III. DEPLETED URANIUM -- A SHORT COURSE

This section discusses DU's chemical, physical, and radiological properties, the ways those properties may affect human health, and the principles and standards for protecting soldiers and the public from harm. These discussions address DU's chemical toxicity, which is the primary concern, and summarize DU's radiological toxicity.

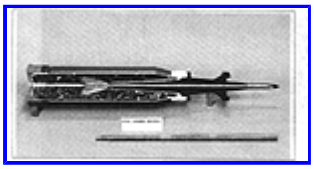

Figure 4. Cutaway of DU sabot round

Very little literature directly addresses DU's health effects. However, extensive material deals with the effects of natural uranium, which is relevant to assessing DU's effects. Chemically, DU has the same properties as natural uranium. Radiologically, DU emits types of radiation similar to natural uranium's, but DU is 40% less radioactive than natural uranium.[12]

DoD evaluated DU's chemical, physical and radiological properties and their health and environmental implications as part of the standard acquisition, test, and evaluation process for new weapons systems. Throughout the DU weapons development program, DoD has adhered to a highly regulated development and procurement process involving extensive hazard assessments, tests, and evaluations. (Tab E comprehensively discusses the DU research and development program, including specific tests and evaluations; Tab L summarizes research reports.)

A. Health Effects from the Chemical Toxicity of Depleted Uranium

1. DU's Chemical Properties

Uranium is all around us. A heavy metal similar to tungsten and lead, it occurs in soils in typical concentrations of a few parts per million (equivalent to about half a teaspoon of uranium in a typical 8-cubic yard dump truck-load of dirt). The Agency for Toxic Substances and Disease Registry (ATSDR) estimates there are typically 4 tons of uranium in 1 square mile of soil 1 foot deep[13] and that we add 180 metric tons (about 198 US tons) of uranium decay products to US agricultural lands each year due to the trace amounts of uranium in phosphate fertilizer.[14] We all take in uranium every day from the air we breathe, the water we drink, and the foods we eat. On average, every day each of us takes in 1.9 micrograms (about two-millionths of a gram) of uranium from food and water and inhales a very small fraction (7×10^{-3} or 0.007) of a microgram.[15]

When DU rounds strike an armored target they generate fragments and uranium oxides. (See Tab M for more information on DU oxides or aerosols.) The particle sizes vary greatly, from larger, easily visible fragments to very fine, respirable particles that can settle in the lungs. Whether large enough to see or too small to observe, DU particles and oxides retained in the body have different solubilities -- that is, they dissolve at different rates in bodily fluids, which act as solvents.

Some have suggested these aerosols can kill anyone in a tank, travel tens of miles from the source, and thus present a hazard to everyone on the battlefield. In reality, while respirable-size particles can travel

with air flow for some distance, test data indicate airborne concentrations at even 5 to 10 meters from the point of impact are not a radiological or chemical concern.[16] Airborne particles are transported according to physical laws that disperse, mix, and dilute the concentration of material in the air. Typically, the farther a person moves away from a source, the lower the concentration, intake, and radiation dose for the same exposure time. In this context, the correct question is not "Have I been exposed?" but rather "How much was my exposure?"

The solubility of uranium compounds determines how quickly the body absorbs them from the lung and how efficiently the body absorbs them from the intestines. Uranium solubility varies greatly depending on the particular compound -- or form of uranium -- and the solvent. The human body's natural fluids, water-based, form the solvent that acts on DU once it has entered the body. In this report, "soluble" and "insoluble" depleted uranium refer to their rate of uptake by the body. "Soluble" chemical forms are absorbed from the lungs within days while "insoluble" forms generally take months to years. Toxic chemical effects, if any, are more likely to be associated with the more soluble forms of uranium while radiation effects, if any, are more likely to be associated with the insoluble forms, such as particles that are deposited in the lungs and retained for extended periods of time.

2. Chemical Effects

Uranium can be chemically toxic when large amounts enter and are retained in the body, absorbed into the blood, and carried to body tissues and organs. The severity of the toxic effect depends on the amount the blood absorbs, how that amount is distributed among the body's organs, and uranium's toxic effects in those organs. In the Gulf War environment, DU entered the body through inhalation, ingestion, or wounds -- in the form of uranium metal (from flying fragments and unoxidized DU) and uranium oxides (mostly depleted triuranium octaoxide (U_3O_8) but also depleted uranium dioxide (UO_2) and depleted uranium trioxide (UO_3) from DU impacts on target vehicles or fires).[17]

The three uranium oxides of primary concern (UO_3, UO_2, and U_3O_8) are relatively insoluble, tending to dissolve slowly (weeks for UO_3 to years for UO_2 and U_3O_8) in bodily fluids.[18] Once dissolved, uranium may react with biological molecules and, in the form of the uranyl ion (UO_2^{2+}) exert its toxic effects. According to research, the kidney is the organ most sensitive to chemical effects from excess uranium. Depending on the concentration of uranium in the kidney, these toxic effects may include damage and death of kidney cells, decreasing the kidney's ability to filter impurities from the blood.[19]

