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REVIEW PAPER

Depleted Uranium Penetrators - Hazards & Safety

S.S. Rao and T. Balakrishna Bhat
Defence Metallurgical Research Laboratory, Hyderabad-500 058

ABSTRACT

The depleted uranium (DU) alloy is a state-of-the-art material for kinetic energy penetrators due to its superior ballistic performance. Several countries use DU penetrators in their main battle tanks. There is no gamma radiation hazard to the crew members from stowage of DU rounds. Open air firing can result in environmental contamination and associated hazards due to airborne particles containing essentially U_3O_8 and UO_2. Inhalation of polluted air only through respirators or nose masks and refraining form ingestion of water or food materials from contaminated environment are safety measures for avoiding exposure to uranium and its toxicity. Infusion of sodium bicarbonate helps in urinary excretion of uranium that may have entered the body.

1. INTRODUCTION

The depleted uranium (DU) is currently the top performing state-of-the-art material for kinetic energy projectiles[1,2]. It possesses high density and strength ideal for high performance penetrators. Besides, it is quite cheap. It is reported[3] that DU penetrators are being procured or developed by many countries that have access to this material and may find widespread use in years to come. Several special applications[4] of the material have also been found, e.g., as armours, counterweights in airplane, missiles and helicopters, oil-well sinker bars, gyroscope rotors, fly wheels for large inertial energy-storage devices, vibration damping in boring bars and machine tools, etc. Uranium counterweights are used in many civilian and military aircraft to maintain the centre of gravity when aerodynamic devices are moved, as in Boeing 747 which holds[4] about 1500 kg of uranium counterweights. However, DU finds predominant use in kinetic energy projectiles (penetrators).

There are some environmental and other concerns associated with the manufacture of DU rounds[5] and its use in the battlefield, subsequent clean up of the battlefield and disposal. The information available on the various safety aspects is summarised here.

2. DU PENETRATORS

2.1 The Material

Natural uranium contains about 0.7 per cent fissile ^{235}U isotope, while the rest is mostly ^{238}U. In the front end of nuclear fuel cycle, by enrichment treatment a low-enriched uranium (LEU : < 20 per cent ^{235}U) for use as nuclear fuels or high-enriched uranium (HEU: > 90 per cent ^{235}U) for use as nuclear weapons is produced. The tailings from the enrichment plant is depleted uranium (< 0.7 per cent ^{235}U). Usually DU from enrichment plant contains < 0.3 per cent ^{235}U. The latter is stored in gaseous (UF_6) or green salt (UF_4) form. Uranium halides can be converted to uranium metal by magnesio or calciothermic reduction.

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Thus, DU is a byproduct of uranium enrichment plants and is produced in amounts of about 5 kg for every 1 kg of enriched uranium[6]. Alloying of DU with elements, like titanium or molybdenum and fabrication of penetrators and their assembly into ammunition rounds are complex technological processes requiring stringent quality control measures not available in open literature.

2.2 Ballistic Performance

The most commonly used uranium alloy is *U*-0.75 wt per cent *Ti*, and the most common tungsten heavy alloys (WHA) are liquid phase sintered *W-Ni-Fe* or *W-Ni-Fe-Co* alloys. In a one-to-one comparison against a spectrum of targets, the DU alloys consistently demonstrated superior terminal ballistic performance[7] at ordnance velocities upto 1.8 km/s and today DU alloys are acknowledged superior ballistic performers[8]. The WHA penetrators deform into a mushroom head during penetration which effectively causes decrease in energy density and penetration capability. In contrast, the DU penetrators exhibit localised deformation and maintain chisel-like sharp pointed end. This difference underlies the superior performance of DU over WHA. Thus, DU penetrators consistently outperform WHA penetrators[9] and are being increasingly used. Some of the known ammunitions using DU penetrators the worldover are given in Table 1.

