Risk assessment: exposure to depleted uranium

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RISK ASSESSMENT is the characterisation of potential adverse effects of human exposures to hazardous agents or activities. The size of this potential in relation to chemical–biological–radiological hazards is judged on the basis of population data comparing exposed and non-exposed groups — that is, through epidemiological studies. The harmful potential of an exposure (the size of the risk) will be measured in terms of the dose to sensitive or target tissues. When there is no current or potential exposure there can be no risk.

The potential pathways of exposure for environmental chemicals are the same for depleted uranium as for any other chemical: ingestion, inhalation and skin contact (including wound contamination). These are pathways for external or internal exposure and do not equate with dose. An exposure may occur, but if the agent is not absorbed no dose may be received. It is the dose to the target organs that contributes to the risk of adverse outcomes.

Risk assessment for depleted uranium exposure

External contact

Manufacture and storage of depleted uranium

Based on extensive study of the health of uranium process workers, the risk from depleted uranium manufacture and storage is negligible.

Abstract

- Close proximity to depleted uranium metal, as in storage facilities, carrying shells or driving tanks, even when prolonged, produces negligible internal radiation exposure and levels of external radiation exposure well below the recommended levels for occupational safety.
- The estimates of depleted uranium intake, chemical dose, and radiation dose calculated by the US Department of Defense for personnel exposed to depleted uranium through operations in areas where depleted uranium munitions had exploded, or through clean-up and repair operations on vehicles damaged by depleted uranium munitions, indicate that those veterans experienced air concentrations well below the short-term exposure limits. Estimated exposures were far below any relevant US federal or industrial guideline for chemical or radiation exposure.
- Recent risk assessments by the Royal Society show that, while studies of large cohorts of veterans are vitally important to explore and understand the experiences and exposures which may affect the health status of veterans, most veterans of conflicts involving depleted uranium munitions would have had very low or negligible exposure to depleted uranium.

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External exposure to depleted uranium containing munitions

There is no evidence that skin contact with natural or depleted uranium by humans can lead to chemical toxicity. A number of reviews have considered the external radiation doses from depleted uranium. Some have used theoretical calculations,[1] others have attempted direct measurement.[2] This exposure could occur in unprotected handling of the depleted uranium munitions, such as loading and working with depleted uranium munitions, and in handling fragments of these munitions. Usually gloves would be worn. Skin exposure could also occur in rescue or clean-up operations after the use of depleted uranium munitions or fires, as in the Camp Doha incident during the Gulf War.[2]

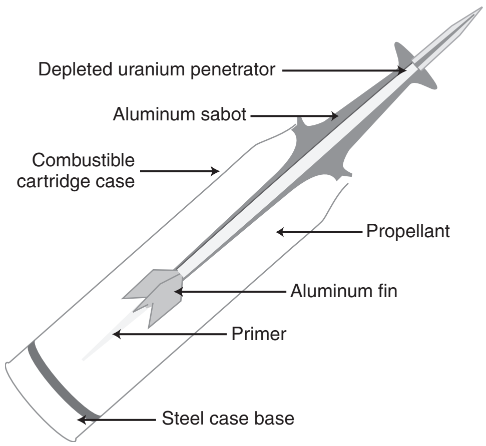

Diagram of an armour-piercing depleted uranium shell.

Depleted uranium is predominantly an emitter of alpha radiation, but small amounts of beta emissions and photons (x-rays and gamma rays) also are produced.[3] The inert outermost layers of the skin stop alpha particles. Beta particles can travel about a centimetre into the body. Photons (x-rays and gamma rays) are more penetrating and can pass straight through the body. Depleted uranium external to the body is a potential source of small amounts of gamma and beta radiation. Intact depleted uranium anti-tank shells are partially enclosed in metal casing. The 30-mm Gatling gun munitions have a 0.8 mm aluminium jacket. The metal casing would absorb alpha and beta emissions from the enclosed depleted uranium.