DU oxides, formed during the Gulf War when DU struck armor or burned in fires, could enter soldiers' bodies when they inhaled them from the air inside combat vehicles or from plumes outside the vehicles, or when they ingested residues inside vehicles by transfer from contaminated surfaces to the hands and then to the mouth. About 95 percent of larger (greater than 10 µm [micrometer] Aerodynamic Equivalent Diameter [AED]) inhaled particles deposit in the upper respiratory tract. Most of these clear to the pharynx and are swallowed or blown out of the nose. Swallowed particles clear through the GI tract or the blood. Below 10 µm AED, deposition decreases in the upper respiratory tract, but increases in the deeper pulmonary region (bronchioles and alveoli). The amount of DU that gets absorbed into the blood and deposited in the kidneys and other organs depends on several factors (e.g., particle size, solubility, and breathing rate of the exposed person). USACHHPM determined that 6.4 percent of inhaled soluble DU and 0.3 percent of inhaled insoluble DU are ultimately transferred to the kidneys.[20] Current information indicates 2 to 5 percent of ingested, soluble DU is absorbed into the blood from the

intestines.[21] The remaining 95 to 98 percent of the ingested, soluble DU is eliminated rapidly through the intestines. Only about 0.2 percent of ingested, insoluble DU is absorbed into the blood[22] from the GI tract and the remaining 99.8 percent is eliminated quickly through the intestines.

Once absorbed in the blood, up to 90 percent of the dissolved uranium is excreted within the first few days after a single exposure.[23] The remaining 10 percent deposits in the bones and other organs, where it is excreted over a longer period of time. Insoluble uranium oxides, if inhaled, can remain in the lungs for years, slowly absorbing into the blood and then being excreted in urine.[24]

Numerous studies of the effects of inhaled or ingested uranium in humans have not conclusively documented increased death rates or effects on the immune or nervous systems.[25] Other studies have looked at several common effects uranium could cause. Uranium miners have experienced an increased risk of lung cancer, which scientists agree is attributable to other substances, such as tobacco smoke, radon, and radon's short-lived radioactive decay products.[26] Heavy metals also may affect the liver, but high doses are required to produce observable effects. Although animal studies have suggested possible liver injury from uranium, it has not been found in anyone exposed to DU, including workers at uranium testing sites, even when exposures were much longer and much higher than Gulf War veterans'.[27] Some studies have noted reproductive effects in some groups of workers handling uranium, but the exposures always were combined with exposures to other substances (e.g., radon or tobacco products) that the studies usually identified as the cause. Animal studies show some effects on DNA and other systems, but the exposure levels are orders of magnitude higher than those possible in military or industrial settings. Research on embedded DU (see Section V) indicates possible effects on litter size in rats.[28]

Particularly susceptible to damage from high doses of uranium is the kidney, where uranyl-carbonate complexes (the primary form of uranium circulating in the blood) decompose in the acidic urine, causing health concerns. Uranium's toxic effects on the kidney resemble those caused by other heavy metals, such as lead or cadmium. As the target organ for uranium, medical experts would expect the kidney to show the most dramatic effects from uranium exposure. Nevertheless, although animal studies have shown effects in the kidney, these kinds of effects rarely have been seen in humans -- especially for exposures to insoluble uranium oxides.[29]

3. Chemical Toxicity Standards and Guidelines

Since the kidney is recognized as the target (most sensitive) organ for uranium exposure, regulators have attempted to set a standard for permissible uranium concentration in the kidneys based on studies of uranium's effects in animals and humans. In 1959 the International Commission on Radiological Protection (ICRP) calculated a value of 3 micrograms (m g) of uranium per gram of kidney tissue as a maximum permissible organ concentration (MPOC) in the kidney based on radioactivity rather than chemical toxicity.[30] Reviews of this MPOC have raised several questions about its validity.[31] In those reviews, animal species tested, chemical form of uranium, total dose, and rate of administration contributed to the variability of the amount of uranium in the kidney needed to produce effects. Some observations reported mild kidney effects even at amounts about 10 times lower than 3 m g of uranium per gram of kidney tissue. Nevertheless, occupational exposure guidelines based on the MPOC seem to have protected humans adequately. Therefore, we have selected 3 m g of uranium per gram of kidney

tissue as a guideline for assessing exposures in our investigation.

Operational guidelines based on the MPOC suggest temporary and permanent kidney effects may occur for inhaled soluble DU intakes above 8 milligrams (mg) and 40 mg, respectively.[32] These values may need to be adjusted for specific situations.[33] For example, in 10 CFR 20.1201(e),[34] the Nuclear Regulatory Commission (NRC) includes a requirement to limit soluble uranium intakes to 10 mg in a week in consideration of uranium's chemical toxicity. The NRC extended this guidance in 10 CFR 76 to assessing the adequacy of protecting the health of the public from accidents involving uranium at gaseous diffusion plants. The final guidance establishing 10 CFR 76 (59 Federal Register (FR) 48944, September 23, 1994) specifically stated, "The NRC will consider whether the potential consequences of a reasonable spectrum of postulated accident scenarios exceed 0.25 Sv (25 rem), or uranium intakes of 30 mg."

