU, that is U-234, U-235, U-236 and U-238, and on a 1 mg intake of a 5 μm AMAD aerosol inhaled by a mouth breather having a BR (or ventilation rate) of 3 m^3/hr (or 50 L/min). (See Appendix J for a discussion of computer models, dose calculations and derivations of the DCFs listed below.) The Radiological Bioassay and Dosimetry (RBD) program (ORNL/TM-11858, 1993) and the Code of Internal Dosimetry (CINDY) (PNL-7493, 1992) were used to verify the dose estimates. A discussion of these three codes is found in Appendix J. The inhalation DCFs used for the dose calculations are provided in Table 29.

Table 29. Summary of Inhalation DCFs

Clearance Class	DCF	Appendix J Reference
Class D	8.52 E-4 rem/mg	Table J-18
Class W	1.25 E-2 rem/mg	Table J-17
Class Y	2.18 E-2 rem/mg	Table J-16

The Fliszar et al., (1989) report indicates that a range for the ratio of soluble-to-insoluble aerosolized DU fraction exists. However, Fliszar et al., (1989), did not differentiate between the soluble and insoluble percentage and the chemical form of the aerosolized DU that had been collected inside the tank. Therefore, professional judgment based on the technical literature reviewed assumed that 17 percent Class W (or Type M) would be the moderately soluble fraction and 83 percent Class Y (or Type S) would be the insoluble fraction. Therefore, the resultant inhalation DCF is—

$$(0.83 * 2.18E\text{-}2) + (0.17 * 1.25E\text{-}2) = 2.0219E\text{-}02 \text{ or } 2.02E\text{-}02 \text{ rem/mg}$$

Therefore, the CEDE for an inhalation intake of 79 mg based on the percentages above is—

$$(79 \text{ mg}) * (2.02E\text{-}2 \text{ rem/mg}) \cong 1.6 \text{ rem}$$

For example, for DU solubility percentages of 60 percent Class Y (or Type S), 20 percent Class W (or Type M) and 20 percent Class D (or Type F), the inhalation DCF is—

$$(0.60 * 2.18E\text{-}2) + (0.20 * 1.25E\text{-}2) + (0.20 * 8.52E\text{-}4) = 1.58E\text{-}2 \text{ rem/mg}$$

Therefore, the CEDE for an inhalation intake of 79 mg based on the percentages above is—

$$(79 \text{ mg}) * (1.58E\text{-}2 \text{ rem/mg}) = 1.25 \text{ rem or} \cong 1.3 \text{ rem}$$

Appendix O discusses the uncertainty and sensitivity analysis. The calculation of the intake of DU and the resultant dose was based on a 5 μm AMAD aerosol. See Appendix J for a discussion on respiratory tract and the inhalation DCFs for both a 1 μm and 5 μm AMAD aerosol.

4.9 Methodology for Estimating DU Lung CDE for Inhalation

The following equation was used to estimate the range of DU lung CDEs.

$$CDE_{lung}\ (rem) = CEDE\ (rem) / W_T \qquad \text{(Equation 8)}$$

In the adult, it is satisfactory to consider the respiratory tract, which is composed of the trachea, bronchi, and pulmonary region and associated lymph nodes as one composite organ of mass 1,000 g to which the CDE is applied (ICRP-23 and ICRP-26). The lifetime risk factor for fatal lung cancer in 1977 was according to ICRP-26 2×10^{-5}/rem. The lifetime risk factor for fatal lung cancer in 1990 according to ICRP-60 was 8.5×10^{-5}/rem. (See Appendix G for a discussion of risk coefficients.)

The W_T represents the proportion of the stochastic risk resulting from the tissue to the total risk, when the whole body is irradiated uniformly. The W_T is obtained from ICRP-26 and ICRP-60. The W_T for the lung is 0.12 or 12 percent of the total risk (see Appendix G).

The CDE for the lung is—

$$CDE_{lung} = CEDE / 0.12 \qquad \text{(Equation 8a)}$$

or

$$CDE_{lung} = CEDE * 8.33 \qquad \text{(Equation 8b)}$$

Since the lung is regarded as having a greater sensitivity to radiation than the lymphatic tissue, it is assumed that the irradiation of the lung is more limiting than the lymphatic tissue in determining the dose limitation for such inhaled insoluble radioactive particulates.

4.10 Methodology for Estimating the Kidney DU Concentration for Inhalation Exposure

The following equations were used to estimate the range of kidney concentrations. This is done by first calculating the amount of DU reaching the kidney, and then expressing that amount as a concentration.

$$K_y = I * \sum_{Class}^{D,W,Y} (f_b * f_k) \qquad \text{(Equation 9)}$$

Where:

- K_y = Amount of DU reaching the kidneys (mg)
- I = Intake (mg)

- f_b = Fraction transferred to blood (see Appendix J)
- f_k = Fraction transferred to kidney (see Appendix J)

$$\text{Kidney Concentration (µg DU/g of kidney)} = \frac{\text{mg to kidney} \times (1000\ \mu g / mg)}{M_{kidney}}$$

Where: M_{kidney} = Mass of kidneys (310 g)

Transport of DU to the Kidney. The amount of DU reaching the kidney is related to the AMAD of the aerosol inhaled and the solubility of the DU. (See Appendix J for a discussion of DU in the human body and the derivation of the following fractions that reach the kidney.) The fractions that reach the kidney will do so over varying time intervals. In this kidney concentration analysis, it is assumed that all DU that reaches the kidney will do so at the same time.

The fraction of DU reaching the kidney for a particle size of 5 µm AMAD for each respiratory clearance class (that is, $f_b * f_k$) is summarized in Table 30.

Table 30. Fraction of DU Reaching the Kidney

Class	Fraction Reaching Kidney at 5 µm AMAD
D	0.0642
W	0.0174
Y	0.0034

The amount (mg) of DU reaching the kidney is calculated as follows:

$$K_y = I * \sum_{Class}^{D,W,Y} (f_b * f_k)$$

- **Assumptions:**

Intake (I)	=	25.19 mg
Fraction of Class D	=	0.00
Fraction of Class W	=	0.17
Fraction of Class Y	=	0.83
Fraction of Class Y reaching the kidney	=	0.0034
Fraction of Class W reaching the kidney	=	0.0174
Particle size	=	5 μm AMAD
Mass of kidneys	=	310 g (ICRP-23)

The amount of a 5 μm AMAD aerosol reaching the kidney is:

$$(25.19 * 0.83 * 0.0034) + (25.19 * 0.17 * 0.0174) = 0.1456 \text{ mg}$$

Therefore, the concentration of DU in the kidney is (0.1456 mg ∗ 1000 μg/mg)/310 g or 0.4 μg DU/g of kidney.

4.11 Summary of Inhalation Exposures

Summaries of the input parameters and results from the Crystal Ball Monte Carlo simulations for Assumption 1 and Assumption 2 are provided below. Additional details are provided in Appendix O. Also, included in Appendix O are results of the sensitivity analyses from each simulation. The sensitivity charts in Appendix O display the influence each input parameter has on a particular result.

4.11.1 Summary of Input Parameters for Inhalation Exposures

The input probability distributions for Assumption 1 and Assumption 2 are summarized in Table 31 and Table 32, respectively. The rationale for the various distributions and values was presented in Sections 4.5.5 through 4.7. Appendix O contains the Crystal Ball input parameters reports for the two simulations along with charts displaying the input probability distributions.

Table 31. Assumption 1 Input Parameters

Parameter	Distribution Type	Minimum	Likeliest	Maximum	Simulation Mean
Areal Mass Average – $\mu g/cm^2$	Triangular	0.40	17.90	41.0	19.77
Wipe CE	Triangular	0.10	0.25	1.00	0.45
Interior SA – m^2	Triangular	32	48	64	47.96
Surface DF	Triangular	0.90	0.90	1.00	0.93
Tank Volume – m^3	Triangular	6.48	7.20	7.92	7.20
Collection Fraction	Triangular	0.50	0.75	1.00	0.75
Sampler FR – m^3/sec	Triangular	5.00E-5	6.67E-5	8.37E-5	6.67E-5
Mass Collected – mg	Uniform	3.0	NA	3.7	3.35
RF	Triangular	0.60	0.96	0.96	0.84
BR – m^3/sec	Triangular	3.33E-4	8.33E-4	8.33E-4	6.66E-4
Crew t_{exp} – sec	Triangular	10	60	120	63.18

Table 32. Assumption 2 Input Parameters

Parameter	Distribution Type	Minimum	Likeliest	Maximum	Simulation Mean
Sampler Run-Time – sec	Triangular	61	120	298	159.87
Sampler FR – m^3/sec	Triangular	5.00E-5	6.67E-5	8.37E-5	6.68E-5
Mass Collected – mg	Triangular	2.40	2.67	2.94	2.67
RF	Triangular	0.60	0.96	0.96	0.84
BR – m^3/sec	Triangular	3.33E-4	8.33E-4	8.33E-4	6.67E-4
Crew t_{exp} – sec	Triangular	10	60	120	63.05

4.11.2 Summary of Probabilistic Results for Inhalation Exposures

A summary of the Assumption 1 and Assumption 2 statistical results from the Crystal Ball Monte Carlo simulations is provided in Table 33. The statistics, percentiles, and probability distribution charts are provided for each value forecast in the Crystal Ball Monte Carlo simulations in Appendix O.

Table 33. Summary of Assumption 1 and Assumption 2 Results

Result	Assumption	2.5 %tile	Median	Mean	97.5 %tile
t (sec)	1	5.69	21.23	30.30	112.0
	2	NA	NA	NA	NA
C (mg/m^3)	1	468	2410	2990	8690
	2	147	267	286	530
I (mg)	1	11.86	78.56	105.6	366.0
	2	2.553	8.871	10.07	24.40
CEDE (rem)	1	0.240	1.59	2.13	7.39
	2	0.0516	0.179	0.203	0.493
Lung CDE (rem)	1	2.0	13.2	17.8	61.6
	2	0.430	1.49	1.69	4.11
Kidney Concentration (µg DU/g)	1	0.22	1.46	1.97	6.82
	2	0.05	0.17	0.19	0.45

4.12 Secondary Ingestion (Hand-to-Mouth)

The methodology for this estimate is contained in Appendix F. The upper-bound CEDE is 0.0006 rem for an individual inside an Abrams series tank, following a single-round perforation by secondary ingestion (hand-to-mouth) of DU surface contamination. The CEDE was calculated

using a total secondary ingestion intake of 24 mg [insoluble intake of 20 mg and a soluble intake of 4.0 mg (83 percent slow absorption and 17 percent moderate absorption)]. The intake of 24 mg of DU by secondary ingestion would result in a conservative estimate of 0.12 mg [(4 mg x 0.02) + (20 mg x 0.002)] being absorbed into blood via the GI tract.

The lower-bound CEDE is 0.0003 rem for an individual inside an Abrams series tank following a single-round perforation by secondary ingestion (hand-to-mouth) of DU surface contamination. The CEDE was calculated using a total secondary ingestion intake of 12 mg [insoluble secondary ingestion intake of 10 mg and a soluble secondary ingestion intake of 2 mg (83 percent slow absorption and 17 percent moderate absorption)]. This intake of 12 mg (~50 percent of the upper bound) of DU by secondary ingestion would result in a conservative estimate of 0.06 mg [(10 mg x 0.002) + (2 mg x 0.02)] being absorbed into blood via the GI tract.

4.13 External (Gamma) Radiation Deep Dose

During the Gulf War, veterans in Abrams series tanks uploaded with DU munitions were potentially exposed to external gamma radiation. The following provide generic dose rates in the tank:

- The average deep-dose rate for the driver of an Abrams tank is 0.00013 rem/hr with the bustle fully loaded with DU ammunition pointing forward and with the Driver's hatch open. When the

gun tube is pointed forward in a non-DU-armored vehicle, the average dose rate is 0.00003 rem/hr. In a DU-armored vehicle, the average dose rate is 0.0001 rem/hr.

- The average deep-dose rate is 0.00002 rem/hr for the gunner, loader, and commander of an Abrams series tank, with a DU combat load.

- The maximum deep-dose rate directly on the front surface of the turret outside an M1AI DU armored tank is about 0.0003 rem/hr.

- Appendix L provides the dose rates to crewmembers of an Abrams series tank uploaded with DU munitions.

- Based on anecdotal information, a tanker may have spent up to three months "pretty much continuously" in his Abrams series tank. The highest external dose for this period would be approximately 0.3 rem (deep-dose).

- An external radiation deep dose will not be calculated for any individual who may have occupied an Abrams series tank uploaded with DU munitions during the Gulf War because of unknown exposure durations. However, by using the data in this report and knowing the exposure time, estimates of an individual's dose may be calculated.

- For example, if the driver of a non-DU armored Abrams series tank drove with the bustle fully loaded with DU ammunition pointed forward and with the driver's hatch open for 20 hours, his

estimated deep dose would be 0.003 rem (20 hrs x 0.00013 rem/hr). If the driver drove for 40 hours with the gun pointed forward, his estimated deep dose would be 0.0012 rem (0.00003 rem/hr x 40 hrs).

4.14 Other Exposure Scenarios

4.14.1 Inside a Struck Vehicle, Armor not Perforated

Table 34 summarizes the intake and the 50-year CEDE to individuals inside the Abrams series tanks when the DU round did not penetrate the Crew Compartment. From Fliszar et al., (1989), the highest estimated intake inside the turret Crew Compartment was 0.042 mg of DU when perforation did not occur. These data assume:

- An intake of 0.042 mg of DU
- A 2-minute exposure duration (a conservative assumption)
- The isotopic composition
- A 5 μm AMAD aerosol
- Solubility of the DU oxide (17 percent moderate absorption and 83 percent slow absorption)

Table 34. Estimated DU Intake of 0.042 mg and CEDE to Individuals Inside the Abrams Series Tanks During the Time When a DU Round Did Not Perforate the Crew Compartment (5 μm AMAD Aerosol)

0.035 mg 83% Class Y Solubility or slow absorption, DUO_2, DU_3O_8		0.007 mg 17% Class D Solubility or fast absorption, DUO_2		0.035 mg 83% Class Y Solubility or slow absorption, DUO_2, DU_3O_8		0.007 mg 17% Class W Solubility or moderate absorption, DUO_2		0.024 mg 57% Class Y Solubility or slow absorption, DUO_2, DU_3O_8		0.018 mg 43% Class D Solubility or fast absorption, DUO_2	
Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
0.035	0.001	0.007	0	0.035	0.001	0.007	0	0.024	0.001	0.018	0

4.14.2 Intake from Embedded DU Fragments and Wound Contamination

As discussed in McDiarmid et. al., (1999), some Level I Gulf War Veterans involved in DU friendly fire incidents had wounds contaminated with DU and retained embedded fragments. The dose assessment models required to estimate the radiation doses and chemical intakes from these exposures are not available at this time. The National Council on Radiation Protection and Measurements is in the process of developing the models required for this assessment.

There are limited data available for radiation dose estimates. The VA has been monitoring a subset of these veterans in a voluntary program initiated in the 1993-94 timeframe. Those veterans with embedded fragments have had constant, elevated urine DU levels throughout the monitoring period with the highest on the order of 31 μg of uranium per gram of creatinine. McDiarmid et. al., (2000) developed a method for estimating the radiation dose based upon the results of in vivo and in vitro

measurements. This technique yielded CEDE dose estimates ranging from 0.01 rem to 0.1 rem per year from this constant excretion. The reliability of this novel technique used to estimate these doses has not as of yet been verified.

4.14.3 Intake of Contaminated Foodstuffs, Soil, and Water

The intake of contaminated foodstuffs, soil, and water are modes of direct ingestion. Data are not available to estimate the intake of DU from these media. See Appendix F for a discussion of the calculational methodologies for direct ingestion.

4.14.4 Depleted Uranium Contamination of Gun Tubes

Radiological surveys have identified both fixed and removable radioactive contamination in gun tubes that fired developmental and production DU munitions. These DU-contamination levels were well below levels that could pose an adverse health effect for individuals who may be potentially exposed to DU contamination, Parkhurst et el., (1995a).