Fetter and von Hippel provide the only comprehensive theoretical assessment of the hazards from depleted uranium munitions which has been published in a peer-reviewed journal (Royal Society, 2001).[1,4] They estimate that the theoretical maximum whole-body gamma-ray dose-rate from external exposure to depleted uranium is 0.025 mSv per hour. They suggest dose rates in this range may be experienced by a person completely surrounded by depleted uranium munitions in a uranium store or in a vehicle reinforced by depleted uranium containing armour and armed with its complement of depleted uranium munitions. Measurements by the US Army have demonstrated that the highest exposures from gamma radiation are likely to arise in a depleted uranium armoured vehicle carrying depleted uranium ammunition. According to the US Army, the whole-body dose rate in a tank fully loaded with depleted uranium munitions is less than 0.002 mSv per hour.[5] Thus, driving a fully loaded tank for 2000 hours would result in a dose roughly equal to the average annual dose from natural background radiation in the US (3.0 mSv per year).[1,5,6] This is equivalent to driving a tank every working day of the year for the whole of an eight-hour working day and results in a radiation dose that is 15% of the allowed occupational exposure for ionising radiation.

Fetter and von Hippel have calculated the dose rate to a person standing on flat ground uniformly contaminated with 1 ton of depleted uranium per square kilometre at about 0.01 mSv per year.[1] The dose rate from natural uranium in soil is ten times greater, at about 0.1 mSv per year.[1] Even in the area immediately surrounding a vehicle destroyed by depleted uranium munitions, the generated dose rate from external radiation is unlikely to exceed 0.3 mSv per year — a tenth of the natural background dose rate for the US. US regulatory limits for public exposure to other than background sources of ionising radiation is 1 mSv per year.[7]

The World Health Organization calculated the amount and fate of depleted uranium deposited at an “average” attack site in Kosovo.[8] The calculations are shown in Appendix 11 to the report and demonstrate that, if all the depleted uranium munitions expended during an attack remained within one kilometre, the increase of uranium in the soil would be five per cent. The additional contribution of depleted uranium from military use to background radiation dose in Kosovo is within the natural variations found for background levels.

The WHO report suggests that “picking up a penetrator and keeping it in a pocket is the only realistic way of a long period of exposure to external (beta) radiation from depleted uranium.”[8] Snihs and Åkerblom, of the Swedish Radiation Protection Institute, considered that “by keeping a piece of DU in the pocket for several weeks in the same position it might be possible that the skin dose will exceed values corresponding to the limit for the general public and radiation workers, though not that of radiation workers. It is out of question that there will be any deterministic effects (skin burns).”[9]

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The available evidence indicates that external contact with depleted uranium in intact penetrators or as uranium oxide dusts does not convey an appreciable excess risk of adverse health effects.

Internal exposure

Inhalation

When a hard target such as an armoured tank or a rocky outcrop is hit by depleted uranium munitions, a proportion of the original depleted uranium metal (usually 10%–35%, up to a maximum of 70%) forms an aerosol of the metal and its combustion products, which are predominantly uranium oxides. Aerosols and dusts containing depleted uranium and its oxides may be inhaled into the lungs. Based on particle size, it has been estimated that about 60%–69% of the aerosolised fraction of this depleted uranium is respirable.[2,5]

The fate of these particles depends on their size. Some will be exhaled, some will deposit in the upper airways (the nose, mouth and bronchial tree), and some will deposit deep in the lungs. Ninety-five per cent of particles larger than 10 μm aerodynamic equivalent diameter are deposited in the upper respiratory tract (bronchioles, bronchi, trachea). Most of these particles are cleared by the normal bronchial mucociliary clearance mechanism and swallowed or blown out of the nose. "As such, it is only the smaller respirable particles which represent a potential health hazard from inhaled (natural) uranium. As particle size decreases below 10 μm, deposition decreases in the extrathoracic and bronchial regions but increases in the bronchioles and alveoli (pulmonary regions) such that, at particle sizes below 0.5 μm, the alveoli represent the major site of deposition. Retention of particles in various lung compartments depends on the efficiency of the mucociliary clearance mechanism which decreases in the deeper portions of the lung, or by macrophage action and solubilisation."[10]