Few human studies verify kidney damage at these thresholds -- even under exposure conditions of a single exposure to soluble uranium compounds that exceed occupational limits. These intake thresholds are worst-case benchmarks because they assume intakes of soluble uranium during a single exposure and therefore do not take into account the body's ability to eliminate 90 percent of uranium from the blood every 3 days. Gulf War veterans who were exposed to depleted uranium generally experienced repeated, small contacts with insoluble forms of uranium, an exposure scenario that would be expected to produce even less kidney damage.

The Occupational Safety and Health Administration (OSHA) and American Conference of Governmental Industrial Hygienists (ACGIH) have established long- and short-term occupational exposure standards for uranium inhalation by workers based on uranium's chemical toxicity to the kidney. OSHA's Permissible Exposure Levels (PELs) and the ACGIH's Threshold Limit Values (TLV®) are based on the principle that a threshold exists below which no adverse health effects occur. As the exposure increases above the threshold, the adverse health effect becomes more severe. Both the PEL and the TLV® are "time-weighted average concentration[35] for a conventional 8-hour workday and 40-hour workweek, to which it is believed nearly all workers may be repeatedly exposed, day after day, without adverse effect."[36]

Table 2 lists PELs for various metals as a general comparison of the metals' relative toxicity. Although the PELs for uranium are for natural uranium, DU's chemical effects are identical.[37]

Table 2. Comparison of OSHA PELs for metals from inhalation exposures[38]

Metal	Permissible Exposure Limit (mg/m^3)
Lead	0.05
Cobalt metal, dust, and fume (as Co)	0.1
Uranium (as U) USoluble compounds UInsoluble compounds	 0.05 0.25
Nickel metal and insoluble/soluble compounds (as Ni)	1

Tungsten (as W) TSoluble compounds UInsoluble compounds	 1 5
Beryllium and beryllium compounds	0.002

ACGIH established a Threshold Limit Value (TLV®) of 0.2 mg of uranium per cubic meter of air (mg/m^3) for both soluble and insoluble compounds. For brief exposures, ACGIH also set a short-term exposure limit (STEL), an average concentration over a 15-minute period that allows a brief exposure higher than the TLV® of 0.6 mg/m^3.[39]

Risk assessors cannot directly compare Gulf War DU exposures to occupational workplace standards because no air sampling was performed during the Gulf War and because the exposure scenarios are different. PELs and TLVs® are averaged over an 8-hour workday for a 40-hour workweek over a working lifetime. The ACGIH-established short-term exposure limit (STEL), a 15-minute time-weighted average a person should not exceed at any time during the workday, allows brief exposures higher than the 8-hour time-weighted average provided the daily average exposure is less than the 8-hour standard. The STEL (i.e., less than a 15 minute exposure followed by periods of minimal or no exposure) would apply to the shorter-term exposures occurring in the Gulf War (e.g., entering damaged equipment).

4. Implications for the Military

Scientists have shown that elevated concentrations of uranium in kidney tissue may cause an effect called proximal tubular necrosis -- cell damage in the first part of the collecting tubules of the kidney. The damage in research animals was either temporary or permanent depending on the amount of excess uranium. We believe the Level I DU exposures from friendly fire during the Gulf War constitute the highest DU exposures as a result of inhalation, ingestion, wound contamination, and retained DU fragments. While there were no specific measurements for kidney damage when individuals were wounded, kidney function could have decreased due to burns, blood loss, and hypovolemia (water and sodium loss leading to insufficient blood volume). However, the Baltimore VA's studies on 33 Gulf War veterans severely wounded by DU friendly fire have shown no subtle or persistent kidney abnormalities from their DU exposure. The VA conducted extensive testing in 1993-1994, 1997, and 1999 and documented no kidney abnormalities, even in veterans with retained DU fragments who are excreting elevated levels of uranium in their urine. Their testing included measuring retinol-binding protein and $ß_2$-microglobulin, which would indicate the presence or absence of proximal tubular damage.[40] (Tab P further discusses the medical results noted to date in the DU medical follow-up program.)

Kidney damage results from many different causes, most commonly infections, diabetes, and autoimmune diseases. From the time of the Gulf War through 1998, no Gulf War veterans identified as having Level I (140 people) or Level II (127 people)[41] DU exposures have been hospitalized in military facilities for kidney disease (nephritis, nephrotic syndrome, and nephrosis) of the type associated with depleted uranium's chemical toxicity.[42]

B. Health Effects from the Radiological Toxicity of Depleted Uranium

1. General Considerations of Radiation Effects

Radiation is everywhere. People live their lives bombarded by gamma rays, neutrons, and charged particles produced by materials in nature and even in their own bodies. This ever-present background radiation has always existed. During the past century, the development of nuclear and radiation technology introduced other sources of radiation exposure for people. Depleted uranium is one of the many radioactive materials among these new sources.