4.14.5 Gun Tube Flareback or Blowback

When an Abrams Tank fires a 120mm DU round there is flareback or blowback of some of the propellant gases. Radiological surveys indicate that airborne levels of DU near the gun tube breech

and in the Crew Compartment were indistinquishable from background levels, even when the bore evacuator was made inoperable, Parkhurst et al., (1995a).

4.15 Health Risk Characterization for OSAGWI Level I DU Exposures

Both the impact and perforation of a DU penetrator on a hard target and the burning of DU munitions produce DU dust or aerosol particles. The high temperature created during impact or perforation and fires act to oxidize the DU metal to a series of complex DU oxides (predominately DU_3O_8 and DUO_2). These are considered to be insoluble and Class Y (or Type S) in the open literature. However, Army test data have shown that these same oxides, when formed in impact or perforation events of hard targets, produce a measurable percentage of more soluble DU compounds (Class D/W or Type F/M).

Since the exposure assessments are not for a specific individual, the anatomical and physiological characteristics of Reference Man (ICRP-23, ICRP-66 and ICRP-70) are used for the dose estimates.

Appendix M provides a theoretical tank battle scenario for calculating internal dose to soldiers on the battlefield.

Appendix N provides data input for modeling DU exposure on the battlefield [83 percent insoluble Class Y (or Type S) and 17 percent moderately soluble Class W (or Type M)].

Appendix O summarizes the uncertainty and sensitivity analysis for OSAGWI Level I Scenarios.

Appendix P summarizes the data gaps for OSAGWI Level I Scenarios and those extracted from Shelton et al., (1995)[25].

Appendix Q summarizes the sensitive parameters used in the DU assessment of OSAGWI Level I Scenarios.

4.15.1 Chemical Risk

The toxic effects of uranium vary according to its route of exposure and its chemical form. In general, ingested uranium is less toxic than inhaled uranium. This is attributable in part to the low GI absorption of uranium compounds (0.2 percent to 2 percent). Solubility, which is dependent on the chemical form, correlates positively with toxicity, with the most soluble compounds being the most toxic. Regardless of the chemical form which uranium takes, once it is in the bloodstream its primary target organ is the kidney. While this does not exclude the possibility of the DU inflicting functional lesions in other organ systems such as bone and liver, it is believed that the kidney is the most sensitive target organ to uranium toxicity. Upon entering the bloodstream, approximately 60 percent of the uranium in plasma exists in stable complexes with carbonate or bicarbonate. These complexes are filtered in the kidney at the glomerulus. As glomerular filtrate passes along the proximal tubules, the complexed uranium dissociates with decreasing pH. This liberates the

reactive uranyl ion, which can interact with and damage components to the proximal tubule membrane prior to being excreted in the urine.

The necessary toxicity benchmark values, exposure criteria, and methodology do not exist to retrospectively or quantitatively assess chemical risk following a battlefield exposure. The methodology currently in place for Health Risk Assessments (HRAs) is not intended to be used for retrospective studies following a chemical exposure. Rather, HRAs are intended to be prospective and thus protective. In a quantitative risk characterization and in risk assessments, a predicted exposure value is compared to an appropriate exposure guideline or reference value. If the ratio of these values is greater than unity, then steps may be taken to decrease the predicted exposure value. In a qualitative risk characterization, risk is described with words rather than equations. Neither quantitative nor qualitative risk characterizations are used to determine whether or not an effect has occurred. Whether quantitative or qualitative, the reference values used in HRAs are intended to be protective of all individuals, including sensitive individuals. Occupational exposure guidelines are also intended to be protective. They represent concentrations that are believed to be safe; however, they do not generally represent concentrations that are believed to be a threshold for safety. Because of this, it cannot be concluded that adverse health effects will result if a guideline is exceeded, nor can the degree of a potential effect be accurately predicted. When an exposure has occurred and a guideline has been exceeded, the health of the exposed individual is monitored, as is being done in the case of Gulf War Veterans with the greatest potential for DU exposure. However,

because the guidelines are meant to be protective, if the guidelines are not exceeded, it can usually be stated with confidence that adverse health effects are not expected to occur.

In the present effort, which is a qualitative risk characterization, predicted exposure levels are presented together with the most appropriate guidelines available. However, for the reasons stated above, they are only compared descriptively; a quantitative evaluation is not given.

The most applicable guideline values for use in OSAGWI Level I Scenarios are the Short Term Exposure Limit (STEL) and the Temporary Emergency Exposure Limits (TEELs) (see Appendix K). The STELs are derived by the American Conference of Governmental Industrial Hygienists (ACGIH) and are defined as the 15-minute Time-Weighted Average (TWA) that should not be exceeded at any time during a workday. The STEL for inhaled natural uranium, soluble and insoluble forms, is 0.6 mg/m^3. The TEELs are derived by the Subcommittee on Consequences Assessment and Protective Actions (SCAPA). They are intended to serve as temporary Emergency Response Guidelines (ERPGs), mass concentrations below which are not predicted to result in irreversible or life-threatening health effects following an exposure of up to one hour. The methodology for deriving TEELS is based on a hierarchy of existing concentration limits for other standards of exposure, for example, PELs and Immediately Dangerous to Life or Health (IDLH) levels. Because many chemicals lack such limits, the methodology was expanded to include use of published toxicity parameters [for example, dose causing 50 percent lethality (LD_{50}), lowest

published lethal dose (LD_{LO}), lowest published toxic dose (TD_{LO}), concentration causing 50 percent lethality (LC_{50}), lowest published lethal concentration (LC_{LO}), and lowest published lethal toxic cencentration (TC_{LO})]. The values for soluble and insoluble forms of uranium are 0.05, 0.6, 1.0, and 10.0 mg/m^3 for TEELs 0, 1, 2, and 3, respectively. These values were derived from the PEL-TWA, the STEL, and the IDLH (Craig, personal communication, March 2000).

Guidelines for uranium issued by American National Standards Institute (ANSI) indicate that 40 mg and 8 mg inhalation intakes of soluble uranium are thresholds for permanent and transient renal injury, respectively. In addition to being intended for soluble forms of uranium only, these guidelines are based on a default particle size of 1 µm AMAD and 50 percent absorption from the lungs (National Defense Research Institute, 1999). Based on findings on the chemical toxicity of uranium, a guideline of 3 µg uranium/g of kidney was adopted in 1959 by the ICRP (Spoor and Hursh, 1973). Data that have become available since this guideline and were adopted suggest that this value may need to be re-evaluated and may be lowered. (Leggett, 1989; Zhao and Zhao, 1990).

4.15.2 Radiation Risk

The upper-bound internal radiation dose (CEDE) from inhalation and ingestion (direct, indirect and secondary) of DU particles for Level I individuals (excluding those with embedded DU fragments) when a single DU penetrator entered the Crew Compartment is estimated to be 1.6 rem for a 2-minute exposure. For two perforations, the upper-bound dose will be less than 5 rem

(1.6 rem x 3), and the lower-bound dose will be less than 0.6 rem (0.2 rem * 3). If a DU penetrator struck a tank but did not enter the Crew Compartment, the CEDE will be reduced even further.

The total detriment after low-dose, low dose-rate exposure to ionizing radiation is the sum of the contributions due to fatal cancer, non-fatal cancer, and severe hereditary disorders weighted for length of life lost (see Appendix G). This total detriment attributed to stochastic effects is 7.3×10^{-4}/rem. The upper-bound risk estimate for the dose estimate of 1.6 rem (CEDE) is 0.001 [that is, $(7.3 \times 10^{-4}$/rem) (1.6 rem) = 1.17×10^{-3} (based on 1.6 rem]. This is equivalent to about 1 in 800 estimated lifetime total risk from a 1.6 rem dose[26]. For two perforations, the total detriment is estimated to be 3.5×10^{-3} or about 1 in 300 for a 4.8 rem CEDE.

Individuals within the U.S. population receive an average annual effective dose equivalent of 0.3 rem or about 0.001 rem/day, from various sources of natural background radiation. Background radiation includes cosmic, cosmogenic, terrestrial, radon and its total progeny and other radionuclides in the body[27, 28]. If the radon is excluded then the average annual effective dose equivalent is 0.1 rem or about 0.00027 rem/day. The total radiation dose that an individual would receive from natural background for 50 years would be 15 rem (0.3 rem/yr x 50 yrs). This dose is equivalent to a 1 in 90 estimated lifetime total risk from a 15-rem dose[27].

Following an acute inhalation intake of insoluble Class Y (or Type S) DU, the major target organ is the lung[3]. The insoluble Class Y (or Type S) DU is also transferred to the pulmonary lymph nodes

where it dissolves into the blood. The primary hazard from inhaled DU particles is related to the amount of material taken into the respiratory tract, the chemical form, particle-size distribution, the solubility of the DU, the rate of transfer of inhaled DU to the blood, and the amount of DU reaching the kidney. Two factors that influence the health effects are—

- The site of deposition of DU particles in the respiratory tract.
- The fate of DU in the respiratory tract, which is dependent on the physical and chemical form of the particles, such as the solubility, exposed SA, and inter-crystalline forces. A radiation dose is delivered to the respiratory tract while the DU remains in the respiratory tract. (See Appendix J.)

All isotopes of a particular uranium compound exhibit the same chemical behavior in the body. Thus, the chemical toxicities of the same uranium compound whether formed with natural, depleted, or enriched uranium are identical.

The organs for long-term retention of soluble Class D (or Type F) DU are the bone, liver and muscle. The sites for long-term retention for the inhaled insoluble Class Y (or Type S) DU are the deep respiratory tract and pulmonary lymph nodes.

4.15.3 DU Intake for Chemical Toxicity Considerations

Review of available data from existing test documents generally supported assumptions that the inhaled DU particles of concern were those less than 10 μm in diameter (AED). (See Appendix D.)

For individuals inside an Abrams series tank at the time of impact by a single DU round (excluding those with embedded DU fragments), the total DU intake by inhalation and indirect ingestion is estimated to be 79 mg (upper bound) of which 13 mg intake or 17 percent is moderately soluble DU (see Appendices F and J for calculations). The intake of insoluble particles is estimated (upper bound) to be 66 mg. The soluble DU intake (13 mg) is below the ANSI standard[29] threshold for permanent renal damage (40 mg inhaled soluble uranium); a comparable standard for the intake of insoluble forms of uranium does not exist.

The upper bound, when individuals were in an Abrams series tank when a single DU penetrator entered the Crew Compartment, for total DU inhalation and indirect ingestion intake is estimated to be 79 mg. (See Appendix O.) For two perforations, the intake could be 1.5 to 3 times a single perforation. The total intake by inhalation and indirect ingestion of 237 mg (79 mg * 3) for two perforations is estimated to include 40 mg or 17 percent moderately soluble Class W (or Type M) DU and 197 mg or 83 percent insoluble Class Y (or Type S) DU. The upper-bound estimate of the kidney concentration (1.37×10^3 μg DU per 310 g) is about 4.4 μg DU/g of kidney. This value is

above the ICRP guidelines of 3 μg uranium/g of kidney. However, as is discussed in Section 4.15.1, exceeding a guideline does not imply that adverse health effects will result.

The lower bound, when individuals were in an Abrams series tank when a single DU penetrator entered the Crew Compartment, for the total DU inhalation and indirect ingestion intake is estimated to be 9 mg. The total intake includes 2 mg or 17 percent moderately soluble Class W (or Type M) DU and 7 mg or 83 percent insoluble Class Y (or Type S) DU. These values are considered to be the lower bound for chemical toxicity considerations. The lower-bound estimate of the kidney concentration (52 μg DU per 310 g) is about 0.2 μg DU/g of kidney. This is below the ICRP guidelines of 3 μg uranium/g of kidney.

For individuals who were in an Abrams series tank when a single DU penetrator impacted or perforated the tank but did not enter the Crew Compartment, the total DU inhalation and indirect ingestion intake is estimated to be 0.042 mg (Fliszar et al., 1989). The total intake includes a 0.007 mg inhalation and indirect ingestion or 17 percent moderately soluble Class W (or Type M) DU and 0.035 mg inhalation and indirect ingestion or 83 percent insoluble Class Y (or Type S) DU.

Appendix J provides a discussion of the respiratory tract model, the fate of DU in the body, and the estimated kidney concentrations of DU for those individuals with the highest intake.

Section 4.6 provides calculations of the estimated airborne concentration of DU, and Section 4.7 provides calculations for the estimated intake of DU for personnel inside the Abrams series tank from the Fliszar et al., (1989) Test 5A.

4.16 Discussion

4.16.1. First Responders

A separate dose range was not calculated for the First Responders. They are included in the dose range for the crew inside the vehicle at the time the vehicle was penetrated by DU munitions. Data available from Test 5A and in the remainder of the literature were not robust enough to allow separate estimates of intake for the First Responders. The DU airborne concentration at the time of entry by First Responders as well as their duration of exposure and level of physical activity will dictate their DU intake. At the present time, the intake estimates for the crew generated using data from Test 5A provide an upper bound for the First Responder intakes for the following reasons.

It is important to remember that the mechanisms for crew exposures (and the exposures to the air samplers in Test 5A) are significantly different from the First Responders. Video footage of vehicle perforations show that at the moment of perforation there is a spray of material into the Crew Compartment and the almost immediate ignition of small particles of DU which burn rapidly creating an aerosol which rapidly cools forming larger particles as it cools and coalesces. During

the penetration process, DU aerosols are being formed by the burning and are removed through gravitational settling and deposition onto the cooler walls of the vehicle. Once the penetration process ceases (hundreds of milliseconds), aerosols are no longer being formed and the predominant mechanisms are gravitational settling and impaction.

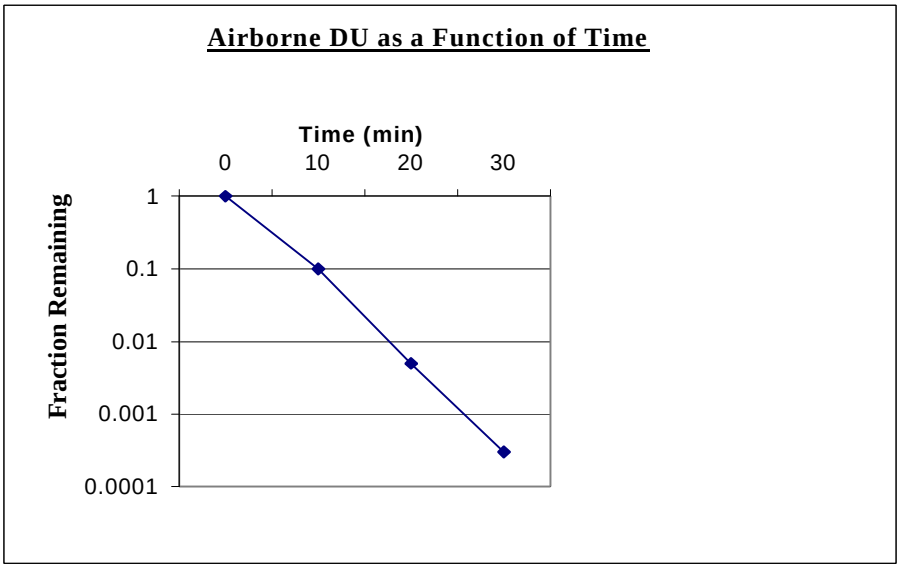
With the exception of the Driver's Compartment, the air samplers used to estimate crew doses were probably in the spray in Test 5A. Supporting evidence is the damage to the samplers and filter papers and the locations of the air samplers – across from the point of perforation. All samplers, including the one in the Driver's Compartment may have been exposed to the initial high temperature aerosol.

Particle-size distribution data could not be used to estimate the decay (decrease in particle size), as a function of time, in the aerosol mass concentrations seen by the sampler's in Test 5A for two reasons. First, no usable particle-size distributions are available. As discussed in Part III, the particle-size distributions for impact only considered particle sizes less than 10 μm AED and not the range of particles collected by the air samplers in Test 5A. For all other available particle-size distributions, the scenarios are substantially different from the conditions in Test 5A. Second, the theory required to model how particle size varies in the spray is not available. Simple gravitational settling models are not sufficient.

