# Chapter 13

# DEPLETED URANIUM AND ITS HEALTH PHYSICS


9/19/2019

## 13.1 INTRODUCTION

Depleted Uranium (DU) is what is left as tailings from the fuel enrichment process used in different types of reactor designs for land-based applications and nuclear propulsion, as well as nuclear devices. In the enrichment process, the uranium fuel has its isotopic content in the isotope $U^{235}$ increased from its natural atomic abundance of 0.72 percent to higher levels suitable to the particular application. The increase is to 3-5 percent for Light Water Reactors (LWRs) applications, to 10-20 percent for research and fast reactors applications, to 93.5 percent for nuclear warheads applications and from 40 to 97.3 percent for naval propulsion and space reactors applications. The tailings of depleted uranium contain from 0.2 to 0.3 weight percent in the $U^{235}$ isotope.

Because of its high density it has been used in recent conflicts in both anti-armor projectiles and as protective armor against conventional as well as DU rounds. DU is the perfect alternative for when you need cheap dead weight that does not occupy much space, like aircraft ballast and trim weights. Early Boeing 747s used depleted uranium counterweights. If the aircraft crashed there was as risk of radioactive contamination to the persons, wreckage, and the crash-site. This first became widely known after a 747 crash in Amsterdam in 1992 when crash investigators noticed high radioactivity on the crash debris.

The Abrams M1A1 tank which uses depleted uranium and sometimes reactive explosive armor plates and depleted uranium munitions. Uranium is alloyed with titanium and cast into a hardened crystollaphic structure. A lattice structure of finer chaotic mess of tiny crystals is much stronger than a mono-crystalline piece. A future weapon against tank armor may use pellets inside shells that have acid that melt the target. Mercury would melt aluminum components such as aircraft wings.

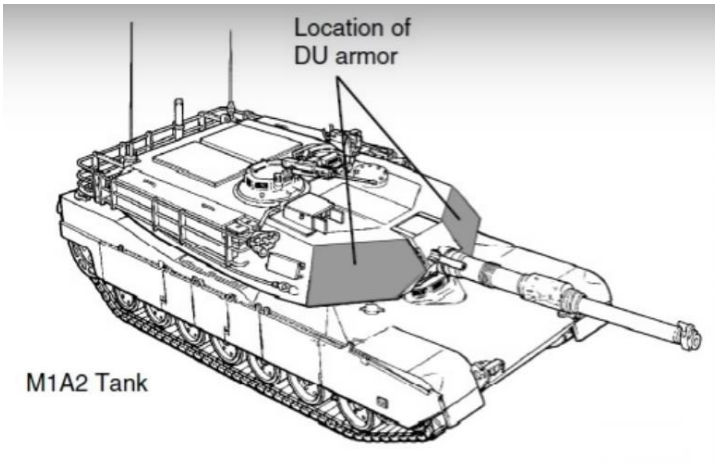



Figure 1. The USA Abrams M1A1 tank uses depleted uranium shields at the front of the turret and boron ceramic armor plates and fires depleted uranium munitions. High carbon steel and composite boron ceramic act as shield against radiation. Source: USA Army.

Armor penetration is increased by concentrating the force of a shell into as small an area as possible, so the projectiles are giant darts. The denser the projectile, the harder the impact for a given size, hence Depleted Uranium is used. The other metal used for anti-tank rounds is tungsten, which is also very hard and dense. Gold, platinum, indium and osmium are even denser, but gold is the cheapest one of these four.

When a tungsten dart strikes armor, it deforms and mushrooms, making it progressively blunter. Uranium is "pyrophoric": at the point of impact it burns away into vapor, so the projectile have a “self-sharpening” ability. When it breaks through the steel armor, the burning DU turns the inside of a vehicle into an inferno of radioactive hot gas and sparks. A controversy about DU rounds is because their impact pulverizes the projectile and creates a fine heavy metal dust that would be inhaled.

Unlike Tungsten and the other very heavy metals, U is easy to machine. The machining must be done in an argon inert atmosphere because the stuff is so flammable. The government and contractors machine it in large glove-boxes. A private entity who has only a small amount of machining to do can simply wrap the machine tool in plastic sheeting and feed in the argon.


Figure 2. The A10 Warthog 30 mm Gatling gun fires DU rounds.

Figure 3. Depleted Uranium Gatling gun radar assembly on the USS Missouri, Pearl Harbor, Hawaii, for interception of oncoming missiles and attacking fast boats. Photo: M. Ragheb.

Figure 4. DU projectile penetration of tank turret. An explosive tip identifies for the gunners the point of impact.

Pyrophoricity is the property of a substance to spontaneously ignite and burn in air such as Potassium or white phosphorous. Uranium, along with aluminum and magnesium, would do so except that as any of these metals sit in air, an oxide shield forms. Aluminum's oxide is so tough and tenacious that it is not considered flammable. Magnesium forms a less tenacious oxide layer so that it can be ignited in air. Once lit, it burns to completion and not much short of a Class D fire extinguisher will extinguish the fire. U also forms a tenacious oxide layer but as it grows, the oxide layer separates into thin, very sharp oxide plane that provide just enough protection to prevent spontaneous combustion. In a lathe cutting, strings of burning metal results. If the workpiece gets too hot, it too will catch fire. U will react with nitrogen to form uranium nitride. It will strip the oxygen out of water molecules. It will strip the oxygen out of the carbonate charge used in dry chemical extinguisher. It will do the same thing to sand. Only a Class D extinguisher which consists of very finely powdered copper can do the job on a small fire. Bigger fires are allowed to simply burn out.

Combatants are exposed to DU effects during conflict, and noncombatants should be educated about its potential radiological and chemical toxicity after the end of a conflict. Combat vehicles exposed to, or destroyed by depleted uranium munitions should be decontaminated or decommissioned and properly disposed-of at the end of a conflict. Areas exposed to depleted uranium munitions in combat, training purposes, or accidental fires or explosions, need to be identified and either isolated or decontaminated. Individuals exposed to dust or fires of depleted uranium munitions need to be monitored over a sufficient period of time for uranium content in their urine and for possible health effects.

Originally meant for countering the armored divisions of the Warsaw Pact nations in a contemplated war on the European continent, 300 tons were used in 1991 in the first Gulf War. The use was extended to the second 2003 “Shock and Awe” Gulf War in Iraq as well as in Afghanistan, Somalia, Kosovo, Lybia and Mali. It was used in 30 mm machine gun munitions, particularly those used by the A-10 Warthog ground attack airplane. It was used in the Abrams M1A1 tank projectiles and the 1-2 tons each, GBU-28, GBU-37 and AGM-130 ground

penetrating bunker-buster munitions. It was used as ballast in cruise missiles such as the Tomahawk.

Troops in the field have been instructed to avoid any sites where DU has been used and to wear protective face masks around them. Affected vehicles were brought back to the USA for decontamination or burial at designated sites. Contaminated sand from Kuwait was shipped to the USA for disposal in the desert area of the state of Idaho in the USA.

When the uranium metal is oxidized into uranium oxide, the inhalation or intake affects the lungs, liver, kidneys, testicles and ovaries. In 2003, DU was used in the cities of Samara, Mosul and Baghdad. The November 2004 combat at the city of Fallujah, Iraq contaminated the city's environment.

The criteria that are recommended in dealing with the Health Physics aspects of depleted uranium are discussed. In this regards we identify three possible forms in which it can be identified concerning its health effects: fresh, aged and mixed-source depleted uranium:

1. Fresh depleted uranium results when uranium is extracted from its ores and purified with nearly all the radium$^{226}$ and its immediate parent thorium$^{230}$ are removed, hence such uranium does not constitute an appreciable health hazard; in fact the uranium decay chain daughters being absent, its activity is lower than that for uranium fresh out of a mine.
2. Aged uranium results after a few years from the time of manufacturing, and would contain gaseous radon$^{222}$ and its solid alpha emitting daughter products.
3. Mixed-source depleted uranium is a mixture of natural depleted uranium from the enrichment process, and recycled uranium from reprocessing; the latter possibly containing fission products and transuranic elements such as Pu and Technetium$^{99}$; a potential health hazard.

The bioremediation and phyto-remediation methods that can be used for decontamination are discussed. Tungsten or tantalum are suggested as substitutes for depleted uranium with their high densities avoiding the radioactivity associated with depleted uranium.

## 13.2 PROPERTIES OF DEPLETED URANIUM

Care must be applied in using depleted uranium and its compounds. An external radiation dose results from proximity and its handling. More significant is the dose resulting from its internal body intake because of its chemical toxicity as a heavy element as well as its radiological toxicity as a radioactive substance.

Its finely divided powder is pyrophyric presenting an explosion and fire hazard. The Maximum Permissible Concentration (MPC) of soluble uranium compounds in air based on its chemical toxicity is 0.05 [mg / m$^3$]. It is set at 0.25 [mg / m$^3$] for insoluble compounds. The maximum permissible body burden based on radio-toxicity is 0.2 micro curie (μCi) for soluble compounds, and 0.009 μCi for insoluble compounds. In air the MPC is 1.7 x $10^{-11}$ [μCi / cm$^3$].

Depleted uranium would have a lower level of activity than natural uranium, since the removed isotopes U$^{235}$, and to a certain extent the U$^{234}$ isotope, possess the shorter half-lives as shown in Table 1, and consequently the highest levels of activity. The activity A(t) as shown in Eqn. 1 is inversely proportional to the half-life $T_{1/2}$ of the radioactive isotope:

$$A(t) = \left|\frac{dN(t)}{dt}\right| = \left|-\lambda N(t)\right| = \frac{\ln 2}{T_{1/2}} N(t) = \frac{\ln 2}{T_{1/2}} N_0(t) e^{-\lambda t} \qquad (1)$$

where: $\lambda$ is the decay constant of the isotope,
$N_0$ is the initial number of nuclei present at time t = 0.

The unit of activity is the Becquerel (Bq) in the Système International (SI) system of units, and the Curie (Ci) in the conventional system of units. The relationship between them being:

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}.$$

From the chemical perspective, however, the outer number of electrons in depleted uranium is still the same as uranium, and the chemical behavior is indistinguishable from uranium.