Scientists recognized that radioactive materials and radiation from x-ray machines could harm people if not controlled. They developed an understanding of how radiation could affect the body and developed ways to measure and control the exposures. Before discussing how DU's radiation could affect a person's health, we briefly summarize the key concepts and issues.

a. Radioactivity and Radiation Emissions

Atoms consist of atomic particles called neutrons (neutral particles), protons (positively charged particles), and electrons (relatively small in mass, negatively charged particles). For any element, including uranium, the number of protons and electrons determines the chemical properties, while the relative number of protons and neutrons determines the nuclear properties. Isotopes -- atoms of the same element -- can have different numbers of neutrons. Isotopes have the same chemical properties, but may have different nuclear or radiological properties.

The ratio of neutrons to protons in the atom's nucleus determines the isotope's stability. Unstable isotopes decay through a nuclear transformation process into new isotopes called progeny or daughter products. This process of decay, which we know as radioactivity, emits one or more forms of ionizing radiation (among them, alpha particles, beta particles, x-rays, or gamma rays) during each nuclear transformation. This decay process continues until it produces a stable (non-radioactive) element. For example, after completing the radioactive decay process, ^{238}U eventually becomes stable elemental lead (^{206}Pb).[43] (Tab C more thoroughly describes the origins of depleted uranium.)

b. Radiation Effects

Scientists categorize the effects of ionizing radiation as either acute or delayed, based on the time frame in which the effects are observed. Acute effects (e.g., nausea, vomiting, hair loss, changes in blood counts, genetic effects, reproductive effects, rapid death and others) occur when people receive high doses in a short period of time (minutes to a few days). Acute effects usually appear quite soon after exposure, although some, such as cataracts, may take longer. The dose received in a given period of time is called dose rate. Delayed effects, such as cancer, can occur when the combined dose and dose rate are too small to cause acute effects. Both animal experiments and human exposures to high levels of radiation (above those normally experienced by radiation workers or the public) show that ionizing radiation can cause some cancers.

Experts who study radiation effects have used the results from high-dose studies to set dose limits for workers and the public. The easiest way to do this is to assume effects occur whenever the dose is above zero. Also, since scientists estimate the rate at which effects occur based on effects from higher doses, they assume the effect increases linearly (at an equal rate) with dose. These two assumptions are called the "linear-dose-response, non-threshold" (LNT) hypothesis, which implies the same number of additional cancers would occur from exposing 100 persons to 100 rem, or 10,000 persons to 1 rem, or 10,000,000 persons to 0.001 rem. However, scientists have never reliably observed non-threshold effects, such as increased cancer rates, in humans below about 10 rem.[44] Reports from Japanese atomic bomb survivor studies conclude that the location or even the mere existence of a threshold is difficult to

assess.[45] Nevertheless, the Health Physics Society states, "Below 10 rem (which includes occupational and environmental exposures), risks of health effects are either too small to be observed or are non-existent."[46] Furthermore, a recent international conference on radiation concluded, "the lowest dose at which a statistically significant radiation risk has been shown is ~ 100 mSv," [about 10 rem].[47] This does not mean that medical effects do not occur below this level, only that if they do occur, they cannot be distinguished from effects due to other causes.

c. Exposure to Radiation

People can be exposed to ionizing radiation from outside the body, called external radiation, or from radioactive material taken inside the body, called internal radiation. External exposures come from natural and man-made sources of ionizing radiation outside the body. Natural radiation comes from space, from radioactive materials in the soil, and in building materials around us. For example, soil contains radioactive potassium, uranium, radium, etc. Other external radiation comes from man's activities, such as processing fertilizers, burning coal in power plants, and mining and processing uranium. Other human activities, such as x-ray machines, industrial radioactive sources, and nuclear medicine tests or therapy, add to the external radiation. Gamma rays, which are like x-rays, pass through our bodies at the speed of light and are the main cause of external exposure. When they pass through our bodies, a small part of their energy remains and may cause damage. Alpha and beta particles also hit our bodies, but they normally do not leave enough energy to cause harm. According to the ATSDR, the average yearly dose from external radiation in the United States is about 0.1 rem per person.[48]

