EUROPEAN PARLIAMENT

DIRECTORATE-GENERAL FOR RESEARCH

WORKING PAPER

DEPLETED URANIUM: ENVIRONMENTAL AND HEALTH EFFECTS IN THE GULF WAR, BOSNIA AND KOSOVO

Scientific and Technological Options Assessment Series

STOA 100 EN

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DEPLETED URANIUM: ENVIRONMENTAL AND HEALTH EFFECTS IN THE GULF WAR, BOSNIA AND KOSOVO

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Foreword

In the alternative press, the electronic media and in reports from "states of concern" there have been and still are claims of a connection between the use of ammunition made of depleted uranium (DU) and a number of diseases and genetic defects among soldiers and the civilian population of the former battlefields in Iraq and the Balkans. In contrast, in the specialized literature, generally considered as trustworthy, nothing can be found which would point to a causal relation between uranium exposure and the incidence of diseases except at extremely high exposures, which can only be realized in animal experiments. Epidemiological studies, which stand up to a critical examination (peer-reviewed), show no statistically significant differences in the incidence of cancer between population groups inside and outside the former battlefields. In particular there is no evidence of a link between a contamination in the former battlefields and the occurrence of leukemia.

Taking into account the abundance of uranium in the earth's crust, it is not to be expected, that due to the depleted uranium in the battlefields, an extensive increase in the uranium concentration will occur in the environment. In particular, the uranium concentration in the food chain will not rise to values representing a health risk. Selectively, on areas of about one hundred square meters apiece, "hot spots" may be found with contaminations beyond civil radiological protection norms. Depending on actual data, it might be necessary to take measures there. This concerns among others the ground water system where a contamination cannot be ruled out for good.

Executive Summary

In the aftermath of the use of ammunition containing Depleted Uranium (DU) during the Gulf War in 1991 and in the Balkans in the nineties, a controversy emerged in the public opinion on the alleged effects of DU on man's health and on the environment. Official reports, mainly of military origin, are strongly questioned in the public opinion, being often interpreted as a justification or part of a cover-up. This controversy reached its peak towards the end of the year 2000, when DU was held responsible for the incidence of leukemia in soldiers of the Italian peace-keeping force.

Having in mind how difficult it is to get scientific facts across to the general public and how strong a distrust there is against official statements, particularly when radioactivity is involved, this report summarizes the present state of knowledge about the effects of DU on man and environment. It bases on a comprehensive re-examination and critical review of the scientific literature, in particular the medical literature and reflects the authors' collective experience and expertise.
The executive summary is divided into main parts. Marginal notes refer to the main report.

The first part summarizes some basic facts and knowledge on DU and on its military use in ammunition, judged necessary for the understanding and interpretation of its effects on men and environment.
The second part deals with the long-term effects on the environment in the target areas of the former battlefields, while
the third part is predominantly concerned with the various DU effects on man's health.

This executive summary concludes with a statement and recommendations pertinent to the principal findings of the report.

Part 1: Basic information

This part contains facts and figures on uranium (U) and depleted uranium (DU). In short it can be stated that:

- Uranium is abundant

Uranium (U) is a chemical element quite abundant in nature. In the earth's crust the top 20 cm of soil contain on average about one metric ton of uranium per square kilometer with large local variations. Uranium is thus encountered everywhere in daily life. 2.1.1 2.1.4

- Uranium is radioactive and chemically toxic

Natural Uranium consists of three different **isotopes:** mainly ^{238}U, some ^{235}U, and very little ^{234}U. Isotopes are chemically barely distinguishable atoms of one and the same element, however they differ in their mass and nuclear properties. All uranium isotopes are **radioactive.** Uranium is a heavy metal and chemically toxic like other poisonous heavy metals such as e.g. lead and mercury 2.1.1 2.1.3

- Uranium is important

Uranium has achieved its significance in civil and military nuclear technology through its **isotope ^{235}U,** where under specific conditions a nuclear chain reaction can build-up releasing large amounts of energy. For most applications in nuclear technology, the comparatively small fraction of ^{235}U in natural uranium is not sufficient and must be increased. This process is performed in an enrichment plant. To this end natural uranium is separated into two different mixtures, one with more ^{235}U and one with less ^{235}U, the latter being called **depleted uranium**. 2.1.2

- Depleted Uranium (DU)

DU is a byproduct of enrichment, a process in the nuclear fuel-cycle. Depleted uranium is less radioactive than natural uranium, but its chemical properties are identical to those of natural uranium. The USA alone store more than 500'000 metric tons of DU. Worldwide the stocks of DU might be beyond one million metric tons. 2.1.2

- Properties of DU

DU is a very dense and chemically very reactive material. As a fine powder it can ignite spontaneously. Both of these properties are important with respect to the military uses of DU. Uranium oxides are produced when DU burns. The main part of these oxides is poorly soluble in water and in body fluids. 2.1.1

- Other Uranium isotopes and Plutonium in DU

If both natural uranium and recycled uranium from a nuclear power plant are used as feed material in the enrichment process, the resulting DU will contain traces of other uranium isotopes e.g. ^{236}U and Plutonium in concentrations which are at the detection limit of today's best analytical instruments and methods. The report concludes that the traces of Plutonium and other impurities found in DU can be neglected in assessing its effects on man and environment. 2.1.2 2.1.4

- DU is difficult to identify and measure

Field measurement techniques are capable of detecting DU penetrators, fragments, hot spots (hit of a penetrator into the soil or target) and surface-soil and air contaminations. The sensitivity of all these techniques is limited, therefore large-scale field mapping is almost impossible. Laboratory analysis provides reliable numerical values of radionuclide concentrations in food and environmental samples. Very sensitive analytical methods like mass spectrometry and alpha-spectroscopy are required to determine the isotopic composition in order to discriminate between DU and natural uranium. 2.2

- Military applications of DU

In tanks, such as in the US "M1 Abrams", DU plates are built in to enhance the protective properties of the armour. 3

Alloyed with small amounts of molybdenum or titanium uranium is hard and dense, thus a first choice for the production of armour-piercing ammunition. In addition, on striking and penetrating armour, small particles break off and burst spontaneously into flames, often igniting fuel and causing the explosion of the tanks ammunition. 3.1

- Two types of ammunition

On one hand there is the armour-piercing ammunition used in tank battles, rounds which are fired from 105 mm and 120 mm guns. On the other hand there are the air-to-ground 25 mm and 30 mm rounds of which only a small fraction per salvo hits the target. 3.1

- Quantities engaged in the Gulf War and in the Balkans 3.2

The first battlefield use of DU in armor-piercing munitions and reinforced tank armour took place during the Gulf War in 1991. In Iraq altogether about 300 metric tons of DU were expended, mainly by air to ground attacks and about 50 tons of DU were fired from tanks. In the Balkans DU was used exclusively in air-to-ground attacks. About 3 tons of DU were fired in Bosnia and about 10 tons in Kosovo. 3.3 3.4

- Pathways of DU into environment and man

Upon impact on armour and while penetrating it, a part of the DU-projectile is transformed into an extremely fine powder called aerosol, which predominantly burns into poorly soluble uranium oxides. These can remain in the air at relatively high concentration in the closed space of a tank for quite some time and eventually get into the lungs of surviving crew members. Moreover, the crew can get injured by DU-fragments. Apart from these direct effects, DU can contaminate the environment and thus indirectly strain man. DU-aerosol is deposited on the soil in the vicinity of the destroyed vehicle. DU-fragments or penetrators, which missed their targets can remain in metallic form on the soil's surface. This DU acts by its radioactivity and irradiates people from outside of the body (externally). DU-aerosols can get into the lungs by respiration, and on their way via surface water into plants and into the food chain. After intake of DU, the body is chemically burdened and irradiated from the inside (internally). In this case, the radiotoxicity as well as the chemical toxicity contribute to the overall effect. 4 5.3 5.4

Part 2: Long-term effects on environment

- Basic information

A reliable, comprehensive and scientifically founded judgment on the problem of long term effects of DU in the environment is very difficult. The main reason is that neither for the Gulf region nor for Bosnia and only on very few and geographically limited areas in Kosovo reliable data are available that would allow such an assessment. 6.1 6.2

In particular, with the exception of Kosovo, there are no data for the DU-contamination of the soil. The samples yielding these data were collected by the UNEP-mission in late 2000. In the target areas only rough estimates can be made about the location and distribution of penetrators and fragments. Taking into account the climatic and geological conditions in the Balkans the conclusions drawn for Kosovo can probably also be applied to Bosnia and to some extent perhaps even to Iraq. The report identifies the possible sources of a long-term contamination of the environment, which are DU-penetrators/-fragments and DU-aerosols. 6.3

- Contamination by DU-penetrators/-fragments and DU-aerosols in Kosovo

Penetrators or fragments lying on the surface can be picked up and carried away by unaware persons, which could lead to a contamination in unexpected places. As environmental effect, this is considered to be insignificant.

Penetrators and fragments oxidize and the oxide layer on their surface is easily removed by mechanical abrasion or rain, Thereby they contaminate their surroundings, especially the soil below. The report recommends that penetrators and fragments should be collected by trained personnel and properly disposed of. 6.2.2

Surface contaminations by DU are limited to zones of the order of 20 x 20 cm, where penetrators have hit the ground (so-called "hot-spots"). However the volume of soil of such a zone of impact with an upper limit of contamination of a few grams of DU per kilogram is too small to represent a serious environmental problem. 5.4.2 6.2.1 6.2.2

A more widespread contamination in form of DU-oxide dust exists but is limited to 2.2.2

about a hundred square meters around the localized points of impact. This contamination is not detectable by field measurement techniques; the samples need to be analysed in a laboratory, where contamination values far below the natural uranium content of the soil are found. Taking into account the levels of surface soil contamination a significant risk arising from resuspension is excluded.

- Contamination of the food chain

Due to the very low transfer factors of Uranium into biological material the ingestion of DU- contaminated food could result in doses of some microsieverts per year, which are considered negligible. 5.4.4

- Contamination of ground water and drinking water

So far no indication of contaminated ground water was found, not even close to zones of attack. However, a possible contamination of drinking water must be considered, since this is a possible pathway of exposure if very large amounts of DU were on the surface or buried in the soil. 5.4.3

Part 3: Effects of DU on man's health

In contrast to the limited experience with the effects of a DU contamination on the environment, there is a vast amount of data pertinent to the effects of uranium on man's health. This is the result of decades of medical observations on the workforce in the uranium industry and of extended research and experiments with animals.

- Toxic and radiotoxic effects of uranium and depleted uranium

For the chemical toxicity of U/DU there is a threshold concentration below which no adverse health effects can be observed in most of the individuals of a population. The damaging radiological effects of U/DU are the result of the energy absorption by the body tissues, called radiation dose. In the same way as in the case of chemical toxicity, a threshold dose also exists for ionising radiation, below which no acute radiation damage can be observed. It is still unknown whether or not there is a threshold dose for the occurrence of late-time damages from radiation in the form of an increased probability of cancer or genetic defects. 5.1

The radiation dose arising from a DU-contamination has to be interpreted in terms of the inevitable radiation doses from naturally occurring radioactivity.

- Possible effects of U/DU on man; external irradiation

Outside the human body U/DU acts only through its radiation. The dose rate in the vicinity of DU is very low and orders of magnitude too small to induce acute radiation damages or an increase in the incidence of late-time effects e.g. tumors. Even a very improbable skin contact for several days would only result in a barely quantifiable increase of the risk of skin cancer. Therefore, if a protracted direct skin contact with penetrators/fragments is avoided, the effects of external irradiation by DU are negligible. 5.3.1

- Possible effects of U/DU on man; internal irradiation

Inhalation of DU-aerosols 5.3.2

The solubility of DU-aerosols in the body fluids is decisive in assessing the effects. For soluble DU-compounds the kidneys are the target organ and the chemical toxicity is determinant. Poorly soluble DU-particles remain in the lungs for a long time, irradiating and possibly damaging the surrounding tissue. Inhalation is identified as the critical pathway in exposed persons, but a health risk is practically only to be feared from the chemical toxicity of DU.

Ingestion of DU

5.3.3

DU in the form of poorly soluble oxides is practically not taken up by the digestive tract, and therefore, even in gram quantities, has no chemically toxic effect. Since ingested uranium is either not taken up or quickly eliminated by the kidneys, the accumulated DU radiation dose is orders of magnitude less than that through the inhalation pathway. Therefore, compared to the chemico-toxic effect the radiation dose can practically be neglected.

Inoculation of DU

5.3.4

When DU is incorporated through wounds, the toxicological effect is determined by its disintegration characteristics in the tissue. Soluble uranium compounds are eliminated by the kidneys and can damage them. Insoluble DU remains in the tissue for a long time, causing a relatively high, but locally confined radiation dose, leading to a slight increase in the long-term risk of cancer.

- Two main sources of information

The main sources allowing to judge the effects of uranium and depleted uranium on man on the basis of scientifically established knowledge are:

- The experience obtained over decades with the workforce of the uranium industry
- The results from animal experiments

- Epidemiological studies on the workforce in the uranium industry

7.2

There is a great number of epidemiological studies on health effects in the uranium industry; some of these studies are very comprehensive, involving ten thousands of persons who had been working with uranium for decades. Evaluating a great number of these studies neither a causal relation nor an association between exposures to uranium and the primarily expected diseases - lung cancer and clinically significant impairment of the kidney functions – could be demonstrated. On the other hand, the possibility of a slight increase in the risk can never be entirely ruled out, not even if tens of thousands of workers have been under medical observation for decades. The fact, that there is no evidence of an association between exposures - sometimes high and lasting since the beginning of the uranium industry - and health damages such as bone cancer, lymphatic or other forms of leukemia shows that these diseases as a consequence of an uranium exposure are either not present or very exceptional.