Table 1. Comparison of the measured values of isotopic compositions of natural and depleted uranium in atomic percent [a/o]. Source: Knolls Atomic Power Laboratory (KAPL).

| | $U^{234}$ | $U^{235}$ | $U^{236}$ | $U^{238}$ |
|---|---|---|---|---|
| Natural Uranium | 0.0054 | 0.720 | 0.0000 | 99.2746 |
| Depleted Uranium | 0.0008 | 0.2015 | 0.0030 | 99.7947 |
| Half-life $T_{1/2}$ (years) | $2.44 \times 10^5$ | $7.04 \times 10^8$ | $2.342 \times 10^7$ | $4.468 \times 10^9$ |
| Atomic mass (amu) | 234.040947 | 235.043925 | 236.045563 | 238.050786 |

Depleted uranium has still the notorious high density of uranium (18.9 [gm / $cm^3$]), compared to other known dense elements as shown in Table 2. It can be usefully converted into a fissile fuel, $Pu^{239}$ and generate energy in the fast reactor design concept.

Depleted uranium with the percentage of $U^{235}$ decreased to about 0.2 - 0.3 percent is a tailing from the uranium enrichment process. It is used in civilian and military nuclear reactors and nuclear devices applications. It is used in anti-tank ordnance and armor shields due to its high specific gravity at 18.9. It is also used in inertial guidance devices, gyroscopic compasses, counterweight for aircraft control surfaces, ballast for missile reentry vehicles and in ships, and as x-ray and gamma ray shielding material.

Table 2. Elements ordered by increasing density [gm / $cm^3$].*

| Density, [gm / $cm^3$] | Element | Atomic Number, Z |
|---|---|---|
| 0.0000899 | Hydrogen | 1 |
| 0.0001787 | Helium | 2 |
| 0.0009000 | Neon | 10 |
| 0.0012506 | Nitrogen | 7 |
| 0.0014290 | Oxygen | 8 |
| 0.0016960 | Fluorine | 9 |
| 0.0017824 | Argon | 18 |
| 0.0032140 | Chlorine | 17 |
| 0.0037080 | Krypton | 36 |

| | | |
|---|---|---|
| 0.0058800 | Xenon | 54 |
| 0.0097300 | Radon | 86 |
| 0.530 | Lithium | 3 |
| 0.862 | Potassium | 19 |
| 0.971 | Sodium | 11 |
| 1.530 | Rubidium | 37 |
| 1.550 | Calcium | 20 |
| 1.738 | Magnesium | 12 |
| 1.820 | Phosphorous | 15 |
| 1.848 | Beryllium | 4 |
| 1.873 | Cesium | 55 |
| 2.070 | Sulfur | 16 |
| 2.330 | Silicon | 14 |
| 2.340 | Boron | 5 |
| 2.600 | Strontium | 38 |
| 2.620 | Carbon | 6 |
| 2.702 | Aluminum | 13 |
| 3.000 | Scandium | 21 |
| 3.119 | Bromine | 35 |
| 3.510 | Barium | 56 |
| 4.470 | Yttrium | 39 |
| 4.500 | Titanium | 22 |
| 4.790 | Selenium | 34 |
| 4.930 | Iodine | 53 |
| 5.000 | Radium | 88 |
| 5.259 | Europium | 63 |
| 5.323 | Germanium | 32 |
| 5.720 | Arsenic | 33 |
| 5.800 | Vanadium | 23 |
| 5.907 | Gallium | 31 |
| 6.240 | Tellurium | 52 |
| 6.400 | Zirconium | 40 |
| 6.475 | Promethium | 61 |
| 6.684 | Antimony | 51 |
| 6.700 | Lanthanum | 57 |
| 6.980 | Ytterbium | 70 |
| 7.000 | Neodymium | 60 |
| 7.140 | Zinc | 30 |
| 7.190 | Chromium | 24 |
| 7.300 | Tin | 50 |
| 7.310 | Indium | 49 |
| 7.430 | Manganese | 25 |
| 7.540 | Samarium | 62 |
| 7.860 | Iron | 26 |
| 7.895 | Gadolinium | 64 |

| | | |
|---|---|---|
| 8.270 | Terbium | 65 |
| 8.536 | Dysprosium | 66 |
| 8.570 | Niobium | 41 |
| 8.650 | Cadmium | 48 |
| 8.800 | Holmium | 67 |
| 8.900 | Nickel | 28 |
| 8.900 | Cobalt | 27 |
| 8.960 | Copper | 29 |
| 9.050 | Erbium | 68 |
| 9.330 | Thulium | 69 |
| 9.400 | Polonium | 84 |
| 9.800 | Bismuth | 83 |
| 9.850 | Lutetium | 71 |
| 10.070 | Actinium | 89 |
| 10.200 | Molybdenum | 42 |
| 10.500 | Silver | 47 |
| 11.340 | Lead | 82 |
| 11.500 | Technetium | 43 |
| 11.340 | Lead | 82 |
| 11.500 | Silver | 47 |
| 11.700 | Thorium | 90 |
| 11.850 | Thallium | 81 |
| 12.020 | Palladium | 46 |
| 12.400 | Rhodium | 45 |
| 13.200 | Hafnium | 72 |
| 13.500 | Curium | 96 |
| 13.546 | Mercury | 80 |
| 13.600 | Americium | 95 |
| 15.400 | Protactinium | 91 |
| 16.600 | Tantalum | 73 |
| 18.900 | Uranium | 92 |
| 19.300 | Tungsten | 74 |
| 19.320 | Gold | 79 |
| 19.800 | Plutonium | 94 |
| 20.450 | Neptunium | 93 |
| 22.400 | Osmium | 76 |
| 22.420 | Iridium | 77 |

About one billion ($10^{9)}$ pounds of depleted uranium accumulated in the USA as a residual from the enrichment process. This found use early-on as a tamper and fast neutron reflector and energy multiplier material between the explosive lenses and the inner $Pu^{239}$ core pits of fission devices. About 20 percent of the 21 kiloton (kT) of Tri-Nitro-Toluene (TNT) equivalent yield from the Nagasaki device is attributed to the fast neutrons fissions in the uranium tamper. It has also been used in earlier thermonuclear devices as an energy multiplier, being fissionable by the fast 14.06 MeV neutrons released from the DT fusion reaction:

$$ {}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1 (14.06\ MeV) \quad (2) $$

Up to 50 percent of the 15 Megatons (MT) TNT equivalent yield of the 1954 Bravo thermonuclear test is attributable to the uranium casing fissions.

A comparison between the isotopic compositions of natural and depleted uranium measured by mass spectrometry at Knolls Atomic Power Laboratory is shown in Table 1.

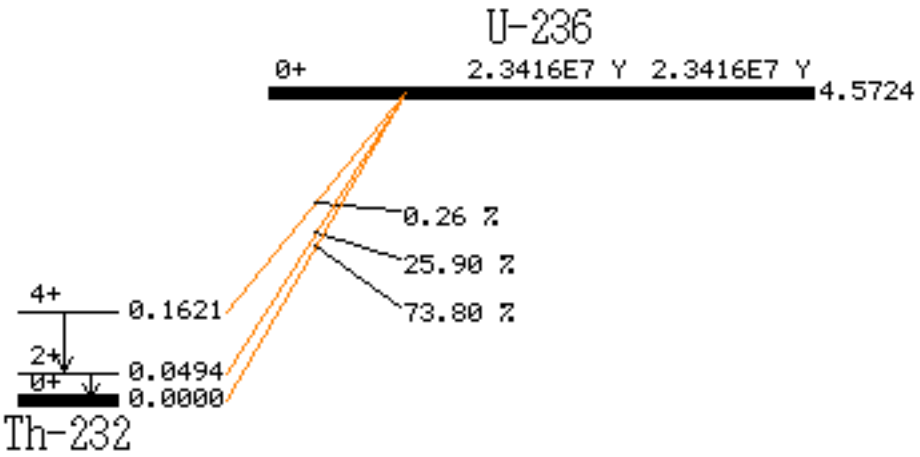



Figure 5. Alpha decay scheme of $U^{236}$. Source: Chart of the Nuclides.

It must be noticed that natural uranium does not contain measurable amounts of the $U^{236}$ isotope. Spontaneous fission may generate some neutrons that could be absorbed in $U^{235}$ generating trace amounts of $U^{236}$. Strictly speaking, depleted uranium from the enrichment process decreases the concentration of $U^{235}$ from the natural value of 0.7196 percent to the depleted value of 0.2015 percent. However, it cannot increase the value of the $U^{236}$ concentration from zero to 0.0030 percent. The $U^{236}$ isotope results from neutron radiative capture in $U^{235}$ in a reactor environment, particularly when highly enriched fuels are used. At some point, the rise of its concentration in naval propulsion fuel has to be decreased by a fuel enrichment process.

The $U^{236}$ isotope decays through Internal Transition (IT) to its ground sate emitting gamma-ray photons with a branching ratio of 87 percent, and through alpha decay with a branching ratio of 13 percent to $Th^{232}$ as shown in Fig. 5 with a half-life of $2.3 \times 10^7$ years, and it can undergo spontaneous fission (SF).

The isotope $U^{236}$ does not occur in nature and can be formed by several processes. It can be generated through the beta decay of $Pa^{226}$:

$$ {}_{91}P_a^{226} \rightarrow {}_{-1}e^0 + {}_{92}U^{236} \quad (3) $$

It can result from the electron capture in $Np^{236}$:

$$ {}_{-1}e^0 + {}_{93}Np^{226} \rightarrow {}_{92}U^{236} \quad (4) $$

It can result from the alpha decay of $Pu^{240}$:

$$_{94}Pu^{240} \rightarrow {}_{2}He^{4} + {}_{92}U^{236} \quad (5)$$

It can be generated by neutron capture process in $U^{235}$:

$$_{0}n^{1} + {}_{92}U^{235} \rightarrow {}_{92}U^{236} + \gamma \quad (6)$$

This last reaction can occur in a neutron flux in a nuclear reactor, and to a minute amount due to the neutrons generated by the spontaneous fissions in the depleted uranium.

The partial spontaneous fission half-lives for several odd-A and odd Z-odd N isotopes are shown in Table 3. Here A is the mass number, N is the neutron number, and Z is the atomic number. For $U^{235}$, the spontaneous fission half-life is $1.9 \times 10^{17}$ years. Thus spontaneous fission constitutes a negligible contribution to the uranium's decay process, which has a total half-life of $7.1 \times 10^{8}$ years.