Internal exposures can occur from internal radiation caused by natural and man-made radioactive materials that get inside the body. Everyone takes in some radioactive materials every day in the air we breathe, the food we eat, and the water we drink. Radioactive forms of potassium, carbon, radium, and radon are some of the natural materials we all take into our bodies. Man-made radioactive materials from past nuclear weapons tests, hospitals, coal-fired power plants, and nuclear reactors also may enter the body, where they can build up if they are taken in faster than the body can eliminate them. Each radioactive material has its own unique behavior while in the body. Some leave very quickly (a few days), while others remain for a long time, even years. These materials emit alpha particles, beta particles, and gamma rays that can deposit energy in tissues and potentially cause damage. Generally, alpha and beta particles leave behind all their energy inside the body, while gamma rays leave behind a small fraction of their energy. ATSDR estimates that the average yearly dose from internal radiation in the United States is about 0.26 rem per person.[49]

d. Radiation Exposure Quantities and Units

When radiation interacts with a material, such as body tissue, it can leave some of its energy behind. The different types of ionizing radiation (alpha particles, beta particles, and gamma rays) interact in different ways and have different abilities for causing possible damage. Scientists have developed methods for assessing whether an exposure will be harmful. These methods use several quantities -- each with unique units -- to describe ionizing radiation's behavior in causing effects. These units include absorbed dose, dose equivalent, effective dose equivalent, quality factor, weighting factor, and committed effective dose equivalent. These quantities are described here to provide the basis for the remaining discussion.

It also is important to recognize two systems of units are currently used to describe these quantities, the traditional system and the International System (or SI). Although the SI system is becoming more standard, we chose to use the traditional system because it was the system DoD commonly used during

the Gulf War and because veterans will be more familiar with it.

Absorbed dose is the energy left (deposited) by radiation in a unit mass of irradiated material. The unit of absorbed dose in the traditional system is the rad and represents 100 ergs of energy per gram of material. The SI unit for absorbed dose is the gray (Gy), which equals 100 rads (1 Gy = 100 rads; 1 rad = 0.01 Gy, see Table 3).

Table 3. Radiation unit conversions

Measure	Multiply: SI Units	By:	To get: Traditional Units
Absorbed dose	Gray (Gy)	100	rads
Dose equivalent	Sievert (Sv)	100	rem

Dose equivalent accounts for the differences in the effectiveness of the types of radiation (alpha, beta, and gamma) for producing effects. This means that the same amount of energy placed in tissue (absorbed dose) by alpha particles, beta particles, or gamma rays can produce a different effect. In radiobiology, relative biological effectiveness (RBE) accounts for this difference among radiation types. For radiation safety purposes, a normalizing factor, called the Quality Factor (Q) and derived from RBEs, is normally used. Thus, the absorbed dose multiplied by Q gives dose equivalent, which is expressed as rem in the traditional system and sieverts (Sv) in the SI system (1 Sv = 100 rem; and 1 rem = 0.01 Sv, see Table 3).

Committed effective dose equivalent (CEDE) is the effective dose equivalent to organs and tissues from a radioactive material inside the body, normally calculated over a 50-year time period after an intake occurs and expressed in rem or sieverts. Some radioactive materials clear the body quickly; others clear the body very slowly, taking months or years. While inside the body, these materials continue to expose organs and tissues and deliver their dose. As used in radiation safety, CEDE estimates the effective dose equivalent from a radioactive material while it is in the body. Generally, 50 years is selected as a standard time for workers. This approach allows experts to compare (or combine) the dose from internal radiation with the dose from external radiation to provide an overall assessment of risk.

In radiation safety, **effective dose equivalent** accounts for differences in sensitivity (or susceptibility) of various organs and tissues to developing delayed effects, such as cancer from a radiation exposure. The effective dose equivalent concept attempts to provide the same probability (or risk) of effects such as cancer from a non-uniform exposure to a few organs or tissues as from a uniform exposure to the entire body. The effective dose equivalent is determined by multiplying the dose equivalent in each organ by a tissue weighting factor, and then adding the products for all tissues to produce a whole body, effective dose equivalent, expressed in rem in the traditional system and sieverts in the SI system.

Quality factor (Q) is the factor applied to absorbed dose to account for the relative biological effectiveness of the different radiation types (alpha, beta, and gamma). Committees of experts set quality factors developed from a conservative upper limit on the RBE for the radiation effect most important to humans. Quality factors vary from a value of 1 for x-rays and gamma rays to 20 for alpha particles.

The **tissue weighting factor** is the fraction of the committed dose equivalent in an organ that contributes to the CEDE. This factor represents the relative risk of harm from the radiation dose in the organ to the total risk from a uniform exposure to the entire body.

e. Sources of Exposure

People are exposed to natural and man-made radiation constantly. Today, the average American receives an effective dose equivalent of 0.3 rem every year from natural sources, that is, radioactive materials in rocks and soil, cosmic radiation, radon, and radioactivity in our bodies, and about 0.06 rem from man-made sources, including medical testing and treatment, nuclear power generation, etc. Over a 70-year lifetime, the cumulative average dose equivalent is 21 rem from natural sources, which, according to one model, represents a 1 in 100 increase in lifetime risk of cancer death. In some areas of the world, people receive much higher doses from background radiation. For example, in areas of India and Brazil, the ground is covered with monazite sand, a radioactive ore. Radiation exposure rates there are many times the average background levels elsewhere. People who live in these areas receive doses of up to about 0.7 rem each year from gamma radiation alone. These levels, combined with the other sources of background radiation (cosmic rays, radon, etc.), cause average doses about three times higher than the US average. People who live in these areas show chromosome aberrations as expected for the radiation dose, but they show no different rates of cancer or other diseases linked to radiation than among people who live in low background regions.[50]

