WISE Uranium Project - FAQ

Depleted Uranium in Urine of Soldiers

Contents

Why is DU dangerous?

It is radioactive, and it is toxic.
Depleted uranium (DU) is a waste from the uranium enrichment process used for nuclear fuel and nuclear weapons production. In the U.S. alone, more than 700,000 metric tonnes are currently stored in the chemical form of uranium hexafluoride (UF_6). It is called „depleted“, since the abundance of the fissile uranium-isotope U-235 is lower than in natural uranium, where it has 0.71 weight-percent.

Some of the depleted uranium stored in the U.S. has been converted to uranium metal, alloyed with titanium, and manufactured into ammunition, but also into tank armor. Due to their high density and strength, uranium weapons are capable to penetrate heavy armor. Their first reported use in the battlefield was in the 1991 Gulf War.
Upon impact with heavy armor, a DU penetrator becomes partly aerosolized. The dust ignites due to the pyrophoricity of finely divided uranium metal, and thus converts into a dust composed of various uranium oxides. This dust might get inhaled by surviving tank crews, from bystanders, or rescue personnel. And, specific hazards exist from embedded DU shrapnel.

As a radioactive substance, incorporated uranium presents a radiation hazard - mainly to the lung, and, as a heavy metal, it is toxic - mainly for the kidney.
These are only the main hazards. Other hazards currently under investigation are, for example, its potential to cause chromosome aberrations [Schröder 2003], and its reproductive and developmental toxicity [Domingo 2001]. A comprehensive review of uranium toxicity is compiled in [ATSDR 1999].

In addition, there also exists an external radiation hazard from DU, mainly for crews in tanks fully loaded with DU ammunition or equipped with DU armor. This paper, however, only looks at the hazard from incorporated DU.

What happens to the DU once it gets into the body?

There exist three major exposure pathways: inhalation, ingestion, and embedded shrapnel. Each of them has to be looked at separately.

Inhalation

Upon inhalation, a fraction of the material is deposited in the lung, where it irradiates the lung tissue. The fraction of the material reaching the radiation-sensitive areas of the lung is depending on the particle size distribution of the dust, in particular of its respirable fraction.
Via dissolution, the material slowly reaches the blood and is transported to other organs, where it forms smaller secondary deposits. Excretion occurs via exhaust, faeces and urine.

Single inhalation of moderately soluble uranium (Type M): most of the inhaled material is excreted, via exhaust, faeces, and, to a minor degree, urine. The organ holding the largest uranium deposit by far is the lung (thoracic airways). Minor amounts are deposited in bones, kidney and other soft tissue. After approx 3 years, the lung deposit is cleared, and the bones remain the organ with the largest residual uranium deposit, see Fig.1 (note logarithmic time scale!). For a zoom-in after 500 days, see Fig. 2.
Note: these are stacked diagrams, so the total amount retained in the whole body after 1 day would be

330 µg. In addition to the amounts retained in the organs, the amounts of uranium excreted in faeces and urine cumulated over time are shown in pastel colors; the remainder not accounted for is the cumulated exhalation.

