The health hazards of depleted uranium

Ian Fairlie

For over two decades, there has been considerable public debate about the health effects of depleted uranium (DU). Military services in many countries use depleted uranium in munitions and to strengthen armour in vehicles. This is because uranium is a very dense metal (approximately 70% more dense than lead), which is useful in a military context—and the chemical and physical properties of natural uranium metal and DU metal are very similar. DU alloys are very hard and pyrophoric, properties which make them superior to tungsten armour-piercing munitions. DU armour-plating is also more resistant to penetration by conventional anti-tank munitions. DU munitions were first used extensively in the First Gulf War (1991), in Bosnia (1995) and Kosovo (1999), and continue to be used in Iraq since 2003 and perhaps in Afghanistan since 2002. Table 1 indicates the amounts of DU used in recent wars by the United States (US) armed forces—the most frequent user of DU munitions.

Table 1. Depleted uranium used by the United States in recent wars (metric tons)

First Gulf War	*Balkan wars*	*Second Gulf War*
286	11	75

Source: National Research Council, 2008, *Review of Toxicologic and Radiologic Risks to Military Personnel from Exposure to Depleted Uranium during and after Combat*, Washington, DC, National Academies Press, Tables 1–4.

On impact, DU may be dispersed as aerosols, which can be inhaled or ingested, or imbedded in tissue as shrapnel. Frequent, continuing reports of illnesses suffered by combatants[1] and civilians[2] in these wars have resulted in speculation that these may be due to DU exposures. (See Box 1 for a discussion of Gulf War Syndrome.)

DU is obtained as a waste product of nuclear power and of the manufacture of nuclear weapons. It is a radioactive heavy metal that can be hazardous to humans in four ways:

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- as a toxic heavy metal;
- as a genotoxic (i.e. carcinogenic and mutagenic) agent from its chemical properties;
- as a genotoxic agent from its radiation; and
- as an endocrine disruptor.

Box 1. Gulf War Syndrome

Many soldiers and civilians from Gulf War areas have self-reported a variety of symptoms, often collectively termed Gulf War Syndrome. The syndrome appears to be a complex, progressive, incapacitating multi-organ system disorder whose symptoms can include fatigue, musculoskeletal and joint pains, headaches, neuropsychiatric disorders, confusion, visual problems, changes of gait, loss of memory, swollen or enlarged lymph nodes, respiratory impairment, impotence and urinary tract morphological and functional alterations.

Whatever the causes, it is clear that the suffering is widespread, measurable and real to those affected. Nearly 20% of all US personnel deployed to the 1991 Gulf War were receiving some form of disability compensation due to these effects by 2001.[a] A number of studies, summarized by Komaroff, have found that armed forces from several countries deployed to the Persian Gulf region were statistically significantly more likely to report chronic, debilitating symptoms than military personnel deployed to other areas.[b] Eisen et al. measured the prevalence of self-reported chronic illness among Gulf War combatants compared to a control group of non-deployed veterans. They found that deployed veterans reported dyspepsia, a group of common skin conditions (fibromyalgia), and chronic fatigue syndrome much more often than the control group. The most striking association was chronic fatigue syndrome.[c]

Some authors[d] have alleged these symptoms may be due, at least in part, to DU exposures. However, many soldiers and civilians reporting these symptoms were clearly unexposed to DU, or were exposed to very small amounts, so the single explanation of DU exposure is highly unlikely.

In addition, many Gulf War personnel were exposed to many substances that in theory could have produced chronic tissue damage: solvents, insecticides, smoke and other combustion products, agents of chemical warfare (irreversible anticholinesterase inhibitors, such as sarin), and pyridostigmine bromide (a reversible anticholinesterase inhibitor taken to prevent the effects of sarin). Also, they received an intensive battery of simultaneously administered immunizations, which some believe[a] could have produced chronic debility.

In conclusion, although our understanding of the aetiologies of these symptoms remains poor to say the least, it is difficult to ascribe anything more than a minor role to DU exposures.