2. DU's Radiological Properties

Depleted uranium is composed of three uranium isotopes (^{234}U, ^{235}U, and ^{238}U). Like uranium and all other elements, depleted uranium is composed of atoms, the basic building blocks of nature. In nature, uranium consists of the isotopes ^{234}U, ^{235}U, and ^{238}U (each with 92 protons and electrons and 142, 143, and 146 neutrons, respectively) in a certain ratio. Depleted uranium has less ^{234}U and ^{235}U than natural uranium because the uranium enrichment process partially removes these isotopes, resulting in a radioactivity around 40 percent less than that of the original natural uranium.

The Department of Energy (DOE) recently reported that the DU stock it provided to DoD for manufacturing armor plates and munitions may contain trace levels (a few parts per billion parts) of transuranics (neptunium, plutonium, and americium). Transuranics are radioactive elements with higher atomic numbers (more protons and electrons) than uranium. To verify the level of transuranics in the DU stock material received from DOE, the Army tested representative samples from various batches of DU stock used to manufacture DU armor plate. From a radiological perspective, the transuranic contamination in DU armor contributed an additional 0.8 percent to the radiation dose from the DU itself. Scientists consider this insignificant considering the very low radiological hazard associated with the primary material, DU.[51] While this issue has received considerable attention at certain DOE facilities and in the press, the implications for DoD are minimal -- the quantities are so small they add very little to the radiation dose from depleted uranium itself. Both DOE and DoD concluded that measures designed to protect personnel from the DU itself are more than adequate to protect them from the trace quantities of transuranics.

3. Radiological Effects of Depleted Uranium

Section III.A.2., Chemical Effects, discussed uranium's behavior inside the body and the possible health effects from chemical toxicity. As they decay, DU and its decay products emit alpha, beta, and gamma radiation that can cause external and internal exposure to those who handle munitions or encounter DU-contaminated combat equipment. Natural and depleted uranium are much more likely to be chemical than radiation hazards. Recently, the Agency for Toxic Substances and Disease Registry (ATSDR) concluded, "Natural uranium is radioactive but poses little radioactive danger because it gives off very

small amounts of radiation."[52] Studies have associated lung cancer reported in uranium miners with exposure to other substances, e.g., radon decay products and tobacco smoke.[53] More specifically, ATSDR found that no human cancers have ever been associated with natural or depleted uranium exposure.[54] To illustrate this point more clearly, ATSDR reported, "…the mass equivalents for natural and depleted uranium for potential radiological effects [that is, the amounts that may pose a radiological health hazard] are 3,600 and 76,500 times higher, respectively, than the occupational exposure limits (short-term exposure) [based on chemical toxicity] recommended by the National Institute for Occupational Safety and Health (NIOSH 1997)." (The citation in the Toxicological Profile for Uranium of 3,600 is in error according to ATSDR. The correct value of 36,000 is obtained from Table 2-9 on page 193 of the Toxicological Profile for Uranium by dividing 7.2 g/m^3 by 0.0002 g/m^3.)[55]

A small fraction of the uranium taken into the body deposits in the skeleton, leading to suggestions that uranium's radioactivity could increase the risk of bone cancer above natural background levels. The low levels of radiation DU emits and the results of scientific studies indicate DU does not cause bone cancer. In fact, scientists have never observed bone cancer in populations exposed to any form of uranium, including enriched uranium, which is much more radioactive than DU.[56] As to other possible health effects, the ATSDR concluded it would not expect any radiological health hazard from exposure to inhaled or ingested natural or depleted uranium because their radioactivity is low.[57]

In a process called external radiation, depleted uranium outside the body also can expose people. DU found in DU penetrators, heavy armor packages containing DU plates, or transport aircraft containing DU counterweights, emits alpha, beta, and gamma radiation. The Army Environmental Policy Institute (AEPI) reported that a spent DU penetrator could deliver a skin dose of about 0.2 rem per hour from beta and gamma radiation.[58] DU's alpha radiation does not penetrate the dead layer of the skin. AEPI also reported a dose rate of 0.00124 rem per hour between two rows of M829 A2 120mm munitions in storage.[59] Those exposure scenarios involved a few pounds of DU in the spent penetrator up to hundreds to thousands of pounds of DU in stored rounds. For comparison, one pound of cobalt-60 (^{60}Co) -- a radioactive material used in cancer treatment sources -- delivers a radiation dose of more than 800,000 rem per hour to someone standing 3 feet away. Even one minute's exposure (13,333 rem) to that source means certain death because the dose is almost 17 times the lethal whole body dose.[60] Fortunately, DU's low-level radiation presents much more easily controlled exposure situations.

