REVIEW

Toxicological aspects of depleted uranium

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Summary
Depleted uranium is a byproduct of the uranium enrichment process and has been used for decades
in different applications. Recently depleted uranium is used as an anti-armour munition because of
its profitable physical properties. One of these, the ability to ignite and burn at very high
temperatures, may result in the formation of an aerosol of very small uranium oxide clusters, which
may be inhaled. It is alleged that these particles represent a new battlefield hazard because of the
radioactivity and chemical toxicity of uranium.

Keywords: absinthe – thujone – composition – metabolites – detoxification

INTRODUCTION

Depleted uranium (DU) is a byproduct of the
uranium enrichment process and has been used for
decades in medical and industrial applications,
radiation shielding, counterbalance weights in
aircraft and ships, and more recently, in military
armour and ammunition.
It was used in the development of major weapon
systems because of its high density and superior
mechanical properties. In addition, it is relatively
wide-spread and cheap. Recently it has substituted
for lead in bullets and missiles. DU is used in
kinetic energy weapons consisting of a penetrator
rod of DU which, when fired at high velocity, can
penetrate the heavy armour of modern battle tanks.
DU in weapons, used for military purposes, can
change into various compounds by burning when
the projectiles hit a target. It can enter tanks and
armoured cars as an aerosol of uranium. Because
DU is low level radioactive and a toxic heavy

metal, it is potentially dangerous as an environment
pollutant for military personnel as well as civilians.
It is relatively toxic to humans, both chemically as
a heavy metal and radiologically as an alpha
particle emitter, which is dangerous in cases of
internal contamination (Patočka et al. 2000). The
possibility of exposure to DU represents a new
battlefield hazard (Murray et al. 2002).

CHEMICAL AND PHYSICAL PROPERTIES OF DU

DU strongly differs from natural uranium since it
has been separated chemically and physically from
all other elements, especially from the daughters of
the various decay chains. DU contains about 99.7%
U 238 and less than 0.3% U 235 while natural
uranium contains 99.3% U 238 and 0.7% U 235. In
addition, it is alloyed with 1.75% Nb. Uranium
alone is a very heavy metal with a melting point of

1130 °C, and it decays with a mean half-life of 6.510 years, yielding a decay rate of 12.2 Bq/g. DU is only hazardous in case of inhalation or ingestion exposure. Its radioactivity is less than 50 % of the radioactivity in natural uranium.

Uranium as a metal is autopyrophoric and can burn spontaneously at room temperature in the presence of air, oxygen and water. At temperatures of 200-400 °C, uranium powder is able to self-ignite in atmospheres of carbon dioxide and nitrogen. Oxidation of uranium under certain conditions may generate sufficient energy to cause an explosion (Gindler 1973). Friction caused by the penetration of bullets or missiles into a tank or armoured vehicle can cause the ignition of uranium, forming a concentrated ceramic aerosol composed of insoluble particles of uranium oxide, UO_2 or UO_3, in a mist or a fog, capable of killing most personnel in the vehicle. Insoluble uranium oxide particles when they are inhaled and scavenged to the lymph nodes, represents dangerous material (Priest 2001). In addition, on explosion DU generates a great many very chemically reactive uranium oxide clusters, which can retain hitherto unrecognized biological effects.
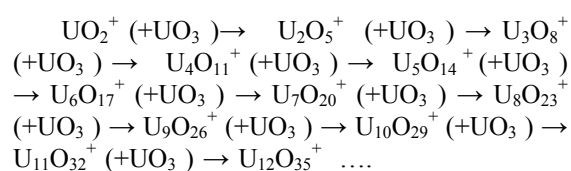
The formation of superfine uranium oxide clusters has been described for example, during Fast Atom Bombardment (FAB) of uranium(VI) salts in organic matrices which produces clusters of general formula $(UO_2)_xO_y^+$ with x up to 40 where for each value of x there is a series of values y. The O:U ratio depends not only on the size of the cluster (x) but also if x is even or odd. However, as x tends to 40 all cluster series tend to a final stoichiometry of O:U = 2.5 : 1 (Kemp et al. 1995).