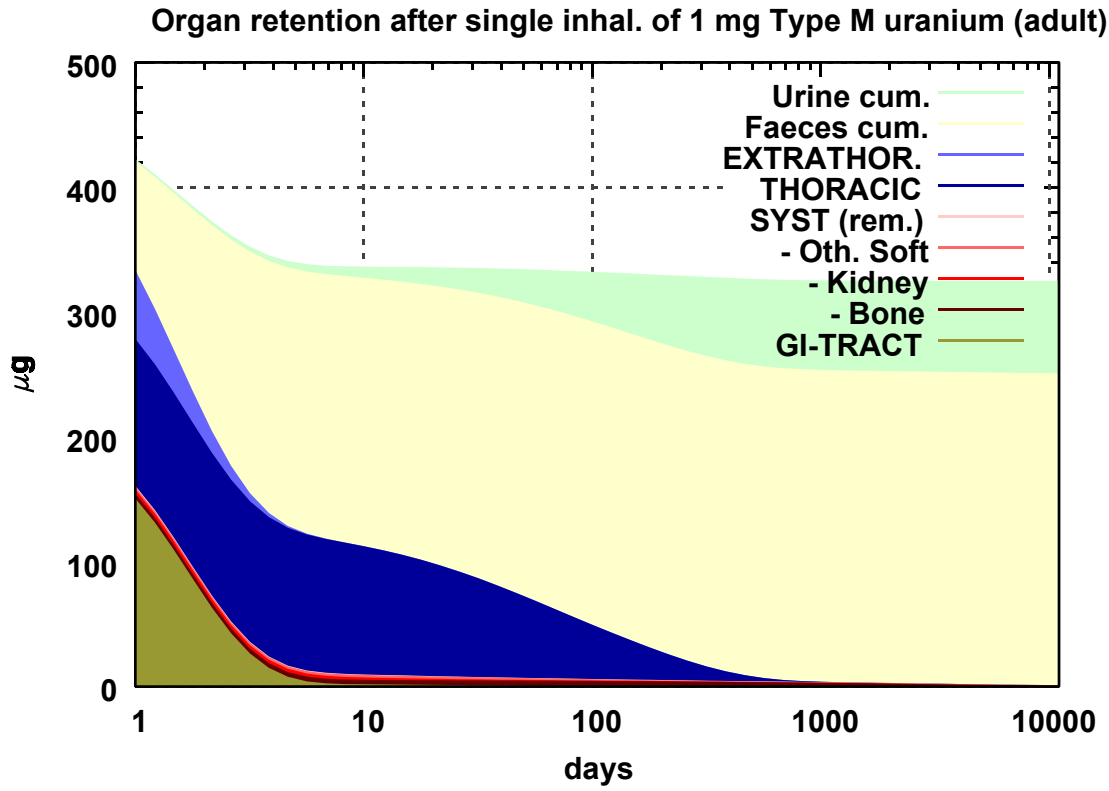


Fig.1

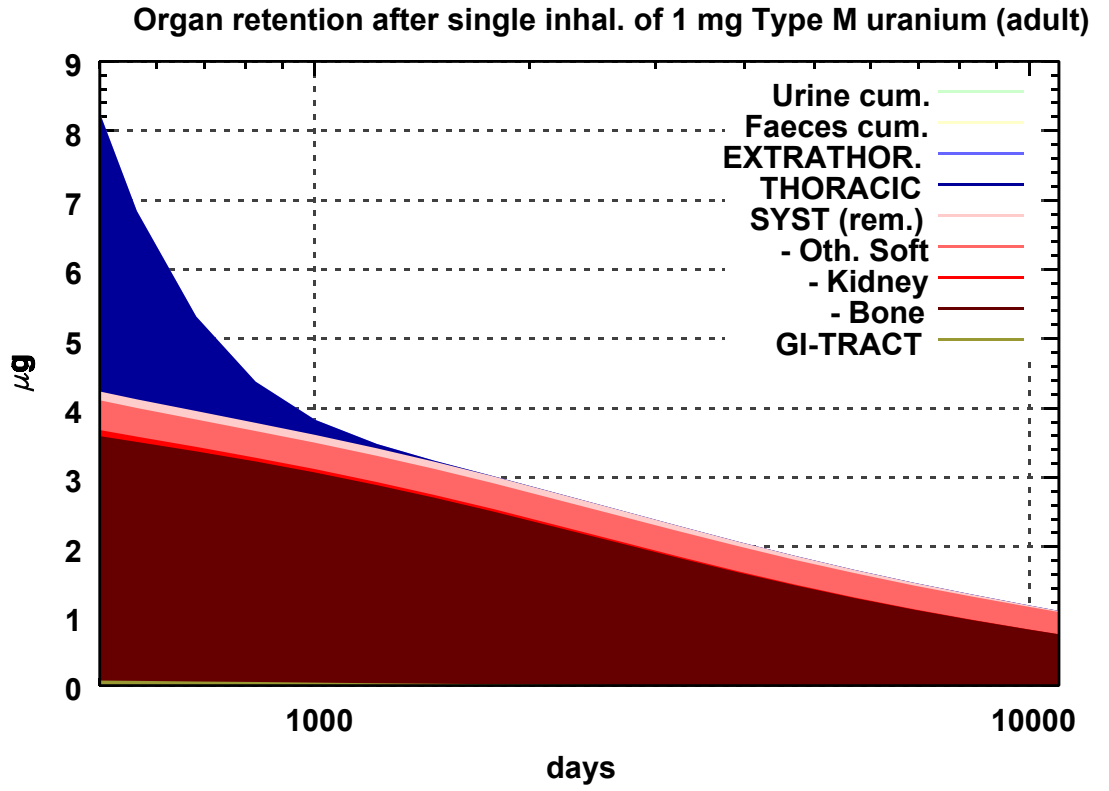


Fig.2

Single inhalation of slowly soluble uranium (Type S): The fraction deposited in bones and soft tissue is even smaller, the clearance of the lung takes longer, the excretion via urine is smaller, see Fig.3 (stacked diagram).