4. Radiological Protection Standards and Guidelines

Ionizing radiation offers many benefits to society -- for example, medical diagnosis and treatment, food sterilization, and nuclear power. At the same time, it carries safety and health risks as discussed above, if not managed according to standard practices.

Within the first 30 years after the discovery of x-rays, scientists developed radiation measurement standards and set maximum permissible exposure levels. The first level, known as the "tolerance dose," or that amount of radiation a person could tolerate, was set at the amount of radiation that would burn skin, equivalent to about 156 rem per year. Later, the limits evolved until a limit based on actual measurements of damage to human tissue -- about 0.1 rem per day or 30 rem per year -- was published.

Responding to increased concern about radiation effects, expanded radiation use, and improved radiation

safety technologies from World War II to the early 1980s, scientists recommended reductions in radiation dose limits. Established in the 1930s, the National Council on Radiation Protection and Measurements (NCRP) developed the recommended radiation safety standards for the United States. During that time, scientists recommended reducing the occupational limit from 0.3 rem in a six-day period in 1946 to 5 rem per year in the mid-1950s. At the same time, they limited internal doses to 15 rem per year to any organ. This "organ" limit was set higher than the whole body limit because scientists reasoned that a dose to one organ was less significant than the same dose to the entire body. To provide an additional margin of safety, scientists recommended a limit for the public at one-tenth of the workers' limit, or 0.5 rem in a year.[61]

While there is evidence of a radiation dose below which excess cancer will not be seen, existing standards are prudently based on the assumption that any amount of radiation, no matter how small, will increase a person's chances of developing a health effect such as cancer. Accordingly, the NCRP adopted three radiation protection principles: (a) a practice (use of radiation) shall be carried out only if it produces a positive net benefit (sometimes called "justification"); (b) all exposures shall be kept as low as reasonably achievable (ALARA), taking into account economic and social factors (called "optimization"); and (c) individuals' dose equivalent shall not exceed the recommended limits (called "limitation").[62] These principles work together to prevent both acute and delayed effects of radiation in workers and the general public and thus provide a radiologically safe environment.

In 1993, the NCRP released a new set of national recommendations based on the International Commission on Radiological Protection's (ICRP) 1990 recommendations, which contained separate limits for acute and delayed effects. The limits for acute effects became 50 rem per year to any tissue or organ and 15 rem to the lens of the eye to avoid cataract formation. The NCRP's recommended limit on whole-body doses (the "annual occupational effective dose") for delayed effects, first set at 5 rem per year in 1958, is now a maximum of 5 rem in any one year and a lifetime average of 1 rem per year.[63] The ICRP recommends limiting the lifetime average to 2 rem per year.[64]

On January 20, 1987, President Reagan signed "Radiation Protection Guidance to Federal Agencies for Occupational Exposure," 52 FR 1717, establishing current occupational radiation exposure limits for Federal agencies. The Nuclear Regulatory Commission (NRC) implemented that guidance in its regulations on radiation protection (10 CFR 20), applying it to all licensed uses of radioactive material, including DU, under the NRC's jurisdiction. As a matter of policy and directive, other Federal agencies (including DoD) also observe this guidance.[65]

The current established protection standards are:

- 5 rem in a year for workers (to protect against delayed effects such as cancer);
- 50 rem in a year to any organ for workers (to protect against acute effects, such as changes in blood counts, etc.);
- 50 rem in a year to the skin or any extremity for workers (to protect against acute effects such as hair loss or radiation burns);
- 15 rem in a year to the lens of the eye for workers (to protect against cataracts);
- 0.1 rem in a year (during a 70-year lifetime) for members of the public (to protect against delayed effects, such as cancer).[66]

These limits are in addition to the doses a person normally receives from natural background radiation,

medical testing and treatment, and other sources.[67]

Table 4. Annual Whole Body Radiation Standards (CEDE)

Protected Population	Traditional	SI
Public	0.1 rem	0.001 Sv or 1 mSv
Radiation Workers	5 rem	0.05 Sv or 50 mSv

These safety standards provide regulatory guidelines primarily for designing radiation protection programs and facilities. Their intent is to provide a working environment that is as safe as that of the so-called "safe industries," such as transportation, construction, and agriculture.[68] Limits for the public perform the same purpose, but generally include additional margins of safety to account for a wider range of ages (childhood to senior citizen), more diverse health conditions, and individual sensitivities.

Radiation exposure limits assist risk managers, health and safety personnel, and designers in designing facilities and developing procedures so potential exposures produce acceptable risks. Once an overexposure (above the limits) occurs, however, regulators may use the limits as a basis for imposing sanctions or penalties on violators. For the overexposed person(s), the primary concern, of course, is the impact on health, as determined by the best available scientific and medical assessment. For radiation, this usually means thoroughly evaluating the dose combined with what is known about the effects of radiation at that dosage. Even when doses are not high enough to produce so-called "acute" effects, science and medicine can estimate the total lifetime risk to an individual.