Table 1. Ammunition using DU penetrators

Name	Country/other particulars	Reference
PHALANX	USA (Navy); Ship-borne close-in weapon system; to defend against ship-to-ship missile; *U-2 Mo*; weight about 0.07 kg	4,6,10
GAU-8 GAU-8/A	USA (Air Force); penetrator weight about 0.272 kg; to be fired from A-10 aircraft against armoured tanks; *U*- 0.75 *Ti*	4,6,10
XM 774	USA (Army); penetrator weighing about 3.4 kg in projectiles for 105 mm battle tank gun APFSDS-T ammunition	
M 833	105 mm APFSDS ammunition APFSDS-T ammunition	16 12-15
M 919	USA (Army); APFSDS-T ammunition	17
XM 735 A1	USA (Army); For use with M68 gun	13
OFL 120 E2	France; 120 mm penetrator round for Leopard-2 MBT	15,18
CHARM 1 (L26 A1)	UK (Army); APFSDS projectile for Challenger-2 MBT	19, 20
CHARM 3	As above but length-to-diameter ratio of 3:1	21

3. HAZARDS OF URANIUM

Uranium is a radioactive element emitting alpha particles and is hazardous. It is susceptible to oxidation and hydrolysis, and in powder form, it is pyrophoric. It is a ubiquitous element occurring with an average concentration of 4.10^{-4} per cent in earth's crust and about 3.3 µg/l in sea water[22]. It is absorbed from the soil into plants to various degrees depending on the plant species and the depth of its root system. Drinking water in urban Japan contained 4.8 to 11.4 ng/l of uranium[23]. Tap water in New York contained about 32 µg/l of uranium[24]. Ambient air in New York contained an average concentration[24] of 0.4 µg/m^3 while its concentration[25] in UK was about 0.02 µg/m^3. In working environment, the concentration of uranium dust particles continuously change. Concentrations between a few µg/m^3 to several mg/m^3 have been recorded in different work environment[26]. Food and food products, such as potatoes, bakery products, meat, cereals, vegetables and table salt contribute to daily intake of uranium by man to the extent of about 1.5 µg[26]. Larger amounts may, however, enter by inhalation or ingestion of uranium salts in contaminated environment. Hazards of high intake of uranium are chemical toxicity and radiological damage. The

extent of damages from exposure to uranium compounds depends on the solubility, route of administration and isotope composition.

3.1 Chemical Toxicity

There is no known beneficial role for absorbed uranium in humans or other mammals[26]; only toxic effects are known. Though, there is dose dependence for absorption of soluble uranium, only about 5 per cent of ingested uranium is absorbed into the blood stream and the rest is excreted. For insoluble uranium compounds, such as oxides, only about 0.2 per cent is absorbed by the body. Up to 47 per cent of the absorbed dose in blood is held in plasma as a soluble complex with bicarbonate, and about 32 per cent are bound with plasma proteins and 20 per cent with red blood cells[25]. About 85 per cent of body burden of uranium (excluding that deposited in lungs) is found in bones, replacing calcium in hydroxyapatite complex[27]. In living systems, uranium occurs in tetravalent or hexavalent form, both of which are soluble and can complex with anions, such as bicarbonates, citrates, phosphate containing molecules, carboxyl and hydroxyl groups of proteins and nucleotides. Tetravalent uranium can be oxidised in the body to the more soluble hexavalent form.

The soluble uranyl-bicarbonate complex of blood is filtered by the glomeruli in kidney and excreted. However, the excretion or reabsorption of uranium from the kidney is controlled by the p*H* of the urine in the renal tubules, a higher p*H* favouring almost total excretion with only small amounts of uranium retained in the walls of the renal tubules. At a lower p*H*, uranyl ion splits from the bicarbonate complex and combines with the proteins on the renal tubule walls thus impairing their normal function[26,28]. The earliest indication of uranium-induced kidney damage in animal and human experiments was increased levels of excretion of proteins (albumin) and the enzyme catalase in urine[29, 30]. Thus kidney is the critical organ for chemical toxicity of uranium[26] and there is evidence of only renal injury in humans exposed to uranium.