The acute hazard from inhaled uranium aerosols is related to the extent and rate of transfer of inhaled uranium to the blood and the presumed amounts reaching the primary targets in the kidney. "Two factors will influence the degree of hazard: the site of deposition in the respiratory tract, dependent on the aerodynamic equivalent diameter, and the fate in the lung, dependent on the physical and chemical characteristics of the particles, such as the solubility, exposed surface areas, and intercrystalline forces."[2] A radiation dose predominantly from alpha decay is delivered to the airway and lung while the uranium remains in the respiratory system. Absorption of depleted uranium in the body following inhalation is very limited. Mean absorption following inhalation exposure is about 0.8% to 0.9%, with less soluble compounds remaining in the lungs as uranium oxides.[11]

The United Nations Environmental Program has estimated that the inhalation and ingestion of depleted uranium contaminated dust, even under extreme conditions shortly after the impact of projectiles, would be less than 10 mSv (based on the amount of dust that can be inhaled in these conditions).[12] This represents about half the annual dose limit for radiation workers. For people in open areas near destroyed tanks or near burning depleted uranium, the aerosol dose is considerably less. For people who entered the tanks or the vicinity of the former fire sites after the aerosol had settled, the internal contamination is also much smaller. At the most, a smaller portion of the aerosol is resuspended and could be inhaled. Over time this potential exposure is further reduced by climatic influences, such as rain or snow.

Ingestion

Ingestion may occur via hand-to-mouth transfer of depleted uranium dusts, or consumption of soil, water or foodstuffs containing depleted uranium. Typical worldwide dietary intake is estimated to be between 0.9–4.5 μg/day, with an average of 1.5 μg/day.[7] Only about 2% of uranium in easily soluble form is taken up into the bloodstream from the digestive tract; the rest is eliminated rapidly through the intestines. Uranium in the form of uranium oxide, which is poorly soluble in the body, is taken up by the digestive tract at a negligible rate (about 0.2%).

The absorbed fraction is taken into the blood and is rapidly cleared (in a few minutes), with about 90% leaving the body in urine within the first week, and the remainder being distributed to tissues. The evidence available indicates that this route would provide a negligible systemic dose of insoluble uranium oxides for personnel in combat situations.

Agricultural route

Food may become a vehicle for uptake of depleted uranium. Plants may take up uranium from the soil and soil may adhere to the root surface. Calculations used by the European Union indicate that consumption of 100 kg/year of vegetables grown in soil with 70 mg of depleted uranium per kilogram of soil would yield a radiation dose of 0.0026 mSv/year.[13] Consumption of unwashed root vegetables may increase exposure due to ingestion of soil. Washing reduces soil intake by 99%.

It is known that aquatic macrophytes accumulate uranium and there are species of plants in the Alligator River region of Australia that show preferential concentration of uranium. The 2001 WHO mission to Kosovo explored the theory that uranium dust might become incorporated in vegetables and crops. "The mission was advised by the Food and Agricultural Organisation of the United Nations (FAO) that in the published literature there are no known (cultivated) plants that preferentially accumulate uranium and the normal amounts of uranium taken up in plants would not be expected to be dangerous to humans, birds or other animals."[8]

Drinking water route

Drinking water can contain naturally occurring uranium over a wide range of concentrations, from below 0.01 μg/L to in excess of 1500 μg/L. After environmental incorporation of depleted uranium a number of physical, chemical and geological factors affect the potential for exposure to additional uranium.

The European Union estimated that a radiation dose of about 0.0001 mSv/yr (worst case 0.024 mSv/yr) could result from consumption of drinking water.[13] This calculation was based on the assumptions of 10 kg of depleted uranium spread over 1000 m^3 of soil surface eventually dissolving, a proportion of this entering the groundwater each year, and this water being used for drinking.