[a] M. Davis, 2003, "Overview of Illnesses in Gulf War Veterans", in J.M. Colwill (ed.), *Gulf War and Health. Volume 2: Insecticides and Solvents,* Washington, DC, National Academies Press, pp. 533–561.
[b] A.L. Komaroff, 2005, "Unexplained Suffering in the Aftermath of War", *Annals of Internal Medicine,* vol. 142, no. 11, pp. 938–939.
[c] S.A. Eisen et al., 2005, "Gulf War Veterans' Health: Medical Evaluation of a US Cohort", *Annals of Internal Medicine,* vol. 142, no. 11, pp. 881–890.
[d] A. Durakovic, 2003, "Undiagnosed Illnesses and Radioactive Warfare", *Croatian Medical Journal,* vol. 44, no. 5, pp. 520–532; R. Bertell, 2006, "Depleted Uranium: All the Questions about DU and Gulf War Syndrome Are Not Yet Answered", *International Journal of Health Services,* vol. 36, no. 3, pp. 503–520.

DU has about 75% of the radioactivity of natural uranium (see below), and the same chemical toxicity, endocrine disruptive property and mutagenicity as natural uranium.

Because of the controversy over DU, uranium is now one of the most studied radionuclides. Over the past decade, there have been at least nine official reports on the toxicity and health effects of uranium and DU.[3] There have also been a number of informative reviews.[4] Until the recent United States' National Research Council (NRC) report, perhaps the most authoritative were the two reports of the United Kingdom's Royal Society on chemically toxic risks and radiation risks, respectively. These stated that there were legitimate concerns about the possible health consequences of using a radioactive and chemically toxic material for munitions, but they concluded that the risks of DU

munitions to soldiers were very low.[5] However, since the Royal Society's reports, much new evidence from radiation biology studies has emerged.

There are two main sources of information on DU health risks. The first is epidemiology studies—i.e. studies of DU exposures and possible added risks to human populations. The second is radiation biology studies in cells and animals. As we shall see, much more information on DU's health effects is available from the latter than the former source.

What is depleted uranium?

Natural uranium (U) is a constituent of the Earth's crust at a concentration of about 3 parts per million on average. Some uranium ore regions of the world contain much higher concentrations of uranium—typically about 1,000 parts per million.

In the nuclear power fuel cycle, uranium ore is mined, and uranium is leached from ore and refined to almost pure uranium dioxide (UO_2) for use in nuclear fuel.[6] This natural uranium consists of three main isotopes, U-238, U-235 and U-234 (see Table 2). U-238 and U-235 are primordial—that is, they were created at the same time as the Earth about 4.5 billion years ago. U-234, on the other hand, is a decay product of U-238.

The vital consideration is that U-235 is *fissile,* which means that it can maintain fission in nuclear power stations and can be used in nuclear weapons. Most reactors are designed for uranium fuel that has been slightly enriched in U-235. Typically, the U-235 concentration is required to be increased from 0.7% to between 2% and 4%. This is known as low-enriched uranium (LEU). This concentration is effected by the process of enrichment, whereby UO_2 is converted to a gas (uranium hexafluoride, UF_6) and passed through gaseous diffusion or centrifuge facilities. U-235 is also a vital ingredient of many nuclear weapons but here the enrichment required is to about 90% U-235. This is termed highly enriched uranium (HEU).

The enrichment processes for nuclear weapons and nuclear fuel create about 7 metric tons of depleted uranium for each metric ton of enriched uranium produced. The result is that very large quantities of depleted uranium are produced as waste streams. In 1996, worldwide production of DU was estimated by the European Parliament's Science and Technology Options Assessment (STOA) panel at about 35,000 metric tons.[7] As a result, it is estimated that over 1.2 million metric tons of DU are currently stockpiled worldwide, mostly in the United States.[8]

DU is used in radiation screens and, in the past, has been issued in counterweights in aeroplane wings; however these uses are small in comparison with the amounts generated each year. The largest users of DU are military services, although the STOA report estimated that the total quantity of DU in ammunition used in Iraq and Kosovo corresponded to only four days of DU production worldwide. Therefore DU stockpiles worldwide are increasing at the rate of about 35,000 metric tons per year and they pose serious disposal problems to governments involved with uranium enrichment.