3.2 Radiological Damage

External radiation hazard from DU or freshly prepared natural uranium and its compounds is very low since DU is a 'low specific activity' material with specific activity of 13.32 kBq/g as against 25.05 kBq/g for natural uranium[4]. Besides, uranium emits mainly alpha radiation of average energy 4. 5 MeV. This is inadequate to penetrate even the dead layer of skin (7 mg/cm^2) which requires about 7.25 MeV[31].

Radiological damage can be significant however, if finely divided insoluble particles (dust) of the material are inhaled, deposited and retained in the lungs for a long time[26]. Airborne particles of size less than about 7 μm can enter the respiratory system and get deposited in the naso-pharyngeal, tracheo-bronchial or pulmonary regions depending upon activity median aerodynamic diameter[32] (AMAD). The soluble compounds are rapidly absorbed from the lungs and distributed through blood for final urinary excretion. Insoluble compounds are mainly removed from lungs by muco-ciliary action and faecal excretion[31]. Another mode is phagocytosis of insoluble particles by macrophages.

Entrapment in lymph nodes and deposition in lungs can cause local injury and degenerative changes. Inhalation of large amount of uranium dioxide dusts for 2-5 years caused lung cancer in rats and dogs[33,34].

3.3 Pyrophoricity

Finely divided uranium is pyrophoric[4] and since pyrophoric reactions take place at the surface, surface conditions and extent of exposed surface area are important factors determining the pyrophoricity. Clouds of uranium dust ignite in air at 100 °C or even lower[31]. However, large pieces of uranium undergo slow combustion only on heating in air above 500 °C. Uranium dioxide and U_3O_8, the oxidation products of uranium fires, are inhalation hazards.

Machining of DU needs extreme care due to pyrophoricity which can cause sparking, burning

and possible aerial dispersal of finely divided metal oxides. Hazards due to pyrophoricity can be avoided by the use of a liberal amount of machining fluid, keeping machining waste submerged in oil or water and frequent removal of chips from tools and work areas.

Providing heavy ventilation and properly enclosing all the machines can also minimise hazards. Personnel working in machining area should wear protective footgear and clothing. Material that falls on the shop floor should not be tracked throughout the plant. Fine scrap and machining swarf should be kept under water or mineral oil till it is suitably disposed off. Usually, transport to disposal sites earmarked for burial of the material necessitates mixing of the scrap with sand or concrete.

4. HAZARDS OF DU PENETRATORS

Safety considerations are necessary during storage in combat vehicles as well as during handling and firing. The after-effects through inhalation or environmental contamination need to be considered. Body injuries due to embedded penetrator fragments, inhaling uranium-contaminated air, or drinking water containing uranium are the direct cause of uranium-related hazards. Indirect causes could be the consumption of plants and animals containing uranium.

4.1 Exposure to Radiation

Health problems associated with the assembly, stowage and use of 105 mm armour piercing fin stabilised discarding sabot (APFSDS-T), XM-774 ammunition have been given attention[14]. Gamma-ray exposure hazard due to storage of M-774 rounds in a Leopard C-1 main battle tank has also been studied[15]. Measurements at each of the four-crew locations and for two-turret orientations with 59 rounds stowed in the vehicle indicated that the M-774 rounds do not represent a significant gamma radiation hazard to Leopard C-1 crew members. Certainly, solid DU pieces or rods are not sufficiently radioactive to present any radiation hazard[4].

'Desert storm sickness' alleged to be afflicting a number of Gulf War veterans was initially linked to the use of DU during the 1991 conflict, but medical diagnosis has not attributed any of the British cases to the possible toxicity of alpha-radiation effects of DU particles[21].

Embedded DU fragments, if not removed, can be a source of local radiation and a cause of damage. Studies have been initiated[35] for assessment of the risks with Gulf War veterans known or suspected to be embedded with DU fragments. Results, however, are not yet available.