In addition, it was observed recently in a Matrix Assisted Laser Desorption Ionisation Time of Flight Mass Spectrometry (MALDI TOF MS) analysis of uranium (Havel et al. 1999), (sensitive uranium determination with a detection limit down to 10^{-12} Mole is possible) that the formation of another type of cluster takes place during intensive laser beam shot. The structure of clusters has been resolved and details published recently (Soto-Guerrero et al. 2001). In this case, a different series of the uranium clusters than those with FAB were observed. Three different families of formula $(UO_2)_xO_y^+$, and two of formula $(UO_2)_xO_y^{2+}$ were found. For these five groups, as x increases, the O:U ratio tends to 3. The relationship between neighboring clusters can be described as

$$(UO_2)_xO_y^+ \leftrightarrow (UO_2)_{x-1}O_{y-1}^+ + UO_3.$$

An example of mass spectra showing the evidence of the clusters uranium oxide clusters formation is given in Fig. 1.

An example of the scheme of the compounds formed is given below for one of the series:

UO_2^+ $(+UO_3)\rightarrow$ $U_2O_5^+$ $(+UO_3) \rightarrow U_3O_8^+$ $(+UO_3) \rightarrow$ $U_4O_{11}^+$ $(+UO_3) \rightarrow U_5O_{14}^+$ $(+UO_3)$ $\rightarrow U_6O_{17}^+$ $(+UO_3) \rightarrow U_7O_{20}^+$ $(+UO_3)$ $\rightarrow U_8O_{23}^+$ $(+UO_3) \rightarrow U_9O_{26}^+$ $(+UO_3) \rightarrow U_{10}O_{29}^+$ $(+UO_3) \rightarrow$ $U_{11}O_{32}^+$ $(+UO_3) \rightarrow U_{12}O_{35}^+$ ....

The clusters are formed starting from UO_3^+, UO_2^+ or UO^+ ions formed by laser ablation aggregating step by step with UO_3 oxide.

We would like to express our strong opinion that conditions at DU penetrator impact with the target are very similar to those of high energy laser shot impact to uranium compounds and that such super-fine particles are formed because similar temperatures are reached as well as light emission and the pyrophoric properties of metallic uranium. Such superfine uranium oxide clusters could represent a hazard to soldiers and the environment, and attention should be paid to this in the light of the hundreds of tons of DU already dispersed in former battlefields or with respect to the increased military use of DU.

CHEMICAL AND RADIOLOGICAL HAZARDS OF DU

Uranium presents both chemical and radiological hazards, but there are some problems with the comparison of these hazards (Ebinger and Hansen 1994). Different reports on the health hazard of DU munitions have concluded that this metal used on the battlefield probably does not lead to any measurable excess of cancers. The explosion of uranium missile can kill everyone in the target tank, but radioactive aerosol of uranium is able to disperse in the air, tens of kilometers from the point of release. It can be also be stirred up in dust and re-suspended in the air with wind or human movement. Following inhalation exposure, very small uranium particles can stay in the human body for years, irradiating the tissue with powerful alpha particles within about a 30 micron sphere, causing damage to cells.

Uranium can also be ingested and damage the gastrointestinal tract. In addition, it penetrates through lung tissue to the blood stream and can be stored in liver, kidney, bone or other tissues for years, irradiating all tissues located near its storage place. It has also an influence on the blood cells that are the important part of the immune system, and can damage the renal system in the case of urine elimination . It can also initiate cancer or promote cancers which have been initiated by other carcinogens. This radiological toxicity is combined with the chemical toxicity of uranium, comparable with the toxicity of other heavy metals, for example with lead, or nickel.
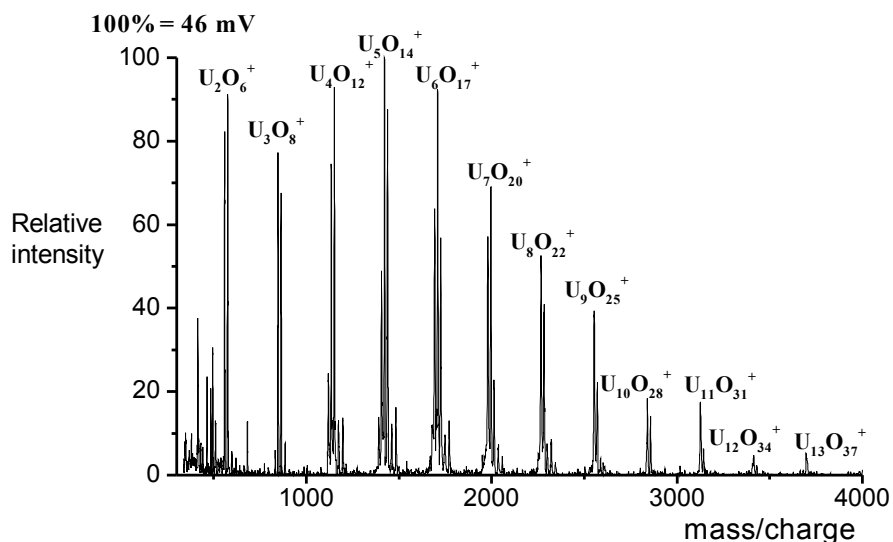
100% = 46 mV