How radioactive is DU compared to natural uranium?

This is an easy question to ask, but difficult to answer. Many reports state that DU has 60% of the radioactivity of natural uranium. However, the correct figure is closer to 75% for two reasons: enrichment facilities sometimes use reprocessed uranium (as opposed to 100% mined uranium), and all forms of DU contain decay products.

Table 2. Main isotopes in natural and depleted uranium at the factory

Isotope	*Half-life (years)*	*Specific alpha activity (Bq per gram)*	*Concentration in natural uranium (weight %)*	*Concentration in depleted uranium (weight %)*
U-234	2.46×10^5	2.31×10^6	0.0055	0.001
U-235	7.04×10^8	7.99×10^4	0.72	0.2
U-236	2.34×10^7	2.40×10^6	nil	0.0003 from reprocessed uranium
U-238	4.47×10^9	1.24×10^4	99.3	99.8
Natural U	-	2.53×10^4	-	-
Depleted U	-	1.42×10^4	-	-

Source: Royal Society, 2001, *The Health Hazards of Depleted Uranium Munitions: Part I,* London.

The use of reprocessed uranium in DU

Depleted uranium as used by the US military contains the isotope U-236 (see Table 2), which is not present in natural uranium. This isotope arises only in nuclear reactors and its presence indicates that the DU batch contains some uranium from the waste streams of reprocessing spent nuclear fuel—carried out mainly by France, the Russian Federation, the United Kingdom and the United States. Thus there are two types of depleted uranium—both come from the enrichment process, but one includes small amounts of reprocessed uranium from spent nuclear fuel.

This is a problematic matter because reprocessed uranium is contaminated with the fission and activation products of spent fuel. In particular, the fission product Tc-99 and the activation products Np-237, Pu-238, Pu-239, Pu-240 and Am-241 are sometimes found in DU munitions.[9] Depleted uranium made with some reprocessed uranium is therefore more radioactive than the DU derived solely from mining uranium ores.[10] Most reports state that the amounts of contaminants in DU munitions from spent nuclear fuel are low. According to the US Office of the Special Assistant for Gulf War Illnesses, the dose from these contaminants amounts to less than 1% of the equivalent dose from DU exposures, and the authors concluded that their risk impact was low.[11] The Royal Society also stated that these concentrations had been found to be low in the DU batches it had examined, but it recommended continued vigilance on the matter.[12]

Uranium decay products

Once DU has been made into munitions and placed in a warehouse, its U-238 and U-235 isotopes decay and create various daughter products as shown in Tables 3 and 4, respectively. Within about six months, these daughters are in secular equilibrium with their parents, i.e. the amounts of the daughters being created by the parent are equal to the amounts of the daughters disintegrating. Therefore the radiation from these decay products should be added when assessing the dangers of DU. The key matter is that the decay products are beta emitters, especially Pa-234m, which emits very energetic beta particles. As explained in the Royal Society report of 2001, these beta radiations may constitute as much as 40% of the absorbed dose[13] to tissues near embedded DU. It is important to realize that this additional risk from the beta particles of decay products is currently not taken into account by the International Commission on Radiological Protection (ICRP) in its dose coefficients (which estimate the radiation doses from incorporated radioactive substances) for uranium isotopes.

Bishop[14] has estimated the total alpha, beta and gamma emissions per year from 1g samples of natural uranium and DU. He concluded that DU together with its decay products in equilibrium are 75% as radioactive as natural uranium plus its decay products. The report to the European Parliament's STOA panel, using a cruder method, estimated that DU is 80% as radioactive as natural uranium. This means that the adjective "depleted" may give a misleading impression: a more accurate description would be the phrase "slightly less radioactive".