We selected 5 rem (cumulative, whole body dose) as the benchmark for evaluating the consequences of DU exposure in the Gulf War. This represents the dose from one year of exposure at the annual occupational limit in the United States. Selecting this value does not mean DoD considers Gulf War participants to be radiation workers. Rather, it means 5 rem in a year represents a very conservative upper limit on the acceptable risk for workers in our society. The NCRP recommends limiting a lifetime dose to 50 rem (1 rem per year on average), while the ICRP recommends 100 rem (2 rem per year on average). These limits represent theoretical increases in lifetime cancer risk of about 2.5 to 5 percent. Numerically, the 5 rem benchmark is identical to the guide for evacuating the public in a nuclear emergency. It is much less than the highest doses (50-70 rem) addressed in the Institute of Medicine's 1999 Potential Radiation Exposure in Military Operations: Protecting the Soldier Before, During, and After. These doses represent a theoretical increase of about 10 percent in the current incidence of cancer (two in five, or approximately 40 percent) in the United States.[69]

5. Implications for the Military

DU's primary type of radiation, alpha, does not pose an external radiation hazard.[70] Although DU's beta and gamma radiation are extremely low, external radiation exposures may occur when personnel are close to DU. Radiation from the DU armor panel is reduced because the DU is sandwiched between two layers of rolled homogenous steel. Similarly, the design of the ammunition storage area of the Abrams HA tank minimizes radiation exposure to the crew. For example, studies of external radiation measurements inside tanks show that the tank commander, gunner, and loader receive a whole-body radiation dose rate above background of about 0.00001 to 0.00002 rem/hour from the DU armor and load of DU munitions. When the driver's hatch is open, the tank driver may receive slightly higher dose

rates above background of 0.00003 rem/hour (when the gun is pointed forward) to 0.00013 rem/hour (when the gun is pointed rearward and the ammunition compartment is fully loaded with only DU ammunition rather than the basic load, which is a mission-dependent mixture of types).[71] This means a hypothetical driver who stays continuously inside a "heavy armor" (HA) tank (a model using DU armor panels), fully loaded with only DU ammunition with the gun pointed to the rear -- 24 hours a day, 365 days a year -- would receive a dose of approximately 1.14 rem (8,760 hours at 0.00013 rem/hr),[72] or less than 25 percent of the current, annual occupational limit of 5 rem. Studies also have shown the maximum dose rate outside the tank approaches 0.0003 rem/hour at the front of a heavy armor turret or over a fully loaded ammunition compartment.[73] Continuous exposure at that rate for 24 hours a day for 365 days would produce an annual dose of about 2.6 rem (8,760 hours at 0.0003 rem/hr), slightly more than half the annual occupational limit. Fortunately, these continuous exposure scenarios represent impossible situations. Actual exposures based on realistic times spent in the tanks (904 hours per training year) are likely to be less than 0.1 rem in a year.[74]

Figure 5. M1A1 tanks in the Gulf

Contact with bare skin presents another external radiation exposure path. DU produces a dose rate of about 0.2 rem/hour, largely from beta radiation, when in contact with bare skin.[75] A person would exceed the current occupational dose limit for skin (50 rem in a year) only if unshielded DU (e.g., bare penetrators) directly contacted the skin for more than 250 hours in a year.[76] Some reports mistakenly have applied the total effective dose equivalent (whole body dose) criterion of 0.1 rem/year for members of the public to this exposure of the skin only, leading to the erroneous conclusion that contact with one exposed DU penetrator could subject a person to a dose of radiation thousands of times higher than the recommended limit. This conclusion is erroneous because contact with a DU penetrator exposes only a very small part of the body, namely the skin in direct contact with the DU. The radiation limit for the public assumes the exposure is to the entire body and that the partial body exposure carries a smaller risk than whole-body exposure. In addition, the risk from skin exposure is much less than the risk associated with exposure to more sensitive internal organs.

In fires and during impact, DU forms mixtures of both soluble and insoluble oxide aerosols. Although there was a well-founded concern about possible adverse health effects from inhaling these aerosols, exposure assessments (presented in Section IV) and medical monitoring conducted to date indicate no health hazard from inhaled DU aerosols. As noted in Section IV below, the estimated doses for the worst-case Gulf War scenario were smaller than 5 rem and well below the radiation levels known to cause health effects in people.

Some veterans have expressed concern about the possibility of cancer from their Gulf War DU exposure. The scientific evidence on this issue is clear. ATSDR stated: "No human cancer of any type has ever been seen as a result of exposure to natural or depleted uranium."[77] Similarly, RAND concluded: "Although any increase in radiation to the human body can be calculated to be harmful from

extrapolation from higher levels, there are no peer reviewed published reports of detectable increases of cancer or other negative health effects from radiation exposure to inhaled or ingested natural uranium at levels far exceeding those likely in the Gulf."[78]

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