Table 3. Partial Spontaneous Fission (SF) half-lives for some nuclides.

| Isotope | Primary decay mode | Total half-life | Partial SF half-life |
|---|---|---|---|
| $_{91}Pa^{231}$ | α | $3.5 \times 10^{4}$ a | $1.0 \times 10^{16}$ a |
| $_{92}U^{233}$ | α | $1.6 \times 10^{5}$ a | $3.0 \times 10^{17}$ a |
| $_{92}U^{235}$ | α | $7.1 \times 10^{8}$ a | $1.9 \times 10^{17}$ a |
| $_{93}Np^{237}$ | α | $2.2 \times 10^{6}$ a | $1.0 \times 10^{18}$ a |
| $_{93}Np^{239}$ | $\beta^-$ | 2.35 d | $5.0 \times 10^{12}$ a |
| $_{94}Pu^{239}$ | α | $2.44 \times 10^{4}$ a | $5.5 \times 10^{15}$ a |
| $_{95}Am^{241}$ | α | 458 a | $2.0 \times 10^{14}$ a |
| $_{97}Bk^{249}$ | $\beta^-$ | 314 d | $1.4 \times 10^{9}$ a |
| $_{98}Cf^{249}$ | α | 360 y | $1.5 \times 10^{9}$ a |
| $_{99}Es^{253}$ | α | 20 d | $3.0 \times 10^{5}$ a |
| $_{99}Es^{254}$ | α | 480 d | $1.5 \times 10^{5}$ a |
| $_{100}F^{255}$ | α | 20 h | $1.0 \times 10^{4}$ a |

The implication from the data in Table 2 is that what is referred to, as depleted uranium is in fact an analysis of a sample consisting of a mixture of depleted uranium and recycled uranium. Thus, it can be inferred that some contamination from fuel recycling has found its way into the depleted uranium sample that has been analyzed in the Table 2 data. This could have occurred inadvertently. However economic reasons may have led to a mixing of depleted uranium from the fuel enrichment process with uranium from the fuel recycling process particularly of highly enriched naval propulsion fuel. This unfortunate occurrence would suggest the possible presence of other trace impurities from the recycling process in depleted uranium, in the form of fission products and transuranics such as plutonium.

A possible source of depleted uranium contamination with fission products and transuranics is the process of what is designated as: "Excess Highly Enriched Uranium (HEU) blend down" from highly enriched naval propulsion fuel. An enrichment process reducing the

fraction of the $U^{236}$ isotope and hence increasing the fraction of the $U^{235}$ isotope in naval propulsion fuel may have led to the contamination. If fed to the enrichment process, this could have led to the contamination of part of the existing depleted uranium stockpile.

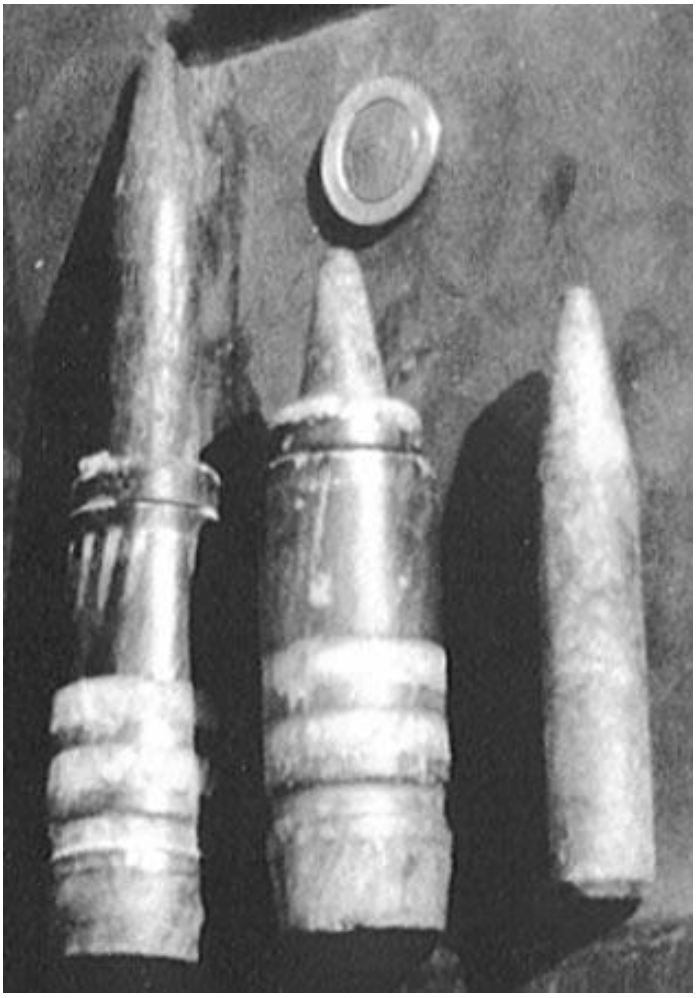


Figure 6. Tips of depleted uranium munitions used in the Kosovo conflict.

It has been suggested that the alpha activity in depleted uranium is 40 percent less than what is present in natural uranium. This is based on the observation that there are less of the isotopes $U^{234}$ and $U^{235}$ in depleted uranium than in natural uranium. It must be noted, however, that uranium occurs in nature at very low concentrations around 1 - 3 parts per million (ppm) by weight in soils, whereas depleted uranium is used in the 100 weight percent (w/o) metallic or alloyed form. Whereas the main radioactive transformation mode of the natural uranium is alpha emission, some gamma-ray emission occurs, as well as some neutrons from spontaneous fission.

If fission products and transuranics are present, another contribution to the activity level can be expected. In addition, the neutrons from the spontaneous fission process can generate gamma radiation though interaction with any fluorine and oxygen traces left from the recycling process, if indeed recycled uranium became intermingled with the depleted uranium stockpile. It could have occurred based on purely economic reasons. This contamination may have affected

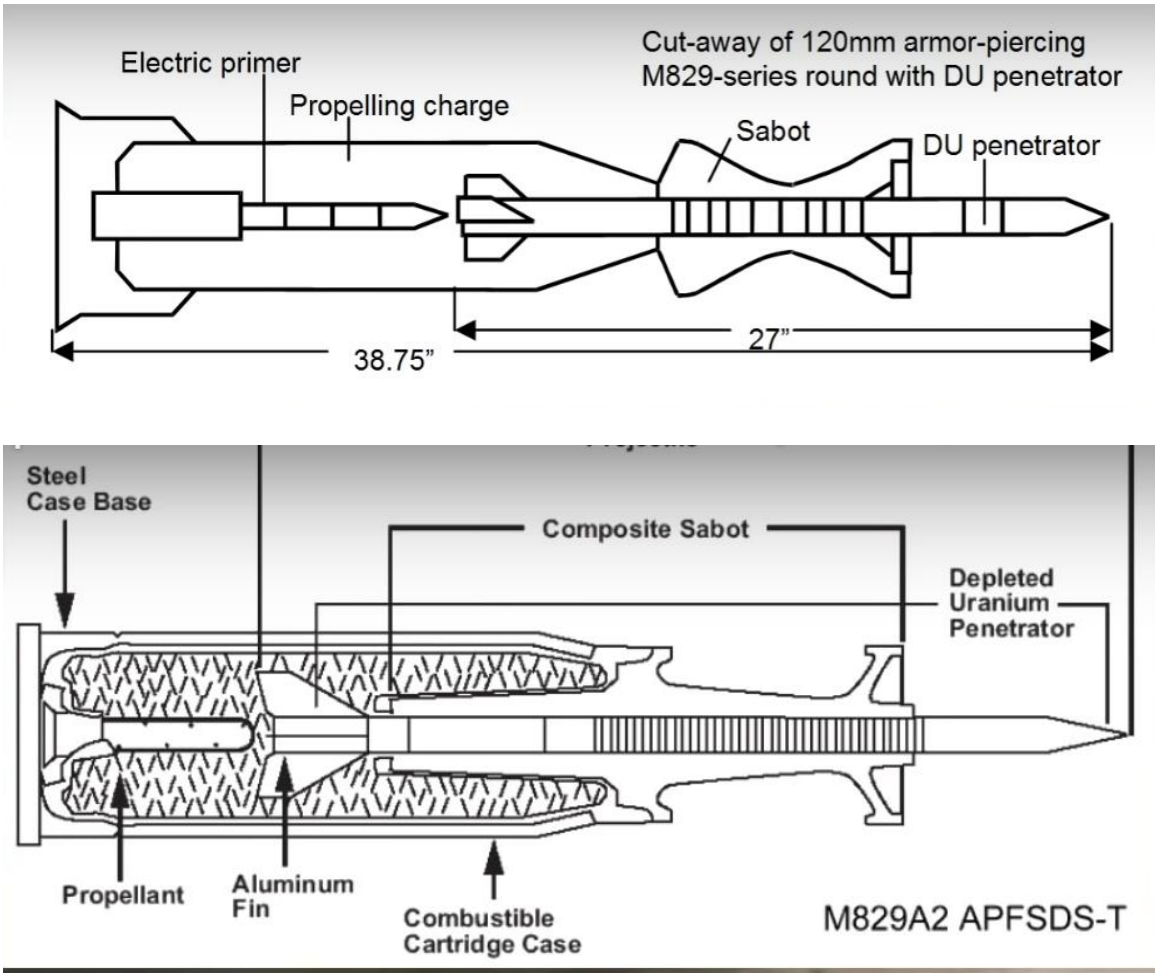
only small batches that can be isolated and not the whole stockpile, and this needs to be corroborated by detailed testing of depleted uranium samples.

## 13.3 DEPLETED URANIUM USES

Combat munitions and armor using depleted uranium were employed for the first time in warfare in 1991 during the first Gulf War. Operation Desert Storm / Desert Shield consumed over 940,000 30-millimeter uranium tipped bullets and more than 14,000 large caliber (105-millimeter and 120-millimeter) depleted uranium rounds.

The Fairchild A10A Thunderbolt II airplane, also known as the Warthog used a GAU-8/A Avenger 30 mm seven-barrel cannon capable of firing 4,200 depleted uranium rounds per minute, against Iraqi armor and troops in the Gulf War. Each 30 mm round contained a 300-gram depleted uranium penetrator. Figure 3 shows some depleted uranium munitions tips.