The WHO mission to Kosovo considered exposure of the population via drinking water contaminated by migration of soluble depleted uranium compounds in ground or surface water. "In particular, possible contamination of wells or spring protection tanks close to an attack site from pieces of depleted uranium might be an isolated occurrence and its relevance should be considered further."[8] The very small amounts of depleted uranium in comparison with the natural uranium present in soils and rocks is not likely to significantly increase the amount of uranium already present in drinking water.

Exposure standards for uranium

Both heavy metal toxicity and radioactivity risks of uranium have been assessed. Exposure standards have been defined for the general population and for workers in the radiation industry. The World Health Organization has been involved in setting guidelines on uranium exposure which apply to depleted uranium.[14] Currently these are:

- Permissible exposure limit time-weighted average of 0.05 mg/m^3 for soluble uranium compounds and 0.25 mg/m^3 for insoluble uranium compounds[7]
- The tolerable intake for soluble uranium compounds is 0.5 μg/kg/day and is 5.0 μg/kg of body weight/day for insoluble compounds[15]
- Limits of ionising radiation exposure of 1 mSv/year for the general public and 20 mSv/year averaged over five years for radiation workers.[7]

Combat-related exposure assessments

In assessing internal exposures to depleted uranium during the Gulf War, three levels of "battle-related" exposure have been considered. These levels do not consider exposure to intact munitions or depleted uranium armour, as no depleted uranium is taken into the body from these exposures. The two available models[2,4] differ slightly, but the framework is as follows:

Level One exposure refers to the most highly exposed personnel: personnel in a vehicle at the time it was struck by depleted uranium munitions, or who entered the vehicle immediately afterwards. The exposure was through inhalation and ingestion of depleted uranium, wound contamination and retention of depleted uranium fragments.

Level Two exposure refers to less highly exposed personnel: personnel working for hours on or in contaminated vehicles to carry out cleaning and repairs. The exposure was through inhalation of resuspended depleted uranium and by hand-to-mouth transfer and ingestion.

Level Three exposure includes all lesser internal exposures, such as being downwind of impacts or fires or brief entries into contaminated vehicles.

Mathematical modelling was used to estimate doses for these levels. Such modelling requires many assumptions. No direct measurements of exposure were undertaken at the time. Differences in modelling contribute to the differing assessments by US and UK scientists.[2,4] The US Army has been tasked to more fully characterise the actual exposure to depleted uranium in combat vehicles struck by depleted uranium munitions.[4]

Table 1 summarises the US military upper limit estimates for all levels of exposure during the Gulf War.[2] The estimates are based on the upper extremes of exposure for a given scenario; for example, Level Two estimates assume each individual was exposed to all 31 US vehicles contaminated with depleted uranium, and Level Three estimates assume exposures of 100 vehicle-hours, such as from one-hour exposures in 100 vehicles. As such, they serve as upper limit assessments of modelled exposure and secondarily modelled dose.

The potential for exposure and uptake of depleted uranium into the body was analysed in detail by the Office of the Special Assistant for Gulf War Illnesses (OSAGWI),[2] which considered the following sources of depleted uranium exposure:

- airborne depleted uranium from 120 mm munitions penetrating Abrams tanks and Bradley fighting vehicles
- residues inside vehicles contaminated with depleted uranium, including both vehicles struck by depleted uranium munitions and burned-out vehicles with onboard munitions, resuspended (stirred up) by personnel entering and working
- depleted uranium on the ground resuspended by vehicle and personnel traffic
- depleted uranium in smoke from burning vehicles and munition
- depleted uranium residues inside and outside contaminated vehicles that personnel could ingest or transfer to wounds.