Table 3. U-238 decay series[a]

Nuclide	*Half-life*	*Decay*	*Energy (MeV)*
U-238	4.5 x 10^9 years	alpha	4.198
Th-234	24 days	beta	0.199
Pa-234m	1.2 minutes	beta	2.271
Pa-234	6.7 hours	beta	0.471
U-234	2.5 x 10^5 years	alpha	4.775

[a] truncated after U-234 because its very long half-life ends the decay chain for practical purposes.

Table 4. Truncated U-235 decay series

Nuclide	*Half-life*	*Decay*	*Energy (MeV)*
U-235	7.0 x 10^8 years	alpha	4.596
Th-231	26 hours	beta	0.390
Pa-231	3.3 x 10^4 years	alpha	5.059

Pathways for DU exposures

DU in the environment

DU exposures can occur via several pathways. One is external radiation, whereby beta radiation (and, to a much lesser degree, gamma radiation) from the decay products of DU irradiate the body, but in most cases such exposures are very small. More important are the internal exposures resulting from inhalation of DU aerosols and dusts, from ingestion of DU-contaminated water and food, and from wounds, i.e. inoculation by DU shrapnel.

When DU projectiles penetrate armoured vehicles, their occupants are often injured by DU shrapnel, which can remain in the body for lengthy periods. When tanks are struck by DU projectiles, depending on the material and thickness of their armour, about 10%[15] is volatilized into an aerosol that immediately burns to form poorly soluble uranium oxides that may remain in high concentrations in enclosed spaces, i.e. tanks and bunkers. These aerosols can contain very small particles of uranium oxide of between 0.1 and 10 microns[16] in diameter, which can be inhaled and deposit in the lungs. White blood cells scavenge these particles and transport them to tracheobronchial lymph nodes for lengthy periods. These particles are usually insoluble, and are unlikely to be detected in urine samples. Therefore the practice of routine urine sampling of returning soldiers may be ineffectual at detecting uranium oxide exposure.

DU in humans

Initial distribution of uranium compounds strongly depends on their solubility and absorption route. Large fractions of administered soluble uranium compounds are absorbed. For example, 20% to 30% was found in the bones of male rats within 2.5 hours of uranium administration, and 90% of the uranium remaining after 40 days was in the bone.[17]

Uranium compounds are distributed to all tissues, preferentially bone, kidneys, liver and testes.[18] Rats implanted with DU pellets also show uranium concentrations in the heart, lung tissue, ovaries and lymph nodes.[19] Like many heavy metals, uranium reacts with DNA and ions and blood proteins to form compounds (called complexes). Uranium can cross the placenta and the blood–brain barrier and accumulate in the brain. Soluble uranium compounds are cleared more rapidly than insoluble compounds: two-thirds of uranium in blood is excreted in urine over the first 24 hours. Elimination of

soluble uranium is primarily by the kidneys and urine. The release of DU from embedded particles in shrapnel is slow: it takes 1.5 years for 80–90% of uranium in bone to be excreted.[20]

Health effects of DU

Since the Second World War, it has been known that uranium, a radioactive heavy metal, is hazardous to humans in at least two ways. Like other heavy metals, such as chromium, lead, nickel and mercury, uranium is chemically toxic to kidneys, the cardiovascular system, liver, muscle and the nervous system. Also, since all uranium isotopes are radioactive, they emit radiation—a known carcinogenic agent. This was thought to be of concern mainly when uranium was inhaled as aerosols or dusts because their long residence times in the lung could result in lung cancers.

This means that, in the United States, which perhaps has the most detailed regulations covering uranium, uranium exposures are regulated by radiation protection and chemical regulation authorities in two different ways: by maximum doses from uranium radiation exposures to the lung via insoluble uranium particles; and by maximum concentrations of soluble uranium chemicals, particularly in the kidney.[21] Uranium's chemical toxicity effects generally occur at lower uranium concentrations than its radiation effects.[22]

Chemical carcinogenicity of DU

Scientists are increasingly aware that uranium and DU are hazardous to humans in a third way: they are chemically (as well as radiologically) carcinogenic. This considerably increases our perception of the hazards of DU and natural uranium because low concentrations of soluble uranium throughout the body—previously considered to be harmless (and therefore neglected)—may be carcinogenic without threshold. In other words, no matter how low the DU or uranium concentration, a small risk of chemical carcinogenesis remains. However, Taylor and Taylor estimated that these risks were very low.[23]

Low concentrations of soluble uranium throughout the body—previously considered to be harmless—may be carcinogenic.