Fig. 1. **An example of mass spectra of uranium observed in Laser Desorption Ionisation** (LDI). The clusters are formed starting from UO_3^+, UO_2^+ or UO^+ ions formed by laser ablation aggregating step by step with UO_3 oxide

TOXICOKINETICS AND TOXICODYNAMICS OF DU

The soluble compounds of uranium, such as uranium hexafluoride, uranyl fluoride, uranium tetrachloride, and uranyl nitrate hexahydrate, can penetrate to the blood from the alveolar pockets in the lungs within days of exposure. Although inhalation products are also transported through coughing and mucocilliary action to the gastro-intestinal tract, only about 2 per cent of this fraction is actually absorbed into the body fluids through the intestines. Therefore, all of the research papers on the acute effects of uranium describe the inhalation exposure to these soluble uranium compounds. The main acute effect of inhalation of soluble uranium compounds is damage to the renal system. The bone seems to be the main long term storage place of these compounds in the human body.

Particles of uranium smaller than 2.5 microns are usually deposited in the lungs and pulmonary lymph nodes where they can remain for years. According to research done in the UK by the NRPB, ceramic uranium is formed when uranium ignites through friction, as happened in the Gulf War. In this form, uranium usually penetrates the lungs to the blood twice more slowly than non-ceramic uranium. A very small portion of inhaled uranium (2%) can be transported to the gastro-intestinal tract, where is absorbed through the intestines. This fraction of the inhaled compound can damage the gastro-intestinal (GI) tract as it passes through because it emits damaging alpha particles with statistical regularity. The residence time of the insoluble uranium compounds in the GI tract is estimated in years.

The chemical action of all isotopic mixtures of uranium (depleted, natural and enriched) is identical. Current evidence from animal studies suggests that the chemical toxicity is largely due to its chemical effect on kidney tubular cells, leading to nephritis. The differences in toxicity based on the solubility of the uranium compound are more striking: water soluble salts are primarily renal and systemic chemical toxicants; insoluble chemical compounds are primarily lung chemical toxicants and systemic radiological hazards. Immediately following uranium dioxide entering the blood, hexavalent uranium is formed, which is also a systemic chemical toxicant. The slow excretion rate of the uranium oxide is favorable for kidney and tubule repair and regeneration. Moreover, much uranium is still being stored in the body and has not yet passed through the kidneys because of the long biological half-life . The direct damage to lungs and kidneys by uranium compounds is thought to be the result of their combined radiation and chemical properties. It is difficult to assign a portion of the damage to these separate factors because they cannot be separated in life (Stradling et al. 1988).

Animal and human research indicate that inhalation of insoluble uranium dioxide is associated with general damage to pulmonary tissue, usually non-cancerous damage to alveo- lar epithelium. This pulmonary damage can lead to emphysema or pulmonary fibrosis (Cooper et al. 1982, Dungworth 1989, Saccamanno et al. 1989, Stokinger 1981, Wedeen 1992). Animal studies demonstrate that uranium compounds cause adverse hematological disturbances (Dygert 1949, Spiegel 1949, Stokinger et al. 1953, Cross et al. 1981).

GENOTOXICITY OF DU

During the Persian Gulf War several US military personnel were wounded by shrapnel fragments containing DU. Analyses indicated a significant increase in urine uranium levels above natural background levels. An examination of the potential mutagenicity of DU internalization is necessary for the understanding of the etiology of potential disease development. Miller et al. (1998a) followed the mutagenicity of urine of rats, to which DU pellets, were implanted subcutaneously. The authors found a dose- and time- dependent increase of urine mutagenicity, tested by Ames Salmonella typhimurium test by strains TA 98 and mixed strains TA-7001-7006. DU internalization presents a unique toxicological problem, because it combines chemical toxicity with radiological exposure.