- Leukemia

5.3.5

Leukemia is the generic term for more than twenty different malignant diseases of the white blood cells. Among the possible causes chemical substances, ionising radiation, viruses and genetic abnormities are mentioned. DU cannot be blamed to be the only reason for observed cases of leukemia. Single cases due to late effects of uranium deposition in the body cannot be excluded but are considered to be utterly exceptional.

- Biological effects of uranium in animal experiments

5.2

Animal experiments are the only possibility to determine the complex chemical and radiological effects of uranium and its compounds in the living organism as a whole. Often extremely high doses and long exposure times are required to see an effect at all. The results of these animal experiments show, that uranium and its compounds by no means preferably induce leukemia.

After ingestion, inhalation or inoculation in easily soluble form, uranium accumulates mainly in the kidneys and bones of the laboratory animal. When the burden is high, mainly a chemically induced functional damage of the kidneys can be observed. Due to the limited range of the emitted radiation, the damaging effect is locally confined.

Uranium deposited in the lungs in poorly soluble form exhibits its radiotoxic effect only after a dose massively exceeding the recommended exposure limit for man. This means, that the probability for late-time damages in the form of carcinoma of the lung will increase in the laboratory animal.

- Epidemiological studies on persons exposed to DU in Iraq and the Balkans

Verifiable epidemiological studies on groups of persons potentially exposed to DU exist up to now only for groups of US and GB soldiers from the Gulf War as well as for groups of SFOR- and KFOR-troops and members of civilian humanitarian organisations from the Balkans. 7.3

Among a relatively small group of soldiers who evidently had been exposed to DU during the Gulf War, no health problems attributable to DU could be found. Among the British Gulf War veterans neither the overall death rate nor the occurrence of specific causes of death, such as cancer, are significantly different from those of a reference population. No association between the health problems of many Gulf War veterans (Gulf War Syndrom) and a suspected DU exposition could be found. In the case of German KFOR soldiers in Kosovo potentially exposed to DU, it could be demonstrated, that no significant intake had occurred. Preliminary results of a medical expertise show, that the incidence of leukemia among the Italian KFOR troops is not significantly higher than the incidence in a reference population. Thus it can be concluded, that up to now there is no scientific evidence for health damages among army personal or the civilian population as a consequence of the use of DU-ammunition in the Gulf War and the war in the Balkans.

Controversial Information and reports about dramatic health effects of DU among soldiers of the Iraqi and Yugoslavian army as well as among the civilian population in the areas concerned do not withstand a peer-review. Therefore they were not considered any further.

Final statement and recommendations

- *Having* comprehensively *reviewed* and cross-examined most of the specialized scientific literature, in particular the medical literature, judged reliable and trustworthy,
- *Having in mind* the results provided by the medical observation over decades of workers of the uranium industry as well as by the experiments with animals,
- *Taking into account* the results of the recent investigations in Iraq and in the Balkans of the effects on man and on the environment following the use of DU,

the report concludes that the use of DU-ammunition in Iraq and the Balkans neither has led to a serious widespread contamination of the environment nor represents an acute or appreciable long-term hazard for man's health.

Nevertheless

- *Remembering* that in the very vicinity of the impact of DU ammunition the radioactive contamination might exceed civilian norms,
- *Recalling* that a direct contact with remaining penetrators and fragments should be avoided,
- *Considering* the anxiety and concern in the population and in the peace keeping forces living near the former battlefields, where DU-ammunition was used,

the authors recommend that:

- **areas of concern should be identified,**
- **the population and the peace keeping forces should be instructed how to deal with penetrators and fragments lying on the surface,**
- **such penetrators and fragments should be collected by trained personnel and properly disposed of,**
- **a periodic survey of the drinking water in the areas of concern should be performed.**

Contents

Introduction

The study in the context of the public controversy

When in the seventies the USA started developing and testing armour-piercing ammunition made of depleted uranium, this was a topic left to the experts of the armaments industry. The various applications of uranium in the civilian sector, too, e.g. as balancing weights in the control surfaces of wide-bodied planes or as efficient shielding against ionising radiation were mainly known to insiders. On a large scale, DU ammunition was used by the USA and Great Britain in 1991 in Iraq. Concerning the use of DU, only the forces' medical experts knew about the secondary effects on the own troops' health. It is thanks to the "apocalyptical" rundown of events in the alternative press, that towards the end of the nineties the more problematic side of DU, such as its effects on the civil population and environment, made headlines and was noticed by the public at large. While critically looking at the existing information, it has turned out that in the USA the decision on the deployment of DU ammunition has been carefully thought over and taken on balance of the pros and cons and on basis of scientific research. This could be done not least because of the decades of experience in uranium mining and in the uranium processing industry. However, the investigations predominantly have looked into the potential danger for the own troops and less into the effects on the environment and the population in the former battlefields. Environmental activists were not prepared to accept this and have demanded a worldwide ban on this ammunition. Nevertheless, NATO again used DU-ammunition in the Balkans, first in Bosnia and later in Kosovo. Unlike in Iraq, here all operations were air-to-ground. Thus the potential health effects became topical only after the war, namely in context with the NATO peace-keeping force and members of the humanitarian organizations. The controversy surfaced again and reached another peak towards the end of the year 2000, when depleted uranium was blamed for the incidence of leukemia in soldiers of the Italian peace-keeping force. The result, an almost hysterical media campaign, has made it perfectly clear how difficult it is to get scientific facts across to the general public and how strong a distrust there is against official statements, particularly when radioactivity is involved.

Aims

The goal of this study is to summarize the current state of knowledge, based on a critical examination of the relevant specialized literature, on the following topic: effects on man and environment resulting from the use of DU-ammunition. A scientific approach has been chosen with special weight on medical and radiological aspects. The study is intended to be an overall view on all the problems related to depleted uranium. Special attention will be paid to the possible long-term effects and the incidence of leukemia. Comprehensive reports by the Group of Experts of the European Commission (Kaiser 2001), the World Health Organization (WHO 2001) and the UN Environmental Program (UNEP 2001) have been published or will be published soon. The former two are in-depth studies on the health effects of DU used in the Balkans and Iraq, while in the latter the environmental aspects are considered in detail.

Structure of the study

Following these introductory remarks, **part 2** gives a compilation of the physical properties as well as the civilian and military uses of DU. It is explained where the difficulties are when DU is to be detected in the field or after taking samples. **Part 3** is about the properties and types of DU-ammunition and how much was used and where. The ways by which DU can contaminate man and environment are described in **part 4. Part 5** is a review on the possible effects of radioactive contaminations on man and environment. People who were exposed to uranium in the battlefields have undergone a medical examination. These results and those of samples from the environment of the contaminated areas are summarized in **parts 6 and 7**. The final part is an attempt to sum up the findings of this study on DU-hazards.

1. From uranium to depleted uranium (DU)

1.1. Physical properties, occurrence and uses

1.1.1. Uranium and uranium compounds

Uranium is the chemical element with atomic number 92. It is a silver-grey metal with an average occurrence in the earth's crust of about 3 grams per metric ton (3 mg/kg). It is more abundant than elements such as mercury, silver, or gold. This means, that per square kilometer the top 20 cm of soil contain about one metric ton of uranium with of course large local variations. Natural uranium consists of three different isotopes[1)], 99.283% ^{238}U, 0.711% ^{235}U, and 0.0054% ^{234}U.

All uranium isotopes are **radioactive**, i.e. their nuclei are unstable; they transform spontaneously into the nuclei of another element while emitting radiation. The nuclei of the new element themselves can decay too. The isotope ^{238}U is at the beginning of a decay series which ends after 14 decays at the stable ^{206}Pb (lead). This series comprises among others ^{234}Th (thorium), ^{234}Pa (protactinium) ^{234}U (uranium), ^{226}Ra (radium), ^{222}Rn (radon) and ^{218}Po (polonium).

In the equilibrium which has been reached in the earth's crust after millions of years, for each of the 14 radio-active elements in the ^{238}U-decay series the number of decays per unit time is equal.

The isotope ^{235}U belongs to a different decay series whose activity is lower by a factor of about 22.

When uranium is extracted from uranium ore, all radioactive daughter products are separated from the uranium and most of them remain in the ore. The activity of freshly extracted uranium stems from ^{238}U and from ^{234}U in equal parts and only little from ^{235}U. Therefore, freshly processed uranium has about one seventh of the activity of the ore it was extracted from.

The separated uranium immediately starts building up a new decay series. Within a few months, the two first daughter products ^{234}Th (thorium) and ^{234}Pa (protactinium) are approaching their equilibrium activity, which means that "elderly" uranium exhibits an activity of about four fourteenth of the ore it was extracted from. The build-up of additional daughter products lasts much longer, because the next isotope in the series (^{230}Th) has a half-life[2)] of approximately 80'000 years. Thus the activity of separated uranium (together with the first two daughter products) remains practically constant for hundreds of years.

Uranium has a very high density of 19.07 g/cm^3, only slightly lower than tungsten (19.3 g/cm^3) and much higher than lead (11.35 g/cm^3). Metallic uranium is chemically very reactive. In the form of powder it can react with the atmospheric oxygen and ignite spontaneously.

Some important uranium compounds

The uranium oxides **UO_2 and UO_3** are produced when uranium burns; they are poorly soluble in water. Of the uranium oxides **U_3O_8** is the chemically most stable and practically insoluble in water. Uraniumhexafluoride **UF_6** is, at room temperature, a white, crystalline solid easily soluble in water, sublimating at 57°C.

In view of their biological effects, the compounds are divided into three classes depending on their solubility in body fluids and on their biological half-life in the lungs (Fulco 2000).

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[1] Isotopes are chemically barely distinguishable atoms of one and the same element, having the same number of protons in the nucleus. However the isotopes differ in the number of neutrons and correspondingly their mass and nuclear properties. Isotopes are either stable or unstable. Unstable isotopes are called radioactive.

[2] Half-life: length of time after which half of the unstable nuclei originally present have decayed.

To the class F (fast) belongs uraniumhexafluoride $\mathbf{UF_6}$,which is absorbed from the lung's alveoles into the bloodstream within days. Uraniumtrioxide $\mathbf{UO_3}$ is counted among class M (medium); these are substances which remain in the lungs and in the associated lymph nodes for weeks. $\mathbf{UO_2}$ and $\mathbf{U_3O_8}$ belong to class S (slow), which means that these compounds possibly remain in the lungs for several years.

1.1.2. The production of depleted uranium

Uranium has achieved its eminent significance in civilian and military nuclear technology (nuclear power plants for the production of electricity, nuclear weapons) through its isotope ^{235}U being a so-called fissile material. This means, that nuclei of the isotope ^{235}U can split spontaneously into two fragments (not to be mixed up with a decay), and moreover, that they can do so when being hit by a neutron. If this occurs, new neutrons are set free, which themselves may induce fissions of other ^{235}U-nuclei and a self-sustained chain reaction starts building up.

For most applications in nuclear technology, the comparatively small fraction of 0.711% ^{235}U in natural uranium is not sufficient and must be increased. This process is called **enrichment**: The atoms of natural uranium are separated into a mixture containing more ^{235}U, and one with less ^{235}U. The part with more than 0.711% ^{235}U is called **enriched**; the other one **depleted**.

Feed material for the isotope separation is uraniumhexafluoride UF_6 in the gaseous phase, where the small difference of the masses, approx. 1%, between $^{235}UF_6$ and $^{238}UF_6$ can be exploited. Another isotope, ^{234}U is also depleted respectively enriched in the separation process; this effect is even more pronounced than with ^{235}U. Although ^{234}U is the rarest of the three isotopes, due to its short half-life it exhibits the highest activity and is therefore important from this point of view (cf. table 1).

In the past, depletion was usually carried out from the initial 0.7% ^{235}U down to a remaining content of about 0.2% ^{235}U. Given today's lower prices for uranium, it is more economical to deplete to approx. 0.3%. According to US-specifications, the Department of Defence (DoD) is allowed to use DU only when its ^{235}U content is less than 0.3 % .

Figure 1 illustrates the simpler of two cases, where DU is produced by isotope separation using natural uranium as feed material.