These potential sources are similar in most respects to those considered in the Royal Society report.[4]

In a comparison of the tables in Box 1 and Box 2, it is seen that the estimates for intake and effective radiation dose differ considerably in several key aspects. The Royal Society central estimates approximate the upper limit intakes estimated by OSAGWI. The Royal Society intake estimates for "worst case" scenarios are up to 200 times above their central estimates, and would entail theoretical risks for lung cancer at least. Even in the "worst case" scenarios, Level Three exposure is not associated with a theoretical risk to health.

The potential for exposure is obviously greatest inside a struck vehicle at the time of impact by a depleted uranium penetrator. These exposures result from inhalation, ingestion, wound contamination, and retained uranium fragments. The mathematical modelling of these high level exposures has been the subject of greatest variability. Models of dose have then been extrapolated using these exposure estimates and a range of critical assumptions. Validated data are limited. Fetter and von Hippel provide a detailed analysis of exposure and dose based on available evidence.[1] They report that measurements taken inside an M1A1 tank after it was struck by a single 120 mm depleted uranium penetrator corresponded to average and maximum 15-minute intakes of 12 mg and 26 mg, respectively. Also, estimates derived from the concentration of uranium in the urine of 14 soldiers that were in struck vehicles, but who do not have evidence of retained shrapnel, are consistent with inhalation of up to 25 mg of depleted uranium. Fetter and von Hippel consider that "taking into account various uncertainties and the possibility of multiple penetrator strikes, it is possible that individuals inside struck vehicles could inhale 50 or more milligrams of depleted uranium aerosol."[1] These estimates, particularly those based on measurements of urinary uranium in survivors of the "friendly fire" incidents, are a factor of ten less than the upper limit estimates from OSAGWI and 200 times less than the "worst case" estimates from the Royal Society.

It is also useful to consider the physical considerations for inhalation of large masses of dust required in the estimates described above. This approach has been taken by several authors.[11] These authors have noted that instantaneous inhalation of more than one gram (1000 mg) of dust is unendurable, and, assuming 10% of the dust to be depleted uranium, the maximum intake of depleted uranium would be 100 mg. This would give a maximum effective dose of 10 mSv from acute inhalation of depleted uranium.[4] Longer exposures to depleted uranium aerosols and dusts may also be assessed, and "it is very unlikely that any dust except very close to a point of impact would be more than 10% depleted uranium. An air concentration of 100 mg per cubic metre would be noticeably dusty, and normal breathing rates are of the order of one cubic metre per hour. Hence, to inhale 100 mg of depleted uranium, someone would need to inhale dusty air that was heavily contaminated with depleted uranium for ten hours."[4] It is unlikely that anyone would incur a dose greater than 10 mSv in these battlefield conditions. The Royal Society worst case scenario of inhalation of 5000 mg of depleted uranium is based on considerably greater theoretical exposures: breathing air carrying 50 000 mg of dust per cubic metre at 50 L per minute for one minute, followed by 5000 mg of dust per cubic metre at 50 L per minute for 10 minutes. These assumptions do not appear to be supported by the limited information available from survivors of "friendly fire" incidents.

Retained depleted uranium fragments

No NATO forces are recorded to have suffered friendly fire incidents or have retained fragments of depleted uranium due to service in the Balkans. As a result of friendly fire incidents during the Gulf War, depleted uranium munitions struck a

1: Estimated upper limit for depleted uranium (DU) intakes, kidney concentration, and radiation dose (committed effective dose equivalent, CEDE) calculated by Office of the Special Assistant for Gulf War Illnesses[2]