DU-uranyl chloride has the capacity to transform human osteoblastoma (HOS) cells (Miller et al. 1998b). The transformation frequency was slightly higher in comparison to the transformation frequency induced with nickel sulfate. Results showed that the mechanism of the carcinogenic effect of DU might be comparable to other heavy – metal compounds (e.g., nickel). This mechanism might be connected with an inhibition of DNA repair in heavy – metal treated cells. This hypothesis seems to be supported by findings (Au et al. 1995, 1998) of a decreased DNA repair capacity in individuals residing near uranium mining/milling facilities.

MEDICINAL EXPERIENCES WITH HUMAN EXPOSURE TO DU

During the Gulf War, munitions and armoured vehicles containing DU were used for military purposes for first time. Iraq and northern Kuwait were a virtual testing range for depleted-uranium weapons. Over 940,000 30-millimeter uranium tipped bullets and more than 14,000 large caliber DU rounds were disposed during Operation Desert Storm/Desert Shield. (U.S. Army Environmental Policy Institute). Between 300 and 800 tons of DU particles and dust have been scattered over the ground and the water in Kuwait, Saudi Arabia and Iraq. As a result, hundreds of thousands of people, both civilians and soldiers, have suffered from the effects of exposure to these radioactive weapons.

In October 1998, the WHO undertook a two year study of the increasing cancer rates, especially leukemia, in young children, which have been noted in southern Iraq where the war actions took place. The WHO report is not out yet, but recent data from Iraq tell the story of even more dramatic increases in cancer rates, especially among the Iraqi veterans who participated in the war. In the West, thousands of veterans are recognized to be seriously ill with an unknown syndrome, detected in their urine as late as 7 or 8 years after the war. Moreover, DU has been used by the US and Britain not only against Iraq but also in Bosnia and in Kosovo. The Human Rights Commission has requested that the Secretary General prepare a written report on DU and certain other weapons of mass destruction (Resolution 1997/36). Not only are war victims suffering from the various forms of damage, but also genetic damage can be passed on to their offspring.

TOLERABLE DAILY INTAKE (TDU) OF URANIUM

TDU of uranium is dependent on the route of administration because pharmacotoxic parameters are different in the case of inhalation or ingestion.

TDU for Inhalation

The study ATSDR (1997) reviews all published data on animal studies dealing with URAnium toxicity. A study performed by Stokinger (1953)on dogs is used in referring to the hazard from chronic inhalation of soluble forms of uranium: it showed that uranium concentrations of 0.15 mg U/m^3 in air produced no observable adverse effect. From this figure, a "minimal risk" inhalation level for humans of 1 µg/m^3 is derived, applying a number of safety factors. In another review (Jacob et al. 1997), performed for the German Federal Environmental Agency, another study by Stokinger (1953) on rats has been used: The rat study showed slight impacts to the kidneys at uranium resorption rates of 2.6 µg per kg per day. This rate corresponds to uranium concentrations of 40 µg per m^3 in air. Applying a number of safety and conversion factors, the authors obtain a "tolerable" level of 0.07 µg/m^3 uranium in air; this is 14 times lower than the above mentioned ATSDR level.

TDU for Ingestion

The "minimal risk" level for intermediate-duration ingestion proposed by ATSDR (1997) is an oral uptake of 1 µg of uranium per kg body weight per day**.** This is based on adverse effects observed by

Ortega et al. (1989) in rats at uptakes of 1.1 mg per kg per day. Jacob et al. (1997) proposes a "tolerable" uptake of 0.7 µg per kg body weight per day. This value is based on adverse effects observed by McDonald-Taylor et al. (1992) in kidneys of rabbits at resorption rates of 3.2 µg U per kg body weight per day The WHO has established a TDI for uranium of 0.6 µg/kg body weight per day (WHO 1998). This is based on adverse effects observed by Gilman et al. (1998) in kidneys of rats at uptakes of 60 µg U per kg body weight per day.

CONCLUSIONS

The use of depleted uranium on the battlefield can result in its intake in various ways. Of particular concern is that when a DU penetrator hits a hard target, such as armour plate, it can produce a dense cloud of fine dust containing very small particles of different uranium oxide clusters. This dust can be inhaled by personnel in the vicinity and later by people working on struck vehicles or casualties contaminated with the uranium oxide dust. Radioactivity and toxicity of uranium foreshadow a possible risk to the environment and human health, but for a more precise survey of the real risk further research is needed.

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