The Royal Society's report of 2001 discussed the emerging evidence of DU's chemical carcinogenicity, and suggested that uranium's chemical and radiation effects may act synergistically, that is, their effects may need to be multiplied together rather than added together. More recently, the NRC report examined uranium's chemical carcinogenicity and expressed variable views. For example, chapter 7 called for research on "whether" a chemical mechanism of uranium carcinogenesis existed. However, chapter 8 recommended that studies be conducted to determine the relative contributions of the chemical and radiological mechanisms of uranium carcinogenesis.[24]

Uranium as an endocrine disruptor

Recent evidence from the United States suggests that DU may be hazardous to humans in a fourth way: it may act as an endocrine disruptor, that is, a substance that interferes with hormones. A number of studies have indicated that heavy metals may act as endocrine disruptors.[25] For example, cadmium stimulates the proliferation of human breast cancer cells,[26] interacts with estrogen receptors[27] and stimulates estrogenic responses *in vivo*.[28]

Raymond-Whish et al. tested whether depleted uranium added to drinking water caused responses in the female mouse reproductive tract like those caused by the estrogen diethylstilbestrol.

They concluded that uranium is an endocrine-disrupting chemical and that populations exposed to environmental uranium (including indigenous populations in the United States living near uranium mine tailings) should be examined for increased risk of fertility problems and reproductive cancers. [29]

Cell, animal, human and epidemiological studies

Human cell evidence (*in vitro* studies)

A comprehensive body of research indicates that the exposure of human cells *in vitro* to DU results in genotoxic effects and induces cell phenomena closely associated with carcinogenesis. These cell phenomena include the following:

- genomic instability—a process involved in carcinogenesis;[30]
- transformation to a tumorigenic state, whereby affected cells grow as cancers when injected into mice;[31]
- induction of mutations whose presence characterizes most cancers;[32]
- DNA oxidative damage;[33]
- activation of gene expression pathways;[34]
- formation of DNA-U adducts;[35]
- induction of dicentrics in chromosomes—a radiation-specific change in human cells;[36] and
- chromosomal damage.[37]

Animal evidence (*in vivo* studies)

Long-term studies in monkeys of uranium oxide (i.e. insoluble) inhalation indicate the carcinogenicity to the lung of this kind of exposure and possibly its involvement in non-Hodgkins lymphoma.[38] Monleau et al. measured the induction of DNA double strand breaks by inhaled DU in rats.[39] Hahn et al. found an elevated risk of cancer in rats implanted with small DU foils. They concluded that DU fragments embedded in muscle tissue were carcinogenic if large enough; however, they stated the mechanism was unclear.[40]

After mice were exposed to embedded DU for 3 months then injected with progenitor cells, Miller et al. found that 75% of mice developed leukaemia (compared with 10% in control mice). In addition, mice showed changes in the musculoskeletal system, i.e. bone formation and remodelling, after oral, intraperitoneal, intravenous and implantation uranium exposure.[41]

In vivo studies with embedded DU pellets in animals showed aberrant expression of oncogenes and tumour suppressor genes associated with carcinogenesis.[42] Although these effects may be caused by DU radiation, there are many reasons suggesting that its chemical effects predominate. In the *in vitro* transformation and sister chromatid exchange studies, induced effects were very much more frequent than expected from the very small number of cells hit by an alpha particle (1 in 100,000 cells from a 10μm-sized particle of DU). In addition, similar transformation frequencies were observed with the non-radioactive heavy-metal carcinogens nickel and lead; it was speculated that DU's genotoxicity may be due to uranyl ions acting to produce free radicals, especially if the ions are effectively chelated to DNA like other metal ions.[43]