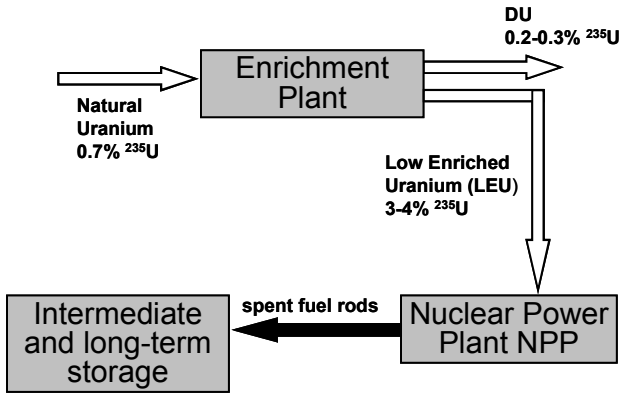
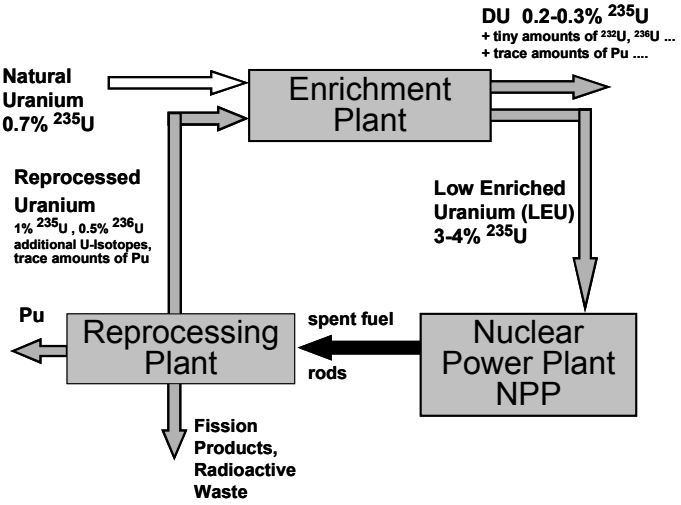


Figure 1: Pathway of ^{235}U using exclusively natural uranium as feed material for the enrichment process

Besides fission products and transuranic elements like plutonium and neptunium, spent fuel rods from a nuclear power plant still contain a substantial amount of ^{235}U. When the fuel rods are **reprocessed,** the uranium is separated from all other elements. In the USA, for decades, this mixture of recycled uranium contaminated by traces of other isotopes has been enriched respectively depleted again(*REP*rocessed *U*ranium: REPU). At Paducah (Kentucky) for example, a

total of approx. 90'000 tons of REPU have been processed. **Figure 2** is a sketch of this uranium cycle.

REPU which is fed into enrichment and thus into the fuel cycle may contain one plutonium atom in 100 million uranium atoms at most (Benedict 1981; DOE 1963). Therefore, traces of plutonium may be detected in the produced DU. A cautious estimate yields an upper value of one plutonium atom in one billion uranium atoms (Labor Spiez 2001a). Actual measurements of individual DU-



penetrators yield noticeably lower values (GSF 2001; Labor Spiez 2001b).

Figure 2: Enrichment with a mixture of both natural uranium and recycled uranium (REPU) as feed material. Unlike the case where pure natural uranium is used, here the uranium isotopes ^{236}U and ^{232}U as well as traces of plutonium and other transuranic elements may be found in the DU (Ramachandra 2000)

Summarizing:

Depleted uranium is a **by-product** from the manufacturing of fuel rods for nuclear power plants and nuclear-powered ships as well as from the production of highly enriched uranium for nuclear weapons.

1.1.3. Physical properties of uranium and DU

Radioactive nuclei transform spontaneously into nuclei of another element. Usually this process is accompanied by the emission of radiation. The unit of measurement for radioactivity is the Becquerel (Bq). An activity of 1 Bq means that one decay takes place per second. There are different types of atomic decay. In an alpha-decay, a nucleus emits an alphaparticle consisting of two protons and two neutrons. In a beta-decay, the nucleus emits an electron, a so-called betaparticle, but its weight remains practically unchanged. Alpha-, as well as beta-decays can be accompanied by gamma radiation, a high energy electromagnetic radiation.

All uranium isotopes discussed here emit alpha-particles.

Nuclide	Half-life [years]	Activity [Bq/g]	Content in natural uranium [% mass]	Contribution to the activity of 1 g of natural uranium [Bq]	Content in DU [% mass]	Contribution to the activity of 1 g of DU [Bq]
^{234}U	245'000	231'000'000	0.0054	12'470	0.0009	2'080
^{235}U	704'000'000	80'010	0.711	570	0.2	160
^{238}U	4'470'000'000	12'440	99.283	12'350	99.8	12'420
^{236}U	23'400'000	2'397'000	~ 0	~ 0	< 0.003	< 72
^{239}Pu	24'100	2'298'000'000	~ 0	~ 0	$< 10^{-7}$	< 3
Natural uranium				**approx. 25'000**		

DU	**approx. 15'000**

Table 1: Alpha-activity of natural uranium, depleted uranium and plutonium

Table 1 shows that the alpha-activity of DU is about 40% less than that of natural uranium.

The newly formed nuclei resulting from the alpha-decay of uranium – called daughter products – are not stable but continue to decay, mostly by emitting beta-particles. Thus the activity of the daughter products has to be added to that of the uranium. The betaradiation of natural uranium and DU have practically the same intensity, amounting to approximately **25'000 Becquerel per gram** (Bq/g).

All in all, together with its daughter products depleted uranium has an activity of approx. 40'000 Bq/g, i.e. about 40'000 decays take place per gram and per second. Only about 100 of these are accompanied by high energy gamma radiation.

A comparison of the activities of a few radioactive materials:

Cesium-137		3'286'000'000'000 Bq/g
Spent fuel rods from a pressurized water reactor (3.3% ^{235}U, burn-up 30 MW/ton, 150 days stored)	ca.	160'000'000'000 Bq/g
Plutonium-239		2'298'000'000 Bq/g
Natural uranium with daughter products	ca.	50'000 Bq/g
Depleted uranium with daughter products	ca.	40'000 Bq/g

1.1.4. Natural uranium in the environment

Due to its natural abundance, uranium can be found anywhere in the environment, in water, in food and in the air. Any person has an average daily intake of one millionth of a gram (1 microgram) of uranium by food and drinking water. There are considerable variations however, as e.g. some mineral waters contain up to 40 micrograms per liter. According to the International Commission on Radiological Protection ICRP (ICRP 1975), the average uranium content of the human body amounts to 90 micrograms, from which about 70 micrograms reside in the skeleton. There is a daily excretion of about 1 microgram mainly by urine.

Plutonium too can be detected worldwide in soil, air and water because of the nuclear weapons tests, which were carried out in the atmosphere until the sixties. Hereby, as an order of magnitude, one metric ton of plutonium has been dispersed into the atmosphere. As an example, Swiss monitoring stations (Fribourg and Weissfluhjoch) come up with readings of the plutonium concentration in air of 0.5 nBq/m^3 to 4 nBq/m^3 (Geering 1999) (1nBq roughly corresponds to one decay every 32 years). Converted, this yields about 500 to 4000 plutonium atoms per m^3 of air. An adult, not working very hard, normally breathes about 0.5 cubic meters per hour, which means that every hour several hundred plutonium atoms pass through the lungs, where some of them may remain. However, uranium and particularly plutonium contribute only little to the average inventory of approx. 7000 Becquerel per man; this inventory mainly consists of the naturally occurring radioactive potassium isotope ^{40}K.

1.1.5. Possible applications of DU

Many civilian applications of DU stem from its high specific weight and its low price. Therefore, depleted uranium is used where maximum mass in a limited volume is required, such as in balancing weights in control surfaces of wide-bodied aircraft, in the keel of racing-yachts or as drill-collars in oil drilling. Another application is due to the excellent shielding properties for gamma radiation; shielding is about five times better for depleted uranium than for lead of equal thickness; so it can be used in containers for spent fuel rods from nuclear power plants and other shielding purposes. In the military field, DU is used in armour and anti-armour ammunition.

1.1.6. Stocks of DU

In June 1998, the US Department of Energy (DoE) stored 734'000 metric tons of uraniumhexafluoride. Two thirds of it - about 500'000 metric tons - are depleted uranium; the rest is fluorine. No figures are published for the "stockpiles" in other countries with enrichment facilities. Together they certainly store at least again as much DU. In 1995 as well as in 1996, the worldwide production was about 35'000 metric tons of uranium. From this fact, it can be estimated, that an additional approx. 30'000 metric tons are piled up onto this already huge stock of DU every year.

The often-heard claim that the war-time use of DU was a cheap way to "solve" a waste problem, is certainly not true. The total quantity of DU in ammunition that was used in Iraq and Kosovo corresponds to barely four days of DU-production worldwide.

1.2. Identifying and quantifying DU in the field and in samples

1.2.1. In general

Uranium or rather DU can be detected by measuring the different types of radiation (X-ray, gamma-, beta- and alpha-radiation) they emit. Any radioactive nuclide emits typical radiation with a specific intensity. Today, a vast choice of equipment for monitoring such radiation is available. Field equipment is usually less sensitive than the one used in the laboratory. Moreover, environmental characteristics (e.g. the natural composition of the soil, the contaminant's concentration) may additionally impair measurements in the field. If these measurements are not or only partly successful, sample material must be analysed in a laboratory in order to obtain a comprehensive assessment of the contamination. In the laboratory one then has to solve the problem of discriminating between DU and natural uranium.

By measuring the isotopic ratio of ^{235}U to ^{238}U in the sample, its DU-content can be estimated. This is because ^{235}U was depleted from 0.711% down to 0.2%. Thus a value of less than 0.711% indicates the presence of DU. From the actual value of the ^{235}U-content the DU-content of the sample can be determined. If, as an example, the isotope analysis yielded 0.52% ^{235}U, then the uranium in this sample would consist of about 40% of depleted uranium. This kind of analysis requires mass-spectrometric or radiochemical methods.

1.2.2. In-situ detection

With an usual hand-held monitor for the detection of radioactivity, a DU metallic fragment can be detected from a distance of some 10 cm without any problem. Since alpha- and beta-radiation have a very limited range in air and only a small amount of gamma radiation is present, it is very difficult to detect remains of DU ammunition from a distance of one meter or more. This holds particularly, if the fragments do not lie at the soil's surface. Very difficult and mostly unsatisfactory is the detection of small amounts of DU dust, which has been deposited near a "hit" resp. "no-hit"-area. In this situation, field-proof equipment like hand-held monitors on the basis of thin window beta-probes, which are sensitive to beta emission, large area Sodium-Iodine probes, which are sensitive to low energy X-rays and gammas and finally Zinc-Sulfide alpha-scintillation probes, which serve for assessing surface contamination from swipes and air contamination from air sampler filters may sometimes be useful. However, the concentration of DU-dust is normally not sufficient for proving a DU-contamination. On the other hand, swipe samples are the method of choice if the contamination of a hit vehicle (Tank, Armoured Personnel Carrier APC) is to be monitored.

Fielded gamma spectrometry based on high purity germanium spectrometers is not sensitive enough, since the distance from which even large amounts of DU can be detected is only a few meters. All this makes it extremely difficult to establish a reliable geographical distribution of the DU contamination based on in-situ detection.

1.2.3. Analysis of samples in a laboratory

Reliable, quantitative information on DU contamination of the air, soils, water and biological material in the former battlefields, must be determined in specially equipped and experienced laboratories, where the in-situ samples are analysed. After the preparation of a sample under strictly controlled conditions, mass-spectrometric methods and/or radiochemical methods based on alpha-spectroscopy are applied. What concerns the laboratory's throughput, as a rule of thumb, 5 times more samples per period of time can be analysed by mass-spectrometry than by the time consuming radiochemical methods.

Taking samples

Sampling is the first step in a process that eventually leads to reliable values of radionuclide concentrations in samples taken in the environment and of food. The level of accuracy of subsequent measurements is not only dependent on the analytical method used by the laboratory, but also on protocols followed in collecting, handling, storing and transporting of the samples by instructed teams. In sampling strategies, priorities should be established in decreasing order of the most significant exposure pathways, which are 1) inhalation, 2) deposition and 3) terrestrial biological material – soil.

Sample Preparation

A detailed description of the steps required to prepare a given sample is beyond the scope of this document. However, said in a few words, the samples must be prepared in such a way, that the subsequent measurement is free of any interference. Sample materials like soil and terrestrial biological material are dried, mixed/homogenized, ground and/or sieved and incinerated. Finally the aliquots[3)] are leached[4)] or digested in acid or alkaline solutions. Liquid sample materials are usually filtered and the aliquots are digested in acid. The International Atomic Energy Agency (IAEA 1999), (IAEA 1989) and others (Green 1993), (Volchok 1982) provide detailed information on this topic.

Radioanalytical procedures and their sensitivities

Non-destructive analysis of gamma emitting radionuclides, that means without chemical preparation of the samples, can be performed on high-resolution hyperpure germanium gammaspectrometers. In general, based on well calibrated geometries and detectors one can expect approximate sensitivities for the measurement of ^{235}U of 0.45 Bq/filter for swipes or air filters, less than 1 Bq/liter of water and milk and finally 5–20 Bq/kg of soil, sediment, biological material or urine.

Destructive radiochemical procedures start with adding artificial isotopes of the element to be analysed in known quantities (spiking). Purification followed by electrodeposition of the isotopes on a steel plate allows an alphaspectrometric measurement by means of surface barrier detectors. The estimated time to perform this kind of analysis on a series of about 10 samples lies between 24–96 hours. One can expect approximate sensitivities for the measurement of uranium-, thorium- or transuranic elements of 0.004 Bq/filter for swipes or air filters, less than 0.1 Bq/liter of water and milk and finally in the range of 0.1–0.3 Bq/kg of soil, sediment, biological material or urine.