There are estimates of about 350 metric tonnes of it used in this campaign. NATO and the European Union forces in Bosnia in 1994 and 1995, as well as in the Kosovo campaign in 1999 in the Former Yugoslavia, also used it (Fig. 4). There are reports that they were also used in Afghanistan, the second Gulf War in Iraq in 2002-2003, Lybia, Somalia and Mali.



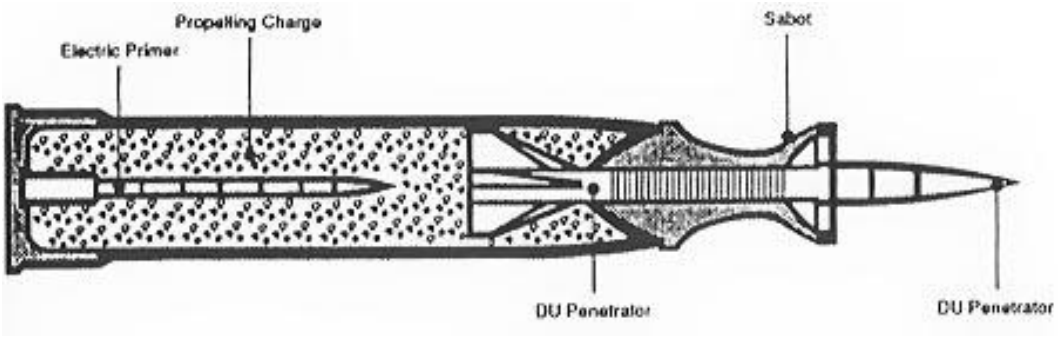



Figure 7. Schematics of a sabot armor piercing rounds with a depleted uranium penetrator.

In the Afghanistan conflict, it is surmised that the Special Forces AC130U gunship would have used depleted uranium munitions, even though no corroborative evidence currently exists to that effect, due to the lack of data about the operations in this conflict.

Depleted uranium penetrators possess a sharpening effect upon impact that allows greater penetration through armor. Upon penetrating the armor of a vehicle, a kinetic energy round fills its interior with dust and fragments. As much as 70 percent of a depleted uranium penetrator can be aerolized when it strikes a tank's armor. Since uranium is pyrophyric, the dust explodes forming uranium oxides that contaminate both the exterior and the interior of the struck vehicle.

Figure 7 shows a schematic of a depleted uranium shell. It can be noticed that the propellant charge gives its kinetic energy to both the projectile as well as a surrounding sabot. A sabot is a light weight carrier used to both position a missile and sub caliber projectile inside a gun tube, and to transmit the kinetic energy from the propellant to the projectile. It works like dart throwing by the human arm, where the arm acts as the propellant gas and the sabot's energy collecting pusher. The sabot is a parasitic weight in terms of target performance, and it flies away along the projectile's trajectory as shown in Fig. 8. The burning propellant transfers the energy to the sabot and projectile combination using an obturator within the gun barrel as shown in Fig. 9.

Figure 8. The sabot detaching from a depleted uranium projectile.

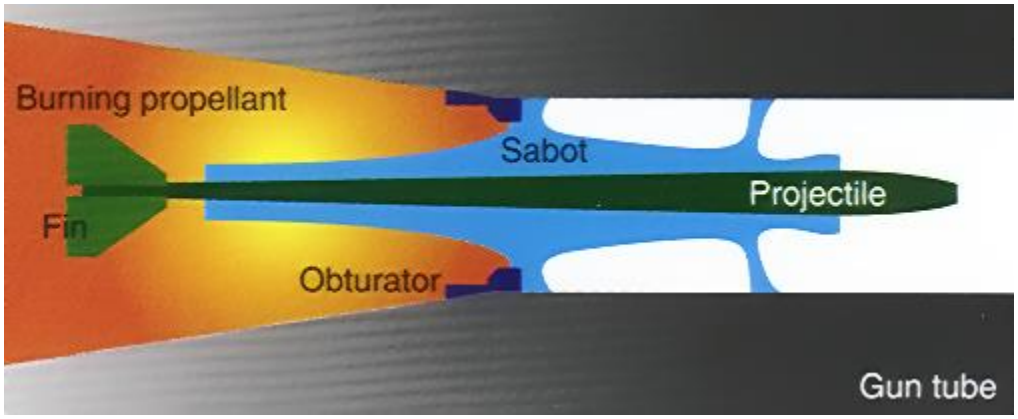



Figure 9. Cross Section of sabot showing kinetic energy transfer from the propellant to the sabot.

Figure 10. Carbon-fiber composite sabot for a depleted uranium projectile.

The depleted uranium munitions are deemed both incendiary and fragmentary. They are a potent offensive weapon, as well as being an effective defensive one. Since depleted uranium has a density of about 18.9 [gm / $cm^3$], as armor it cannot be penetrated by steel projectiles at a density of about 7.86 [gm / $cm^3$], or by lead projectiles at a density of 11.34 [gm / $cm^3$].

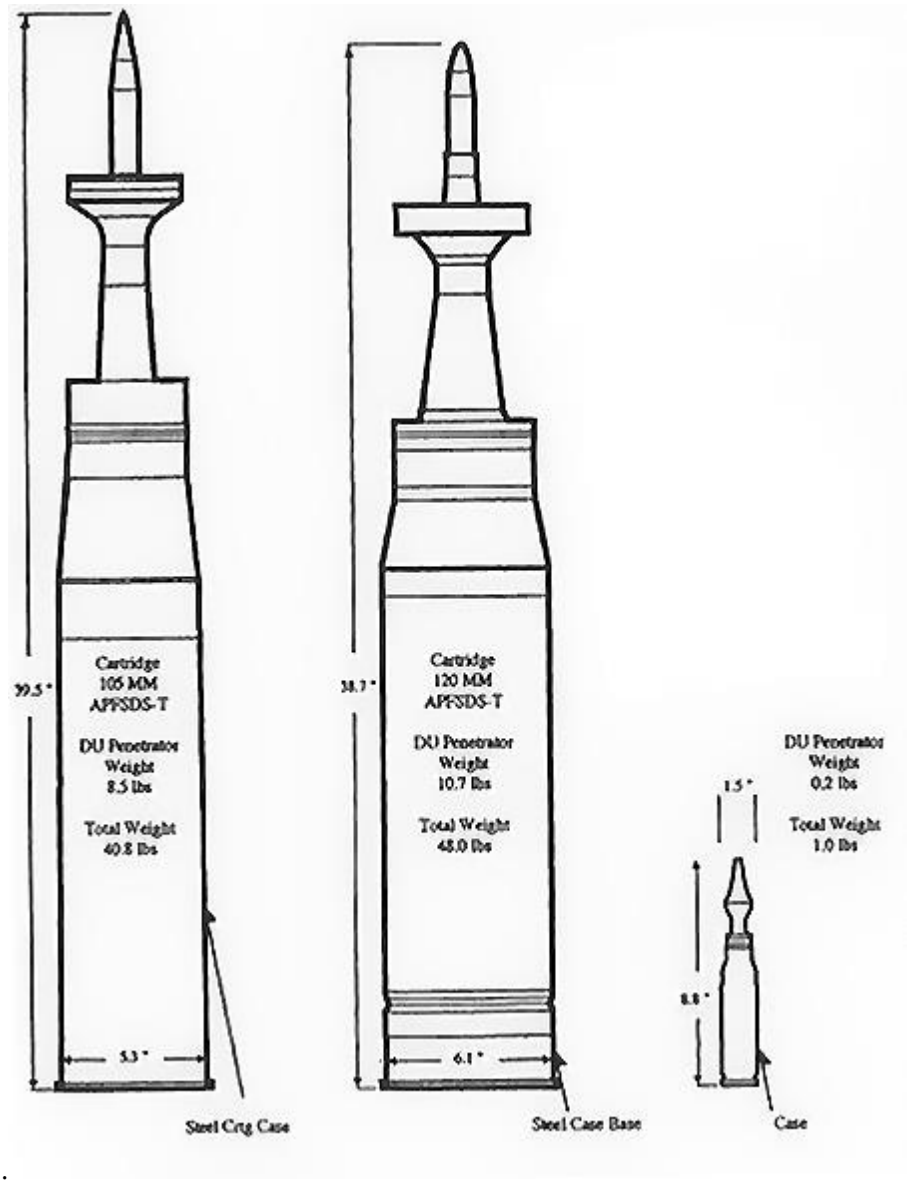

39.5"
Cartridge
105 MM
APFSDS-T
DU Penetrator
Weight
8.5 lbs
Total Weight
40.8 lbs
5.3"
Steel Crtg Case
38.7"
Cartridge
120 MM
APFSDS-T
DU Penetrator
Weight
10.7 lbs
Total Weight
48.0 lbs
6.1"
Steel Case Base
1.5"
DU Penetrator
Weight
0.2 lbs
Total Weight
1.0 lbs
8.8"
Case


Figure 11. Depleted uranium cartridges of different sizes and weights.

The Abrams M1A1 tank in the Gulf War in 1991 (Fig. 1) fired 120 millimeter anti-tank rounds containing a 10.7-pound depleted uranium penetrator core. The dense depleted uranium core is reported to increase the firing range of the Abrams M1A1 tank to between 3 - 3.5 kilometers or about 2 miles. This allowed them to fire on their targets, while remaining out of their opponents' firing range. The Bradley Fighting Vehicle (Fig. 12), the M1 and M60 series tanks, the XM8 Armored Gun System and the M1A2 Abrams tank also use depleted uranium rounds

To allow for larger projectile speed, and consequently higher lethality, the projectile must be made lightweight. Aluminum has been used as sabot material in the past, but is being replaced by even lighter carbon fiber composites as shown in Fig. 7. These are designed to survive multidimensional stresses. They consist of high strength carbon fibers, which are spun and oriented to yield maximum strength and be able to handle maximal stresses. Polymers are used to glue together the layers of carbon fiber in a process that is also used in manufacturing plywood. The grains of adjacent layers are arranged at right angles or at some wide angle to each other. A fabricated part can be machined to the final form. Thick pieces of these composites can withstand high three-dimensional stresses. Because the sabot components as

well as the casings and obturators, as well as the fins come in contact with the depleted uranium projectile, they must be considered as contaminated after use, and should not be allowed to be recycled, put into other uses and should be disposed-of properly. Different sizes and weights of cartridges have been used as shown in Fig. 8.