Human evidence

Uranium is a well-established nephrotoxin (i.e. it is toxic to kidneys) in humans, the primary target being the proximal tubule. Damage occurs when uranium forms complexes with the phosphate ligands and proteins in tubular walls, which impair kidney function. Biomarkers of these tubular effects include enzymuria and increased excretion of small proteins, amino acids and glucose. Uranium is also a bone seeker and is incorporated into the bone matrix by displacing calcium to form complexes with phosphate groups.[44]

McDiarmid et al. observed a statistically significant increase in mutations in peripheral lymphocytes in three US Gulf War veterans with embedded DU fragments reflected in measurements of uranium in urine. However, their continuing surveillance (for 14 years) has yielded no evidence of reproductive system dysfunction in males, abnormalities in sperm or alterations in neuroendocrine function.[45] Nevertheless, it should be recalled that soldiers are a healthy subset of the wider population, and the numbers of exposed soldiers in these studies are relatively small. Monleau et al. found that repeated uranium inhalations tended to potentiate, that is, increase the effect of or act synergistically with uranium's genotoxic effects.[46] Zaire et al. observed the induction of chromosome aberrations in uranium mineworkers in Namibia.[47] Such rearrangements of genetic material in chromosomes are involved in the carcinogenic process.

Epidemiological studies

Few human epidemiology studies have showed convincing effects from DU exposures. The Royal Society examined 14 epidemiological studies of occupational uranium exposures to workers engaged in the extraction, milling and machining of uranium.[48] These showed no sign of excess deaths due to cancer or kidney disease related to inhaling or ingesting uranium. However, the report stressed that these studies should be interpreted with care. First, there were few reliable data on uranium exposure levels to workers, especially in the early years of uranium processing, when exposures due to inhalation of uranium-containing dust were thought to be high. In addition, smoking was a powerful confounder, causing approximately 90% of lung cancers, and information on smoking habits was not available for any of the studies. Another problem was the healthy worker effect, which meant that risk comparisons should be made with other workers and not the general population. The report stressed that these types of epidemiological studies are not able to detect small increases in risk, although a twofold increase might have been detectable.

In addition, a cardinal rule in epidemiology is that absence of evidence in a study should not be used to allege evidence of absence.[49] It many cases, it may mean that the study was not powerful enough to detect an increased risk.

A number of studies have examined health effects in military personnel,[50] but their brief exposures to uranium dusts and aerosols have been much lower than those experienced by uranium mining and milling activities. Unfortunately, very few studies have been made of the many civilians exposed to DU in various conflicts.[51] Those carried out raise as many questions as answers, especially on the unusually low incidence rates of congenital malformations in Iraq pre-1990.[52] Hindin et al. carried out an extensive literature review of congenital malformations following DU exposures in US military personnel and concluded that the human epidemiological evidence was consistent with increased risk of birth defects in offspring of persons exposed to DU.

Possible synergism between radiation effects and chemical effects

Many studies clearly indicate that DU has both chemically induced and radiation induced effects. An important question is whether synergism exists between these two effects, i.e. whether they potentiate one another. There is suggestive evidence for this:

- synergistic responses when nickel exposures are combined with gamma radiation;[53]
- bystander cells (i.e. unirradiated) are vulnerable to both radiation-induced and chemical-induced effects.[54]

A number of authors have theorized that synergism may occur. For example, Miller et al. specifically proposed that DU's radiological and chemical effects might play tumour-initiating and tumour-promoting roles.[55] If this were the case, it would be a clear example of synergism.

In addition, the Royal Society stated:

> One could speculate … that the potential for synergistic effects between the radiation and chemical actions of DU would be greatest in the vicinity of particles or fragments of DU, from which essentially all the surrounding cells are chemically exposed and may thereby be sensitized to the occasional radioactive decay particle.[56]

It concluded that further studies were required to examine the possibility of synergy between the chemical effects and radiation effects of DU. The NRC report also recommended that studies be conducted to determine the relative contribution of chemical and radiological mechanisms of uranium carcinogenesis. It added that if the chemical contribution were found to be substantial, studies should then be undertaken to calculate cancer risks resulting from DU's combined chemical and radiological effects.