4.2 Inhalation

The use of DU penetrators in the field results in the release of uranium into the environment as a cloud leading to contamination[36]; and such a release of cloud can occur in the battlefield, when a large number of shots are fired in a concentrated area. Chemical toxicity hazard is associated mainly with the inhalation of the fine dusts and fumes of uranium[4]. When 105 mm DU penetrators containing about 3.4 kg DU impact against armour plate targets, a cloud of airborne particles is generated[11,37] by the spontaneous ignition of the fragments as a result of a combination of shock and frictional heating. The particles range from microfragments of diameters greater than 50 μm to submicron particulate aerosols. Of the airborne particles, those in the range of 0.1-0.5 μm are respirable. Even those ultrafine DU particles originally below respirable size range can coalesce due to spontaneous diffusion charging to form abundant agglomerates that fall within respirable range[11].

Studies on test firings of 105 mm, APFSDS-T, XM-774 ammunition[12] estimated that approximately 2.4 kg of airborne DU was generated by each test firing. Out of this mass, about 75 per cent was U_3O_8 and the rest was UO_2. It was observed that about half of the airborne DU immediately above the targets was respirable, U_3O_8 being predominant in the respirable range. About 43 per cent of the respirable DU dissolved in simulated lung fluids within seven days[12].

4.3 Environmental Contamination

Chemical toxicity and radioactive nature of uranium harms the quality of environment into which it is released. Open air firing of DU penetrators can adversely affect water quality by settling of airborne uranium on soil and into bodies of water or by oxidation and leaching into surface water or ground water[6,36]. Subsequent transport and uptake by plants, aquatic organisms and wildlife adversely affect the quality of food.

Investigations for DU residues were conducted at Pershing missile impact sites in the White Sands Missile Range in USA[38]. At Chess Site, elevated levels of DU in the sub-surface soil or perched ground water were found. It was observed that seasonal flooding and near-surface water helps in the movement of small fragments on the surface of the impact site. The environmental fate of fragments of DU penetrators in soil and water at Aberdeen Proving Ground (APG) and Yuma Proving Ground (YPG) of USA has also been investigated[39]. At APG, the humid woodland soil samples collected beneath a penetrator fragment showed approx 12 per cent DU by weight in the surface and a DU concentration significantly above the background to a depth of 20 cm. In the arid Sonoran Desert soil samples at YPG, DU was only 0.5 per cent right below a penetrator fragment and the values were almost like background concentrations from 8 to 20 cm below soil surface. The study concluded that DU at APG was redistributed predominantly by dissolution and transport by water and to some extent possibly by migration of DU colloids or DU attached to small particles. At YPG, the erosion of DU fragments from impact area and redeposition in washes that drain the area was considered the mechanism of entry into water[39]

A steady-state model[40] based on study at Jefferson Proving Ground, also in USA, showed that the amount of airborne dust and therefore the amount of DU on the vegetation surface controlled the amount of DU ingested by deer and, in turn, humans who consumed them. It has been suggested that ecological risk assessments should explicitly examine risks not only to human populations but also to nonhuman species[41].

5. MEDICAL & SAFETY ASPECTS

The DU penetrators were used in the Gulf War by the US-led coalition forces, and naturally, the suspected causative agents for the post-war illnesses included DU also. But, it appears that in the complex aetiology of the so-called 'Gulf War Syndrome' or 'Desert Storm Sickness', greater role could have been of pathogens, post-traumatic stress disorders, chemical agents/prophylactics, etc. rather than that of the DU. Nevertheless, it is desirable to know the allowable limits of exposure to uranium and the ways for its diagnosis and treatment.

5.1 Preventive Measures

A limit on the annual effective doses of uranium has been prescribed as 20 mSV for adult workers who are in radiation environment (40 h/week; 40 weeks/year and 18-60 year working life), and as 1 mSV for a member of the public[42]. Regardless of isotope composition, the daily intake of soluble uranium compounds by inhalation is restricted to 2.5 mg/d. A recommended threshold limit value for continuous occupational exposure is a concentration of 0.2 $mg.m^{-3}$ which, with a standard breathing rate of 1.2 m^3/h, corresponds to an average daily intake of 2 mg. For short-term exposure, a limit of 0.6 $mg.m^{-3}$ is permitted for 15 min. While these values hold good for occupational exposures, in war scenario, field conditions demand a different kind of analysis and higher limit prescriptions. Protective apparel, such as gloves, protective suits/uniforms, caps and shoes prevent direct body contact with uranium. High efficiency particulate-air (HEPA) filters fitted in combat vehicles cut off the hazardous uranium oxide dust released in a battlefield environment and protect the crew from the injurious effects of the material. Soldiers in open, who have the risk of inhalation of airborne uranium particulates, can be protected adequately by the use of nose masks or respirators