The only data available showing aerosol decay as a function of time inside an armored vehicle immediately after perforation are from unpublished data from an Army test (Parkhurst, personal communication, July 2000). In this unpublished data, a series of air samplers was remotely activated at 5-minute intervals after the target vehicle (a foreign tank) was struck by DU munitions. These data are shown in Figure 5 and show a rapid decline in the measured mass over time.

However, these data in Figure 5 could not be directly used because it could not be determined if the particle-size distribution of the unpublished data was similar to that in Test 5A. The single DU shot did not penetrate the Crew Compartment nor directly impacted the vehicle's armor. The path for the DU entering the Crew Compartment was not determined.

Figure 5. Airborne DU as a Function of Time Inside the Crew Compartment of a Tank



4.16.2 Level I BFV Personnel with Long Exposure Durations

The after action reports indicated that the exposure durations for at least one BFV crew was substantially longer than the time periods assumed in our estimate of Level I intakes. Estimates of intake for these personnel are hampered by the lack of airborne concentration decay data and a lack of data on how different the initial concentration in the BFV is from Test 5A.

The initial concentrations inside these BFVs will be less than for the Abrams in Test 5A, because the armor is so much lighter than the Abrams armor in Test 5A and because of the presence of DU armor in Test 5A. How much less cannot be determined without further testing. At the writing of this report, the tests needed to obtain this data were being planned.

4.16.3 Comparisons of Estimated Values with Gulf War Veteran Health Data

The most appropriate way to assess potential effects in circumstances where chemical guidelines for uranium have been exceeded is to monitor the health of the exposed individuals. The VA is doing this for 29 exposed individuals with embedded DU fragment(s) and 38 non-exposed veterans. From 1993 to today, the VA has not found any clinical evidence that patients with DU-embedded fragment(s) show kidney injury due to the embedded fragment(s) (Hooper et al., 1999, McDiarmid et al., 2000). It is concluded that these individuals also received similar or greater inhalation and indirect ingestion intakes of soluble and insoluble DU oxides compared to those in the current

scenarios. Therefore, even though the above calculations indicate that the chemical guidelines for uranium may have been exceeded, the absence of clinical evidence of kidney injury in individuals with embedded fragments suggests that there should be a similar lack of kidney injury in those individuals, without DU fragments, in the OSAGWI Level I scenarios.

The VA DU medical monitoring effort provides some support that our estimates are upper bound estimates of the inhalation intake for all Gulf War Exposure Scenarios including those with long exposure durations.

Figure 6 shows the estimated DU concentrations in urine as a function of time after intake under each of the calculated intakes for Assumption 1 and Assumption 2. Figure 6 is based upon NUREG/CR-4884 estimates of urine excretion as a function of time for 1 μm AMAD particle distribution, that is Class Y (NUREG/CR-4884, 1990). The intake amounts used were the median amounts estimated for both Assumption 1 (approximately 100 mg) and Assumption 2 (approximately 10 mg). The detection limits for both kinetic phosphorescence analysis (KPA - 0.06 - 0.02 μg/L) and inductively coupled plasma mass spectroscopy (ICP-MS-0.005 μg/L) are also plotted. The KPA plot is also close to the natural level of uranium in the urine (McDiarmid et al., (2000).

Figure 6. Estimated Urine DU Excretion Rates

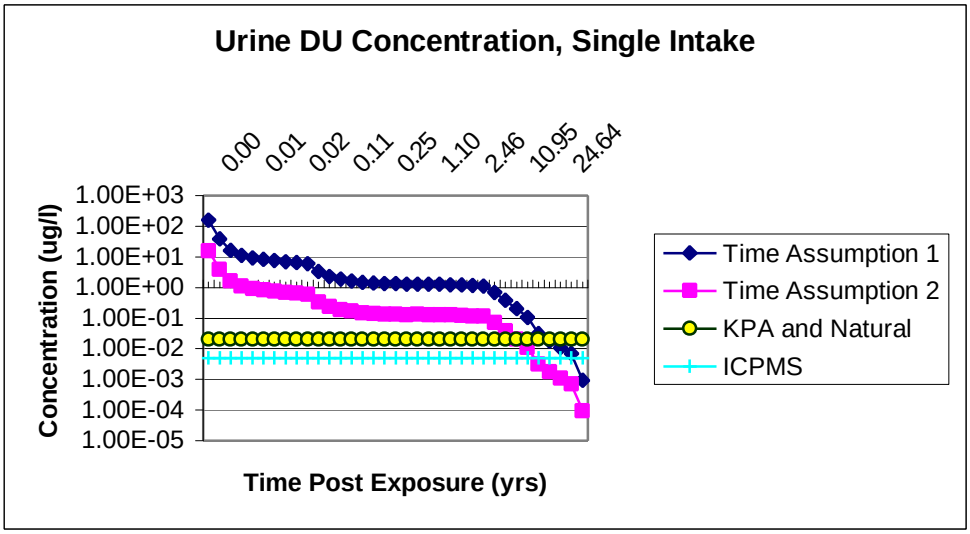


Figure 6 provides a reality check to ensure that our upper-bound estimates for inhalation-exposures are in fact an upper bound. If any of the Gulf War Veterans actually received an exposure equal to or greater than Assumption 1, the level of uranium in the urine would be above natural levels and detectable using KPA and would be readily detectable using ICP-MS to almost 10 years post exposure.

The VA has been monitoring a group of Level I personnel since 1994. In McDiarmid et al, (2000), it was found that the highest urine total uranium (which includes natural uranium from the environment) concentration measured for personnel without retained DU fragments was less than 0.1 µg of uranium per gram of creatinine. The normal urine creatinine range is 1.3 g/24 hrs to

2.6 g/24 hrs. This measurement was taken in the Spring/Summer of 1997, approximately 6 years after the Gulf War, and is consistent with the assumption that our estimates for inhalation exposure for all Level I personnel are upper bounds. The results of the medical surveillance of Level I veterans by the VA are also consistent with these assessments, McDiarmid et al., (2000).

4.16.4 Uncertainty and Sensitivity Analysis

Uncertainty and sensitivity analysis is limited because of the lack of data, but this analysis should identify the importance of changes in the parameters and values used to estimate confidence intervals in the overall exposure assessment. The range in the data may be due to a lack of verified data and to gaps in the field data.

To address the uncertainty and sensitivity analysis of the test data parameters used in this exposure assessment and health risk characterization, a probabilistic analysis, using Crystal Ball Monte Carlo simulations, was used to obtain a statistical basis for a more robust statement of the assessment results and conclusions. The use of this tool provides additional information that will help validate design criteria for future tests.

Three preliminary analyses were performed:

- A probabilistic estimate Crystal Ball Monte Carlo simulation of the DU aerosol mass concentration in the Abrams tank was determined.

- From Fliszar et al., (1989), wipe test data from the interior surfaces of the tank (Test 5A) were used to determine a Crystal Ball Monte Carlo simulation estimate of sampler run-time for Assumption 1.

- For Assumptions 1 and 2, Crystal Ball Monte Carlo simulations were used to determine DU intake(s).

Available data and transport modeling can be used to assess potential health effects to personnel and the general public from many potential accidents and battlefield situations. The exposure and intake of DU by an individual is based upon the airborne concentration, particle-size distribution, and lung solubility of the airborne DU and the individual's physiological characteristics at the time of exposure [for example, BR (or ventilation rate), tidal volume, and the percentage of mouth breathing]. Additional routes of exposure that are of lesser concern are secondary ingestion (from hand-to-mouth) transfer of radioactive contamination from external (environmental) surfaces, indirect ingestion from swallowing of sputum with inhaled DU particles, and direct ingestion of contaminated foodstuff, soil, and water. The factors that determine the characteristics of the airborne DU during and following an accident/battlefield situation, as well as those that may affect airborne transport have been discussed in previous sections of this report. Estimates of the exposures of an individual within or near a vehicle are assumption-driven in most cases. Even for

greater distances downwind, precise estimates of the various meteorological parameters are difficult to obtain in "real world" situations.

How well do the models predict the hazard? The actual exposure of an individual cannot be accurately predicted because of the complexity of actual "real world" situations on the battlefield and the lack of precision in determining the actual behavior of all the components leading to an exposure. The lack of knowledge on the precise sequence of events, the conditions surrounding the DU scenario, and the actions of the individuals involved forces the use of conservative assumptions. However, the upper and lower bounds of the exposure can be estimated.

Some areas where additional data seem particularly desirable still exist. One of these is determining the airborne fraction and concentration within vehicles following perforation and another is the resuspension of material from vehicle entry. The quantity and likely variation of airborne DU inside vehicles following a perforation are in need of further measurements. Closer examination of the adsorption of airborne particulate materials to oily surfaces inside vehicles or as a consequence of airborne combustion products may help define boundaries of exposure for personnel entering vehicles contaminated from fires involving DU. The oxidation of DU penetrators or fragments in the oxygen-depleted atmosphere inside vehicles during a fire could reduce estimates of the source term from any contamination in vehicles burning as a result of accident or battlefield situations. The characteristics of the oxides generated by heated and buried DU penetrators may also provide

additional useful information for the potential source of airborne materials from stray projectiles that impact but do not penetrate armored vehicles.

Although limited in number, the data currently available on the particle-size distribution and lung solubility of the oxide generated by penetrators from impact, perforation, or fires provide a reasonable basis for estimating values for modeling input. The data on dissolution rates are very limited and need to be determined. For useful results, the values chosen must be selected judiciously to reflect the situation analyzed. The particle-size information currently available for fires is mostly for the oxide generated and not airborne from the particular stress caused by events considered. For more accuracy in this parameter, the data from the particle-size distributions generated should be correlated with stresses (for example, aerodynamic stress during specific situations), and the airborne release of "transportable, respirable" particles should be determined from the events (for example, vehicle passage, debris impact on piles of oxide). Data should be sought that can be used to evaluate the particle-size distribution of the oxides generated and airborne concentrations of DU as a function of conditions and time following perforation.

The detailed input and results of this preliminary uncertainty and sensitivity analysis of the test data parameters used in the OSAGWI Level I exposure assessment and human health risk characterization are provided in Appendix O.

4.17 Summary

A critical review and evaluation of DOD available studies conducted over the past 30 years concludes that studies must be specifically designed to produce requisite data. These data must be suitable for use in determining the environmental and health and safety risks from aerosols generated in fires and target impacts, and they should identify and characterize the oxides formed when penetrators are exposed to the environment. At a minimum, these data should include:

- Chemical form
- Mass-mean size
- Surface-mean size
- Particle-size distribution
- Particle-shape factor
- Particle surface area and volume
- Specific gravity by DU oxide
- Solubility in lung fluid and dissolution rates
- Preferably the characteristic AMAD(s) and geometric standard deviations (σ_g) of the DU aerosol

Airborne concentration in the perforated vehicle and the resuspension of DU, both internal and external to the vehicle, remains a particularly awkward parameter to quantify for the battlefield. Efforts to better define DU-airborne concentration and resuspension following tests or incidents and

to reduce uncertainty would contribute effectively to the future selection of appropriate dose modeling factors.

4.18 Conclusions Resulting From Exposure and Intake Estimations

Intake estimations for chemical toxicity and radiation dose have been calculated for the Level I scenarios based on the Fliszar et. al., (1989) Test 5A data. Test 5A was a 120mm DU penetrator that perforated the DU armor in the Crew Compartment of the Abrams tank. The estimated exposure and intake of DU by individuals in, on and near (less than 50 meters) perforated vehicles at the time of perforation and for individuals who entered vehicles immediately following a single DU round perforation represent the Level I Scenarios. No test data are available to model more than a single perforation; therefore, the "worst case" may not be simply doubling the values for two DU round perforations, because the following must be considered:

- Resuspension inside the tank
- The time between perforations
- The types of munitions
- The type of vehicle
- The thickness and type of the armor
- The location of the perforations
- The angle of the perforations

However, based on professional judgment, the intake via inhalation and indirect ingestion of DU for two perforations could be 1.5 to 3 times greater than that for a single perforation. The BFV will offer less resistance to a DU penetrator than a tank (hard target); therefore, less aerosolation of the DU penetator will occur. Some vehicles in the Gulf War may have received two perforations.

The upper-bound median DU intake via inhalation and CEDE for a single penetration under Assumption 1 is 79 mg and 1.6 rem for a 2-minute exposure, respectively. Therefore, two penetrations may result in an intake of 237 mg (79 mg x 3) and a CEDE of less than 5 rem (1.6 rem x 3), respectively. (See Appendix O.) The dose an individual would receive from natural background in 50 years is about 15 rem (50 years x 0.3 rem/year).

4.19 Conclusions

Estimations of the lower and upper bounds of DU exposures, intakes, radiation doses, and chemical toxicity for identified exposure scenarios in OSAGWI Level I have been accomplished. Data gaps have been identified and recommendations for minimizing these gaps have been discussed in Appendix P. Developers' test data in draft reports have been reviewed and evaluated for usefulness and appropriateness for dose modeling.

This section provides exposure, intake, and dose assessments for Level I personnel who do not have wound contamination or embedded DU fragments. The inhalation and indirect ingestion routes of

exposure were the primary routes of entry considered for internalization of DU in this report. Ingestion by hand-to-mouth was considered to be a less significant route of entry. It is estimated that the secondary ingestion doses provided are within a factor of 2 to 5 based on professional judgment.

The intakes and doses of DU by Gulf War veterans are below current NRC and OSHA radiation safety standards of 5 rem in a year. Under Assumption 1, there is a potential for exceeding radiation safety standards for internalization of DU by personnel in or on an armored vehicle at the time the vehicle was perforated by two or more large caliber DU munitions. Under Assumption 2, it is unlikely that the radiation safety standards will be exceeded.

Estimated airborne concentrations of DU at the time of perforation exceeded all recommended guidelines used for this characterization. Intakes of soluble DU by veterans of the Gulf War are below the ANSI guideline of 40 mg soluble acute inhalation intake of soluble uranium as a threshold for permanent renal damage. Calculated kidney concentrations were below the ICRP guideline of 3 μg uranium per gram of kidney assuming that a vehicle was not penetrated by more than one DU munition.

Studies for obtaining health and safety data for human HRA are being planned (by DOD/Department of the Army (DA)) and are designed to produce the requisite data. The studies

are to be a team effort. As new data become available, exposure, intake and risk estimates may be modified.

Table 35 summarizes the range of DU intakes by inhalation, indirect and secondary ingestion for the OSAGWI Level I Scenarios.

Table 36 summarizes the range of DU exposures for chemical toxicity consideration for the OSAGWI Level I Scenarios.

Table 35. Ranges of DU Intakes by Inhalation and Indirect Ingestion, Level I Scenarios

Exposure Scenario	Total Estimated DU Intake Range (mg) in a vehicle[1]	Insoluble DU Intake Range (mg) in a vehicle	Radiation Dose Range (rem) in a vehicle[2]	Possibility Radiation Exposure Limit Exceeded[3]	Radiation Risk (Total Detriment)[4]	Soluble DU Intake Range (mg) in a vehicle	Possibility Chemical Exposure Limit Exceeded[5]	Chemical Toxicity Risk
Individual inside a tank at time of impact or perforation by a single DU round and First Responders	9 (LB) to 79 (UB)[6]	7 (LB) to 66 (UB)	0.2 (LB) to 1.6 (UB)	No	1:7,000 to 1:900	2 (LB) to 13 (UB)	Yes[7]	No
Individual inside a tank at time of impact by a single round, but did not penetrate the turret compartment	0.042	0.035	0.001	No	1:1,000,000	0.007	No	No
Individual inside a tank after perforation by a single round receiving secondary ingestion	12 (LB) to 24 (UB)	10 (LB) to 20 (UB)	0.0003 (LB) to 0.0006 (UB)	No	1:4,600,000 to 1:2,300,000	2 (LB) to 4 (UB)	No	No

[1] No credit for PPE, such as respirators or military protective masks, was given for the calculations in this table.
[2] CEDE dose for a 2-minute exposure spent in the vehicle. (Based on a 5-µm aerosol.)
[3] Internal radiation dose is expressed in terms of CEDE. Radiation standard equals 5 rem per year (10 CFR 20.21201 (a) and (b).
[4] Radiation Risk is expressed in total detriment (7.3×10^{-4}/rem).
[5] Chemical Toxicity Standard: 40 mg of inhaled soluble uranium is threshold for permanent renal damage; 8 mg of inhaled soluble uranium is threshold for transient renal injury (National Defense Research Institute, 1999, and ANSI, 1995).
[6] (UB) – Upper Bound of range is Assumption 1 median value; (LB) – Lower Bound of range is Assumption 2 median value for a single perforation. For two perforations, the intake and dose could increase by a factor of 1.5 to 3. The UB and LB are based on a 5 µm AMAD particle size distribution.
[7] Exceeding a guideline does not imply that adverse health effects will result.