	Intake (mg)	Exceeds health guide	Kidney concentration (µg/g tissue)	Exceeds health guide	CEDE, rem (mSv)	Exceeds health guide
Level One						
Soldiers in or on a US vehicle penetrated by a DU munition	237	Yes	4.38	Yes	4.8 (48)	No
Soldiers who entered US vehicles to rescue occupants immediately after friendly-fire DU impacts	237	Yes	4.38	Yes	4.8 (48)	No
Level Two						
Explosive ordnance disposal	2.5	No	0.05	No	0.016 (0.16)	No
Unit maintenance personnel	7.6	No	0.15	No	0.047 (0.47)	No
Logistics assistance representatives	2.5	No	0.05	No	0.016 (0.16)	No
Battle damage assessment team	7.6	No	0.15	No	0.047 (0.47)	No
144th Service and Supply Company	2.5	No	0.05	No	0.016 (0.16)	No
Radiation control team	3.8	No	0.075	No	0.023 (0.23)	No
Cleanup at Camp Doha's north compound	NR	—	0.095	No	0.065 (0.65)	No
Level Three						
Personnel exposed to smoke at Camp Doha	NR	—	2.8×10^{-7}	No	3.0×10^{-6} (3.0×10^{-5})	No
Personnel exposed to smoke from burning Abrams tanks	0.28	No	0.007	No	0.007 (0.07)	No
Personnel who entered DU-contaminated equipment	8.2	No*	0.012	No	0.01 (0.1)	No
Personnel exposed to smoke from Iraq's DU-impacted equipment	0.44	No	0.02	No	0.001 (0.01)	No

NR = not separately reported. *The total DU intake for 100 vehicle-hours appears to exceed the 8 mg inhalation guideline; however, that guideline pertains to soluble uranium, which in this estimate is about 1.1 milligrams. The remainder is insoluble uranium.

number of US Bradley fighting vehicles and Abrams tanks.[16] As would be expected the probability of death or serious injury is very high in vehicles struck by anti-tank weapons. Of 113 soldiers in about 30 US vehicles struck by depleted uranium penetrators in the Gulf War, 13 were killed and about 50 incurred significant wounds — a casualty rate of over 50%.[1] The risks associated with inhaled, ingested or implanted depleted uranium are very small in comparison, given the design of all such strikes to be "total kill".

In addition to inhaled aerosols generated at impact, personnel in vehicles at the time of impact by a depleted uranium penetrator may also retain fragments of uranium in their bodies. Such fragments deliver a radiation dose to a relatively small volume of surrounding tissue. As the fragments dissolve gradually in body fluids, uranium also is transported to other organs and excreted in the urine.

The US Baltimore Veterans Administration Medical Follow-up Program results provide the most relevant information about these survivors' health and medical conditions. Extensive testing in 1993-1994, 1997, and 1999 has not detected kidney abnormalities, even in veterans with retained depleted uranium fragments who are excreting elevated levels of uranium in their urine. Their testing included measuring retinol-binding protein and β_2-microglobulin, which would indicate the presence or absence of proximal tubular damage.[17] While these veterans have medical disorders resulting from their wartime injuries, they exhibit none of the known clinical manifestations from uranium's chemical or radiological toxicity. No adverse kidney effects have been observed and no cancers have been recorded in this population.[17,18]

From the time of the Gulf War up to 1998, no Gulf War veterans identified as having Level One exposures (140 people) or Level Two exposures (127 people) have been hospitalised in military facilities for kidney disease (nephritis, nephrotic syndrome, or nephrosis) of the type associated with depleted uranium's chemical toxicity.[2]

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2: Summary of estimated intakes (mg) and effective doses (mSv) for different battlefield scenarios calculated by the Royal Society, 2001[4]

	Central estimate		Worst case	
Scenario	Intake (mg)	Dose (mSv)	Intake (mg)	Dose (mSv)
Level One inhalation of impact aerosol	250	22	5000	1100
Level Two inhalation of resuspension aerosol within contaminated vehicle	10	0.5	2000	440
Level Two ingestion within contaminated vehicle	5	0.0005	500	0.3
Level Three inhalation of resuspension aerosol within contaminated vehicle	1	0.05	200	44
Level Three ingestion within contaminated vehicle	0.5	0.00005	50	0.03
Level Three inhalation of plume from impacts	0.07	0.004	5	2.8
Level Three inhalation of plume from fires	0.05	0.004	1	1.2
Level Three inhalation of resuspension from ground	0.8	0.03	80	18