Mass Spectrometry by ICP-MS (inductively coupled plasma mass spectroscopy)

ICP-MS is a mass spectroscopic technique well suited to uranium and long-lived transuranic nuclide analysis. By applying this technique, after sample preparation as described above, samples usually are first leached by acids or digested in acids and diluted appropriately. The sample is then nebulised into a plasma of argon atoms. The temperature of the plasma is about 10'000 °C. At this

[3] aliquot: any small part of the whole mass

[4] leaching: extraction of the elements of interest

temperature the components of the sample are atomised and ionised. The mass spectrometer separates and measures the ionised elements according to their ratio of mass-to-charge. The intensity of the measurement for each sample is compared to a series of standards and the concentration of each element is calculated with a high degree of accuracy. The ICP-MS is a sophisticated instrument used for the detection of extremely low (trace) levels of elements, down to the sub-parts-per-billion level. The method has the ability to improve sensitivities three orders of magnitude above the conventional alpha spectroscopy depending on the half-life of the nuclide of interest. Furthermore this technique, combined with radiochemical separation steps has the additional ability to improve sensitivities four to five orders of magnitude above levels achievable with alpha spectroscopy. ICP-MS allows to analyse nuclide concentrations and/or isotopic ratios of a large number of samples faster than with alpha spectroscopy.

2. Military use of depleted uranium

Alloyed with 2% molybdenum or 0.75% titanium and after a special thermal treatment, uranium is as hard as hardened tool steel. Combined with its high density, it is a material well-suited for armour piercing ammunition (Rostker 2000).
In battle tanks, such as in the new version of the US "M1 Abrams main battle tank", DU plates are built in between layers of conventional steel armour in order to improve the protection against armour piercing ammunition.

2.1. Ammunition made of DU

According to the US technical literature (Magness 1990; Andrew 1992), upon impact on armour a projectile made of DU keeps its form better than one made of tungsten or steel; the penetrator sharpens itself on impact, in contrast to the more expensive tungsten projectiles, which tend to mushroom. Presumably, the low melting point (1132°C) and the pyrophoric properties of DU are responsible for this behaviour. In any case, with DU ammunition the impact results in smaller, but deeper holes in the armour than with conventional ammunition of the same calibre. After penetrating the armour and as soon as the DU projectile again comes into contact with air, the part of DU which is now in form of a liquid or powder starts burning, thereby increasing its destructive effect. Often this leads to setting the fuel tank on fire and/or detonating the ammunition stored in the tank.

Two types of ammunition with accordingly two different uses can be distinguished:

On the one hand there is the armour-piercing ammunition used in tank battles. Into this category belong the armour-piercing rounds, which have been fired from 105 mm and 120 mm guns by the Allied Forces in Iraq. These penetrators contain approx 3.9 kg resp. 4.9 kg of DU each (Rostker 2000).

On the other hand one must mention the air-to-ground 25 mm resp. 30 mm rounds of which only a small fraction per salvo hit the target. These contain 148 g resp. 299 g of DU (Rostker 2000).
Because of the superiority of this type of ammunition, it has already been introduced by the military forces of several countries. "Depleted uranium weapons have been acquired by 17 countries including Britain, France, Russia, Greece, Turkey, Israel, Saudi Arabia, Bahrain, Egypt, Kuwait, Pakistan, Thailand, South Korea, Taiwan, and other countries which the Pentagon will not disclose for national security reasons." (Zajic 1999)

2.2. Use of DU-ammunition in Iraq

After the operation "Desert Storm" the total amount of scattered and/or burnt DU was estimated by the difference between deployed and returned DU-containing rounds. The result is that about three hundred metric tons have been fired by the American and British troops together.

Rostker (Rostker 2000) specifies as follows:

Tank battles:

US Army	9 552	tank-rounds mainly 120 mm	containing approx. 50	(US) tons
UK	100	tank-rounds 120 mm	containing less than 1	(US) tons

Air-ground attacks:

US Air Force	783 514	GAU-8 Gatling-gun 30 mm DU-rounds	containing approx.	259 (US) tons
US Marines	67 436	PGU/20, 25 mm DU rounds	containing approx.	11 (US) tons
Total			approx.	321 (US) tons[5)]

[5] 1 (US) ton = 907.185 kg

No official map is available showing the locations of tank battles and air-to-ground use of DU-rounds. It can be assumed that they are mostly situated in the south-east part of Iraq, along its borders with Saudi-Arabia and Kuwait.

2.3. Use of DU-ammunition in Kosovo

In March 2000 NATO confirmed the use of DU-containing rounds in Kosovo (NATO 2001a; NATO 2001b). In this battlefield, 112 attacks against 96 targets were flown. Hereby, approx. 31 000 rounds have been fired, exclusively 30 mm ammunition. Totally this amounts to about 10 metric tons of DU deposited in Kosovo. **Figure 3** shows an overall view of the areas concerned.

Figure 3: Map published by the UN Environmental Program UNEP), showing the target areas in Kosovo

2.4. Use of DU-ammunition in Bosnia

In Bosnia approx. 10 800 30 mm DU-rounds have been used. This corresponds to an amount of about 3.3 metric tons of DU. In January 2001 NATO published a list and a map showing the areas where DU-containing ammunition had been used. It concerns three target areas of which two are located approx. 20 km south-west of Sarajevo and one about 50 km north-east of Sarajevo. Additional targets were mortar positions in the outskirts of Sarajevo (**Figure 4**). The exact locations, an accurate map, as well as the number of rounds fired, are given at the NATO home page (NATO 2001c and NATO 2001d).

Figure 4: The green dots in the vicinity of Sarajevo give an idea where air-to-ground DU-rounds were used in Bosnia

3. Contamination of man and environment by depleted uranium

Depending on the use of DU, there are various ways whereby DU can enter the environment and man, where it can possibly produce damaging effects. One main exposure pathway is based on the fact that uranium is radioactive and acts as a long-lasting source of ionising radiation[6)], irradiating man from outside the body **(external).** Depending on the uptake into the body through the lungs (inhalation), with water and food through the digestive tract (ingestion), or through wounds (inoculation), it will affect the body from the inside **(internal)**. In this case radioactivity as well as chemical toxicity can contribute to the effects. This second main pathway is shown in **figure 5** in more detail. Aerosols containing uranium are deposited on surfaces in the environment and can be resuspended by the wind or human activities, which will result in an air contamination again. Uranium deposited on the soil can find its way into the biocycle, thus contaminating drinking water, plants and animals belonging to the human food chain. These steps are described by so-called transfer-factors (cf. 5.4.2) .

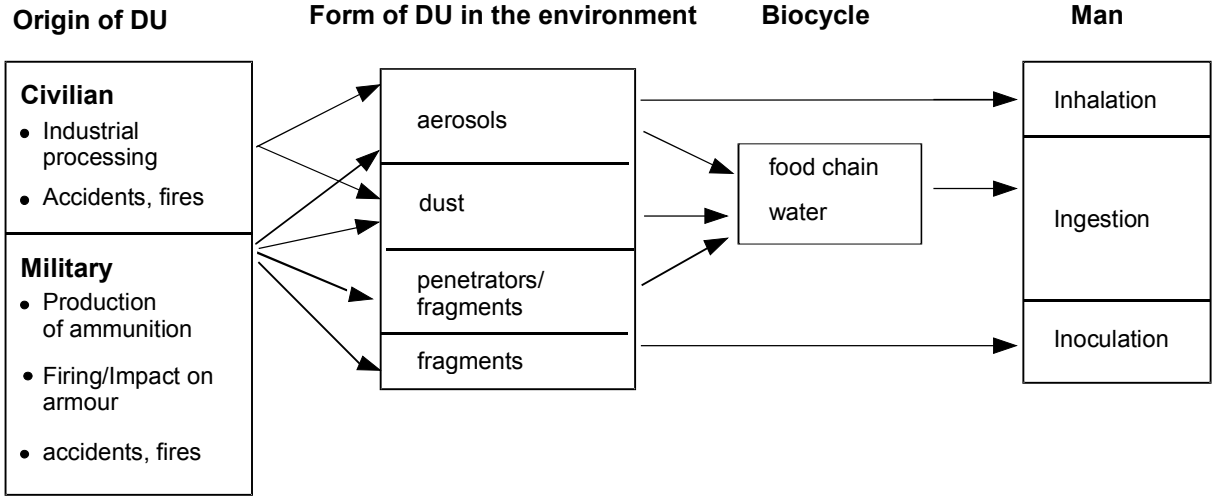


Figure 5: Pathways of DU into the environment, into biological systems and to man

During normal operations in the **industrial processing** of DU as well as in accidents, the formation and emission of fine dust particles (aerosols) are of immediate importance. Through the air inside or in the vicinity of the fabrication plants it can get into the lungs of workers and residents. By deposition of the aerosols, buildings and soil near the plant can be contaminated.

In **fires**, such as in DU ammunition storage facilities or after crashes of airplanes with balancing weights made of DU (e.g. the crash of a jumbo in a suburb of Amsterdam in 1992) DU burns into a poorly soluble DU oxide powder. This contaminates the burning site itself and is also partly carried into the air and thus to the nearby and larger surroundings as a fine aerosol. Hereby it can get into the lungs via the respiratory air. Eventually, the aerosol is deposited on the ground.

In the **penetration through hard objects** (armour of battle tanks) of high speed ammunition, people can be injured by flying DU-shrapnel, which can partly remain in the body for a long time. Depending on the material and thickness of the armour that is struck, a small portion of the DU is transformed into a fine aerosol, typically about 10% in the case of hard armour (Harley 1999). The DU-aerosol quickly burns into poorly soluble uranium oxides (typically 75%), which can remain in the air at relatively high concentrations in closed spaces (tanks, bunkers) for quite some time.

[6] alpha-, beta- and gamma radiation produce ions, i.e. positively or negatively charged atoms or molecules as they interact with matter

Eventually they get into the lungs by respiration. The fraction that reaches the outside is quickly diluted, transported and deposited on the soil. Here the aerosol concentrations are much lower. The rest of the DU-projectiles, as well as those rounds that missed their targets, remain in the tank or in the nearby surroundings in the form of larger or smaller metal fragments.

4. Possible effects of uranium on man and environment

The damaging effects of DU, in other words, its dangerousness for man, are based on two of its properties:

- Uranium is chemically toxic, like other heavy metals such as lead and mercury, etc.
- All uranium-isotopes are radioactive, i.e. they emit ionising radiation.

Outside the body, DU only acts by irradiation. After incorporation, chemical as well as radiological effects must be taken into consideration, possibly also their cumulative effects.

4.1. General remarks on the effects of chemical poisons and ionising radiation

In general, the **chemical toxicity** of a substance is defined by a threshold concentration in the human body resp. in the different organs, below which no health damage can be observed in most of the individuals of a population. By compliance with legal norms for the threshold values of contaminants in air, soil, water and food it can be ensured that even after a long term exposure there is no risk of adverse effects on health. **Table 2** gives a comparison of some threshold values for uranium.

Norm	Threshold values		
	Air		Drinking Water
	Uranium (insoluble compounds, as U)	Uranium (soluble compounds, as U)	Uranium
NIOSH REL	0.25 mg/m^3	0.05 mg/m^3	
STEL	0.6 mg/m^3		
IDLH	10 mg/m^3	10 mg/m^3	
MAC			0.1 mg/L
EPA			0.02 mg/L
WHO			0.002 mg/L

Table 2: Threshold values for uranium in air and drinking water

NIOSH National Institute for Occupational Safety and Health, U.S.
REL Recommended Exposure Limit
STEL Short Term Exposure Limit
IDLH Immediately Dangerous to Life or Health (30 min. exposure time)
MAC Maximum Acceptable Concentration
EPA Environmental Protection Agency
WHO World Health Organisation

The Canadian MAC for uranium in drinking water of 0.1 mg/Liter (100 µg/L) is under revision. The proposed new value is 0.01 mg/L (10 µg/L). The WHO-Guideline for drinking water recommends 2 µg/L, a value considered to be protective for subclinical renal effects reported in epidemiological studies (WHO 1998), while it's expected that the U.S. Environmental Protection Agency will establish a guideline of 20 µg/L. These examples show the continuous and dynamic development of threshold values, reflecting the complexity of effects of uranium on human health.

The damaging effect of **ionising radiation** is essentially a result of the energy absorption by the body tissues, called radiation dose. The unit of measurement for radiation doses is the Sievert (Sv), or the millisievert (1 Sv = 1000 mSv). In order to relate the activity of radioactive material (in Bq) to the radiation dose it produces (in Sv), it must be known if the body is irradiated internally or externally, which type of radiation it is (α,β,γ, neutrons) and what energy the radiation has. The ICRP and other organisations have published corresponding conversion factors for internal and external radiation of man (ICRP 1989-96).

As in the case of chemical toxicity, a threshold dose also exists for ionising radiation, below which no **acute** radiation damage can be observed. It is still unknown whether or not there is a threshold dose for the occurrence of **late-time damages** from radiation in the form of an increased probability of cancer or genetic defects. To be cautious, in the field of radiological protection it is assumed that late-time damages also occur at low doses with a linear dose-effect relation and without threshold. The ICRP estimates an incidence of about 0.05% additional cases of cancer and genetic defects per mSv of whole-body dose (ICRP 1990). In the case of a partial irradiation of the body, the sensitivity to radiation of the different organs and tissues is taken into consideration by appropriate weight factors.

In order to avoid acute radiation damage and to limit late-time damages to a very low level, international recommendations and national laws for dose limits, as well as threshold values for the concentrations of artificial radioactive materials in the environment, air and food were established**.** **Table 3** contains an excerpt from the dose limits according to the ICRP recommendations.