Table 36. Ranges of DU Exposures for Chemical Toxicity Consideration, Level I Scenarios

Exposure Scenario	Total Estimated DU Intake Range (mg) in a vehicle[1]	Calculated Kidney Concentration (µg DU/g tissue)	Possibility Chemical Exposure Guideline Exceeded[2]	Estimated Air Concentration[3] (mg/m^3)	Possibility Chemical Exposure Guideline Exceeded[4]
Individual inside a tank at time of impact or perforation by a single DU round	9 (LB) to 79 (UB)[5]	0.2 LB	No	270 to 2,400	Yes
		1.5 UB	No		

[1] No credit for PPE, such as respirators or military protective masks, was given for the calculations in this table.
[2] Toxicity Guideline: 3.0 µg uranium per gram of kidney tissue is the derived guideline (Spoor and Hursh, 1973).
[3] Air concentration guidelines used for comparisons are DOE TEELs (0.5 mg/m^3 – 10 mg/m^3) and ACGIH, STELs (0.60 mg/m^3) (Craig 1998 and ACGIH, 2000).
[4] (UB) - Upper Bound of range is Assumption 1 median value; (LB) - Lower Bound of range is Assumption 2 median value for a single perforation. For two perforations, the intake and concentrations could increase by a factor of 1.5 to 3. The UB and LB are based on a 5 µm AMAD particle size distribution.
[5] Exceeding a guideline does not imply that adverse health effects will result.

PART: LEVEL II AND III EXPOSURE SCENARIOS

5.1 Exposure Estimates Under Consideration for OSAGWI Level II and III Scenarios

The individuals identified by occupation in the OSAGWI Level II scenarios (comprised of a few hundred personnel) with the greatest potential to being exposed to DU residue working in, on, or near DU damaged or destroyed vehicles (OSAGWI 1998) are as follows:

- Explosive Ordnance Disposal (EOD) personnel
- Radiation Control Teams (RADCON)
- Battle Damage Assessment Teams (BDATs)
- Logistics Assistance Representatives (LARs)
- Unit maintenance, service, and supply (salvage) personnel
- 144th Service and Supply Company
- Personnel exposed to DU during cleanup operations at Camp Doha
- Representative examples of DU exposure for Level II personnel

It is assumed that the EOD, RADCON, BDAT, and LAR personnel received some form of training and appropriate equipment to carry out their specific missions in an NBC, as well as a DU-contaminated environment. Team members should have known how to properly use PPE and how to perform personal decontamination procedures.

On 20 December 1990, the U.S. Army Armaments, Munitions, and Chemical Command (AMCCOM) sent a message to the LARs advising them on the proper precautions and assessment, repair, and recovery techniques of DU damaged vehicles (OSAGWI, 1998).

The unit maintenance personnel and other salvage crews may not have had DU training.

In addition to the Level II scenarios, potential exposures of the following groups in Level III scenarios (comprised of several thousand personnel) have also been evaluated:

- Personnel exposed to DU-airborne smoke from burning DU rounds at Camp Doha.

- Personnel exposed to DU-airborne smoke from a burning, uploaded Abrams tank, which includes personnel exposed during entry of the tank following the fire.

- Personnel exposed to DU from entering DU-contaminated Iraqi vehicles and equipment to include Cavalry Scouts and souvenir hunters.

- Personnel exposed to DU-airborne smoke downwind of a vehicle perforated by a DU round, which includes personnel exposed to DU-airborne smoke from DU-perforated Iraqi vehicles and personnel who traversed (walking or riding) in a DU-contaminated area.

Level III individuals may not have had DU training. The OSAGWI indicated that the Cavalry Scouts, who checked out enemy vehicles, may not have had DU training before their assignments to Southwest Asia and the Gulf War, OSAGWI, (1998).

The primary pathways for DU intake by Level II and III personnel are by inhalation, indirect ingestion, secondary ingestion, and wound contamination. The resuspension of DU particles is a major contributor to the inhalation pathway.

5.2 Available Data for the OSAGWI Levels II and III Scenarios

A review of published DOD DU munitions test reports identified data concerning the DU munitions used in the Gulf War (that is, chemical composition, particle size, isotopic composition, equilibrium of progeny, and solubility in body fluids). The test data were collected during various testing conditions including fires involving DU munitions; downwind puffs or plumes from DU penetrator impacts or perforations and reentry activities involving DU-damaged vehicles and equipment.

This exposure assessment uses data from a test involving 120mm DU munitions against an Abrams Heavy (DU armored) tank. This represents the most appropriate set of data available to model exposure assessments involving DU munitions. Many factors will influence the actual DU aerosol concentration including resuspension, the time between perforations, munitions type, vehicle type, armor type, perforation angle, as well as perforation location. If two perforations occurred, then intakes and dose could possibly be increased. Currently, there are no test data for multiple perforations; simply multiplying the single perforation data by the number of perforations may not be appropriate. Since no appropriate test data are available, it has been assumed, based solely on professional judgment, that the intake via inhalation and indirect ingestion of DU for two perforations may be a factor from 1.5 to 3 times greater than a single

perforation considering the uncertainties to include two perforations could possibly increase the estimated intakes and dose by secondary ingestion by a factor of 2 to 5 times.

Development of the DU Exposure Source Term. Describing the risk (either quantitatively or qualitatively) from material released into the environment involves several components of a generic risk assessment equation (see Appendix F) that must be known or assumed.

- These include the source term, the environmental transport and fate of the contaminant, and specific usage factors (characteristics of individuals and the exposure scenario).

- Appendix V lists the sensitive parameters and additional assumptions used in this DU exposure assessment and health risk characterization for soldiers potentially exposed to DU as described in the Levels II and III scenarios.

- Real data have been considered, when appropriate and available, for doing the exposure and health risk characterizations for the Level II and III scenarios. The degree of uncertainty for estimating a health risk increases as the number of assumptions that are factored into the equation increases.

Fratricide "Friendly Fire" Incidents During the Gulf War Involved the Abrams Tank and the BFV:

- Depleted uranium munitions perforated 6 Abrams tanks and 15 BFVs in fratricide incidents during the Gulf War.

- The BFV is less armored than the Abrams tank. Battle-damage assessments and interviews of involved individuals regarding fratricide incidents with these armored vehicles vary in their accounts of the events.

- The Abrams tank offers more resistance to anti-tank munitions than the BFV. This aspect leads weapons systems developers to conclude that a greater amount of aerosolized DU particles are generated when a 120mm DU munition penetrates an Abrams tank. No perforation tests involving the BFV and DU munitions have been conducted. There has been one hard target perforation test involving a single 120mm DU munition against an Abrams Heavy (DU armor) tank.

- Data from a test involving a DU munition against an M1A1 Abrams Heavy tank, Fliszar et al., (1989) were used to estimate the exposure and intake assessments. To date, this represents the most appropriate set of data available to model a fratricide incident involving DU munitions. There are no test data for DU penetration of BFVs. However, because of its light armor, the BFV would offer less resistance to DU penetration, and thus, it is assumed that aerosol production would not be as great as in the case with a DU penetration of an Abrams tank.

Physical Concept of DU Particles Resuspended into the Air. The resuspension of DU particles became a concern following Operation Desert Storm. During battle and during cleanup following battle, vehicles damaged by DU through fires and projectile perforations can become sources of DU particles that could be mechanically resuspended in, on, or near the vehicles. The degree of health risk due to inhalation and ingestion of DU particles depends upon numerous and

varying exposure factors. Appendix V describes the sensitive parameters used in the OSAGWI Levels II and III Exposure scenarios.

The use of resuspension factors or resuspension rates varies considerably for a given exposure scenario. In addition, resuspension factors do not indicate how rapidly a contaminant is removed from the ground surface and transported by the wind. The DU-airborne concentrations used to estimate the exposure for individuals in the OSAGWI Levels II and III scenarios are based on air sampling results from hard target testing involving DU munitions which are measured in the breathing zone of individuals during reentry, approaching a vehicle, and climbing onto, into, and out of the vehicle during the Fliszar et al., (1989) Tests 5A, 5B, and 6B. Therefore, this approach has provided an accurate estimate of the DU intake, because a direct measurement of the resuspension of DU particles exists.

When using the mass-loading method to calculate resuspension for soil, the contaminant must be uniformly mixed within the top 1 cm or more layer of soil. This does not always occur.

Resuspension rates for respirable particles (<10 μm AED) vary from 2.2×10^{-10}/sec for the 1.3-meter/sec to 3.6-meter/sec surface wind-speed interval to 2×10^{-8}/sec for the 5.8-meter/sec to 20.1-meter/sec surface wind-speed interval. This is a range of over two orders of magnitude.

The surface wind speeds during the Gulf War Ground Campaign varied from 5 to 36 knots (2.6 meter/sec to 18.5 meter/sec). With these wind speeds, dust and sandstorms occurred [U.S. Air Force-Europe Tactical Air Command (USAFE TAC, 1992)]. This range results in a two

orders-of-magnitude change in the resuspension rate and complicates any estimation of the DU intake.

Therefore, using DU-airborne concentrations ($\mu Ci/cm^3$) or mass concentrations (mg/m^3), determined for the given scenarios is the preferred method to estimate the DU intake via inhalation and indirect ingestion. The DU-airborne concentration is derived from measuring the amount of DU available from the perforation puff, ground surface soil, and surfaces on and within a DU-damaged vehicle.

The DU Available for Aerosolization and Resuspension in the Air. Table 37 provides a summary of environmental soil test data for the highest soil surface DU activity collected on 100 cm^2 deposition trays in the puff path downwind from the Fliszar et al., (1989) Test 5A.

Table 37. Soil Surface Concentration vs. Distance From Target for Test 5A

Location	Distance (m)	Concentration ($\mu g/100\ cm^2$)	Concentration (mg/m^2)
I-1R	5	11,000	1100
H-CL	5 (edge)	9,400	940
I-2R	10	4,300	430
K-4R	23	230	23
K-6R	33	42	4.2
L-12R	63	76	7.6
L-15R	77	10	1.0
AA-46	100	84	8.4
NA*	200	140	14.0
NA*	300	3.3	0.33
NA*	400	0.96	0.096

* Not Available

Reference: Fliszar et al., (1989), with minor editorial addition of mass concentration.

Based on observed data, Fliszar et al., (1989) from soil samples taken 8 to 10 meters from the target, the range of values is from 1.0 µg to 3.1 µg of DU/g of soil (or 0.4 pCi to 1.2 pCi DU/g of soil). The values are well below the NRC and DOE guidance of 35 pCi of DU/g of soil (site release criteria for unrestricted use[30]). The values are also two orders of magnitude lower than guidance levels set by the U.S. Environmental Protection Agency (USEPA) for residential areas (USEPA, 1999). These levels are intended to be protective of sensitive individuals (that is, children).

Removable DU-Surface Contamination Available for Inhalation and Ingestion (Direct or Secondary) Exposures. Removable DU-contamination may be found on all interior and exterior surfaces of armored vehicles and equipment damaged by DU munitions perforation or from fires involving DU munitions.

The limited space within an armored vehicle when occupied by individuals can result in body contact with the interior surfaces of the vehicle. Entry into and access to areas inside armored vehicles can also result in body contact with exterior surfaces as well as:

- Body contact with interior and exterior surfaces can increase the possibility of secondary ingestion of DU particles by way of hand-to-mouth transfer.

- Body contact with DU-contaminated equipment and surfaces may also result in trauma or injury producing a wound. At this time, dose assessment from a DU-contaminated wound will not be addressed because of inadequate data.

- Also, any activity causing movement within the armored vehicle by crewmembers increases the airborne concentration of DU by resuspension, therefore, increasing possible DU intake by inhalation.

Table 38 summarizes the total DU activity attributed to DU-contamination levels of the exterior surfaces of a DU-contaminated armored vehicle from the Fliszar et al., (1989) Test 5A. In the DU used in military applications, 1.79 beta particles are emitted for every alpha particle. See Part IV, Section 4.5.4, Table 27 for a discussion of the derivation of the value of 1.79 beta particles for every alpha particle.

Table 38. Results of Swipes on Exterior Surfaces of Armored Vehicle Turret for Test 5A

Surface	Total DU (dpm/100 cm^2)	Mass/Unit Area (mg/m^2)
Turret Left Side	179	21
Machine Gun Mount	129	15
Area Around Test 5A Perforation Hole	17 to 36	2 to 9
Hull Top Below Perforation	106	13
Left Turret Top	240	29

Reference: Fliszar et al., (1989), with minor editorial addition of mass removed per unit area.

Table 39 provides a summary of the total alpha activity attributed to DU-contamination levels of interior surfaces of a DU-contaminated armored vehicle from the Fliszar et al., (1989) Test 5A.

Table 39. Results of Swipes on Interior Surfaces for Test 5A

Surface	Total DU (dpm/100 cm^2)	Mass/Unit Area (mg/m^2)
Dummy Loader	307	37
Loader's Area	4815	575
Hole at Inside Wall	917	109
Driver's Compartment	34 to 1813	4 to 216
Ammunition Compartment	32 to 112	4 to 13

Reference: Fliszar et al., (1989), with minor editorial addition of mass removed per unit area.

Table 40 provides a summary of the total alpha activity attributed to DU-contamination levels of the exterior surfaces of a DU-contaminated armored vehicle from the Fliszar et al., (1989) Test 6B.

Table 40. Results of Swipes on Exterior Surfaces of Armored Vehicle Turret for Test 6B

Surface	Total DU (dpm/100 cm^2)	Mass/Unit Area (mg/m^2)
Turret Right Side	21	3
Right Turret Front	59	315
Area Around Test 6B Perforation Hole	None detected	None Detected
Loader's Machine Gun Ring	628 to 2056	162 to 245

Source: Fliszar et al., (1989), with minor editorial addition of mass removed per unit area.

Table 41 provides a summary of the total alpha activity attributed to DU-contamination levels of interior surfaces of a DU-contaminated armored vehicle from the Fliszar et al., (1989) Test 6B.

Table 41. Results of Swipes on Interior Surfaces for Test 6B

Surface	Total DU (dpm/100 cm^2)	Mass/Unit Area (mg/m^2)
Crew Compartment	11 to 1565	1 to 187
Interior Wall of Test 6B Hole	112	13
Turret Ceiling	22	3
Crew Compartment Floor	1174	140
Loader's Hatch Opening-Side	100	12
Driver's Floor	50	6

Source: Fliszar et al., (1989), with minor editorial addition of mass removed per unit area.

Additional surface-contamination data and information are contained in Part IV, Section 4.15 of this report. The total alpha activities that exceed 1,000 dpm/100 cm^2 may exceed allowable guidelines for removable surface contamination (see Appendix U).

Airborne Concentrations and Estimations of DU Intakes. Using DU airborne concentration data from Fliszar et al., (1989), the exposure and intake of DU particles is estimated, for individuals considered in Levels II and III, by using established national and international computer models for calculational purposes. The United Kingdom National Radiological Protection Board LUDEP program is the primary computer code used to estimate internal doses from DU intakes. (See Appendix J for a discussion of computer programs.)

Intake of DU particles. Intake is the amount of material that is internalized into the human body. The amount of material that is absorbed into the body fluids and deposited in target organs is referred to as an uptake. The ICRP models used take into consideration both the intake and uptake of internalized material:

- Intake is usually a function of the type of breathing (mouth or nose), BR (or ventilation rate), airborne concentration, particle size, and exposure duration.

- The uptake of material is usually a function of the chemical form and the solubility (either in the GI or respiratory tract).