Conclusions

Despite the existence of many reports on DU, it remains difficult to assess whether (and if so to what degree) DU exposures have caused increased incidences of ill health among exposed soldiers and others. This is because of the inconclusive findings of some of the reports; the large uncertainties in the assessed doses and risks from DU exposures; the possible presence of confounders; and the paucity of data from battlefield and other exposures. In other words, the available epidemiological data are sparse and inconclusive.

However, as shown above, we have two main sources of data to derive uranium's risks—animal and cell studies as well as epidemiological studies. In fact, uranium's chemical risks are derived from the former for safety regulation purposes. In general terms, the risks of almost all chemicals are based on the concentrations found not to be harmful in animals. These concentrations are divided by safety factors of 10 to 1,000 then applied to humans, i.e. acceptable concentrations for humans are 10 to 1,000 times safer than those in animals. This rather simple system works well and is clearly precautionary.

With radionuclides, this precautionary approach is not used. Instead, radiation scientists insist that human data (i.e. from epidemiology studies) must be used to derive risks. Many may think that these are a better source because humans are different from animals and cells, and in theory this is correct. But in practice it is less clear cut: there are a large number of practical difficulties with epidemiology studies. In essence, they are a blunt tool for investigating risks, and insisting on using such studies alone rather than relying on cell and animal studies as well means that we might be underestimating DU risks.

The problem is that sole reliance on epidemiological data tends to downplay the substantial body of radiobiological evidence that overwhelmingly points to DU as a very hazardous substance.[57] This evidence points to DU being:

- a chemical carcinogen mutagen and teratogen;
- a radiological carcinogen mutagen and teratogen;
- a chemical toxin with pronounced effects on kidneys and other organs; and
- an endocrine disruptor.

Indeed, continued reluctance to act on the many research findings from radiobiology could be considered a breach of the precautionary principle in law.[58]

Sole reliance on epidemiological data tends to downplay the substantial body of radiobiological evidence that overwhelmingly points to DU as a very hazardous substance.

Given the preponderance of cell and animal studies indicating that DU is a very hazardous substance, the safest approach would be to seek a moratorium on its use. It is notable that, in December 2007, the UN General Assembly carried a motion by 136 votes to 5, recognizing the health concerns over the use of uranium weapons and requesting that states report to the Secretary-General on the matter.[59] Also in May 2008, the European Parliament carried a motion that strongly reiterated its call on all European Union member states and North Atlantic Treaty Organization countries to impose a moratorium on the use of depleted uranium weapons and to redouble efforts toward a global ban. The resolution was adopted with 491 votes in favour, 18 against and 12 abstentions.[60]

Recommendations

It is recommended that, for practical purposes, DU should be treated as being equally as radioactive as natural uranium. As regards the dose coefficients for DU and uranium, a precautionary approach would be to assume that their uranium isotopes coexist in equilibrium with their main decay products (the ICRP assumes the opposite). This means that the dose coefficients for U-238 should be increased by about 40%. This would result in uranium and DU doses (and risks) being increased by about 40%.

It is also recommended that isotope surveillance should be maintained on new batches of DU to ensure that reprocessed DU is not being added to DU obtained from uranium ore.

Further research

There have been many attempts in the literature to assess likely exposures and risks to military personnel from Gulf War operations and correspondingly few among civilians. Most military studies have concluded that the estimated exposures and resulting risks are minor and too small to be detected in epidemiology studies among the relatively few DU-exposed soldiers. In light of this, further studies of military personnel do not seem to be merited. Instead, research should be carried out on the health impacts among the tens of thousands of Iraqi civilians estimated to have been exposed to DU and their offspring. Populations exposed to DU and natural uranium should be examined for increased risk of fertility problems and reproductive cancers.

It is also recommended that further radiobiological research be carried out into possible synergistic effects of DU exposures. Finally, further research should investigate the properties of DU as a possible endocrine disruptor.