The National Lead Industries plant in Colonie, at the western side of Albany New York, which has been fabricating airplane counterweights and depleted uranium penetrators for 30-mm cannon rounds, exceeded a New York State radioactivity limit of 150 microcuries for airborne emissions in a given month. The plant was forced by court order to cease production in 1980, and was closed in 1983. Some of the workers at the plant had concentrations of uranium in their urine of 30 [picoCuries / liter] or 77 [micrograms uranium/liter], indicating a substantial body burden of uranium.

At the army base at Al Doha, Qatar, on July 11, 1991, a Field Artillery Ammunition Support Vehicle (FAASV) loaded with ammunition, caught fire and burned in the motor pool and ammunition storage area. The fire spread to other vehicles and artillery. Explosions happened over a six hours period, and residual fires ensued. Four M1A1 Abrams tanks with depleted uranium armor, as well as 660 tank rounds and 9,720 small caliber 25mm depleted uranium rounds, were involved in the fire. These represent about 9,000 pounds of depleted uranium. A steady wind of 8 knots from the northwest was blowing at the time. Fifty two American, 6 British, and 2 civilian workers were reported injured, by falling debris, or fleeing the explosions.

Catch boxes like those used at USA's target ranges, may have collected most of the spent shells that were used at a firing range in Kuwait, where about one third of the ammunition fired in the Gulf war was used for training purposes.

Depleted uranium proved its effectiveness at a proverbial level in the Gulf War. In the ground war alone, rounds fired from the Iraqi Russian-made T-72 tanks, with none seriously damaged, hit only seven M1A1 tanks. The Iraqi armed forces were not able to fully destroy any Abrams tanks at all. Seven were destroyed by friendly fire, and two were destroyed intentionally to avoid their capture by the Iraqi troops after becoming disabled. Six Abrams tanks, as well as 15 Bradley fighting vehicles, were destroyed by friendly depleted uranium munitions. A total of 13 USA soldiers were killed and 50 were wounded in friendly fire incidents involving depleted uranium munitions. Twenty two of the wounded retained uranium shrapnel in their bodies. The Depleted Uranium Program at the Baltimore, Maryland, Veterans Administration (VA) Medical Center monitored 30 of the soldiers wounded in the friendly fire incidents for uranium in their urine, chronic kidney toxicity, granulomas-induction and cancer.

An anecdotal account involves depleted uranium armor and rounds. An M1A1 tank became stuck in the mud in Southern Iraq. The unit, part of the 24$^{th}$ Infantry Division had gone on, leaving this tank to wait for a recovery vehicle. Three T-72s Iraqi tanks appeared and attacked it. The first fired from under 1,000 meters, scoring a hit with a shaped charge high-explosive round on the M1A1's frontal armor. The hit did no damage. The stuck M1A1 tank fired back a 120 mm armor-piercing depleted uranium round that penetrated the T-72 turret, causing an explosion that blew the turret in the air. The second T-72 fired another shaped-charge round, hit the frontal armor, and did no damage. The T-72 turned to run, and took a 120 mm round in the engine compartment, which blew the engine into the air. The last T-72 fired a solid shot (sabot) round from 400 meters. This left a groove in the M1A1's frontal armor and bounced off. The T-72 then backed up behind a sand berm and was completely concealed from view.

The M1A1 gunner fired its gun and put a depleted uranium sabot round right through the berm, into the T-72, causing an explosion.

It is interesting to note how the use of depleted uranium in the Gulf War made friendly fire a greater hazard than enemy fire for the troops using it, a fact worth noting in the history of modern warfare. In the Gulf War, about one fourth of the 148 USA casualties in the war are attributed to friendly fire. This success in its usage has prompted many other armies to adopt it in anti-armor munitions and as an anti-projectile shield. Depleted uranium munitions are also used in Gatling gun munitions on surface vessels (Fig. 9) for protection against oncoming missiles. It is used as a counter weight in airplane tail assemblies. Depleted uranium mixed with concrete (Ducete) is used in radiation shielding casks (Fig. 10.

Figure 12. Depleted Uranium used as a DUCRETE concrete aggregate in a radiation shielding cask.

It is certain to be encountered in future conflicts since a multitude of armed forces acquired or developed on their own depleted uranium munitions after they observed their effectiveness after the 1991 Gulf war. The health physics aspects of the post-conflict environment become a consideration for the long term protection of noncombatants and civilian populations.

## 13.4 ENRICHMENT OF RECYCLED URANIUM

In some countries spent fuel is recycled to recover its uranium and plutonium, and to reduce the final volume of high-level wastes. The plutonium is normally recycled promptly into mixed oxide (MOX) fuel, by mixing it with depleted uranium.

Where uranium recovered from recycling spent nuclear fuel is to be re-used, it needs to be converted and re-enriched. This is complicated by the presence of impurities and two new isotopes in particular: $U^{232}$ and $U^{236}$, which are formed by neutron capture in the reactor. Both

decay with a higher activity, since they possess shorter half-lives than $U^{235}$ and $U^{238}$. Thallium$^{208}$, one of the daughter products of $U^{232}$ emits very strong gamma radiation, which means that shielding is necessary in the plant.

$U^{236}$ is an even mass number A isotope. It is considered fissionable but not fissile and is a neutron absorber which impedes the neutron chain reaction in a nuclear reactor. This means that a higher level of $U^{235}$ enrichment is required in the product to compensate for its presence. Being lighter, both the $U^{232}$ and $U^{236}$ isotopes tend to concentrate in the enriched rather than the depleted output of an enrichment plant stream, so reprocessed uranium which is re-enriched for fuel ought to be segregated from enriched fresh uranium.

Both the diffusion and centrifuge processes can be used for re-enrichment, though contamination issues prevent commercial application of the former. A laser process would theoretically be ideal as it would ignore all but the desired $U^{235}$.

The Savannah River Plant (SRP) in the USA under contract with the TRW Company developed the Plasma Separation Process (PSP) to recover the isotope $U^{236}$ and to a lesser extent $U^{234}$ and $U^{238}$ from irradiated naval reactors fuel. All three build up during continued fuel recycle and irradiation as shown in Table 4.

Table 4. Percent isotopic content of recycled fuel.

| | Without Plasma Separation Process | With Plasma Separation Process |
|---|---|---|
| $U^{234}$ | 1.6 | 1.2 |
| $U^{235}$ | 49.0 | 68.7 |
| $U^{236}$ | 35.0 | 25.8 |
| $U^{238}$ | 14.4 | 4.3 |

The concentration of $U^{236}$ may reach 35 percent. Left in highly enriched fuel, the fissionable but non-fissile isotopes absorb neutrons and result in significant deteriorated performance during reactor operation. Upon the removal of the fissionable non-fissile isotopes the reactor efficiency increases and the need for additional Highly Enriched Uranium (HEU) decreases.

## 13.5 HEALTH PHYSICS ASPECTS

### FRESH DEPLETED URANIUM

More than 99 percent of depleted uranium is in the form of the $U^{238}$ isotope. Fresh depleted uranium results when uranium is extracted from its ores and purified with nearly all the radium$^{226}$ and its immediate parent thorium$^{230}$ are removed, hence such uranium does not constitute an appreciable health hazard. In its decay chain shown in Fig. 11, other isotopes such as $Th^{234}$, $Pa^{234}$, and $U^{234}$ are formed, and reach secular equilibrium with the parent nuclide. Under secular equilibrium, the daughter nuclides decay with the same activity as the parent nuclide, albeit with different modes of decay as negative beta and gamma-ray emissions. The isomeric state $Pa^{234m}$, in particular, has a half-life of 1.18 minute and emits some energetic negative beta particles with an energy of 2.29 MeV. The ground state of $Pa^{234}$ has a half-life of 6.7 hours, decaying through beta emission into $U^{234}$.

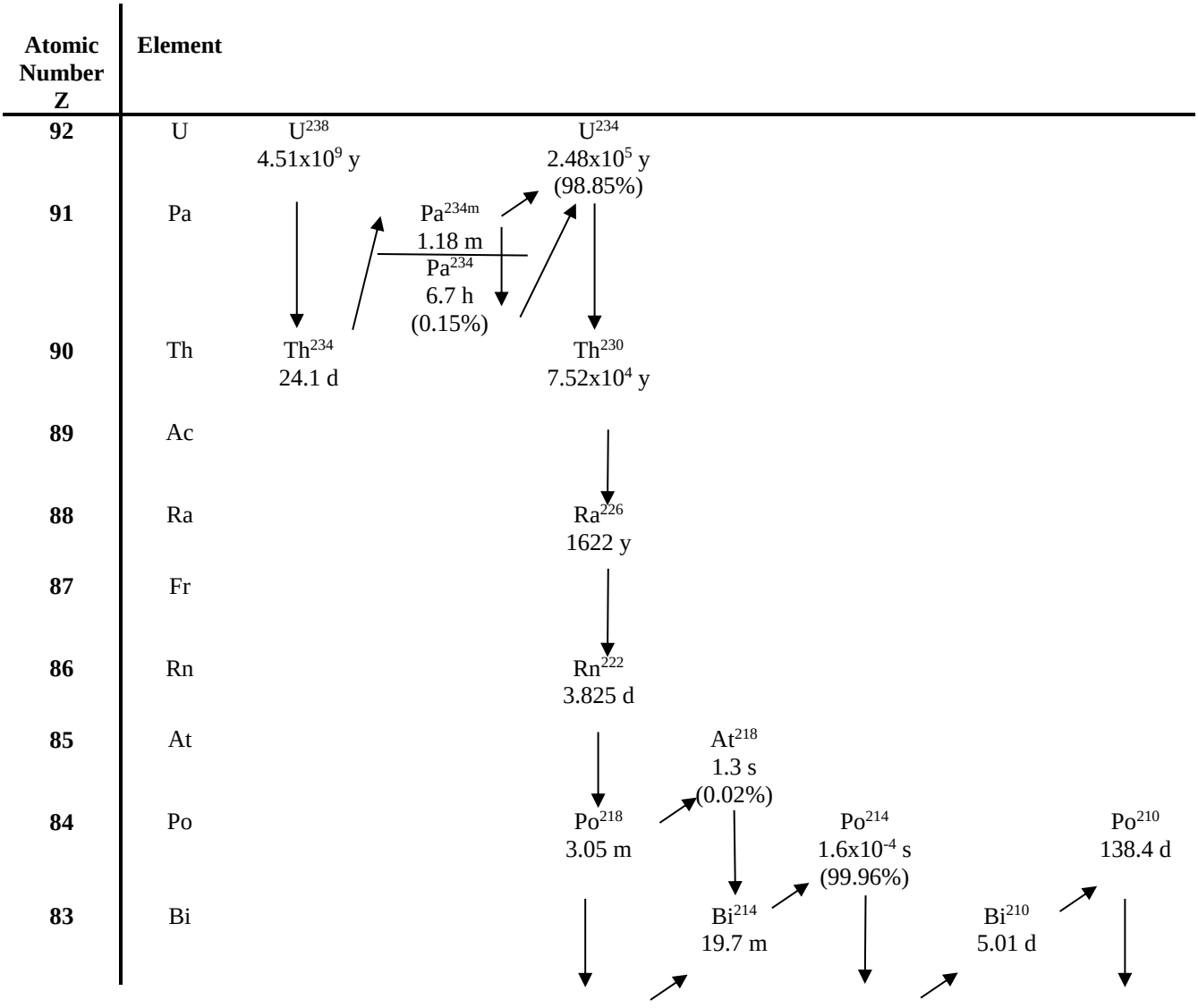
Upon manufacturing depleted uranium, the decay chain is broken during the process of the chemical reduction of uranium hexafluoride $UF_6$ into the depleted uranium metal. It is broken up a second time during the melting and the processing of the metal into a penetrator. As a result of these two breaks into the chain, freshly processed depleted uranium does not contain the lower members of the chain shown in Fig. 11, such as radon$^{222}$.