in addition to the protective apparel. Goggles can also be used for protecting the eyes from the dust. These measures can give a near total protection from exposure. In accidental external contamination, washing with solution of detergent or complexing substances, such as bicarbonates, citrates, or oxalates removes uranium. Frequent change of contaminated clothes and if feasible, shower baths minimise the spread of the contamination.

Injury from DU shots and fragments can be treated like any other injury. However, it is desirable that embedded pieces, if any, be removed within a reasonable time to avoid long-term exposure and toxicity.

5.2 Diagnostic & Therapeutic Measures

Firing of DU penetrators produces dust which contain U_3O_8 and UO_2 both of which belong to the insoluble, slightly transportable category[26], or Y class[42], which are liable to be retained longer in the lungs if inhaled. In such an instance, lung is the critical organ and radiation injury may be the effect. Measurement of pulmonary uranium burden by whole body scintillation counting can be used for routine check up when lung is the critical organ[26]. Kidney damage is the effect of soluble uranium compounds. For evaluation of kidney function in uranium exposure, determination of urinary catalase combined with tests for proteinuria are recommended. Urinary excretion of uranium may also indicate exposure levels. Uranium concentration of 2.85 mg/l of urine was without clinical signs of kidney damage[43] though presence in urine of more than 250 µg uranium/l was considered unsafe after a workshift[44]

Infusion of sodium bicarbonate is recommended in uranium poisoning since bicarbonate binds with uranium in the blood facilitating its excretion and preventing reabsorption in the kidney tubules[45]. Recently, efficacy of Tiron (4,5-dihydroxy-1,3-benzene disulfonic acid), gallic acid and diethylene triamine penta acetic acid (DTPA) in helping urinary excretion of uranium in experimental acute uranyl intoxication, has been indicated. The DTPA alone appears to be in clinical use for toxic metals like plutonium[46]. However, the administration of chelating agents, such as DTPA was not advised since increased migrant fraction to the kidneys results in increased kidney burden and the risk of serious toxic effects. Hence intravenous administration of bicarbonate solution is the preferred basic treatment for internal decontamination[31]

6. CONCLUSION

Despite several concerns about health and environmental hazards, the production and use of DU ammunition is a reality since the Gulf War. Also, the supplies are not restricted to countries producing the penetrators, but are open to other countries[16] as well. Though, several NATO countries do not permit stockpiling or firing of DU ammunition within their borders[6], others, like France are committed to their nationally-developed DU penetrator rounds for their tanks[18]. Although, new tungsten alloys are being investigated for altering their material properties to match or surpass the ballistic performance of DU penetrators, it is assumed that DU penetrators will stay in war weaponry for many years to come and awareness of their hazards and ways of safety is indispensable for all. Fortunately, an adequate knowledge exists to take preventive, diagnostic and remedial measures against the DU penetrators.

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Contributors

Dr S.S. Rao, Sci. 'E' is working at Defence Metallurgical Research Laboratory, Hyderabad from 1992 and his current interest is in armour materials. While working at Defence Research & Development Establishment, Gwalior and Defence Research Laboratory, Tezpur, he published about 30 papers. His major contribution had been in safety evaluation and analytical aspects. He is the founder-life member of Society of Toxicology (India).

Dr T. Balakrishna Bhat is the Head of Kanchan Armour Development Division at Defence Metallurgical Research Laboratory, Hyderabad. He received his PhD in Metallurgy from Indian Institute of Technology, Madras. He is the recipient of several awards, including *VASVIK Award, National Metallurgist Award* and *NASA Award.* He has more than 40 papers and a patent to his credit. Dr Bhat had been a visiting scientist at Jet Propulsion Laboratory, Pasadena, USA, for three years.