Fires involving DU munitions tend to produce more insoluble DU oxides versus hard target impacts involving DU munitions. Studies indicate that the DU particles are not readily soluble in lung fluid. For fires involving DU munitions, about 93 to 100 percent of the DU particles are insoluble (Class Y), which indicates a transportable half time from the respiratory tract to the blood stream greater than 100 days. Hard target impacts involving DU munitions produce a

greater range of DU oxides, with a greater fraction (17 percent) exhibiting Class W/D solubility. The remaining fraction (83 percent) exhibits Class Y solubility.

When considering secondary ingestion, the GI transfer coefficients for soluble uranium or DU for Class D and W (or Types F and M) are 2 percent, and for insoluble Class Y (or Type S), the GI transfer coefficient is 0.2 percent (ICRP-69).

Intake values used were either calculated or obtained from Fliszar et al., (1989) DU test data or other studies listed in Appendix A and Appendix B involving a hard-target perforation and fires involving DU munitions, Fliszar et al., (1989).

In some cases, intake values were entered into the LUDEP computer program; whereas, other cases involved the input of airborne concentrations into the LUDEP computer program. Parameter values, such as, type of breathing, BR, exposure duration, particle size, solubility, and density of the DU oxide, were also inputted into the LUDEP computer program to calculate an internal dose. In addition, the calculated doses for all of the uranium isotopes and their progeny in equilibrium that comprise DU (using the mass percentage of the uranium isotopes in DU) were calculated.

The intake values, used in the exposure assessment, include lower-bound and upper-bound values and are calculated from data reported in the reviewed DU test reports.

Using the estimated DU intake ranges (quantification of exposure), these values are compared with regulatory standards and toxicity values for chemical and ionizing radiation health effects (see Section 5.3).

In reviewing the exposure and toxicity assessments for both chemical and ionizing radiation toxicity, a description of health risk characterization is provided (see Section 5.4).

5.3 OSAGWI Level II Scenario Exposure Assessments

Level II individuals may have been exposed to a range of DU-airborne concentrations when reentering vehicles and equipment contaminated with DU: From 8.4×10^{-3} mg/m^3 (32×10^{-13} µCi/cm^3) inside a tank that had been involved in a fire to 2.6×10^{-4} mg/m^3 (1×10^{-13} µCi/cm^3) for a vehicle that had not been involved in a fire but had been perforated by a DU munition, Fliszar et al., (1989). These values were obtained from Table 16 of the Fliszar et al., 1989 report.

Based on the Fliszar et al., (1989) report, individuals who were exposed to the smoke plume downwind of a burning, uploaded Abrams tank may have been exposed to a range of DU-airborne concentrations. This range is estimated to be from a maximum airborne DU concentration of 9.3×10^{-4} mg/m^3 (3.5×10^{-13} µCi/cm^3) at 40 meters to a concentration of 1.3×10^{-6} mg/m^3 (0.005×10^{-13} µCi/cm^3) at 100 meters from the burning vehicle (see Table 42). In Parkhurst et al., (1990). the particle size distribution of oxide residue collected at the fire site, from fires involving DU munitions indicated that 99.5 percent of the particles are greater than

10 μm AED; therefore, only about 0.5 percent of the particles would be within the respirable range (< 10 μm AED) (see Table 15). Ninety-three to one hundred percent of the DU particles are Class Y, which indicates that the transportable half time from the respiratory tract to the blood stream is greater than 100 days.

In a more recent test, a BFV uploaded with 25mm DU rounds was intentionally set on fire. This represents the first time DU oxides were collected from the surface of the remains of a BFV armored vehicle. The results of this test match prior stack/pallet burn tests involving DU munitions with approximately 100 percent Class Y DU oxide being formed. However, a greater percentage of respirable size particles (33 percent of the oxide less than 10 μm AED) were found in this test versus stack/pallet burn tests (less than 1 percent), Parkhurst et al., (1999). BFVs uploaded with 25mm DU munitions were not fielded during the Gulf War. Because of differences in the armor composition of the BFV and Abrams tanks and because of the larger surface area of the 25mm rounds present, data from this report were not used.

During the fire after the Fliszar Test 6B, the plume had the characteristic shape of a "trapping plume", Fliszar et al., (1989). The plume went toward the ground almost immediately after leaving the target. Table 42 provides a summary of DU-airborne concentrations in the smoke from a burning, uploaded Abrams tank versus downwind distance from Test 6B, Fliszar et al., (1989). It should be noted that the air samplers were running for three hours before the first DU munitions "cooked-off".

Table 42. DU Airborne Concentration vs. Distance from Target for Test 6B

			DU Activity Concentration ($\times 10^{-13}$ μCi/cm^3)
M-4L	28	5.8	0.022
O-6R	40	926.9	3.5
X-CL	75	58.3	0.22
X-6R	80	172.1	0.65
U-96	75	3.4	0.013
AA-21	100	1.3	0.005

Reference: Fliszar et al., (1989), with minor editorial addition of mass concentrations.

The exposure of personnel during reentry of an uploaded Abrams tank following a fire must also be addressed. According to the Fliszar et al., (1989) report, air samples were taken close to the target during reentry after each test. A member of the initial reentry team wore a personal air sampler at the breathing zone level. The data collected by this air sampler represent DU resuspension at the following locations: the test pad, walking on the outside of the tank, and climbing inside and out of the fire-damaged tank.

Reentry data reported by Fliszar et al., (1989) indicate that the DU-airborne concentration, within an Abrams tank that had been perforated by an ATGM, ranged from 1.9×10^{-3} mg/m^3 (7.3×10^{-13} μCi/cm^3) to 8.4×10^{-3} mg/m^3 (32×10^{-13} μCi/cm^3), following a fire in the DU uploaded Abrams tank. The fire occurred after Test 6B; no fire resulted after Test 5B. The concentration obtained from Test 5B was used as the lower-bound value and the concentration obtained from Test 6B was used as the upper-bound value. These data were obtained by analysis of samples from personal air samplers worn by personnel during reentry of the Abrams tank.

Table 43 provides a summary of DU-airborne concentrations that were determined from DU particle resuspension data from personal air samplers worn by personnel during reentry into a burned, uploaded Abrams tank.

Table 43. DU-Airborne Concentration Following Reentry After Tests 5B and 6B

Test	DU Mass Concentration ($x\ 10^{-3}$ mg/m^3)	DU Activity Concentration ($x\ 10^{-13}$ µCi/cm^3)	Target Surface
5B	1.9	7.2	Right Front Turret
6B	8.4	32	Right Front Turret

Source: Fliszar et al., (1989), with minor editorial addition of mass concentrations.

The Fliszar et al., (1989) report indicated that no personal reentry air samples for analysis were obtained from Test 5A. Test 5B used a 120mm KE-Tungsten round which penetrated the DU armor and entered the tank's Crew Compartment but did not result in a fire. A full complement of twenty-seven DU rounds and thirteen high explosive, anti-tank rounds were stowed in the Abrams tank for Test 6B. Three 120mm DU rounds and three high explosive, anti-tank rounds were stowed in the hull-stowage compartment; the remaining thirty-four rounds were stowed in the ready and semi-ready racks. Test 6B used an ATGM, which resulted in a fire inside the target. The fire was caused by an unrelated, malfunctioning experimental setup. The fire began about 20 minutes after perforation and resulted in a DU munitions "cook-off" three hours later. Reentry into the tank was not until 4 days after Test 6B.

The OSAGWI Interim Environmental Exposure Report, Tab J, *Accidental Tank Fires* (OSAGWI, 1998) documents accidental tank fires.

Exposure of individuals working in or on contaminated vehicles would depend on the following:

- Their physical activity level.
- The vehicle-contamination levels, outside as well as inside the vehicle.
- The amount of time spent in, on, or near a vehicle.
- Their use of any respiratory protection or other PPE.
- Personal hygiene (for example, hand washing).

Table 44 provides a summary of DU-airborne concentrations determined from air samplers placed downwind from the target for the Fliszar et al., (1989) Test 5A. The round used was a 120mm DU penetrator.

Samplers ran for approximately 23 hours and the concentration presented below represents the averaged concentration that would include the impact puff and any resuspended DU due to wind action during the sampling period as well as mechanical action from personnel re-entering the test area. An external cover plate (installed for security reasons to drop over the impact hole) activated prematurely right after Test 5A impact. It is not known to what degree it had affected (reduced) exterior airborne concentrations.

Table 44. Averaged Airborne Concentration vs. Distance from Target for Test 5A

Sample Location	Distance from Target (m)	DU Mass Concentration ($x\ 10^{-3}$ mg/m^3)	DU Activity Concentration ($x\ 10^{-14}$ µCi/cm^3)
J4R	22	1.48	56.3
K2L	13	0.002	0.076
KCL	10	0.003	0.115
K2R	13	0.093	3.54
L12R	63	0.036	1.36
M6L	35	0.0005	0.018
HCL	5	0.075	2.85
AA43	100	0.021	0.76

Reference: Fliszar et al., (1989), with minor editorial addition of mass concentrations.

Intake rates, internal dose rates, and kidney concentrations are estimated below. These estimates are presented as rates since occupancy times and the total number of potentially contaminated vehicles entered is unknown. Wound contamination and TEDEs were considered but not estimated due to the lack of adequate data.

DU Exposure, Intake, Internal Dose Rates, and Kidney Concentrations from Inhalation and Indirect Ingestion.

- The estimated lower-bound inhalation and indirect ingestion intake per individual (that is, a nose breather with a BR of 3.0 m^3/hr and 5 µm AMAD aerosol) is 0.00078 mg of DU (0.00065 mg insoluble and 0.00013 mg soluble) for each hour of exposure.

- This intake estimate considers a DU-airborne concentration of 2.6×10^{-4} mg/m^3 (1×10^{-13} µCi/cm^3) where 83 percent of the DU particles are insoluble and 17 percent of the DU particles are soluble.

- The internal radiation dose estimate (lower-bound CEDE) per individual would be 0.00001 rem.

- Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.00001 mg (0.0000022 mg insoluble and 0.00008 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.000032 μg DU/g of kidney. See Appendix J for a more detailed discussion.

- The estimated upper-bound inhalation and indirect ingestion intake per individual (that is, a nose breather with a BR of 3.0 m^3/hr and 5 μm AMAD aerosol) is 0.025 mg of DU (0.023 mg insoluble and 0.002 mg soluble) for each hour of exposure.

- This intake estimate considers a DU-airborne concentration of 8.4×10^{-3} mg/m^3 (32×10^{-13} μCi/cm^3) (see Table 43) where 93 percent of the DU particles are insoluble and 7 percent of the DU particles are soluble.

- The internal radiation dose estimate (upper-bound CEDE) per individual would be 0.0005 rem.

- Using the fraction of 5 μm AMAD DU aerosol that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.00021 mg (0.000078 mg insoluble and 0.00013 mg soluble). Assuming a kidney weight of

310 grams, this would result in a kidney concentration of 0.00067 µg DU/g of kidney. See Appendix J for a more detailed discussion.

DU Exposure, Intake, and Internal Dose from Secondary Ingestion. OSAGWI Level II personnel may have been exposed to DU by secondary ingestion (hand-to-mouth transfer) from contact with DU-contaminated surfaces:

- The estimated upper-bound intake by secondary ingestion for an individual is 0.057 mg of DU (0.047 mg insoluble and 0.01 mg soluble) for each hour of exposure. The amount of DU that passes through the kidney is 0.00029 mg (0.00009 mg insoluble and 0.0002 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.00095 µg DU/g of kidney per hour spent in a vehicle. The internal radiation dose estimate (CEDE) per individual would be 0.000002 rem for a 1-hour exposure per vehicle or contaminating event. (See Appendix F for calculation of secondary ingestion intake.)

- The estimated lower-bound intake by secondary ingestion for an individual is 0.028 mg of DU (0.023 mg insoluble and 0.005 mg soluble) for each hour of exposure. The amount of DU that passes through the kidney is 0.00015 mg (0.000046 mg insoluble and 0.0001 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.00047 µg DU/g of kidney per hour spent in a vehicle. The internal radiation dose estimate (CEDE) per individual would be 0.000002 rem for a 1-hour exposure per vehicle or contaminating event. (See Appendix F for calculation of secondary ingestion intake.)

- The upper-bound and lower-bound secondary ingestion intakes were derived from the surface-contamination results listed in Table 39. (See Appendix F for calculation of secondary ingestion intake.) Surface-contamination results reported in Table 39 were obtained after a single DU munition perforated DU armor, Fliszar et al., (1989).

External Radiation Dose. In addition to the above considerations, EOD personnel may have handled penetrators with their bare hands resulting in an external dose. An estimate of the potential external dose follows:

- Their bare hands may have been exposed externally to beta/gamma radiation from handling spent penetrators, and exposed externally to gamma radiation from downloading intact DU munitions. The contact dose rate to the skin of the hand from an intact DU penetrator is about 0.2 rad/hr, with approximately 90 percent of the dose resulting from beta radiation.

- The external dose that an individual could have received would depend on the number of spent penetrators handled, intact rounds, or projectile remains, the length of exposure per item, and whether or not they were wearing gloves or using bare hands during the handling of the DU munitions or remains.

Individuals comprising other Level II and III scenarios, except those that participated in the cleanup operations at Camp Doha, would not be expected to have experienced external radiation dose rates similar to EOD individuals.

5.3.1 EOD Personnel

The EOD individuals primarily downloaded munitions from DU-contaminated vehicles/systems. Other unit personnel could have assisted EOD with this responsibility. EOD team members, in entering DU-perforated vehicles or vehicles involved in a DU fire to download munitons, may have been subjected to DU exposures similar to those for the DU intakes and internal dose rates estimated in Section 5.3.

5.3.2 RADCON Team Members

In addition to the assigned unit EOD personnel already in the Gulf region, at least two U.S. Army Materiel Command (AMC) assets were on temporary duty in theater: RADCON teams of the U. S. Army Operations Support Command (formerly the USAMCCOM) and the U.S. Army Communications-Electronics Command.

- The AMC deployed these health physics personnel to identify, assess, and respond to incidents involving DU.

- The RADCON teams performed their duties at King Khalid Military City and at Camp Doha, although they had limited excursions to other locations, OSAGWI, (1998).

- The RADCON team members, in entering DU-perforated vehicles or vehicles involved in a DU fire, may have been subjected to DU exposures, similar to those for the DU intakes and

internal dose rates estimated in Section 5.3. Appendix C addresses mission work done by RADCON teams at Camp Doha following the depot fire.

5.3.3 BDAT Members

The BDATs conducted battle-damage assessments on damaged or destroyed U.S. ground combat vehicles. The close, in-depth inspections entailed frequent entry into disabled, often DU-contaminated vehicles. The BDATs when entering DU-perforated vehicles or vehicles involved in a DU fire may have been subjected to DU exposures, similar to those for the DU intakes and internal dose rates estimated in Section 5.3.

5.3.4 LARs

The LARs were often requested to determine the disposition of damaged or destroyed equipment, OSAGWI, (1998). The LARs, when entering DU-perforated vehicles or vehicles involved in a DU fire, may have been subjected to DU exposures, similar to those for the DU intakes and internal dose rates estimated in Section 5.3.

5.3.5 Unit Maintenance Personnel

Unit maintenance personnel and other salvage crews, that worked in or on DU-damaged or destroyed vehicles being processed for repair or that worked in processing equipment for disposal, may have been exposed to a range of airborne DU concentrations.

The Unit maintenance personnel, when entering DU-perforated vehicles or vehicles involved in a DU fire, may have been subjected to DU exposures, similar to those for the DU intakes and internal dose rates estimated in Section 5.3.

In addition to the scenario of individuals working in or on DU-contaminated vehicles, unit maintenance personnel may have also been involved with the following additional types of scenarios:

Welding Operations Involving DU Armor. The exposure of personnel during the welding of vehicle (tank) penetrations is a special maintenance operation that is not believed to have happened in the Gulf region during or following the Gulf War. However, if it did, then the exposure of individuals during welding operations would depend on the following:

- Length of time it took to weld a patch.
- Number of patches to be welded on a vehicle.
- Number of vehicles that required patching.
- Use of any respiratory protection or other PPE.

- If an armored vehicle's armor is perforated, either by accident or during combat, the hole on its surface must be sealed for security reasons and to prevent the spread of DU-contamination. A steel cover plate would be welded over this hole; however, the DU armor would not be welded directly.