It can be inferred that for fresh depleted uranium, only the first three isotopes in its decay chain are relevant in determining its radioactivity. These isotopes are: $Th^{234}$, $Pa^{234}$, and $U^{234}$. The specific activity, or the activity per gram of uranium, assuming it is primarily $U^{238}$ is from Eqn.1:

$$A_0^{'} = \lambda N_0 = \frac{\ln 2}{T_{1/2}} \frac{1}{238} A_v \qquad (7)$$

where: $T_{1/2}$ is the half-life,

$A_v$ is Avogadro's Number (0.6023 x $10^{24}$ nuclei / mole).



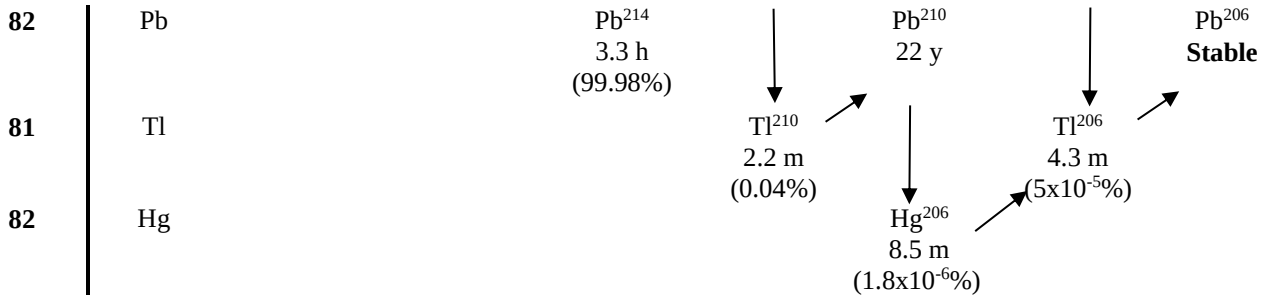



Figure 13. The $U^{238}$ (4n+2) radioactive decay chain.

Substituting for the half-life:

$$T_{1/2} = 4.51 \times 10^9 \text{ years} = (4.51 \times 10^9).(3.1536 \times 10^7) \text{ secs},$$
$$= 1.42 \times 10^{17} \text{ secs}$$

and Avogadro's number:

$$A_v = 6.023 \times 10^{23}$$

we get for the specific activity of $U^{238}$:

$$A'_0 = (0.6931/1.42 \times 10^{17}).(6.023 \times 10^{23}/238)$$
$$= 12{,}352 \text{ [transformations / (gm.sec)] or [Becquerels / gm], [Bq / gm].}$$

Within a few weeks the other two isotopes would have reached secular equilibrium with $U^{238}$ and their activities will be equal:

$$A'(U^{238}) = A'(Th^{234}) = A'(Pa^{234}) = 12{,}352 \text{ [Bq/gm]} \qquad (8)$$

The total activity per gram of uranium becomes:

$$A'_{total} = 3\ A'(U^{238}) = 3 \times 12{,}352 = 37{,}056 \text{ [Bq/gm]} \qquad (9)$$

$U^{238}$ emits alpha particles and some gamma-rays, and its daughters would emit both beta particles and gamma rays. The composite radioactivity would yield 37,056 transformations per second per gram of uranium.


Figure 14. The maintenance segregation of Bradley Fighting Vehicles that used depleted uranium munitions, where the radioactive caution sign is visible on the enclosing fence

Recovery and maintenance crews working in and around depleted uranium contaminated vehicles can inhale or ingest re-suspended depleted uranium particles, and must follow radiological safety procedures when carrying out such activities. Figure 12 shows the maintenance segregation of Bradley Fighting Vehicles that used depleted uranium munitions, where the radioactive caution sign is visible on the enclosing fence. Firing of depleted uranium shells could also release some uranium particulates into the air, and their inhalation by the tank crews should be avoided.

Soils in areas where depleted uranium has been used would contain particles of uranium as shown in Fig. 13.

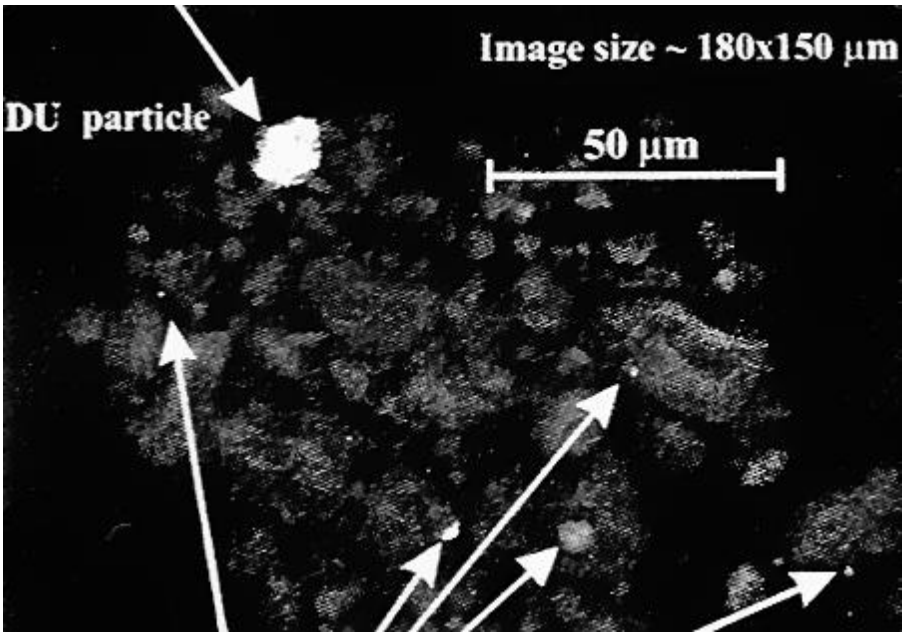



Figure 15. Depleted uranium particles can be detected in contaminated soil using a Scanning Electron Microscope (SEM) that is equipped with an Energy Dispersive X-ray Fluorescence detector.

A gamma dose equivalent rate of 250 millirems (mrems) per hour at the surface of a depleted uranium armor penetrator has been reported. A chest x-ray delivers an approximate dose of about 10 mrems. Without surface contact, the dose received is much lower, since radiation can be shielded by other vehicular enclosures and its intensity also reduces as a function of distance according to the inverse square law. Tank crews equipped with depleted uranium penetrators are reported to receive about 0.25 mrems per hour as a gamma-ray dose equivalent rate. This is assessed as one thousandth of the surface dose equivalent rate. For a mission time of 20 hours, the total dose equivalent becomes 0.25 x 20 = 5 mrems. This can be compared to the 360 mrem per year that the average American receives from natural and human-made sources of radiation, as shown in Table 5. This suggests that the dose received per mission is minimal compared with the average annual dose, and amounts to half a chest x-ray dose per 20-hours mission.

A surface dose for a 20 hours mission time however can be significant at 5,000 mrem or 5 rem or centiSievert (cSv). This value of 5 rems or cSv is the maximum allowable annual radiation dose for occupational workers. A single 20-hr mission could result in a surface dose equal to a yearly occupational dose if the depleted uranium rounds are handled. Thus direct contact with depleted uranium should be avoided for extensive periods of time. This includes the traditional urge of trophy-taking by combatants or inadvertent collection by unsuspecting civilian population and usage for other purposes in areas of past conflicts.

Table 5: Average effective doses from exposure to radiation in [cSv, rem].

| Source | Effective dose |
|---|---|

| | [cSv, rem] |
|---|---|
| Annual maximum allowable occupational effective dose | 5 |
| Annual maximum allowable dose,<br>member of the public | 0.5 |
| Annual maximum allowable dose,<br>member of the public at large | 0.170 |
| Global average exposure to natural sources | 0.240 |
| Range of global exposure depending on location | 0.1 - 1.0 |
| Average USA exposure from natural and medical sources | 0.360 |
| Average exposure from nuclear power plants operation | 0.00002 |
| Exposure from a typical chest X-ray | 0.010 |
| Surface dose from depleted uranium,<br>20 hours surface contact time | 5.0 |
| Tank crews, non-surface dose,<br>20 hours mission time | 0.005 |

## AGED DEPLETED URANIUM

As depleted uranium is stored for years, other members of the decay chain should be expected to start appearing. Figure 14 shows a storage yard for cylinders containing depleted uranium hexafluoride gas ($UF_6$) at the Portsmouth enrichment plant in Ohio.

Depleted uranium health physics aspects would then become similar to those applied to uranium in general.

Thorium$^{230}$, a daughter of $U^{238}$ decays into radium$^{226}$, the common isotope of radium. It decays in turn into radon$^{222}$, which can escape to the atmosphere since it has a low boiling point and hence is gaseous at room temperature. Radon$^{222}$ has a half-life of 92 hours and it decays into polonium$^{218}$, which is now a solid product with a half-life of 3 minutes. In turn, polonium$^{228}$ decays into lead$^{214}$, then bismuth$^{214}$, and polonium$^{214}$. All of the latter are solid elements at room temperature with short half-lives, and consequently high activity levels, as shown in Table 6. Polonium$^{214}$ decays into lead$^{210}$, which has a comparatively long half-life of 20 years. This group of radionuclides is referred to as the short-lived daughters of radon$^{222}$. Since radon$^{222}$ has a short half-life itself, these daughters are present whenever radon$^{222}$ is present.