Dose limits		
Occupationally exposed persons	Whole body irradiation	20 mSv per year
	Skin, extremities	500 mSv per year
General public	Whole body irradiation	1 mSv per year

Table 3: Dose limits according to ICRP for irradiation from **artificial** sources

In this context it should be kept in mind that a typical European accumulates an annual dose from natural radioactive sources of 4 to 5 mSv on the average; a dose which is inevitable and can, depending on local conditions (altitude, increased radon content in the soil) also be considerably higher. There is an additional dose of 1.5 mSv from medical examinations and treatment.

4.2. Biological effects of uranium in animal experiments

The issue of the effects of uranium on man has been under consideration for more than fifty years. Animal experiments are the only possibility to determine the effects of uranium in vivo, under controlled conditions, known uranium compounds, known exposure time and, often very high doses.

The non cancerous alterations thus seen are mainly due to the chemical toxicity of uranium and its compounds. Among the cancerous alterations it can usually not be distinguished whether they have been induced by chemical or radiotoxic effects. With the necessary caution and appropriate safety factors, the results from animal experiments can be translated into man.

For the assessment of the chemical toxicity, all uranium isotopes can be considered as equally toxic. Important to the effects are the kind of uranium compound and the way of application. The soluble uranium compounds are generally more toxic and will be eliminated more quickly from the body than the insoluble compounds. As an extreme example of an easily soluble compound may be mentioned UF_6 , which gives by hydrolysis in the body very quickly the strongly caustic hydrofluoric acid. In case of the practically insoluble uranium compounds, animals must be exposed to very large amounts for months and years before damages become manifest. Leukemia as a consequence of an exposure to uranium in animal experiments is mentioned only as an exception (Filippova 1978). However for that, highly enriched uranium (with a ^{235}U content of 90 %) in amounts of roughly 0.5–19 mg/kg body weight had to be applied by the intratracheal route. The radiation doses caused by this highly enriched uranium are more than a hundred times higher than

the ones caused by the same amount of DU.

4.2.1. Inhalation

Many experiments with inhalation have been carried out with uranium compounds, which are important in context with the workplaces in the uranium industry, but are hardly related to uranium containing ammunition. Some of these uranium compounds caused after inhalation no histologically detectable damage in the lungs of rats, rabbits, Guinea pigs, and dogs. Applied concentrations were 0.05–10 mg U/m^3 during 7–13 months (Cross 1981a,b).
Of particular interest in context with DU-ammunition are the findings by Leach (Leach 1970). Rats and dogs were exposed to 5 mg U/m^3 in form of uranium dioxide dust during 1–5 years (5.4 hours a day, 5 days a week). No lung damages could be found. In dogs and monkeys one could observe only minor alterations in lymph node tissue, this after at least 3 years of exposition at concentrations as mentioned above.

4.2.2. Ingestion

The following table 4 shows the range from the lethal dose (LD) to the dose where no adverse effects are observed (NOAEL). The values cannot directly be compared, since the different compounds were fed to the different species for different periods of time.

Substance	Dose	Duration	Effect	Species	Source
$UO_2(NO_3)_2$ x $6H_2O$ uranyl-nitrate-hexahydrate	12 mg/ kg body weight	acute	LD	dog	(Spector 1956)
	238 mg/kg body weight	acute	LD	cat	(Spector 1956)
	0.96 mg/kg body weight per day	91 days (3 months)	LOAEL	rat	(Gilman 1998a)
$C_4H_6O_6U$ x 2 H_2O uranyl-ethanoate-dihydrate	2 mg/kg body weight per day	4 weeks (1 month)	NOAEL	rat	(Ortega 1989)

Table 4: Range from Lethal Dose to No Effect Level of diverse **easily soluble** uranium compounds in different species and for different durations of exposure

LD = Lethal Dose
NOAEL = No Observed Adverse Effect Level
LOAEL = Lowest Observed Adverse Effect Level

Lethal doses (LD) for dog and cat are amazingly far from each other in spite of the fact that both animals are carnivores. **For poorly soluble or insoluble** compounds, higher doses are required to obtain the same effects.

4.2.3. Implants

In the rat 1.0 mg U/L was eliminated via urine 12 months after implantation of uranium pellets (4 to 16 in each animal) (Miller 1998). The uranium implants resulted in a significant increase of the uranium concentration in the brain (Pellmar 1999). The functional impact of the accumulated uranium in the brain could not be interpreted, in spite of diverse neurological tests that were performed.

4.2.4. Carcinogenic effects

A carcinogenic effect in the rat of about 0.5 mg to 19 mg highly enriched ^{235}U/kg body weight could be found after intratracheal injection. The incidence of all forms of cancer increased in these animals to 24% compared to the animals of the control population with a 12% incidence. Osteosarcoma, carcinoma of the lungs and kidneys, reticulolymphosarcoma of the lungs, and leukemia were found (Filippova. 1978).

An extraordinarily high incidence of cancer was found by Leach (Leach 1973) in dogs when these had chronically inhaled uranium dioxide (5 mg U/m^3). Involved were pulmonary lymphatic

neoplasms[7]. The incidence of cancer was 50–100 times higher than expected. The author explicitly warns about extrapolating these results because pulmonary lymphatic neoplasms in man are an extraordinarily rare form of cancer. Long-term feeding experiments in different animals, even with high doses, have shown no evidence of cancer (ATSDR 1999).

4.2.5. Effects on kidneys

The kidneys are the primary target organ for the chemico-toxic effect of uranium. However, after inhalation of uranium dioxide for 5 years in a concentration of 5 mg U/m^3 no kidney damage occurred in the dog and in the monkey (Leach 1970). As it seems, a kind of tolerance develops in case of increasing uranium loads. After a nephrotoxic[8] dose kidney damages result on grounds of different mechanisms, such as bonding of uranium to proteins and impairment of cell metabolism in the renal tubules (Brady 1989).

After the exposition is stopped, a quick recovery of the damaged tissue sets in. There are signs, however, that the regenerated cells are not of the same quality as the initial ones.

4.2.6. Effects on reproduction and growth

On normal intake of uranium with feed any influence on the testicles' function in mice can be excluded (Llobet 1991).
On daily feeding mice with high doses of uranyl acetate dihydrate (25 mg/kg per day), beginning 14 days prior to mating and continuing so during gestation, parturition and nursing, the number of dead offspring on the day of birth and on the 4. day after birth increases significantly. The growth rate in the offspring of treated animals is significantly lower (Paternain 1989).
No results are known which would indicate any influence on the foetal development after inhalation of uranium or after dermal exposition.

4.2.7. Effects on white blood cells

Experiments with inhalation of uranium of "intermediate-duration" have shown no effects on blood cells (ATSDR 1999). On application of uranyl nitrate hexahydrate in doses up to 600 mg U/L via drinking water for 91 days, Gilman (Gilman 1998, a, b,c) noticed no alterations in haematological and biochemical parameters of rabbits and rats.

4.2.8. Summarizing

- Most of the uranium in soluble form which is incorporated into the animal's body by inhalation or ingestion is eliminated within a relatively short time (days) via the kidneys by the urine. A small part finds its way into the skeleton and will afterwards be mobilized only slowly in the course of years. If the intake is beyond certain limits, the chemical toxic effect of uranium manifests itself by the occurrence of damages in the kidneys. Temporary, reversible losses of functioning may hereby turn into permanent damages of the renal tissues.
- Uranium aerosol inhaled in poorly soluble form (e.g. certain uranium oxides) remains with a biological half-life of years in the laboratory animal's lungs or the tracheobronchial lymph nodes. There can be seen, if the recommended exposure limit for man is exceeded 10 to 100 times, the uranium's radiotoxic effect as an alpha source: late-time damages in form of an increased incidence of lung carcinoma become manifest. Leukemia as a consequence of an exposure to uranium could be observed only under the most extreme experimental conditions.

[7] pulmonary lymphatic neoplasm: tumour in the lung, developing from lymphatic cells

[8] nephrotoxic: poisonous to the kidneys

4.3. Possible effects of DU on man

4.3.1. External irradiation by DU

DU outside the body acts exclusively via the emitted gamma and beta radiation, since the alpha radiation is absorbed by the outermost layers of the skin and therefore does not affect the living tissue. The dose-rate in the vicinity of DU is very low. One kg DU at a distance of 1 meter produces a dose of less than 1 mSv per year. If a DU surface is touched by the bare skin, a localized dermal dose of about 2 mSv per hour results (Rostker 2000). Radiation doses and dose-rates in this order of magnitude are too small to produce acute radiation damages or to appreciably increase the incidence of cancer, even if one stayed in the vicinity of DU for an extended period of time. The very improbable case of a direct contact for several days with the same part of the skin would not lead to a dermal dose in the region of the yearly allowed dose of 500 mSv for occupationally exposed persons. Sole consequence would be a minimal, barely quantifiable increase of the risk of skin cancer.

4.3.2. Inhalation of DU-aerosols

Uranium in the form of fine particulate dust – such as that produced in the uranium industry by mining uranium ore, or from the impact of high-speed projectiles on armour, or from the burning of uranium – can enter the lungs through inhalation. However, only about 25% of the particles with a diameter smaller than 10 micrometers are deposited in the lungs (Harley 1999). Larger particles are removed from the bronchi and swallowed, finally getting eliminated via the digestive tract. Methods developed by the ICRP model transport and dosimetry of inhaled radioactive substances (ICRP 1994).

The decisive factor for the biological effect is the **solubility** of the inhaled DU in the body fluids (cf. 2.1.1).

If uranium is in a **chemically soluble** form, the main part is relatively quickly eliminated – within days – through the bloodstream and the kidneys. At the same time, the kidneys are the target organ for the chemically-toxic effects of uranium, which can lead to impaired function or even total organ failure. A single inhalation of 8 mg uranium in soluble form is the threshold value for the occurrence of temporary kidney damage, 40 mg being the threshold value for irreversible damage (Harley 1999). The recommended exposure limit (REL) in the air at the workplace today is 0,05 mg Uran /m^3 for soluble uranium compounds, representing the upper limit for exposure concentrations that healthy individuals can normally tolerate for eight hours a day five days a week without harmful effects (cf. Table 2). Due to the short biological half-life of soluble DU, the radiation doses are very low, and compared to the chemical toxicity, practically negligible.

Uranium in a **poorly soluble** form remains in the lungs for years. The kidneys are hardly affected, since the mobilized quantity of uranium is very small. In contrast, the radioactivity of DU produces radiation doses in the lungs and bronchi. The ICRP calculates a dose factor of 0.1 mSv/mg for the inhalation of poorly soluble ^{238}U. Therefore, acute radiation damage is not expected, since these doses are too low. An inhaled quantity of e.g. 100 mg DU, which in soluble form would lead to permanent kidney damage, would cause in insoluble form a slight increase in the risk of cancer of about 0.05%. This purely mathematical calculation for small doses is to be understood as a "worst-case"-assessment. In the US-uranium industry, for poorly soluble uranium compounds in the ambient air at workplaces, a recommended exposure limit (REL) of 0.25 mg U/m^3 is applied.

4.3.3. Ingestion of DU

Only between 2% and 5% of uranium in easily soluble form is taken up into the bloodstream from the digestive tract (Fulco 2000). Thus, the threshold value for the occurrence of kidney damage after a single exposure is about ten times higher than for the inhalation pathway. Uranium in the form of uranium oxide, which is poorly soluble in the body, is practically not taken up by the digestive tract, and therefore, even in gram quantities, has no chemical toxic effect.

Since ingested uranium is either not taken up or quickly eliminated by the kidneys, the accumulated DU radiation dose is orders of magnitude less than that through the inhalation pathway. It therefore can practically be neglected compared to the chemical-toxic effect.

4.3.4. Inoculation of DU (uptake through wounds)

When DU is brought directly into the body through wounds, the toxicological effect is also determined by its solubility. Soluble uranium is eliminated by the kidneys. Insoluble DU remains in the tissues for a long time, causing a relatively high, locally limited radiation dose, leading to a slight increase in the long-term risk of cancer. Soldiers staying in the immediate vicinity of armours being penetrated by DU-projectiles, can be hit by DU-fragments. Metallic DU in the body is diluted and mobilised slowly in the course of the time and most of it will eventually be eliminated by the kidneys.

4.3.5. DU and Leukemia

Leukemia, the disease

Leukemia is the generic term for malignant diseases of the white blood cells, i.e. leucocytes. To the leucocytes belong three types of blood cells, each type being divided into subtypes. All these cell types evolve from stem cells of the blood-forming system. According to the number of cell types and their different stage of development, there is a large number of different syndroms subsumed under the term of leukemia. The classification of leukemia follows different criteria, such as the acute or chronic course of the disease or the origin of the cells. Different types of leukemia are found more or less frequently in certain age groups. E.g. the acute lymphatic leukemia is predominantly found in small children.