- Based on data in the Fliszar et al., (1989) report, a personal air sampler was placed on each welder at the breathing zone level when a cover plate was welded over the perforation hole following Tests 5B and 6B. The surface around the hole was not decontaminated prior to the welding operation. See Table 45 for a summary of DU-airborne concentrations during welding operations. Welding operations were performed both inside and outside the tank, as well as both outdoors and indoors. The usual patchwork took about 20 to 30 minutes.

Table 45. Airborne Concentration of DU for Welding Operation

Test	Action	DU Mass Concentration ($x\ 10^{-2}$ mg/m^3)	DU Activity Concentration ($x\ 10^{-11}$ µCi/cm^3)
5B	Inner and outer patches welded to cover holes	4.7	1.8
6B	Lids welded on turret hatches and patches welded on outside of perforation hole	0.5	0.2
	Lids burned off	0.05	0.02

Source: Fliszar et al., (1989), with minor editorial addition of mass concentrations.
Note: The scientific notation ($x\ 10^{-11}$ µCi/cm^3) = (x 0.00000000001 µCi/cm^3)

- Intake and internal dose rate estimates for personnel exposed while welding vehicle (tank) penetrations are the following:

- Intake by inhalation and indirect ingestion. The estimated lower-bound inhalation and indirect ingestion intake per individual (that is, a mouth breather with a BR of 3.0 m^3/hr and 5 µm AMAD aerosol) while welding is 0.0015 mg of DU (0.0012 mg insoluble and 0.0003 mg soluble) for each hour of welding.

- This intake estimate considers a DU-airborne concentration of 5×10^{-4} mg/m^3 (0.02×10^{-11} µCi/cm^3) (Table 45) with 83 percent of the DU particles insoluble and 17 percent of the DU particles soluble.

- Using the fraction of 5 µm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.000024 mg (0.000004 mg insoluble and 0.00002 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.00008 µg DU/g of kidney per hour of welding. See Appendix J for a more detailed discussion.

- The internal radiation dose estimate (lower-bound CEDE) per individual would be 0.00003 rem for a 1-hour exposure in a vehicle.

- The estimated upper-bound inhalation and indirect ingestion intake per individual (that is, a mouth breather with a BR of 3.0 m^3/hr and 5 µm AMAD aerosol) while welding is 0.14 mg of DU (0.12 mg insoluble and 0.02 mg soluble).

- This intake estimate considers a DU airborne concentration of 4.7×10^{-2} mg/m^3 (1.8×10^{-11} µCi/cm^3) (Table 45) with 83 percent of the DU particles insoluble and 17 percent of the DU particles soluble.

- Using the fraction of 5 µm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.0017 mg (0.0004 mg insoluble and 0.0013 mg soluble). Assuming a kidney weight of 310 grams, this

would result in a kidney concentration of 0.0055 µg DU/g of kidney. See Appendix J for a more detailed discussion.

- The internal radiation dose estimate (upper-bound CEDE) per individual would be 0.003 rem for a 1-hour exposure in a vehicle.

- DU intake by secondary ingestion. This welder may have been exposed to DU by secondary ingestion (hand-to-mouth), similar to those for the DU intake and internal dose rate estimates calculated in Section 5.3.

Removal of the DU Tank Armor. The removal of damaged DU tank armor is a special maintenance operation that is not believed to have happened in the Gulf region during or following the Gulf War. However, since this scenario may happen on future battlefields, an exposure estimate is provided here.

- Intake and internal dose rate estimates for personnel exposed during removal of the DU tank armor are the following:

  - Intake by inhalation and indirect ingestion. The total estimated inhalation and indirect ingestion intake (lower-bound) per individual (that is, a mouth breather with a BR of 3.0 m^3/hr and 5 µm AMAD aerosol) while removing the tank armor, is 0.0024 mg of DU (0.0022 mg insoluble and 0.0002 mg soluble).

- The results of air sampling during the removal of the armor at the end of the M1A1 Abrams heavy armor tank series of tests, Fliszar et al., (1989) show a lower-bound DU air concentration of 7.9×10^{-4} mg/m^3 (0.3×10^{-12} µCi/cm^3). This intake estimate also considers 93 percent of the DU particles to be insoluble and 7 percent of the DU particles to be soluble.

- Using the fraction of 5 µm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.000021 mg (0.0000075 mg insoluble and 0.000013 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.000007 µg DU/g of kidney. See Appendix J for a more detailed discussion.

- The internal radiation dose estimate (lower-bound CEDE) per individual would be 0.00006 rem for a 1-hour exposure in a vehicle.

- The total estimated inhalation and indirect ingestion intake (upper-bound) per individual (that is, a mouth breather with a BR of 3.0 m^3/hr and 5 µm AMAD aerosol) while removing the tank armor, is 0.56 mg of DU (0.52 mg insoluble and 0.04 mg soluble).

- The results of air sampling during the removal of the armor at the end of the M1A1 Abrams heavy armor tank series of tests, Fliszar et al., (1989), show an upper-bound DU air concentration of 1.9×10^{-1} mg/m^3 (72×10^{-12} µCi/cm^3). This intake estimate also considers 93 percent of the DU particles to be insoluble and 7 percent of the DU particles to be soluble.

- Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.0044 mg (0.0018 mg insoluble and 0.0026 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.0014 μg DU/g of kidney. See Appendix J for a more detailed discussion.

- The internal radiation dose estimate (upper-bound CEDE) per individual would be 0.01 rem for a 1-hour exposure in a vehicle.

Intake by Secondary Ingestion. These personnel may be exposed to DU by secondary ingestion (hand-to-mouth). The DU intakes and internal dose rate estimates from secondary ingestion would be similar to those for the DU intake and internal dose rate estimates calculated in Section 5.3.

5.3.6 144th Service and Supply Company

The 144th Service and Supply Company personnel, when entering DU-perforated vehicles or vehicles involved in a DU fire, may have been subjected to DU exposures similar to those for the DU intakes and internal dose rates estimated in Section 5.3.

The U.S. Army collected specimens from some of the individuals assigned to the 144th Service and Supply Company, New Jersey Army National Guard. The DOE's Environmental

Measurements Laboratory analyzed the specimens for uranium by using the alpha spectrometry method. All of the urine results were less than the Lower Limit of Detection (LLD) of 0.01 pCi/L for U-238, which indicates DU was not detected above that level in any of the urine samples.

5.3.7 Personnel Exposed to DU During Cleanup Operations at Camp Doha

The Camp Doha scenarios in Level II and Level III are addressed in Appendix C. This PNNL study estimated the exposures to DU for residents and recovery workers at Camp Doha, Kuwait following the July 1991 fire. Estimated chemical doses for recovery workers (Level II) who spent extensive time in the contaminated areas of the North Compound after the fire range from 3.3×10^{-3} µg DU/g of kidney to 9.5×10^{-2} µg DU/g of kidney, depending on which type of activity they were involved in. 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 which type of activity they were involved in.

5.3.8 Representative Examples of DU Exposures for Level II Personnel

Because the frequency of entry into DU-contaminated vehicles and exposure duration is not well understood, representative examples of DU exposure, intakes, and internal radiation dose estimations for OSAGWI Level II exposure scenarios from the Gulf War are provided in Appendix S. The examples in Appendix S describe how to use the information presented in Tables 47 and 48 to estimate an exposure, intake, and radiation dose to Level II individuals.

Detailed discussions concerning the possible Level II scenarios are not included because of the multitude of permutations that could be factored in representative examples (such as exposure duration, number of entries made into vehicles, number of vehicles, weather conditions, personal hygiene, type of mission, or degree of physical activity). Although it may be difficult and virtually impossible to address all the permutations, Appendix S provides representative examples.

5.4 OSAGWI Level III Exposure Assessments

Level III individuals may have been exposed to DU as a result of the following circumstances:

- Exposure to DU-airborne concentrations downwind of a burning Abrams tank, to include reentry into the vehicle following the fire.

- Exposure from entry into DU-contaminated Iraqi vehicles and equipment, to include Cavalry Scouts and souvenir hunters.

- Exposure to DU-airborne concentrations downwind from burning DU rounds at Camp Doha.

- Exposure to DU-airborne concentrations downwind of a vehicle perforated by a DU round.

5.4.1 Exposure of Personnel to DU-Airborne Concentrations Downwind of a Burning, Uploaded Abrams Tank

The DU exposures to individuals would depend on:

- How close they were to the burning vehicle(s).
- How long they were exposed.
- The number of vehicles they entered.
- The use of any respiratory protection.

Intake by Inhalation and Indirect Ingestion. Based on the Fliszar et al., (1989) report, individuals who were exposed to the smoke plume downwind from a burning, uploaded Abrams tank may have been exposed to a range of DU-airborne concentrations. This range is estimated to be from a maximum airborne DU concentration of 9.3×10^{-4} mg/m^3 (3.5×10^{-13} µCi/cm^3) at 40 meters to a concentration of 1.3×10^{-6} mg/m^3 (0.005×10^{-13} µCi/cm^3) at 100 meters from the burning vehicle (see Table 42).

- The estimated lower-bound inhalation and indirect ingestion intake per individual (that is, a nose breather with a BR of 3.0 m^3/hr and 5 µm AMAD aerosol) is 0.0000039 mg of DU (0.0000036 mg insoluble and 0.0000003 mg soluble) per hour of exposure.

- This intake estimate considers 93 percent of the DU particles insoluble and 7 percent of the DU particles soluble.

- The lower-bound internal dose estimate (CEDE) per individual would be 0.0000001 rem for a 1-hour exposure in a vehicle.

- Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.00000003 mg (0.00000001 mg insoluble and 0.00000002 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.0000001 μg DU/g of kidney per hour exposed. (See Appendix J for a more detailed discussion.)

- The estimated upper-bound inhalation and indirect ingestion intake is 0.0028 mg of DU (0.0026 mg insoluble and 0.0002 mg soluble) per hour of exposure in a vehicle.

- This dose estimate considers 93 percent of the DU particles insoluble and 7 percent of the DU particles soluble.

- The upper-bound internal dose estimate (CEDE) per individual would be 0.00007 rem for a 1-hour exposure in a vehicle.

- Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.000022 mg (0.000009 mg insoluble and 0.000013 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.00007 μg DU/g of kidney per hour of exposure. (See Appendix J for a more detailed discussion.)

The USACHPPM analyzed urine specimens collected from individuals shortly after their exposure to smoke from an Abrams tank that burned on 13 April 1991 using the flurometric method of analysis[31]. This tank fire is described by OSAGWI in their Interim Environmental Exposure Report (OSAGWI, 1998). All the urine results were less than 2 μg total uranium/L urine, the minimum detectable concentration (MDC) for total uranium, which indicates that DU was not detected above that level in any of the urine specimens.

Two of the reasons for the absence of detectable levels of DU in the urine are the size of the DU oxide particles available for potential inhalation when generated in a fire and the solubility of the DU particles in lung fluid. This is demonstrated in a DU munitions developer's test, with results reported in Parkhurst, et al., (1990). This report indicates that 99.5 percent by mass of the DU particles generated in a fire involving uploaded munitions were greater than 10 μm AED, which indicates that these particles were not respirable. Fires involving DU munitions produce insoluble DU oxides. Based on the urine specimens that were analyzed for individuals exposed to smoke from the tank fire on or about 13 April 1991, no urine specimens collected from other individuals exposed to smoke from tank fires would be expected to result in values greater than the MDC for total uranium (2 μg total uranium/L urine).

Internal dose estimates for personnel exposed during reentry of an uploaded Abrams tank following a fire are the following:

- Intake by inhalation and indirect ingestion. The total estimated inhalation and indirect ingestion intake (lower-bound) per individual (that is, a nose breather with a BR of 3.0 m^3/hr and 5 μm AMAD aerosol) is 0.0057 mg of DU (0.0053 mg insoluble and 0.0004 mg soluble) per hour of exposure in a vehicle.

  - This dose estimate considers a DU airborne concentration of 1.9×10^{-3} mg/m^3 (7.2×10^{-13} $\mu Ci/cm^3$) from a tank fire (Table 43) with uploaded DU munitions with 93 percent of the DU particles insoluble and 7 percent of the DU particles soluble.

  - The internal dose estimate (lower-bound CEDE) per individual would be 0.0001 rem for a 1-hour exposure in a vehicle.

  - Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.000045 mg (0.000018 mg insoluble and 0.000027 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.000015 μg DU/g of kidney. (See Appendix J for a more detailed discussion.)

- The total estimated inhalation and indirect ingestion intake (upper bound) per individual is 0.025 mg of DU (0.023 mg insoluble and 0.002 mg soluble).

  - This dose estimate considers a DU-airborne mass concentration of 8.4×10^{-3} mg/m^3 (32×10^{-13} $\mu Ci/cm^3$) with uploaded DU munitions in the tank and with 93 percent of the DU particles insoluble and 7 percent of the DU particles soluble.

- The internal dose estimate (upper-bound CEDE) per individual would be 0.0004 rem for a 1-hour exposure in a vehicle.

- Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.00021 mg (0.000078 mg insoluble and 0.00013 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.00067 μg DU/g of kidney. (See Appendix J for a more detailed discussion.)

The DU exposures to individuals would depend on their activity level, how long they were exposed, the number of vehicles they entered, and their use of any respiratory protection.

5.4.2 Exposure of Personnel Who Entered DU-Contaminated Iraqi Vehicles

The largest number of people potentially exposed to DU consisted of those who entered enemy vehicles out of curiosity or to collect war souvenirs. However, many soldiers, such as Cavalry Scouts, had legitimate, operational requirements to enter damaged Iraqi equipment, such as checking for personnel and equipment, completing destruction of the equipment, or looking for items of military intelligence value, OSAGWI, (1998). It is believed that the majority of the vehicles Level III personnel may have entered were damaged by the aerial use of DU munitions. (See Appendix R for a discussion of the aerial use of DU for OSAGWI-specific scenarios dealing with the small-caliber DU rounds.)

These individuals could have also been exposed to hazardous materials inside damaged Iraqi vehicles.

- Many of the Iraqi tanks had asbestos blankets.
- The Iraqi's Union of Soviet Socialist Republics/Commonwealth of Independent States-built equipment (tanks, armored personnel carriers, and other vehicles) also had items that contained radioactive sources in non-dispersible forms.

    - Some of these items would be radioactive sources contained within chemical agent detectors, radiation monitors, and check sources for radiation survey instruments.

    - Many of the dials, switches, and gauges are painted with self-luminous paints containing radium, tritium, or promethium. These items generally contain small quantities of radioactive material that would not present a safety concern unless the radioactive sources were damaged to the extent that radioactive material was released to the environment, OSAGWI, (1998). Unpublished data from hard-target testing involving a T-72 tank indicated that some of the glass coverings to radium dials were found to be broken after testing.

Those individuals who entered DU-perforated Iraqi vehicles may have been exposed to a range of DU-airborne concentrations, from a minimum airborne concentration of 2.6×10^{-4} mg/m^3 (1×10^{-13} μCi/cm^3) to a maximum concentration of 1.9×10^{-3} mg/m^3 (7.2×10^{-13} μCi/cm^3) (Table 43).

Intake by Inhalation and Indirect Ingestion. Intake and internal dose estimates for personnel exposed while entering DU-contaminated vehicles are the following:

- The total estimated inhalation and indirect ingestion intake (lower bound) per individual is 0.00078 mg of DU (0.00065 mg insoluble and 0.00013 mg soluble) per hour of exposure.

- This intake estimate considers a DU-airborne concentration of 2.6×10^{-4} mg/m^3 (1×10^{-13} μCi/cm^3) with 83 percent of the DU particles insoluble and 17 percent of the DU particles soluble.

- The internal dose estimate (lower-bound CEDE) per individual would be 0.00001 rem for a 1-hour exposure in a vehicle.

- Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.00001 mg (0.0000022 mg insoluble and 0.000008 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.000032 μg DU/g of kidney. (See Appendix J for a more detailed discussion.)

The total estimated inhalation and indirect ingestion intake (upper bound) per individual is 0.0057 mg of DU (0.0047 mg insoluble and 0.0010 mg soluble) per hour of exposure.