Figure 16. Concrete-floor storage yard for depleted uranium $UF_6$ cylinders at the Portsmouth, Ohio enrichment plant.

The solid daughters of radon tend to deposit themselves on small dust particles and droplets of moisture present in the air. If air containing radon$^{222}$ gas and its decay products is breathed, the solid daughter nuclides are retained by the interior lining of the lungs. Here the emission of short-range alpha particles from polonium$^{218}$ and polonium$^{214}$ can cause damage to the alveolar tissue that can lead to the development of lung cancer.

The effect of the beta particles emission from lead$^{214}$ and bismuth$^{214}$ is minimal compared with the effect of the alpha particles. Lead$^{210}$, the daughter of polonium$^{214}$, decays slowly with low activity and emits beta particles. Radon$^{222}$ as a gas does not remain for long in the lung. Thus the main hazard results from the short-lived solid daughters that are deposited in the lungs.

Since the half-life of uranium$^{238}$ is 4.5 billion years, it is very long compared to that of its daughters. Consequently, a state of secular equilibrium is attained in the course of time. In this equilibrium state, equal numbers of nuclei of the radioactive members of the chain disintegrate per unit time. This means that they decay with the same activity level. Consequently equal numbers of Curies or Becquerels of each daughter exist at any given time under equilibrium. Equilibrium here occurs if the radon gas does not escape, such as in uranium ores or solid parts of depleted uranium munitions.

Table 6. Radon$^{222}$ and its daughter nuclides in aged depleted uranium.

| Isotope | Radiation | Half life |
|---|---|---|
| Radon$^{222}$ | α | 92.00 h |
| Polonium$^{218}$ | α | 3.05 m |
| Lead$^{214}$ | β, γ | 26.80 m |
| Bismuth$^{214}$ | β, γ | 19.70 m |
| Polonium$^{214}$ | α | $2.70 \times 10^{-6}$ m |
| Lead$^{210}$ | β | 20.00 a |

## MIXED SOURCE DEPLETED URANIUM

Mixed source depleted uranium is a mixture of natural depleted uranium from the enrichment process, and recycled uranium from reprocessing; the latter possibly containing fission products and transuranic elements; both potential health hazards.

A more thorough analysis should identify traces of the most prominent fission products such as cerium$^{144}$, cesium$^{137}$, promethium$^{147}$, strontium$^{90}$, and technetium$^{99}$, in addition to some transuranics such as the plutonium isotopes.

Natural uranium does not contain measurable amounts of the $U^{236}$ isotope. Strictly speaking, depleted uranium from the enrichment process decreases the concentration of $U^{235}$ from the natural value of 0.7196 percent to the depleted value of 0.2015 percent. However, it cannot increase the value of the $U^{236}$ concentration from zero to 0.0030 percent. The isotope $U^{236}$ does not occur in nature and can be formed by the neutron capture process in $U^{235}$, or the decay of other irradiated fuel products such as $Pa^{226}$, $Np^{236}$ or $Pu^{240}$. Trace amounts may be formed from the absorption of spontaneous fission neutrons in $U^{235}$. Its presence in depleted uranium in significant amounts can only be attributed to some mixing of depleted uranium from

the enrichment process and some undepleted uranium from the recycling of enriched uranium fuel. Such a mixed source could have resulted inadvertently in a number of batches in the manufacturing process, or intentionally for technological or economic reasons. A source of such mixed fuel would be the "blend down" of highly enriched uranium (HEU) from naval reactors fuel.

## 13.6 HEALTH EFFECTS

There have been numerous allegations of deleterious health effects from exposure of depleted uranium to military personnel and civilians in the Gulf, Bosnia, Kosovo, Afghanistan and Iraq conflicts. These included respiratory disease, gastrointestinal problems, neurological disorders, kidney stones, skin and vision problems, and various forms of cancer and birth defects. Five leukemia deaths within a year among 60,000 Italian soldiers serving in Kosovo have been linked to depleted uranium. The incidence rate can be calculated as:

$$\text{Incidence Rate} = 5/60{,}000 = 8.3 \times 10^{-5} \text{ [deaths / (person.year)]},$$

which is less than the World Health Organization's (WHO) figure for the normal Leukemia incidence for Italian men of $13 \times 10^{-5}$, and suggests a natural background cause for the Italian soldiers unfortunate calamity. This also makes many radiologists skeptical about the link, since ingestion of uranium would lead to kidney damage long before Leukemia would occur.

A report sent to the UN General Assembly by Iraq's Minister of Women Affairs since 2006, Dr. Nawal Majeed Al Sammarai, reports on birth defects attributed to exposure to DU. In September 2009, the city of Fallujah's General Hospital reported 170 born babies, of which 24 percent died within their first week, and 75 percent of them were deformed. For comparison, in August 2002, 503 live births were reported with 6 dying within the first week, and with one single deformity.

These allegations are supplemented by other suggestions, attributing the Gulf War syndrome affecting USA troops to the possible exposure of an accidental release of suspected low levels of Iraqi nerve gas. A study was released by the Rand Corporation and funded by the National Defense Research Institute did not provide a final answer to the problem of the Gulf War syndrome. About 100,000 American soldiers were reported exposed to low levels of nerve gas from an ammunition dump at Khamisiyah, Iraq, that USA soldiers blew up several days after the end of the Gulf War. It was later found that one of the nerve agents present there is Cyclosarin, which is 2-3 times more toxic than the ordinary Sarin found in most of the 122 mm rockets destroyed at the depot. Cyclosarin is less volatile than Sarin. The Pentagon informed about 99,000 troops that they were exposed to the plume of Sarin gas from Khamisiyah, and a long term health monitoring program of the exposure to low levels of nerve gas has been established. Later on, 32,806 of these troops were informed that they were not in the path of the Cyclosarin / Sarin plume, and thus were not exposed. On the other hand, 34,819 soldiers earlier believed to have been beyond the plume, were in fact exposed.

Magnetic imaging scans at the University of Texas Southwestern Medical Center at Dallas suggested abnormalities in the brains of some Gulf war veterans. In a meeting of the Radiological Society of North America, researchers studied 22 sick veterans and noted lower than usual levels of the chemical N-acetyl-aspartate in their brain stems and basal ganglia. This damage to the right side basal ganglia causes general confusion, difficulty in understanding

instructions, reading, solving problems and making decisions. Damage to the brain stem could account for vertigo and loss of balance. Twelve of the veterans with the worse symptoms had the lowest levels of the chemical. The researchers believe that the damage was caused by exposure to a combination of low level nerve gas, anti-nerve-gas tablets administered to soldiers in the conflict containing Pyridostigmine Bromide (PB), normally administered for myasthesia gravis, pesticides and insect repellents containing DEET. Insecticides were used to control fleas, flies, ticks and louse, and reportedly include: Baygon, Diazinon, Sevin, DDT, Malathion, Fenitrorthion, Propixor, Deltamethrin and Permethrin.

A survey of the 1991 Gulf War veterans by the Rand Corporation, found that 13,000 troops used at their own initiative a flea / tick collar acquired from pet stores that was deemed "unsafe and illegal" by the Pentagon. Some of the 4,000 or so troop assigned to pesticide spraying and delousing duty did not use masks and other protection. Soldiers who made frequent use of personal pesticides such as insect repellents, also took larger amounts of PB pills.

A suggestion was made that exposure to the combustion products from hydrocarbons released by the burning oil wells was a contributing factor.

Another allegation suggests that sand flies exposed the troops to some infectious agent such as Old World Leishmaniasis. It is suggested that natives there can tolerate the infection, but outsiders cannot. Still another suggestion involves infection by an obscure microbe known as Mycoplasma fermentans. Efforts at replicating the suggested effects of the latter have been elusive.

One further suggestion relates to the biological effects of the intense Electromagnetic spectrum used for radar and communications during the conflict.

The head of the Office of the Special Assistant for Gulf War Illnesses suggested that: "I have not been able to identify a smoking gun, in terms of a single cause. I know there are people that are ill. I can't tell you whether they would have been ill if they did not serve in the Gulf."

Regardless, there exists no conclusive link to depleted uranium per se, and 90,000 troops who served in the Gulf War complain of maladies including memory loss, anxiety, nausea, balance problems and muscle and joint pain. The Institute of Medicine, charged by the USA Congress to look into various studies of Gulf War illnesses, could not find enough evidence to link the illnesses to depleted uranium or for that matter to any single other possible cause.

A British case shed extra light on the situation. Lieutenant-Colonel Graham Howe, clinical director of psychiatry with the British Forces Health Service in Germany, after the War Pensions Agency asked him to look at the case of former Lance-Corporal Alex Izett, who suffered from osteoporosis and acute depression, reported in his unpublished report, dated September 2001 that "secret" injections, maybe involving anthrax vaccines, given to the soldier "most probably led to the development of autoimmune-induced osteoporosis." Lieutenant-Colonel Graham Howe came to that conclusion because in the end Lance-Corporal Alex Izett was never posted to Iraq. Lance-Corporal Alex Izett won a ruling at a war pensions-appeals tribunal which awarded him a 50 percent disability pension.

## 13.7 HEALTH PHYSICS PROTECTION NORMS

The United Nations Environment Program (UNEP) studied 11 sites in Kosovo where depleted uranium munitions were used. The study concluded that surface contamination that is detectable is limited to localized points associated with DU penetrator impacts. Because the contamination at these impact sites was low, no significant risk to air, water and fauna and flora

was identified. The only identified risk is related to hands contamination from touching the contaminated point with subsequent transfer to the mouth or if someone directly ingested the contaminated soil. The UNEP recommends "… a precautionary approach to identify any sites where depleted uranium may remain and assess the need for cleanup." It also suggested: "Further study into possible longer term environmental contamination and depleted uranium contamination of other areas in the region is recommended."