Notes

1. See, for example, Naomi Harley et al., 1999, *A Review of the Scientific Literature as It Pertains to Gulf War Illnesses, Volume 7: Depleted Uranium,* Santa Monica, CA, RAND Corporation.
2. See, for example, M. Aitken, 1999, "Gulf War Leaves Legacy of Cancer", *British Medical Journal,* August, vol. 319, p. 401.
3. National Research Council, 2008, *Review of Toxicologic and Radiologic Risks to Military Personnel from Exposure to Depleted Uranium during and after Combat*, Washington, DC, National Academies Press**;** M.A. Parkhurst et al., 2004, *Depleted Uranium Aerosol Doses and Risks: Summary of U.S. Assessments,* Battelle Press; Royal Society, 2001, *The Health Hazards of Depleted Uranium Munitions: Part I,* London; Royal Society, 2002, *The Health Hazards of Depleted Uranium Munitions: Part II,* London; World Health Organization, 2001, *Depleted Uranium: Sources Exposures and Health Effects,* WHO document WHO/SDE/PHE/01.1, Geneva; Carolyn E. Fulco et al. (eds), 2000, *Gulf War and Health, Volume 1: Depleted Uranium, Sarin, Pyridostigmine Bromide, Vaccines,* Washington, DC, National Academies Press, chapter 4; Office of the Special Assistant for Gulf War Illnesses (OSAGWI), 2000, *Environmental Exposure Report: Depleted Uranium*; Harley et al., op. cit.; Agency for Toxic Substances and Disease Registry, US Department of Health and Human Services, 1999, *Toxicological Profile for Uranium,* Atlanta, GA.
4. D.M. Taylor and S.K. Taylor, 1997, "Environmental Uranium and Human Health", *Reviews on Environmental Health,* vol. 12, no. 3, pp. 147–157; S. Fetter and F.N. von Hippel, 1999, "The Hazard Posed by Depleted Uranium Munitions", *Science & Global Security,* vol. 8, no. 2, pp. 125–161; D. Brugge et al., 2005, "Exposure Pathways and Health Effects Associated with Chemical and Radiological Toxicity of Natural Uranium: A Review", *Reviews on Environmental Health,* vol. 20, no. 3, pp. 177–193; A.C. Miller (ed.), 2007, *Depleted Uranium: Properties, Uses, and Health Consequences,* Boca Raton, FL, CRC Press.
5. The report stated that "Exposure to sufficiently high levels might be expected to increase the incidence of some cancers, notably lung cancer, and possibly leukaemia, and may damage the kidneys". Using a worst-case scenario, they estimated an extra 1.2 deaths per 1000 from lung cancer among those with the highest exposure (e.g. surviving personnel in a vehicle struck by a depleted uranium penetrator) (Royal Society, 2001, op. cit., p. 21).
6. Uranium mining is highly destructive of local environments and uranium refining creates large quantities of radioactive tailings, which continue to release large quantities of the radioactive gases radon and thoron for millennia.
7. Science and Technology Options Assessment, 2001, *Depleted Uranium: Environmental and Health Effects in the Gulf War, Bosnia and Kosovo*, document STOA 100 EN.
8. Wise Uranium Project, *Depleted Uranium Inventories,* at <www.wise-uranium.org/eddat.html>, last updated 21 April 2008.
9. Royal Society, 2002, op. cit.; R.K. Bhat, 2000, *Tank-Automotive and Armaments Command (TACOM) and Army Material Command (AMC) Review of Transuranics (TRU) in Depleted Uranium Armor*, Memorandum, Fort Belvoir, VA, Army Test Measurement and Diagnostic Equipment Activity.
10. E.R. Trueman et al., 2003, "Characterisation of Depleted Uranium (DU) from an Unfired CHARM-3 Penetrator", *Science of the Total Environment,* vol. 327, nos 1–3, pp. 337–340.
11. OSAGWI, op. cit.
12. Royal Society, 2002, op. cit.
13. That is, 2% of the equivalent dose.
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