Causes of Leukemia

There is circumstantial evidence about the causes. Chemical substances are suspected like benzene and alkylating agents, drugs and pollutants, as well as ionising radiation and tumorogenic viruses, like the Human T-cell Leukemia Virus (HTLV) or the Epstein-Barr-Virus, which infiltrate the lymphatic cells. It has been suggested that white blood cells scavenge the DU particles in the lungs and deposit them in the tracheobronchial lymph nodes, part of the immune system. The radiation within the lymph nodes could then damage blood stem cells over long periods causing leukemia. This path towards leukemia cannot be totally excluded, but would have to be rated very, very exceptional. Moreover, there is a whole series of genetic factors and genetic predispositions.
For all these factors neither the clinical relevance is known nor can any single factor be associated to the incidence of a particular type of leukemia.
Opposite the factors bringing on leukaemia, there are the immune system's mechanisms of repair and recovery, which can successfully prevent cancer. The suppression of these immunological mechanisms can be another risk-factor for the occurrence of leukemia. Subtle psychosomatic risk-factors, such as stress, loss of close relatives, anxiety, fears etc. must also be taken into consideration in this context.

DU as an alleged cause of leukemia

When attributing the frequent occurrence of a disease to the action of a noxious substance, here leukemia and DU, it is compelling to compare the number of occurrences in the concerned population with the number of cases in a control group which is the exactest possible replica of the original group in order to find out whether or not there is a statistically significant difference. This

also implies to scrutinize which type of leukemia has been found and its frequency, in order to see if there is an accumulation of a certain type. Such studies are under way, but the results are still pending.
Taken into account the large variety of possible forms of leukemia, it can be practically ruled out, that all these types could be triggered by the same cause, namely uranium.

4.3.6. Summarizing

The expected **external** radiation doses in man by DU are small. If long-lasting direct contacts of one and the same part of the skin with DU are avoided, no health effects are to be feared.

When DU is introduced into the human body, inhalation of DU aerosols and inoculation of DU-fragments are the critical pathways. The ingestion pathway is uncritical.

An acute health risk in exposed persons is practically only to be feared from the **chemical toxicity** of DU and only after intake of larger quantities in soluble form. Hereby, the biological effects expected would be a reversible impairment of the renal functions, possibly even failure of the kidneys.

The **internal** radiation doses which are to be expected especially after inhalation of DU-aerosols are below the dose limits for occupationally exposed persons. The theoretically resulting increase in the incidence of cancer, mainly lung cancer, will not be statistically verifiable.

4.4. Behaviour of DU in the environment

Uranium can be found in relatively large quantities everywhere in the environment (cf. 2.1.1.). Additionally, in the target areas and their surroundings DU has been deposited in form of intact penetrators, fragments or dust.

4.4.1. Penetrators and Fragments

Due to the chemical reactivity of the uranium an oxide layer is formed at the penetrators' or fragments' surface. This oxide layer can get abrased completely or partly by mechanical or environmental effects (wind, rain) which brings about the formation of a new layer. The consequence is a contamination with fine particles of oxidized DU in the soil below the penetrator/fragment. Penetrators from a "no-hit" event which found their way some meters into the ground are less exposed to mechanical influences. In contrast there is the possibility, that the oxidized surface chemically reacts with water, This chemical reaction could either lead to a dissolution of DU or to a removal of the oxide surface. Both can result in a slow disintegration of the uranium metal and a contamination of surface and ground water.

4.4.2. Surface contamination with DU-dust

In general, dusts have a much larger ratio of surface to volume and therefore are more reactive than entire penetrators or fragments. Based on experiences in the Gulf War and on tests with ammunition, the US Army holds the opinion that 90% of DU in case of a hit is deposited in an area of 50 meters around the target (Rostker 2000). These 90% are generated in a first phase while the projectile hits the target and in a second phase by subsequent explosions and when the target is set on fire. The "no-hit" case will result in a substantially smaller contamination. Generally, it can be expected that dust in form of oxides is deposited in the zone around the impact. Dust can partly be raised and carried along by the wind over greater distances.

In a first phase, however, most of the dust remains on the surface, since its density is high even in the form of an oxide. In the next phase, DU-dust will be carried by rain or by natural circulation into the top layer, i.e. the top 10 cm of the soil. In this phase, the uranium oxides' speciation[9)]

[9] speciation: Nature of the chemical composition, as a result of the reaction of the chemical element (here Uranium) with other elements or components existing in its environment (here natural environment)

decides, whether or not the DU can reach deeper layers of the soil or even the ground water. The speciation of DU in the soil is essentially determined by the composition and the pH-value[10)] of the soil and the pH-value of the rain.

4.4.3. Contamination of ground water

The amount of DU that can penetrate into the ground water depends on the solubility of DU-oxides in soil and the subsequent mobility of the DU. This mobility depends on the acidity and reducing properties of the soil, as well as on the hydrological characteristics of the region. Based on geochemical experience the mobility can be usually expected to be very low. Thus, a contamination of ground water by DU could only happen under worst environmental and soil conditions. In such a case, indications of a poor water quality would already exist, based on other relevant elements or parameters**.**

Should there be any suspicion of a contamination of the ground-water, the water could be analysed. Here too, evidence for a DU-contamination would have to be furnished by a change in the natural ratio of the isotopes $^{235}U/^{238}U$ (cf. 2.2.1).

4.4.4. Contamination of the food chain

In order to assess whether or not an area contaminated by DU can be agriculturally exploited, the transfer factors of **table 5** may be applied:

Transfer Soil - biological material		**Transfer biological material - Animal**	
Soil – Food plant	Soil – vegetable	Food plant – milk	Food plant – meat
(Bq/kg) / (Bq/kg) or (mg/kg) / (mg/kg)	(Bq/kg) / (Bq/kg) or (mg/kg) / mg/kg)	Days / kg	Days / kg
0.05	0.005	0.0005	0.0004

Table 5: Factors for the transfer of uranium into the biocycle (HSK 1997)

As an example: A contamination of 10 mg DU/kg soil would result in a contamination of food plants of 0.5 mg DU/kg food plant. With a mean consumption of 65 kg food plant by a cow, this would result in a daily intake in that area of about 30 mg DU, which in turn could yield for the following days a milk containing a maximum of 0.0163 mg DU/kg. It can be seen, that transfer factors from soil to plant are rather small for uranium. The amount of DU deposited in the surface soil or below will be diminished by orders of magnitude on its way into man's food chain.

4.5. Residual problems

In the **vicinity** of the impact point of DU ammunitions, it cannot be excluded that individuals unaware of the contamination and who were exposed for an extended period of time, could have accumulated radiation doses and/or could have incorporated uranium quantities exceeding the internationally recognized limits.

Another problem could arise from **penetrators** and larger fragments lying on the surface. They could be picked up by children, unaware people or trophy hunters, find their way as souvenirs into a showcase or even be used as a toy. Of course it takes more than 200 hours of direct contact with DU to exceed the ICRP recommended skin dose limit of 500 mSv/year for occupational exposures, but since the oxide layer on the penetrator surface is not very stable against mechanical abrasion, a subsequent contamination by DU-oxide dust could result.

[10] pH-value: Measure of the concentration of free hydrogen-ions in a solution

5. Environmental effects observed and to be expected

5.1. Long-term effects

A reliable, comprehensive and scientifically founded judgment on the problem of long term effects of DU on the environment is near to impossible. The main reason is that neither for the Gulf region nor for Bosnia and only on very few and geographically limited areas in Kosovo data are available (UNEP 2001), that would allow such an assessment.

In particular there are no numerical values at all for the spatial distribution and the time histories of DU-aerosol clouds and, with the exception of Kosovo, there are no numerical values for the DU-contamination of the soil. In the target areas only rough estimates can be made about the fate of the penetrators and the numbers of fragments lying on the surface (WHO 2001).

What remains is the finding that the contamination of the soil by the deposition of **fine particles of DU-dust** is the basis for an assessment of long-term effects of DU-oxides on the environment. This dust could in part be resuspended by the wind, but rain and gravity slowly transport the main part into deeper layers of the soil.

Inhalation of resuspended DU in the zone adjacent to the target area, e.g. where a tank was hit by DU, could result in an intake of a maximum of 0.6–60 micrograms of DU (Kaiser 2001). The effective doses of 0.07–7 microsieverts received from this exposure are negligible.

DU deposited as oxide in the soil is expected to be immobile. Concerning the ingestion pathway the EU-group of experts concluded (Kaiser 2001) that due to the very low transfer factors of DU into the biological material even in scenarios with highly contaminated soils, large contaminated areas and a very high consumption of vegetables grown in that contaminated area, the expected dose would be some microsieverts per year, a negligible dose, too.

So far there are no measurements confirming a contamination of ground water by DU, not even close to the zones of attack. Nevertheless, the possibility of a contamination of the **drinking water** in certain areas must be considered, since this is a possible pathway of exposure if very large amounts of DU were on the surface or buried in the soil. A comprehensive assessment, however, yields nothing but very low doses (WHO 2001).

A judgment based on experience with **other pollutants** and similar scenarios would result in estimates of the order of magnitude only.

A verifiable **large-scale contamination of the biosphere** is very unlikely, because compared to the average content of about one metric ton of natural uranium per square kilometer, the contribution from DU is at most locally significant.

5.2. Contamination in the Balkans

In November 2000, the United Nations Environment Program (UNEP) has had a team of Scientific Experts in Kosovo. The mission was to investigate the contamination of some of the 96 sites where DU was used in the Balkans conflict. The team visited eleven of these sites situated in the western and southern parts of Kosovo (Figure 3) and revisited two sites for further in-depth verification. The team was able to measure radioactivity on the sites, take soil and water samples, perform vegetation sampling and took milk samples from cows. The only restriction is that the UNEP-team did not have the opportunity to examine an armoured vehicle hit by DU-ammunition and its immediate surroundings. Correspondingly the study covers only the "no-hit"-case, i.e. the case where the rounds miss their target and penetrate the soil or alternately remain somewhere on the surface.

5.2.1 Field measurements

Field measurement techniques measuring the gamma- and beta-activity allow the detection of "hot spots" arising from the ground impact of DU ammunition i.e. shot holes, penetrators or fragments lying on top of a surface or directly below the surface. Many countries involved in the KFOR-

mission, e.g. Portugal, Greece, Spain and Italy, sent their teams to the Kosovo to measure radioactivity on-site. With the exclusion of the area immediately adjacent to tanks destroyed by DU-ammunition, exposure was considered not distinguishable from the natural background radioactivity (NATO AHCDU 2001) Numerical values for contamination levels have to be determined in laboratories. In five European laboratories uranium studies of the samples were performed using radiochemical methods based on alpha spectroscopy as well as Inductively Coupled Plasma Mass Spectrometry (cf. 2.2). Chemical and isotopic uranium compositions were determined.

5.2.2 Laboratory results

The **natural uranium** level in soil is not a constant value, it depends on the mineralogical composition of a soil, therefore the natural uranium levels of the soils analyzed in the UNEP study, which are in the range of 1.2 to 3.6 mg Uranium per kilogram of soil are representative only for the sites where the samples were taken.

The analysis of **penetrators and jackets** shows a rather constant isotopic composition for DU ammunition and confirms the values published in US military and open literature. The depletion level of ^{235}U in all penetrators investigated has the value of 0.200 % and ^{236}U is present with 0.0028 ± 0.0002 %.

"Hot spots"

The contamination in hot spots varies depending on the hardness of the surface. The highest contamination of a shot hole was found with 7.6 grams of DU per kilogram of soil. The contaminated volume was rather small, with an area of about 10 cm by 10 cm down to a depth of 20 cm. The contaminating penetrator could not be found and below the depth of 20 cm measurements showed no further contamination.

Mean values for the contamination in hot spots are about 1.5 g DU/kg.

The results relating to hot spots allow the following conclusions:

- Only small volumes are contaminated.
- Penetrators hitting a softer surface (soil, asphalt, street) or hitting under an unfavorable angle or hitting a hard object (e.g. large stone) below the surface can result in a contamination by DU of some grams per kilogram of soil for that hole. However, the contaminated volume is small.
- Penetrators hitting a harder surface (e.g. concrete) result in a comparably lower contamination of the hot spot.

DU-Contamination in the area adjacent to a hot spot

The analysis shows that the area around the ground impact of a DU penetrator is contaminated.

In a distance between 1 to 2 meters around a hot spot, contamination levels for DU of 0.5 ± 0.25 mg DU/kg in surface soils (0–5 cm) were found, independently of whether a hard or soft surface had been hit.

Still farther away from the hot spot a difference shows up with regard to the hardness of the surface where the penetrator struck:

- Penetrators hitting a harder surface (e.g. concrete) result in contamination by DU of the top soil of about 0.25 mg DU/kg in an area of at most 50 x 50 meters.
- Penetrators hitting a more or less soft surface (soil, asphalt street) result in contamination by DU of the top soil of below 0.1 mg DU/kg and only in a very close zone around the ground impact not larger than 20 x 20 meters.

These values of the DU-content of top soil are factors below the natural uranium content!

DU-Contamination near penetrators and fragments

The analysis shows that a penetrator lying on a surface contaminates the soil below. In one sample taken from under a penetrator the surface soil 0-10 cm was contaminated with 176 mg DU/kg. This shows that penetrators lying on the surface or slightly below are disintegrating and release DU that afterwards can find its way into the ground water or into the food chain. Therefore UNEP concludes that penetrators, fragments and jackets should be collected by trained personnel and properly disposed of (UNEP 2001).

DU contamination in the form of DU-oxide dust

The only contribution of soluble DU-oxide dust to the contamination of the environment is the small part finding its way into the ground water and finally into drinking water. The UNEP study found no indication of such a contamination.