The International Atomic Energy Agency (IAEA) together with the World Health Organization (WHO), the International Labor Organization, and the Food and Agriculture Organization (FAO) have developed standards for the protection against radiation and the safety of radiation sources. These standards are designated as the International Basic Safety Standards (BSS), and are based on the recommendations of two expert advisory bodies:

1. The International Commission on Radiological Protection (ICRP), providing radiation protection standards, and
2. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), estimating the health effects of radiation.

The BSS assigns limits for exposure to combinations of radioactive isotopes, including those encountered in depleted uranium and sets the limits for the yearly radiation exposure limits for occupational workers and members of the public. Some of these limits are shown in Table 7.

Table 7. International Basic Safety Standards (BBS) for dose equivalents.

| Category | Dose equivalent, Effective Dose [rem / year] [cSv / year] |
|---|---|
| Occupational workers | 2.0 |
| Members of the Public | 0.1 |

To determine whether these limits have been exceeded or not requires studying representative groups of individuals and determining their radiation doses from depleted uranium under the specific conditions of the post conflict zone.

## 13.8 SAMPLING AREAS OF CONTAMINATION AND RISK ASSESSMENT

Samples that are likely to be contaminated by depleted uranium include soil, trees or any structures targeted by depleted uranium munitions. Samples must be forwarded to dedicated laboratories for analysis to determine the potential doses to individuals.

The first aspect of laboratory analysis is to screen for signs of the presence of radioactivity using a gamma spectrometer. If the gamma ray screening determines the presence of radioactivity, radiochemical techniques would then be used to identify and quantify the source of radiation. It becomes also important to determine the physical characteristics of the contamination such as particles size since the most probable cause for human impact is through the inhalation of small particles.

Depleted uranium particles can be detected in contaminated soil by a Scanning Electron Microscope (SEM) that is equipped with an Energy Dispersive X-ray Fluorescence detector, as shown in Fig. 10.

The radiochemical analysis for depleted uranium could use an Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Such an instrument can detect minute amounts of depleted uranium, separate the different isotopes at the parts per trillion level in samples in solution. This way the nature of the depleted uranium as fresh, aged or mixed source can be identified. The presence of other heavy elements isotopes if contamination exists by fission products could probably also be assessed.

If contamination by depleted uranium is ascertained, the radiological situation must now be assessed through a Risk Assessment program:

1. The source terms, $S_i$ must be determined using an environmental monitoring program for each pathway i.
2. Numerical modeling of the pathways of the radionuclides from the environment through air, water and the food supply to humans must be carried out. This would determine the frequencies, likelihood or probabilities $P_i$ of the different pathways.
3. Radiations doses received by individuals or groups of people $D_i$ must be assessed for each pathway.
4. The total risk can be calculated over the identified pathways i =1, … n, as:

$$Risk = \sum_{i=1}^{n} P_i S_i D_i \qquad (10)$$

where n is the number of identified pathways.

The risk can be reported as effective dose, or could be translated into morbidity or mortality figures. Population dose criteria could also be used. The environmental monitoring could involve satellite and aerial sampling in addition to urine sampling and possibly urine sampling and whole body counting of the exposed individuals for uranium and heavy metals contents. Such an environmental monitoring program could build on the experience acquired in monitoring the Hiroshima and Nagasaki victims, bearing in mind that the level of exposure and contamination from depleted uranium is well below those encountered in the case of the atomic bombs victims.

## 13.9 ENVIRONMENTAL REMEDIATION

The most immediate and important remedial action in post conflict areas is to identify the locations of spent depleted uranium munitions through aerial and land surveys. Contaminated equipment and shells immediately identifiable can thus be disposed-of through land burial in remote unfrequented well-monitored sites.

The next important remedial action is information campaigns bringing to the attention of the local population both civilian and military of the potential dangers from surface contact and particles ingestion or inhalation of spent depleted uranium munitions. Monetary rewards could be assigned for help in the identifying the locations of such munitions. This should include the points, as well as the contaminated sabots that would have been fired with them. This would avoid the human tragedy still occurring in previous areas of combat in South East Asia as well as

Iraq, where cluster bombs are still claiming unsuspecting and uninformed individuals, primarily those of young age that have not been exposed to the conflict itself.

It is judged unlikely that extensive soil removal or water filtration as has been necessary for chemical contamination instances would be necessary. However the decision to intervene or not must be based on an objective set of decision criteria.

One can adopt the ICRP differentiated approach to intervention on the basis of individual effective dose equivalents. Another approach would be to consider a population effective dose exposure. If we adopt an individual's exposure approach, the recommendations whether to intervene or not can be deduced based on the data in Table 8.

Table 8. Effective doses (dose equivalents) to individuals and intervention levels.

| [cSv], [rem] | Pathways | Intervention Level |
|---|---|---|
| > 10.0 | Continuous surface contact | Almost always justifiable |
| 1.0-10.0 | Handling of projectiles.<br>Dose equivalent rate of 2-2.5 [mSv / hr] to skin.<br>Person touching projectile 10 percent of time. | May be necessary |
| 0.1-1.0 | Inhalation of depleted uranium dust.<br>Fires, military vehicles hit with depleted uranium munitions, sabots, shell casings. | Should be considered |
| < 0.1 | Inhalation and ingestion of widely dispersed aerosols. | Unlikely to be justifiable |

In situations where the individual effective dose equivalent exceeds 10 cSv or rem, the ICRP recommends that intervention must be "almost always justifiable." From between 1-10 cSv or rem, intervention is "almost always justifiable." For effective doses above 1 cSv or rem, intervention "may be necessary." However for effective doses below 0.1 cSv or rem, intervention is "Unlikely to be justifiable."

## 13.10 BIOREMEDIATION, PHYTOREMEDIATION AND SUBSTITUTION

Digging up contaminated soils and hauling it to landfills is neither economic nor totally environmentally friendly, since the disposal sites must continue to be monitored. Environmental biotechnology can offer a way of dealing with depleted uranium contamination. One can use microorganisms to treat pollution through bioremediation, or use plants to treat it by phytoremediation.

Transgenic plants like grass can be assigned a genetic marker or biomarker that fluoresces under the effect of ultraviolet light with different colors depending on the heavy metal contaminant present. Having located the contaminated area, transgenic bacteria or plants can then be used to eliminate the contamination. At Oak Ridge National Laboratory (ORNL) in the USA, a green fluorescent jellyfish gene has been attached to a bacterial gene that detects the Trinitrotoluene (TNT) chemical high-explosive contamination, and could be used as a mine detection plant. Neal Stewart at the University of North Carolina placed the same fluorescent gene in what would be an explosive detection plant. Sunflower plants have been used at the Chernobyl accident site in the Ukraine to absorb the cesium$^{137}$ soil contamination. Ferns have

been found to soak arsenic contamination from soil and water and are suggested for the treatment of arsenic contaminated water supplies in the USA. Brazil nuts plants are known to concentrate significant amounts of the thorium$^{232}$ isotope from the soil. The same transgenic plants that could be used to detect contaminants could be engineered to clean them up as well.

Research in the Natural and Accelerated Bioremediation Research (NABIR) program administered by the USA's Environmental Protection Agency (EPA) primarily focuses on naturally occurring microorganisms for the transformation of metals and radionuclides. Anna Palmisano, the program manager suggested that transgenic microorganisms may not be needed because naturally occurring metal reducing organisms already exist at contaminated sites. Non-native and bio-engineered microbes could compete against native organisms. The public would also object to the use of non-native and bioengineered microbes. For these reasons, using methods of biomolecular science and engineering, the radiation resistant bacterium Deinococcus Radiodurans is being made to be resistant to mercury. Such basic research could find specialized applications to clean up depleted uranium contamination as well as nuclear wastes. The rapid reproduction rates of naturally-occurring bacteria allows the possibility of using them as a starting point for a process of "guided evolution." This would involve manipulating their environment, buffers, bioreactor hardware, monitoring equipment and nutrients until an efficient bioremediator bacterium appears. The design of the bioreactors could for instance involve the use of an electrostatic charge to attract the bacteria to a matrix of fixed film surfaces.

Substitution of tungsten (wolfram) to depleted uranium in armor and munitions could be used. Table 2 shows that the specific gravity of tungsten is 19.3, which is very close to the specific gravity of uranium of 18.9, and even higher. Tantalum at a specific gravity of 16.6 can also substitute for depleted uranium. Thus tungsten or tantalum can substitute for uranium in armor and anti-armor projectiles avoiding the radiological hazards associated with uranium.

## 13.11 DISCUSSION

Based on current knowledge, there is no evidence of a causal relationship between depleted uranium and the health effects that are allegedly attributed to it. Positive correlation does exist, but correlation does not imply causation from a statistical perspective. In the assessment of its risk, one must recognize that depleted uranium could be encountered in three different forms: fresh, aged and mixed-source depleted uranium.

In the absence of complete information, the prudent way to proceed from a health physics perspective is to educate the civilian and military populations in past, present and future post conflict areas about its potential risks, and properly dispose of spent munitions casings, sabots, as well as contaminated and destroyed vehicles and equipment. Further assessment studies are needed to increase the current accepted observation that depleted uranium present a minor radiological health risk in post-conflict areas.

Releases of depleted uranium are bound to occur in the future in major conflict areas where depleted uranium would be used. It could also be released accidentally in areas of no conflict. Accidental releases of depleted uranium have in fact occurred. In 1992 a Boeing 747 used by the El Al carrier, accidentally crashed into an apartment building in Amsterdam, Holland, and a fire ensued. About 273 kgs of depleted uranium in the tail of the plane burned in the fire. They were used as flight control counterweights in the tail section of the plane. When uranium metal is heated in air at 500 $^{o}$C, it oxidizes rapidly and can sustain slow combustion.

On September 11, 2001, the fire that consumed the two commercial airplanes that were directed at the World Trade Center in New York, would have released as aerosols about 540 kgs of depleted uranium, and the plane that impacted the Pentagon building in Washington D. C. would have released about 270 kgs of depleted uranium. There have been no indications whether depleted uranium indeed was used as counterweight in these particular aircraft and no assessment of the radiological health effects of these two incidents has been undertaken.

Efforts should be directed on isolating mixed source depleted uranium contaminated by the uranium fuel recycling and enrichment process and withdrawing it from usage.

Bioremediation and phytoremediation methods can be used for the decontamination of areas that are currently contaminated. Radioactive exposure and contamination affecting both combatant sides in future conflicts as well as non-combatants can be avoided by using tungsten or tantalum as substitutes for depleted uranium in projectiles and armor.

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