This intake estimate considers a DU-airborne concentration of 1.9×10^{-3} mg/m^3 (7.2×10^{-13} µCi/cm^3) with 83 percent of the DU particles insoluble and 17 percent of the DU particles soluble. The internal dose estimate (upper-bound CEDE) per individual would be 0.0001 rem for a 1-hour exposure.

Using the fraction of 5 µm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.00008 mg (0.000016 mg insoluble and 0.000064 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.00026 µg DU/g of kidney. (See Appendix J for a more detailed discussion.)

Intake by Secondary Ingestion. These personnel may have been exposed to DU by secondary ingestion (hand-to-mouth). Such exposures would be similar to those discussed for Level II personnel.

Exposures of individuals searching enemy equipment would depend on the following:

- Their physical activity level.
- The DU-contamination levels outside as well as inside the vehicle.
- The amount of time spent in a vehicle.
- The number of vehicles entered.

- Use of any respiratory protection.
- Personal hygiene.

5.4.3 Exposure of Personnel to Airborne Concentrations of DU Downwind of a Vehicle Perforated by a DU Round.

The exposure of individuals downwind of a vehicle perforated by a 120mm DU round would depend on the following:

- Their physical activity level.
- Surface wind speed.
- Distance from the perforated vehicle.
- The number of vehicles to which they were exposed.
- The use of any respiratory protection.

According to the Fliszar et al., (1989) report, high-volume air samplers designed for collecting suspended DU particles were located at distances of 10 meters to 100 meters from the target for Test 5A. The air samplers were turned on prior to the event of the hard-target perforation in which the puff of smoke had passed over a series of air samplers. These samplers captured what was in the downwind puff and any resuspension of DU from the mechanical action of wind applied to particles on the ground before the samplers were subsequently shut off. Internal dose estimates for personnel exposed to airborne concentrations of DU downwind of a vehicle perforated by a DU round are the following:

- The total estimated inhalation and indirect ingestion intake (lower bound) per person is 0.000063 mg of DU (0.000052 mg insoluble and 0.000011 mg soluble) per hour of exposure. This intake estimate considers a DU-airborne concentration of 0.021×10^{-3} mg/m^3 (0.079×10^{-13} μCi/cm^3) at the 100 meter location (Table 44) with 83 percent of the DU particles insoluble and 17 percent of the DU particles soluble.

- The internal dose estimate (lower-bound CEDE) per individual would be 0.000001 rem for a 1-hour exposure at a distance of 100 meters downwind of the vehicle. Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.00000088 mg (0.000000177 mg insoluble and 0.00000071 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.000003 μg DU/g of kidney. See Appendix J for a more detailed discussion.

- The total estimated inhalation and indirect ingestion intake (upper bound) per person is 0.0044 mg of DU (0.0037 mg insoluble and 0.00075 mg soluble) per hour of exposure. This intake estimate considers a DU-airborne concentration of 1.48×10^{-3} mg/m^3 (5.63×10^{-13} μCi/cm^3) at the 22-meter location (Table 44) with 83 percent of the DU particles insoluble and 17 percent of the DU particles soluble.

- The internal dose estimate (upper-bound CEDE) per individual would be 0.00001 rem for a 1-hour exposure per vehicle at a distance of 22 meters downwind of the vehicle. Using the fraction of 5 μm AMAD DU particles that are transferred from the respiratory tract to blood, the amount of DU that passes through the kidney is estimated to be 0.000061 mg (0.000013 mg

insoluble and 0.000048 mg soluble). Assuming a kidney weight of 310 grams, this would result in a kidney concentration of 0.0002 µg DU/g of kidney. (See Appendix J for a more detailed discussion.)

5.4.4 Personnel Exposed to DU-Airborne Concentrations From the Camp Doha Fire

The Camp Doha scenarios in Level III are addressed in Appendix C. This PNNL study estimated the exposures to DU for residents and recovery workers at Camp Doha, Kuwait following the July 1991 fire. People who were exposed to airborne concentrations from the fire (Level III) were estimated to have received negligible chemical doses. The upper-bound concentration in the kidney was estimated to be 1.8×10^{-8} µg DU/g of kidney for people assembled in the United Nations Compound at the base and about 2.8×10^{-7} µg DU/g of kidney for a person who was located in the area of highest air concentration. Personnel exposed to airborne concentrations from the fire were estimated to have received negligible radiation doses: about 0.000000062 rem for people assembled in the United Nations Compound at the base and about 0.000003 rem for a person who may have been located in the area of highest air concentration.

5.4.5 Examples of OSAGWI Level II and III Exposure Scenarios

Representative Examples of OSAGWI Level II Exposure Scenarios. Representative examples of OSAGWI Level II scenarios are found in Appendix S. The examples presented in Appendix S include all the vehicles that were involved in the "friendly fire" incidents as well as those

involved in the Camp Doha fire. The assumed exposure durations of the Level II individuals by occupation provided by OSAGWI are also included in the representative examples.

Example of an OSAGWI II and III Combination Exposure Scenario from the Gulf War. In examining the OSAGWI Level II and Level III exposure scenarios, a soldier stationed in Southwest Asia during the Gulf War might indicate that he experienced all of the Level III scenarios. A sample exposure scenario combining all of the OSAGWI Level III exposure scenarios is provided in Appendix T to demonstrate how a generalized exposure assessment can be tailored to a soldier's own experiences in Southwest Asia.

5.5 Health Risk Characterizations for OSAGWI Levels II and III Exposure Scenarios

The uranium compounds present in a military environment are DU metal and its oxides: DU_3O_8, DUO_2, and DUO_3. Both the perforation of a DU penetrator on a hard target and the burning of DU munitions produce DU dust or aerosol particles. The high temperature created during perforation and fires acts to oxidize the DU metal to a series of complex oxides, predominately DU_3O_8 and DUO_2, which are considered to be insoluble (Class Y or absorption Type S). DUO_3 (Class W or absorption Type M) may form as a result of weathering in the environment.

DUO_2 and DU_3O_8 collected from Army tests involving DU impacts and fires have demonstrated increased solubility in simulated lung fluid studies versus what is indicated in the open literature for these compounds.

The main routes of DU into the human body, excluding wounds, are inhalation and ingestion (indirect and secondary).

The primary hazard from inhaled uranium aerosols is related to the extent and the rate of transfer of inhaled uranium to the blood and the quantity that actually reaches the kidney. Insoluble compounds, such as DU_3O_8 and DUO_2, result in longer residence time in the lung thus causing a greater dose to the lung.

Two factors influence the degree of hazard: the deposition site in the respiratory tract and the fate of the DU particles in the lung. It is the respirable DU particles that could present a potential health risk from inhalation of DU particles. (See Appendix J for a more detailed discussion.)

Direct or secondary (hand-to-mouth) ingestion is less efficient as a route of DU exposure into the body compared with inhalation.

The NRC occupational intake limits of insoluble uranium oxides, such as U_3O_8 and UO_2, are based upon their radiation properties; where, the occupational intake limits of soluble uranium oxides, such as UO_3, are based upon their chemical toxicity, National Defense Research Institute, (1999). Figure 7 shows the distribution of a 1 μm AMAD aerosol that is inhaled.

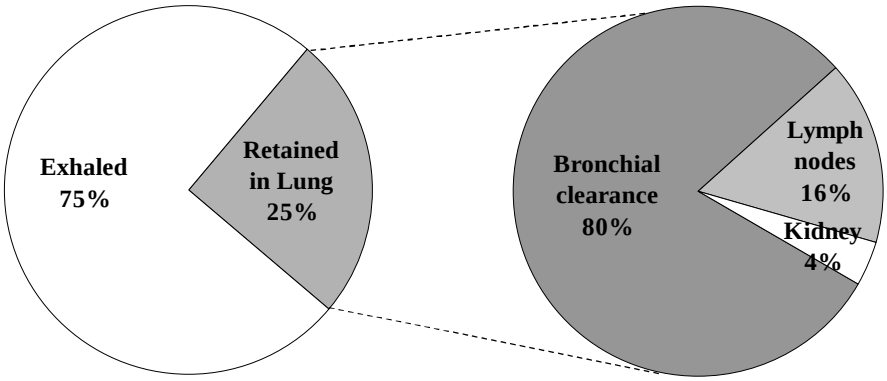


Figure 7. Distribution of Inhaled Uranium
(National Defense Research Institute, 1999)

5.6 Chemical Risk

The chemical toxicity of DU used for military purposes may present a greater potential health risk than the radiological hazard if the DU residue is highly soluble in lung fluid.

The DU is taken up into the body through the respiratory tract (via inhalation), the GI tract (via ingestion), and through wound contamination or embedded fragments. The DU slowly dissolves, presenting a risk of chemical toxicity.

The National Defense Research Institute, RAND, report indicates that through their review of the scientific literature that relatively short-term exposures to uranium oxide particles at mass concentrations up to 10 mg/m^3 of inspired air do not cause renal lesions, National Defense Research Institute, (1999).

The toxicologic effects of uranium vary according to its route of exposure and its chemical form. The toxicologic effects of ingested uranium are less toxic than inhaled uranium. This is attributable in part to the low GI absorption (or GI tract transfer-coefficient) of uranium compounds (< 0.2 - 2 percent). Solubility, which is dependent on the chemical form, correlates positively with toxicity, with the most soluble compounds being the most toxic. Regardless of the chemical form which uranium takes, research has demonstrated that once it is in the bloodstream its primary target organ is the kidney. While this does not exclude the possibility of DU inflicting functional lesions in other organ systems, such as bone and liver, the kidney is the organ most sensitive to the effects of DU. Once the uranium is solubilized in the blood, the kidney will excrete about 90 percent of it in urine over approximately 3 days, National Defense Research Institute, (1999). The chemical toxicity guideline of 3 μg DU/g of kidney for DU in the kidney (Reference Man, the mass of the kidneys is 310 grams) will not be exceeded if the DU concentration in the urine is less than 30 μg/L, National Defense Research Institute, (1999).

The necessary toxicity benchmark values, exposure criteria, and methodology do not exist to retrospectively or quantitatively assess chemical risk following a battlefield exposure. The methodology currently in place for HRAs is not intended to be used for retrospective studies following a chemical exposure. Rather, HRAs are intended to be prospective and thus protective. In a quantitative risk characterization and in risk assessments, a predicted exposure value is compared to an appropriate exposure guideline or reference value. If the ratio of these values is greater than unity, then steps may be taken to decrease the predicted exposure value. In a qualitative risk characterization, risk is described with words rather than equations. Neither quantitative nor qualitative risk characterizations are used to determine whether or not an effect

has occurred. Whether quantitative or qualitative, the reference values used in HRAs are intended to be protective of all individuals, including sensitive individuals. Occupational exposure guidelines are also intended to be protective. They represent concentrations that are believed to be safe; however, they do not generally represent concentrations that are believed to be a threshold for safety. Because of this, it cannot be concluded that adverse health effects will result if a guideline is exceeded, nor can the degree of a potential effect be accurately predicted. When an exposure has occurred and a guideline has been exceeded, the health of the exposed individual is monitored, as is being done in the case of Gulf War Veterans with the greatest potential for DU exposure. However, because the guidelines are meant to be protective, if the guidelines are not exceeded, it can usually be stated with confidence that adverse health effects are not expected to occur.

In the present effort, which is a qualitative risk characterization, predicted exposure levels are presented together with the most appropriate guidelines available. However, for the reasons stated above, they are only compared descriptively; a quantitative evaluation is not given.

The most applicable guideline values for use in OSAGWI Level II and III scenarios are the TEELs (see Appendix K). The TEELs are derived by the SCAPA. They are intended to serve as temporary ERPGs, concentrations below which are not predicted to result in irreversible or life-threatening health effects following an exposure of up to one hour. The values for soluble and insoluble forms of uranium are 0.05, 0.6, 1.0, and 10.0 mg/m^3 for TEELs, 0, 1, 2, and 3, respectively. The TEEL-0 is the most conservative value and is defined as “the threshold

concentration below which most people will experience no appreciable risk of health effects, including mild, transient effects".

Guidelines for uranium issued by ANSI state that 40 mg and 8 mg acute inhalation intakes of soluble uranium are thresholds for permanent and transient renal injury, respectively. In addition to being intended for soluble forms of uranium only, these guidelines are based on a default particle size distribution of 1 µm AMAD and 50 percent absorption from the lungs, National Defense Research Institute, (1999). Based on findings on the chemical toxicity of uranium, a guideline of 3 µg DU/g of kidney was adopted in 1959 by the ICRP.

Based on the upper-bound values in the ranges of the estimated intakes of soluble DU for the Level II and Level III scenarios discussed above, these estimated intakes are three or more orders of magnitude below the suggested acute inhalation values of 40 mg for permanent renal injury in a 70 kg person and 8 mg for transient damage. Air concentrations are one to three orders of magnitude below the most conservative guidelines available. Predicted kidney burdens are more than four orders of magnitude below the 3 µg DU/g of kidney. Because these guidelines are intended to be protective and because levels of DU are so far below these various guidelines, it can be stated with confidence that adverse health effects due to exposure to DU are not expected in the OSAGWI Level II or Level III scenarios.

To date, the VA has not found any clinical evidence that patients with DU embedded fragment(s) show kidney injury resulting from the presence of embedded fragment(s)[32, 33]. Compared to those in the OSAGWI Levels II and III scenarios, it is predicted that these individuals received

greater intakes of soluble and insoluble uranium oxides. Therefore, the absence of clinical evidence of kidney injury in individuals with embedded fragments suggests that there should be a similar lack of injury in those individuals in the OSAGWI Level II and III Scenarios.

5.7 Radiation Risk

Following an acute inhalation intake of insoluble DU, the major target organ is the lung. No evidence is documented in the scientific literature of any adverse health effect that can be related to the radiation received from exposure to natural uranium, whether inhaled or ingested, even at levels far exceeding those likely in the Gulf War, National Defense Research Institute, (1999).

Individuals within the U.S. population receive an average annual effective dose equivalent of 0.3 rem or about 0.001 rem/day, from various sources of natural background radiation[34]. Background radiation includes cosmic, cosmogenic, terrestrial, radon and its total progeny and other radionuclides in the body. The total radiation dose that an individual would receive from natural background for 50 years would be 15 rem. This dose is equivalent to a 1 in 90 estimated lifetime total risk, National Council on Radiation Protection and Measurements (NCRP) Report No. 115, (1993).

The internal radiation dose (CEDE) from inhalation and ingestion of DU particles for the OSAGWI Level II and Level III scenarios discussed is estimated to be less than 0.1 rem. This value is the NRC's annual dose limit for members of the general public. National and

international committees are developing operational guidance for low-level radiation exposure during military operations[35, 36, 37].

The USACHPPM has modified the radiation risk tables provided to include the risk from internalization of radioactive material. Using this operational guidance, the risk category for a radiation exposure of less than 0.1 rem would be "No Risk" to "Normal Risk". Therefore, the health risk of DU radiation toxicity for the OSAGWI Level II and Level III Exposure scenarios is considered acceptable. (See Appendix G for a more detailed discussion of risk from exposure to radiation.)

Based on the upper-bound values in the ranges of the estimated intakes of insoluble DU for the OSAGWI Level II and Level III Exposure scenarios discussed above, these estimated intakes are below any documented adverse health effects.

5.8 Examples of OSAGWI Level II and III Exposure Scenarios

Representative Examples of OSAGWI Level II Exposure Scenarios. Representative examples of OSAGWI Level II exposure scenarios are found in Appendix S. The examples presented in this Appendix include all the vehicles that were involved in the "friendly fire" incidents as well as those involved in the Camp Doha fire. The assumed exposure durations of the Level II individuals by occupation provided by OSAGWI are also included in the representative examples.

Example of an OSAGWI Levels II and III Combination Exposure Scenario from the Gulf War. In examining the OSAGWI Level II and Level III exposure scenarios, a soldier stationed in Southwest Asia during the Gulf War might indicate that he experienced all of the Level III scenarios. A sample exposure scenario combining all of the OSAGWI Level III exposure scenarios is provided in Appendix T to demonstrate how a generalized exposure assessment can be tailored to a soldier's own experiences in Southwest Asia.