5.2.3. Summarizing

Summing up the UNEP-report it can be concluded that using DU-ammunition results in a surface contamination with DU-dust. On a few hundred square centimetres around the shot hole or below a penetrator/fragment lying on the surface the uranium content is higher, usually much higher than the natural values. However, the volume of such "hot spot"-contaminations is always small.
It is pointed out that a possible contamination of drinking water must be taken into consideration even if, until now, no such contamination was ever detected. UNEP recommends to periodically analyze drinking water in the zones where a DU-attack had taken place and corroborates the statements of the World Health Organisation (WHO 2001) with numerical data .

In **Bosnia** the DU-contamination and its effects on the environment are not expected to differ significantly from what was assessed in the Kosovo and what was reported in detail by UNEP.

5.3. Contamination in Iraq

For Iraq no analytical data comparable to those of Kosovo exist. In analogy to what is known from the Kosovo it is assumed that "no-hit" cases in the desert result in a contamination of up to 0.1 mg DU per kg of soil in areas of approximately 20 x 20 meters.
In contrast to the situation in Kosovo many armoured vehicles with hard surfaces have been hit during the Gulf War. American findings for such cases give a DU contamination within an area of 50 x 50 meters, where 90% of the penetrator's mass are deposited (NATO LG/7 2001). After a hit, depending on the type of ammunition, the contamination of this area is expected to be between 100 mg and 1800 mg DU per square meter (ca. 1.8–30 mg DU/kg of the top 0-5 cm of soil). This information is given very comprehensively by WHO (WHO 2001).
Based on findings in the Balkans and on the information from the battlefields in Iraq, it is concluded, that as a consequence of a significant number of hits there may exist limited zones of several hundred square meters with contaminations of several 10 mg DU/kg soil. Even for these concentrations no adverse effects on man, animal and environment must be expected (Kaiser, 2001).
There are no indications in the scientific literature that the specific climatic conditions in a desert would change the overall picture on DU in that environment. It could be speculated that, due to the lack of rain, resuspension of DU present in surface soil or sand could play a bigger role. On the other hand, again due to the absence of rain as transportation medium, one could expect that even less DU would reach the ground water.
There is no doubt that the radon concentrations measured by Iraq on some battlefields (Baghdad Conference 1998), originate from natural uranium.

6. Observed health effects on persons exposed to uranium

6.1. General remarks

Three main sources are available by which the effects of uranium and depleted uranium on man can be judged on base of scientifically established knowledge:

1. The results from animal experiments (cf. 5.2)
2. The experiences obtained over decades with the workforce of the uranium industry
3. The studies on certain groups of persons exposed/potentially exposed to DU in Iraq and the Balkans

6.2. Epidemiological studies on the workforce in the uranium industry

There exists a great number of epidemiological studies on health effects in the uranium industry; some of these studies are very comprehensive, involving tens of thousands of occupied persons who had been working with uranium for decades. Many of the exposures to uranium date back to the forties and fifties of the last century. Again for decades medical disorders and diseases in the exposed workforce have been observed. By means of proved and generally accepted statistical methods, the incidences were compared with those in control groups of people not exposed to uranium. A medical committee of the US National Academy of Science, Institute of Medicine (Fulco 2000) has scientifically evaluated more than a hundred of these studies.

The committee classified the evidence for association between exposure to a specific agent and a health outcome into one of five previously established categories. These five categories describe different strengths of association, with the highest level being sufficient evidence of a causal relationship between exposure to a specific agent and a health outcome. (Hill 1971; Evans 1976).

- *Sufficient Evidence of a **Causal** Relationship*
- *Sufficient Evidence of an Association*
- *Limited/Suggestive Evidence of an Association*
  Evidence is suggestive of an association between exposure to a specific agent and a health outcome in humans, but is limited because chance, bias, and confounding could not be ruled out with confidence.
- *Inadequate/Insufficient Evidence to Determine Whether an Association Does or Does Not Exist*
  This amounts to saying that "The available studies are of insufficient quality, consistency, or statistical power to permit a conclusion regarding the presence or absence of an association between an exposure to a specific agent and a health outcome in humans."
- *Limited/Suggestive Evidence of No Association* (The lowest level of association)
  There are several adequate studies covering the full range of levels of exposure that humans are known to encounter that are mutually consistent in ***not*** showing a positive association between exposure to a specific agent and a health outcome at any level of exposure. A conclusion of no association is inevitably limited to the conditions, levels of exposure, and length of observation covered by the available studies. In addition, the possibility of a very small elevation in risk at the levels of exposure studied can never be excluded.

Regarding the health risks of an uranium exposure the committee concludes that there is neither evidence of a relationship nor of an association, only

*....that there is limited/suggestive evidence of **no** association between exposure to Uranium and the following health outcomes:*

- *Lung cancer at cumulative internal dose levels lower than 200 mSv (.....), or*
- *Clinically significant renal dysfunction*

The committee concludes that there is inadequate/insufficient evidence to determine whether an association does or does not exist between exposure to Uranium and the following health outcomes:

- *Lung cancer at higher levels of cumulative exposure (> 200 mSv …….)*
- *Lymphatic cancer*
- *Bone cancer*
- *Nervous system disease*
- *Non-malignant respiratory disease or*
- *Other health outcomes (gastrointestinal disease,immune-mediated disease, effects on hematological parameters, reproductive or development dysfunction, genotoxic effects, cardiovascular effects, hepatic disease, dermal effects, ocular effects or musculoskeletal effects) (Fulco 2000).*

This means that not even a limited evidence of an association between exposures to uranium and the primarily expected diseases – lung cancer and clinically significant damage of the kidney functions – could be demonstrated. On the other hand, the possibility of a slight increase in the risk can never be entirely ruled out, not even if tens of thousands of workers have been under medical observation for decades. The fact, that there is no evidence of an association between exposures – sometimes high and lasting since the beginning of the uranium industry – and health damages such as bone cancer, lymphatic or other forms of leukemia shows that these diseases as a consequence of an uranium exposure are either not present or very exceptional.

This review of the state of knowledge by an institution of irreproachable reputation represents, according to the authors' opinion, today's "ultima ratio" when health risks of a DU-incorporation are to be assessed.

6.3. Epidemiological studies on persons/groups exposed to DU

Table 6 refers to the different ways of use and to the different groups of persons exposed/potentially exposed to DU. Reliable epidemiological studies exist only in context with British and US soldiers in the Gulf War and the members of humanitarian organizations and peace keeping forces in the Balkans.

Battlefield	**Way of use/amount [tons]**		**Persons/groups exposed to DU**			
	Ground to ground	Air to ground	Attacker	Enemy	Population	"Help Forces" (KFOR, (SFOR, UNMIC etc)
Irak	50	250	X*	X	X	-
Bosnia	-	3.3	-	X	X	X
Kosovo	-	10	-	X	X	X

Table 6: Groups of persons exposed to DU. The shaded boxes denote groups of persons for which reliable medical data exist

* "friendly fire" incidents and "clear-up" troops

6.3.1. Soldiers of the operation "Desert Storm" in the Gulf War

Based on experiments in the US, it has been calculated that the crew of a tank, which has been hit by DU projectiles, could have inhaled about 50 mg uranium aerosols. This could eventually lead to small, reversible toxic effects on the kidneys as well as to a relatively insignificant internal radiation dose below that of the yearly dose limit for occupationally exposed persons (Rostker 2000).

During the operations in the Gulf in 1991, some US-American tanks came under fire with DU-ammunition by their own troops ("friendly fire") and were hit. Among the approx. 100 surviving crew members exists a group of about 30 persons who live with DU fragments embedded in their body, fragments which cannot be removed. The very slow continuous mobilization of the uranium from the fragments leads to an increased excretion of uranium via the urine. In spite of that, the intensive medical tests during the decade since the event have shown no health damages which could be related to DU. This means that the undoubtedly existing, permanent and relatively high systemic[11)] strain by DU has neither resulted in adverse effects on the kidneys nor in radiation induced neoplastic[12)] diseases like cancer and leukemia. Insofar these results seem to confirm what has been expected, however the medical monitoring will be carried on (Harley 1999).

There are tank crews from the "friendly-fire" group who were not hit by fragments as well as another, much larger group of Gulf War veterans who spent time in the vicinity of hit tanks and burning ammunition or who entered such places afterwards. About the DU-burden of those groups can, up to now, be made some rough estimates at the most, because neither data on exposures to DU nor dose calculations exist. This also holds for personnel, who had been involved in repair, service and clear-up work and at first had not been working according to civil norms. Here the opportunity was missed to measure the DU-intake of the persons concerned. This could have been done by analysing of the persons' urine on the first days after the exposition. It can however be estimated that the DU-intake in these groups must have been much lower than the intake by those persons exposed to "friendly fire", presumably not more than one tenth. Studies carried out during the past few years on a sample of this group have shown (McDiarmid 2001) that today a DU-excretion cannot be detected any more.

A remark to the Gulf War Syndrome

After several years, in many Gulf War veterans health problems cropped up, which became known as "Gulf War Syndrome". The DU-intake by these veterans could be estimated within an order of magnitude. When the facts were compared with the comprehensive epidemiological data from the uranium industry, it turned out, that the syndrome could not be explained by the uranium exposure.

In a retrospective study over the period from 1991 to 1999, the state of health, the incidence of diseases and the mortality rate of all 53'462 UK Gulf War Veterans were examined (Macfarlane 2000). The control group consisted of armed forces personnel, who had not participated in the Gulf War. This group was equivalent in size, age, gender, rank, service branch and level of fitness to the group of veterans. In doing so the "healthy soldier effect" could be avoided, consisting in a comparison of a generally healthier population of soldiers with a population of possibly less healthy civilians.

During this period 53 veterans and 48 persons from the control group have died from cancer. This excess is statistically not significant and no increase of a single type of cancer or group of cancerous diseases could be observed. It has been conceded however, that a follow-up time of eight years is presumably too short in order to detect a possible increase in the number of deaths by cancer.

6.3.2. Iraqi soldiers

On the occasion of a conference in Baghdad in 1998, an Iraqi report was presented (Baghdad Conference 1998), in which an association is postulated between the incidence of cancer among

[11] systemic: concerning the organism as a whole.

[12] neoplastic: tumorous.

Iraqi soldiers and their stay in areas where DU-ammunition had been used. The published figures show above all a general increase in all types of cancer which have been diagnosed in the period, not only among the potentially exposed but also among the groups of persons not exposed. The report contains some mistakes and inconsistencies and it appears unlikely that it would withstand a critical scientific "peer review". Therefore, an association between DU-exposition and cancer in Iraqi soldiers cannot be substantiated on grounds of this study. Undoubtedly a more accurate study on the health effects of DU on the surviving Iraqi tank crews would be a worthwhile task. The authors are not aware of any plans for such studies.

6.3.3. Iraqi civilians

To our knowledge there are no studies on the health effects of DU-ammunition used in the Gulf War on the Iraqi civilian population that would withstand a critical scientific peer-review. According to a recent press release (Washington Post 2001) the WHO has sent an expert team to Iraq in order to analyse the health situation of Iraq's population.

6.3.4. Soldiers of the KFOR

In January 2001 a report was published on a screening among soldiers of the German army contingent (Roth 2001). Herein soldiers were examined that had been exposed to a potential risk of incorporation because they had been working in the DU target areas. The analysis concentrates on the excretion of uranium in the soldiers' urine. It was found, that the excretion of uranium was statistically not different from that of a control group, who had been working outside the target areas. Almost all readings were in the range of reference for persons not exposed at all. From this it follows that there are no signs of a DU incorporation by soldiers of the KFOR during their mission in Kosovo. This corresponds with the results of an environmental study by UNEP (UNEP 2001) in which no widespread surface contamination in the target areas could be found, and it is also consistent with the fact that uranium aerosols deposited on the ground are quickly carried into the soil by climatic influences. Resuspension later on and a subsequent inhalation of the uranium then become rather unlikely.

The postulated association between uranium exposition and leukemic diseases in soldiers of KFOR and SFOR contingents in Kosovo and Bosnia is a matter of current investigations. To this end, a careful medical diagnosis of all diseases which have occurred and a statistical comparison with the spontaneous incidence of leukemia in a representative control group must be carried out. Moreover, other environmental factors than DU which can induce leukemia must be taken into account. Without an indication of a direct link it would be merely possible to establish an association between the incidence of leukemia and a stay in the Balkans. Preliminary results of a study on about 40'000 Italian soldiers, who were stationed in the Balkans between 1995 and 2001 have been published (Mandelli 2001). It is true that the rate of Hodgkin's disease and acute lymphoblastic leukemia is two to three times higher among the soldiers than among the Italian control population, however, owing to the small number of cases (nine cases versus an expected value of four and two cases instead of one) this excess is statistically not significant. On the other hand, taken the sum of all cancerous diseases, the rate among the soldiers is about a factor of two lower than the rate in the control population. There will be a follow-up, extended to troop contingents of other states. With this the conclusive power of the statistics will be increased.

6.3.5. Civilian population in Kosovo

In Kosovo, there are no useful health registers covering the past few years. This was stated in January 2001 by a mission of the WHO (WHO 2001). As a consequence, it is not possible at the moment to determine a possible change in the rate of diseases like leukemia and other cancers, which would have occurred since the war.

6.3.6. Soldiers and civilian population in Bosnia

With respect to the SFOR troops stationed in Bosnia, the statements of chapter 7.3.4 also apply here. Concerning the health effects of DU-ammunition on the civilian population living in Bosnia, there are rumours as well as written allegations e.g. about an increase in the cases of cancer. However, no peer-reviewed studies were available to the authors. It may be supposed, that also in Bosnia, inadequate health registers would be an obstacle for working out health studies.

6.3.7. Summarizing

From all the studies published up to now, the conclusion must be drawn that there exists no scientifically proven evidence for health damages in the civilian population or in soldiers due to the use of DU-ammunition in the Gulf War and in the war on the Balkans.

7. Findings

The following statements are valid only for the DU-contaminations in the battlefields of Iraq and the Balkans which have been calculated, estimated and, in Kosovo, measured, taking into account the amount of DU-ammunition engaged. They should not be generalized.

External irradiation by DU

In the former battlefields, DU makes only a tiny contribution to the omnipresent external radiation from natural sources. However, long-lasting direct skin contact with DU-penetrators/fragments should be avoided.

Inhalation of DU-aerosols

The inhalation of DU-aerosols is the critical pathway for human exposure. If there is any damage at all, then this is the relevant pathway. Depending on the solubility of the incorporated DU either radiotoxic or chemically toxic effects dominate. Target organs are primarily the lungs and the kidneys. An acute health risk is only to be feared from the chemical toxicity of DU and only after inhalation of relatively large quantities.

Ingestion of DU

The health risk resulting from an ingestion of DU is negligible.

Inoculation of DU (uptake through wounds)

Inoculation of DU-fragments may pose a problem for tank crews. In soldiers with such fragments in their bodies no adverse health effects have been observed so far.

Leukemia

Neither by animal experiments nor by epidemiological studies on man, an association between an incorporation of natural uranium or DU and the incidence of leukemia has been found.

Leaching of DU into the ground water

Taking into consideration the amount of natural uranium in the soil, neither a health risk stemming from a contamination of the ground water nor a health risk arising from a contamination of drinking water is to be expected.

Intermediate and long-term effects of DU on man

To the best epidemiological knowledge available today there is no link between an incorporation of DU and the incidence of cancer or renal failure. Radiation induced defects in the substances carrying the genetic information leading to an increase in the number of stillborns and deformities in newborns are not to be expected, since the possible doses to the reproductive organs are very small.

Intermediate and long-term effects of DU on the environment

In view of the low mobility of uranium in the soil and the small transfer factors into biological material neither intermediate nor long-term effects on the environment are expected.

Summarizing

The authors conclude that the use of DU ammunition in Iraq and the Balkans neither has led to a serious widespread contamination of the environment nor represents an acute or appreciable long-term hazard for man's health.

References

Andrew, S.P., Caliguri, R.D., Eiselstein, L.E., 1992, "Relationship Between Dynamic Properties and Penetration Mechanisms of Tungsten and Depleted Uranium Penetrators", 13th International Symposium on Ballistics. Stockholm.

ATSDR (Agency for Toxic Substances and Disease Registry), 1999, *Toxicological Profile for Uranium,* GA: ATSDR, Atlanta.

Baghdad Conference 1998, Conference on Health and Environmental Consequences of Depleted Uranium used by U.S. and British forces in the 1991 Gulf War,
http://asterix.phys.unm.edu: 8000/dureport/dureport.html
http://www.web-light.nl/VISIE/DUREPORT/mirror_dureport.html

Benedict, M., Pigford, T.H., Levi, H.W., 1981, *Nuclear Chemical Engineering,* p. 487.

Brady, H.R., et al., 1989. "Early effects of uranyl nitrate on respiration and K^+ transport in rabbit proximal tubule", *Kidney Int.,* 36(1) pp. 27-34.

Cross F.T., et al., 1981b, "Histopathologic, Morphometric, and Physiologic Investigation of Lungs of Dogs Exposed to Uranium-Ore Dust", Richland, W.A., Batelle Pacific Northwest Labs, PNL-SA-9927. Available from the National Technical Information Service, DE82003855/XAB.

Cross, F.T., et al., 1981a, "Development of lesions in Syrian golden hamsters following exposure to radon daughters and uranium ore dust", *Health Phys.,* 41(1) pp. 135-153.

DOE, 1963, "Plutonium Content of Depleted Uranium", http://www.oakridge.doe.gov/Foia/GDP-0002.awd

European Commission, Directorate-General Environment, Kaiser, S., 2001, *Opinion of the Group of Experts Established According to Article 31 of the Euratom Treaty Depleted Uranium*

Evans, A.S., 1976, "Causation and disease: The Henle-Koch postulates revisited", *Yale J Biol Med* 49(2), pp. 175-195.

Filippova, L.G., Nifatov, A.P., Liubchanskii, E.R., 1978, "Some of the long-term sequelae of giving rats enriched uranium", *Radiobiologia* 18(3), pp. 400-405.

Fulco, C.E., Liverman, C.T., Sox, H.C., 2000, *Gulf War and Health.* Vol 1. *Depleted Uranium, Pyridostigmine Bromide, Sarin, Vaccines. Committee on Health Effects Associated with Exposures During the Gulf War,* Division of Health Promotion and Disease Prevention, Institute of Medicine, National Academy Press, Washington D.C., ISBN 0-309-07178-X.
http://books.nap.edu/html/gulf_war/ch4.pdf

Geering, J.J. et al., 1999, "Mesures de plutonium et d'américium dans l'environnement", *Umweltradioaktivität und Strahlendosen in der Schweiz.*

Gilman, A.P., et al., 1998b, "Uranyl nitrate: 91-day exposure and recovery studies in the male New Zealand white rabbit", *Toxicol Sci* 41(1), pp. 138–151.

Gilman, A.P., et al., 1998c, "Uranyl nitrate: 91-day toxicity studies in the New Zealand white rabbits", *Toxicol Sci* 41, pp. 129–137.

Gilman, A.P., et al., 1998a, "Uranyl nitrate: 28-day and 91-day toxicity studies in the Sprague-Dawley rat",. *Toxicol Sci* 41, pp. 117–128.

Green, N., Wilkins, B.T., 1993, "An Assessment of Rapid Methods of Radionuclide Analysis for Use in the Immediate Aftermath of an Accident", *Monitoring and Surveillance in Accident Situation,* Chadwick, K., Menzel, H., Eds, Rep. EUR 12557 EN, Commission of the European Communities.

GSF (Forschungszentrum für Umwelt und Gesundheit) 2001, "Kein Plutonium in Urangeschoss", http://www.gsf.de/Aktuelles/Presse/plutonium.phtml

Harley, N.H., et al., 1999. *Depleted Uranium: A Review of the Scientific Literature as it pertains to Gulf War Illnesses,* Santa Monica, CA: RAND.
http://www.rand.org/publications/MR/MR1018.7/MR1018.7.html

Hill, A.B., 1971, *Principles of Medical Statistics,* Oxford University Press, New York.

HSK (Hauptabteilung für die Sicherheit der Kernanlagen), 1997, "Berechnung der Strahlenexposition in der Umgebung aufgrund von Emissionen radioaktiver Stoffe aus Kernanlagen", HSK-R-41/d.

IAEA (International Atomic Energy Agency), 1989, "Measurement of Radionuclides in Food and the Environment: a Guidebook", *Technical Report Series* No. 295, Vienna.

IAEA (International Atomic Energy Agency), 1999, "Generic Procedures for Monitoring in a Nuclear or Radiological Emergency", *TECDOC-1092,* Vienna.

ICRP (International Commission on Radiological Protection), 1975, *Report of the Task Group on Reference Man.,* ICRP Publication No. 23, Pergamon Press, Oxford.

ICRP, 1989-1996, "Age dependent Doses to Members of the Public from Intake of Radionuclides", ICRP Publications 56, 67, 69, 71 and 72.

ICRP, 1990, "Recommendations of the International Commission on Radiological Protection", ICRP Publication No. 60, ISBN 008 0411 444.

ICRP, 1994, "Human Respiratory Tract Model for Radiological Protection", ICRP Publication No. 66, *Annals of the ICRP* 24(1-3), Pergamon Press, Elmsford, NY.

Labor Spiez, 2001a, "Weitere Informationen zu DU", http://www.vbs.admin.ch/acls/d/h_info/du/information.htm

Labor Spiez, 2001b, "Plutonium - Messungen an Munition aus abgereichertem Uran", http://www.vbs.admin.ch/acls/d/h_info/du/medieninfo.htm

Leach, L.J., et al., 1970, "A five-year inhalation study with natural uranium dioxide (UO_2) dust. I. Retention and biologic effect in the monkey, dog and rat", *Health Phys*, 18(6), pp. 599-612.

Leach, L.J., et al., 1973, "A five-year inhalation study with natural uranium dioxide (UO_2) dust. II. Postexposure retention and biologic effects in the monkey, dog and rat", *Health Phys.* 25(3), pp. 239-258.

Llobet, J.M., et al., 1991, "Influence of chronic exposure to uranium on male reproduction in mice", *Fundam. Appl. Toxicol.,* 16(4), pp. 821–829.

Macfarlane, G.J., Thomas, E., Cherry, N., 2000, "Mortality among UK Gulf War veterans", *The Lancet,* 356, pp. 17-21.

Magness, L.S., Farrand, T.G., 1990, "Deformation Behavior and Its Relationship to the Penetration Performance of High-Density KE Penetrator Materials", Ballistic Research Laboratory, Aberdeen Proving Ground, MD. 21005-5066.

Mandelli, F. et al., 2001, "Relazione preliminare della commissione istituita dal ministro della difesa sull'incidenza di neoplasie maligne tra i militari impiegati in Bosnia e Kossovo", http://www.difesa.it/ministro3/relazione%20mandelli.pdf

McDiarmid, M.A., Engelhardt, S.M., Oliver, M., 2001, "Urinary Uranium Concentrations in an enlarged Gulf War Cohort", *Health Phys*. 80(3), pp. 270-273.

Miller, A.C. et al., 1998, "Urinary and serum mutagenicity studies with rats implanted with depleted uranium or tantalum pellets", *Mutagenesis* 13(6), pp. 643-648.

NATO 2001a, "Map of Depleted Uranium Engagement Points, 6 Apr 99 - 10 Jun 99", http://www.nato.int/du/graphics/b010124k.jpg

NATO 2001b, "Data concerning the locations of depleted uranium ordnance expended during Operation Allied Force (grid co-ordinates)", http://www.nato.int/du/docu/d010124a.htm

NATO 2001c, "Map of Depleted Uranium Engagement Points, 5 Sept 95 - 11 Sept 95", http://www.nato.int/du/graphics/b010124b.jpg

NATO 2001d, "Data concerning the locations of depleted uranium ordnance expended during Allied Operations Deny Flight-Deliberate Force, 1993-95 in Bosnia (grid co-ordinates)", http://www.nato.int/du/docu/d010124b.htm

NATO AHCDU (Ad Hoc Committee on Depleted Uranium), 2001, AHCDU-N(2001)24.

NATO LG/7, 2001, "Depleted Uranium (DU): Technical and Operational Aspects".

Ortega, A., et al., 1989, "Evaluation of the oral toxicity of uranium in a 4-week drinking water study in rats", *Bull. Environ. Contam. Toxicol*., 42, pp. 935-941.

Paternain, J.L., et al., 1989, " The effects of uranium on reproduction, gestation, and postnatal survival in mice", *Ecotoxicol. Environ. Saf.,* 17(3), pp. 291–296.

Pellmar, T.C., et al., 1999, "Electrophysiological changes in hippocampal slices isolated from rats embedded with depleted uranium fragments", *Neurotoxicology* 20(5), pp. 785-792.

Ramachandra, K.B., 2000, "Tank-Automotive and Armaments Command (TACOM) and Army Materiel Command (AMC) Review of Transuranics (TRU) in Depleted Uranium (DU) Armor. U.S. Department of the Army", AMSAM-TMD-SB.

Rostker, B., 2000, "Environmental Exposure Report, Depleted Uranium in the Gulf (II)", http://www.gulflink.osd.mil/du_ii/

Roth, P., Werner, E., Paretzke, H.G., 2001, "*Untersuchungen zur Uranausscheidung im Urin,* Überprüfung von Schutzmassnahmen im Deutschen Heereskontingent KFOR" GSF- Bericht 3 /01, http://www.gsf.de/Aktuelles/Presse/uran.pdf

Spector W.S., 1956, *Handbook of toxicology*, Vol. I. "Acute toxicities", W.B. Saunders Company, Philadelphia, PA., p. 310.

UNEP (United Nations Environment Programme) 2001, *Depleted Uranium in Kosovo,* Post-Conflict Environmental Assessment, UNEP Scientific Mission to Kosovo, 5 -19 November 2000. www.unep.ch/balkans/du/reports/report.html

Volchok, H.L., de Planque, G. (Eds), 1982, HASL-300, Environmental Measurements Laboratory, New York.

Washington Post 2001, *WHO to Test Health Effects of Depleted Uranium in Iraq,* March 15, p. A20.

WHO (World Health Organization) 1998, *Guidelines for drinking-water quality,* 2nd ed., Addendum to Vol. 2, "Health criteria and other supporting information".

WHO (World Health Organization) 2001, "*Depleted Uranium and Health",* Report of the World Health Organization Depleted Uranium Mission to Kosovo, Final Draft.

Zajic, V.S., 1999, *Review of Radioactivity, Military Use, and Health Effects of Depleted Uranium.* http://members.tripod.com/vzajic/

Keller, M., Anet B., Burger M., Wicki A., Wirz Ch.

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