5.9 Examples of Other OSAGWI Exposure Scenarios

Appendix R discusses the aerial use of DU during the Gulf War. This Appendix also addresses an aircraft crash and burning at King Khalid Military City, Saudi Arabia and a "hot gun" or "hang-fire" incident during the Gulf War.

5.10 Conclusions

Using available data on DU-airborne concentrations, potential intakes of DU particles are estimated for individuals considered in Levels II and III by using established computer models. When applying estimated DU intake ranges, these values are compared with regulatory standards and guidelines for chemical and radiological health effects. Finally, reviewing the exposure and toxicity data for chemical and radiation toxicity, a health risk characterization is provided.

Considering the maximum values in the ranges of the estimated intakes of soluble DU for the Level II and III scenarios discussed in this assessment, these estimated intakes are below the suggested guidance levels in national and international safety standards.

The total detriment after low-dose and low-dose rate exposure to ionizing radiation is the sum of the contributions due to fatal cancer, non-fatal cancer, and severe hereditary disorders weighted for length of life lost (see Appendix J). The total detriment attributed to stochastic effects is 7.3×10^{-4}/rem. For the dose estimate of 0.065 rem (CEDE) (see Appendix C, Camp Doha recovery workers), the risk estimate is 4.75×10^{-5} [that is, $(7.3 \times 10^{-4}\text{/rem})$ (0.065 rem) = 4.75×10^{-5}]. This is equivalent to a 1 in 21,052 estimated lifetime total risk from a 0.065 rem dose. These values are a factor of 10 less than the estimated internal dose ranges for the personnel considered in OSAGWI Level I exposure scenarios. It is important to note that given the uncertainties (high- to low-dose extrapolation) in calculating radiation risks at low doses, the actual radiation risk may be zero.

Table 46, as an example for demonstrative purposes, provides a summary of intake and internal radiation dose ranges (inhalation and indirect ingestion) for DU exposures involving 10 vehicles or events (1-hour exposure per vehicle or event). Such range values indicate that the scenario exposure estimates are well below guidance limits.

Table 46. Summary of Intake and Internal Radiation Dose Ranges, Inhalation and Indirect Ingestion, OSAGWI Levels II and III, Assuming 10 Vehicles or Events*

---	LEVEL II	LEVEL III (Smoke from Burning Abrams Tank)	LEVEL III (Entry into Vehicles)	LEVEL III (Smoke from DU-Perforated Iraqi Vehicles)
Total DU Intake (mg)	0.0078-0.25	0.000039-0.028	0.0078-0.057	0.00063-0.044
Soluble DU Intake (mg)	0.0013-0.02	0.000003-0.002	0.0013-0.01	0.00011-0.0075
Radiation Dose (rem)	0.0001-0.004	0.000006-0.0004	0.0001-0.001	0.00001-0.0007

*1-hour exposure per vehicle or event

Table 47 is a summary of the ranges of DU intakes by inhalation and indirect ingestion, resultant ionizing radiation dose, and the chemical toxicity risk due to intake of soluble DU for OSAGWI Levels II and III exposure scenarios.

Table 48 is a summary of the ranges of DU intakes by inhalation and indirect ingestion and resultant toxicological implications for OSAGWI Levels II and III exposure scenarios.

Personnel in the Levels II and III scenarios may also have been exposed to DU by hand-to-mouth transfer of removable DU particles from surfaces on or in DU-contaminated vehicles or other equipment. The total estimated intake by secondary ingestion (upper bound) for an individual is 0.057 mg of DU (0.047 mg insoluble and 0.01 mg soluble) per 1-hour exposure in a vehicle. The internal CEDE dose estimate per individual would be 0.000002 rem per 1-hour exposure in a vehicle. This dose is based on the average of surface-contamination results as indicated in Table 39. Surface-contamination results reported in Table 39 were obtained after a single DU munition perforated DU armor.

5.10.1 Radiation Risk of DU Exposure

Review of the exposure assessments and health risk characterization for the OSAGWI Level II and Level III scenarios discussed herein indicates that the ionizing radiation risk from such potential DU exposure during and following the 1991 Gulf War is below the suggested guidance levels in national and international safety standards. (See Appendix K for a discussion of airborne exposure safety standards.)

5.10.2 Chemical Risk of DU Exposure

Inhalation. Review of the exposure assessments and health risk characterization for the OSAGWI Level II and III scenarios discussed herein indicates that the chemical intake from potential DU exposure via inhalation during and following the 1991 Gulf War is below the suggested guidance levels in national and international safety recommendations.

Secondary Ingestion. Review of the exposure assessments and health risk characterization for the OSAGWI Level II and III scenarios discussed herein indicates that the chemical intake from potential DU exposure via secondary ingestion during and following the 1991 Gulf War is below the recommended guidance level of 3 µg Uranium/g of kidney.

Table 47. Ranges of DU Intakes by Inhalation and Indirect Ingestion, Levels II and III Scenarios

Exposure Classification: Levels and Scenarios	Total DU Intake Range (mg/hr) in a vehicle [See Note 1]	Insoluble DU Intake Range (mg/hr) in a vehicle	Radiation Dose Range (rem/hr) in a vehicle (See Note 2)	Possibility Radiation Exposure Limit Exceeded [See Note 3]	Radiation Risk	Soluble DU Intake Range (mg/hr) in a vehicle	Possibility Chemical Exposure Limit Exceeded [See Note 4]	Chemical Risk	Discussion In Sections of Part V	**Scenario Example:** Estimated Total DU Intake (mg) [See Note 5 & 6]
Level II										
Explosive Ordnance Disposal (EOD) and other unit personnel who downloaded equipment and munitions from DU-contaminated vehicles/systems	0.00078 LB) to 0.025 (UB)	0.00065 to 0.023	0.00001 to 0.0005	No	Acceptable	0.00013 to 0.002	No	Acceptable	5.2 and 5.2.1	Appendix S
Radiation Control (RADCON) Team members	0.00078 (LB) to 0.025 (UB)	0.00065 to 0.023	0.00001 to 0.0005	No	Acceptable	0.00013 to 0.002	No	Acceptable	5.2 and 5.2.2	Appendix S
Battle Damage Assessment Team (BDAT) members who examined U.S. combat vehicles damaged and destroyed by DU	0.00078 (LB) to 0.025 (UB)	0.00065 to 0.023	0.00001 to 0.0005	No	Acceptable	0.00013 to 0.002	No	Acceptable	5.2 and 5.2.3	Appendix S
Logistics Assistance Representatives (LARs) who inspected DU-contaminated vehicles/systems to determine reparability	0.00078 (LB) to 0.025 (UB)	0.00065 to 0.023	0.00001 to 0.0005	No	Acceptable	0.00013 to 0.002	No	Acceptable	5.2 and 5.2.4	Appendix S

Table 47. Ranges of DU Intakes by Inhalation and Indirect Ingestion, Levels II and III Scenarios (con't.)

Exposure Classification: Levels and Scenarios	Total DU Intake Range (mg/hr) in a vehicle [See Note 1]	Insoluble DU Intake Range (mg/hr) in a vehicle	Radiation Dose Range (rem/hr) in a vehicle (See Note 2)	Possibility Radiation Exposure Limit Exceeded [See Note 3]	Radiation Risk	Soluble DU Intake Range (mg/hr) in a vehicle	Possibility Chemical Exposure Limit Exceeded [See Note 4]	Chemical Risk	Discussion In Sections of Part V	**Scenario Example:** Estimated Total DU Intake (mg) [See Note 5 & 6]
Unit maintenance personnel who performed maintenance on or in DU-contaminated vehicles/systems	0.00078 (LB) to 0.025 (UB)	0.00065 to 0.023	0.00001 to 0.0005	No	Acceptable	0.00013 to 0.002	No	Acceptable	5.2 and 5.2.5	Appendix S
144th Service and Supply Co. personnel who processed damaged equipment, including some with DU-contamination	0.00078 (LB) to 0.025 (UB)	0.00065 to 0.023	0.00001 to 0.0005	No	Acceptable	0.00013 to 0.002	No	Acceptable	5.2 and 5.2.6	Appendix S
Personnel exposed to DU-contamination during cleanup operations at Camp Doha's North Compound	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	5.2, 5.2.7, and App S	---
Level III										
Personnel exposed to smoke from burning DU rounds at Camp Doha	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	5.2.7 and App S	---
Personnel exposed to smoke from burning Abrams tanks	0.0000039 (LB) to 0.0028 (UB)	0.0000036 to 0.0026	0.0000001 to 0.00007	No	Acceptable	0.0000003 to 0.0002	No	Acceptable	5.2 and 5.3.1	5.2 and 5.3.1

Table 47. Ranges of DU Intakes by Inhalation and Indirect Ingestion, Levels II and III Scenarios (con't.)

Exposure Classification: Levels and Scenarios	Total DU Intake Range (mg/hr) in a vehicle [See Note 1]	Insoluble DU Intake Range (mg/hr) in a vehicle	Radiation Dose Range (rem/hr) in a vehicle (See Note 2)	Possibility Radiation Exposure Limit Exceeded [See Note 3]	Radiation Risk	Soluble DU Intake Range (mg/hr) in a vehicle	Possibility Chemical Exposure Limit Exceeded [See Note 4]	Chemical Risk	Discussion In Sections of Part V	**Scenario Example:** Estimated Total DU Intake (mg) [See Note 5 & 6]
Personnel who entered DU-contaminated Iraqi vehicles/ equipment	0.00078 (LB) to 0.0057 (UB)	0.00065 to 0.0047	0.00001 to 0.0001	No	Acceptable	0.00013 to 0.001	No	Acceptable	5.2 and 5.3.2	5.2 and 5.3.2
Personnel exposed to smoke from DU-perforated Iraqi vehicles/ equipment	0.000063 (LB) to 0.0044 (UB)	0.000052 to 0.0037	0.000001 to 0.0001	No	Acceptable	0.000011 to 0.00075	No	Acceptable	5.2 and 5.3.3	5.2 and 5.3.3

Note 1. No credit for PPE, such as respirators or military protective masks, was given for the calculations in this report. (UB) - Upper Bound of range; (LB) - Lower Bound of range. The UB and LB are based on a 5 μm AMAD particle size distribution.

Note 2: CEDE dose for each hour spent in the vehicle.

Note 3. Internal radiation dose is expressed in terms of CEDE which is based on a 5 μm AMAD particle size distribution. Radiation Standard: 5 rem/per yr (10 CFR).

Note 4. Chemical Toxicity Standard: 40 mg of soluble uranium as threshold for permanent renal damage; 8 mg of soluble uranium as threshold for transient renal injury (National Defense Research Institute, 1999 and ANSI, 1995).

Note 5. Examples developed from OSAGWI interview data (see Appendix S for dose assessments).

Note 6. Assessment of secondary ingestion (hand-to-mouth) intakes has been considered and is included in Part V.

Note 7. Analysis of Camp Doha scenarios (Level II and Level III) is provided in Appendix C.

Table 48. Ranges of DU Intakes by Inhalation and Indirect Ingestion and Chemical Guidelines, Levels II and III Scenarios

Exposure Classification: Levels and Scenarios	Total DU Intake Range (mg/hr) in : vehicle[1]	Calculated Kidney Concentration (µg DU/g tissue)	Possibility Kidney Concentration Guideline Exceeded[2]	Air Concentration (mg/m^3)	Possibility Air Concentration Guideline Exceeded[3]	Discussion in Sections of Part V	**Scenario Example:** Estimated Total DU Intake (mg) [See Note 5 & 6]
Level II							
Explosive Ordnance Disposal (EOD) and other unit personnel who downloaded equipment and munitions from DU-contaminated vehicles/systems	0.00078 (LB)[4] to 0.025 (UB)	0.000032 to 0.00067	No	2.6×10^{-4} to 8.4×10^{-3}	No	5.2 and 5.2.1	Appendix S
Radiation Control (RADCON) Team- members	0.00078 (LB) to 0.025 (UB)	0.000032 to 0.00067	No	2.6×10^{-4} to 8.4×10^{-3}	No	5.2 and 5.2.2	Appendix S
Battle Damage Assessment Team (BDAT) members who examined U.S. combat vehicles damaged and destroyed by DU	0.00078 (LB) to 0.025 (UB)	0.000032 to 0.00067	No	2.6×10^{-4} to 8.4×10^{-3}	No	5.2 and 5.2.3	Appendix S
Logistics Assistance Representatives (LARs) who inspected DU-contaminated vehicles/systems to determine reparability	0.00078 (LB) to 0.025 (UB)	0.000032 to 0.00067	No	2.6×10^{-4} to 8.4×10^{-3}	No	5.2 and 5.2.4	Appendix S
Unit maintenance personnel who performed maintenance on or in DU-contaminated vehicles/systems	0.00078 (LB) to 0.025 (UB)	0.000032 to 0.00067	No	2.6×10^{-4} to 8.4×10^{-3}	No	5.2 and 5.2.5	Appendix S

Table 48. Ranges of DU Intakes by Inhalation and Indirect Ingestion and Chemical Guidelines, Levels II and III Scenarios (con't.)

Exposure Classification: Levels and Scenarios	Total DU Intake Range (mg/hr) in : vehicle[1]	Calculated Kidney Concentration (µg DU/g tissue)	Possibility Kidney Concentration Guideline Exceeded[2]	Air Concentration (mg/m^3)	Possibility Air Concentration Guideline Exceeded[3]	Discussion in Sections of Part V	**Scenario Example:** Estimated Total DU Intake (mg) [See Note 5 & 6]
144th Service and Supply Co. personnel who processed damaged equipment, including some with DU-contamination	0.00078 (LB) to 0.025 (UB)	0.000032 to 0.00067	No	2.6×10^{-4} to 8.4×10^{-3}	No	5.2 and 5.2.6	Appendix S
Personnel exposed to DU-contamination during cleanup operations at Camp Doha's North Compound	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	5.2.7 and App C	Appendix S
Level III							
Personnel exposed to smoke from burning DU rounds at Camp Doha	[See Note 7] ---	[See Note 7]	[See Note 7]	[See Note 7]	[See Note 7]	5.2.7 and App C	---
Personnel exposed to smoke from burning Abrams tanks	0.0000039 (LB) to 0.0028 (UB)	0.0000001 to 0.00007	No	1.3×10^{-5} to 9.3×10^{-4}	No	5.2 and 5.3.1	5.2 and 5.3.1
Personnel who entered DU-contaminated Iraqi vehicles/equipment	0.00078 (LB) to 0.0057 (UB)	0.000033 to 0.00026	No	2.6×10^{-4} to 1.9×10^{-3}	No	5.2 and 5.3.2	5.2 and 5.3.2

Table 48. Ranges of DU Intakes by Inhalation and Indirect Ingestion and Chemical Guidelines, Levels II and III Scenarios (con't.)

Exposure Classification: Levels and Scenarios	Total DU Intake Range (mg/hr) in a vehicle[1]	Calculated Kidney Concentration (µg DU/g tissue)	Possibility Kidney Concentration Guideline Exceeded[2]	Air Concentration (mg/m^3)	Possibility Air Concentration Guideline Exceeded[3]	Discussion in Sections of Part V	**Scenario Example:** Estimated Total DU Intake (mg) [See Note 5 & 6]
Personnel exposed to smoke from DU-perforated Iraqi vehicles/equipment	0.000063 (LB) to 0.0044 (UB)	0.000003 to 0.0002	No	0.021×10^{-3} to 1.48×10^{-3}	No	5.2 and 5.3.3	5.2 and 5.3.3

Notes:
[1] No credit for PPE, such as respirators or military protective masks, was given for the calculations in this report.
[2] Toxicity Guideline: 3.0 µg uranium/g tissue (Spoor and Hursh, 1973)
[3] Air concentration guidelines used for comparisons are DOE TEELs (0.5 mg/m^3 – 10 mg/m^3) and ACGIH STEL (0.60 mg/m^3).
[4] (UB) - Upper Bound of range; (LB) - Lower Bound of range. The UB and LB are based on a 5 µm AMAD particle size distribution.
Note 5. Examples developed from OSAGWI interview data (see Appendix S for dose assessment).
Note 6. Assessment of secondary ingestion (hand-to-mouth) intakes has been considered and is included in Part V.
Note 7. Analysis of Camp Doha Scenarios (Level II and Level III) is provided in Appendix C.