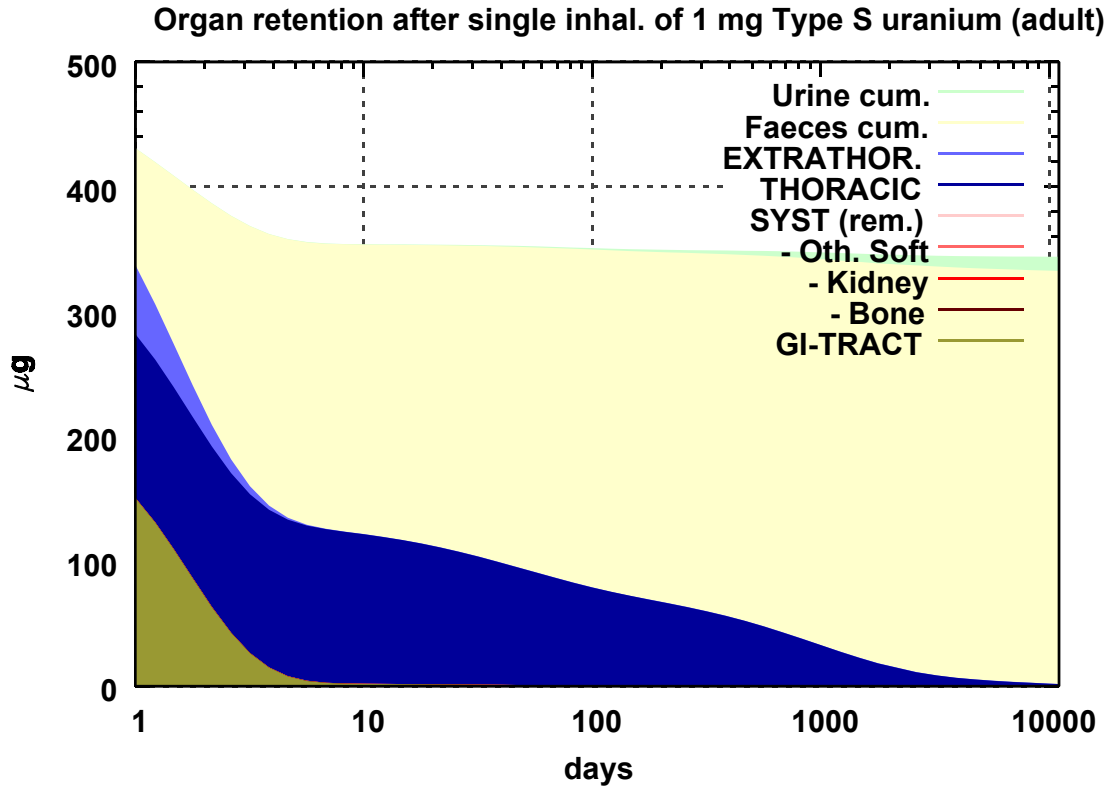


Fig.3

As now has been shown that the behavior of incorporated uranium depends on its chemical properties, a closer look at these properties is warranted.

Chemical compound composition of respirable fraction

Upon impact with a hard target (such as tank armor), some fraction of a DU penetrator aerosolizes. Due to the pyrophoricity of finely divided uranium metal, the particles burn and form various uranium oxides. Tab.1 shows some data of the chemical compound composition of DU dust, as obtained from penetrator impact tests.
In all cases, a mix of oxides was found, with varying percentages of UO_2, U_3O_8, and other oxides.

Data on DU burn tests by [Elder 1980] shows mostly U_3O_8, with only max. a few percent UO_2.

Tab.1: Chemical compound composition of DU dust [weight %]

DU Penetrator impact				
	UO_2	**U_3O_8**	**other**	**Reference**
	9%	44%	47% U_3O_7	[Mitchel 2004]
	-	30-40%	25-40% U_4O_9 20% UO_3	[Chazel 2003]
settled, bulk	97%	3%	-	[Scripsick 1984]
settled, respirable	54%	46%	-	
airborne, bulk	60%	40%	-	
airborne, respirable	18%	62%	20% amorphous	
	25%	75%	-	[Glissmeyer 1979]

Lung absorption parameters of compounds of interest

For the purpose of ICRP's biokinetic model, the dissolution characteristics of inhaled material are described by three parameters:

- f_r (fraction of material undergoing rapid dissolution),
- s_r (dissolution rate for rapid component, as fraction per day), and
- s_s (dissolution rate for the remainder - the slow component, as fraction per day).

These parameters can be determined from *in vitro* experiments with simulated lung fluid, or from *in vivo* experiments with rats. Most experiments are limited to 30 or 60 days, so the accuracy of the slow dissolution rate is rather limited. See also the comments found under References. Tab.2 compiles data obtained from DU penetrator impact tests and DU burn tests, and data on uranium compounds found in the nuclear fuel industry.

For comparison, the ICRP default parameter sets with the classification for the uranium compounds are given in Tab.3.

Tab.2: Lung absorption parameters of uranium dust

DU Penetrator impact test				
	f_r	**s_r [1/d]**	**s_s [1/d]**	**Reference**
tank turret	0.57	0.07	0.00034	[Chazel 2003]
tank glacis	0.47	0.06	0.00018	
settled	0.04	1.7	0.0014	[Scripsick 1984]
airborne	0.25	4.7	0.0040	

DU Burn test				
	f_r	**s_r [1/d]**	**s_s [1/d]**	**Reference**
A774-2	0.07	0.65	0.0019	[Scripsick 1985] (samples burnt at different temperatures and conditions)
A774-4	0.06	0.35	0.0021	
A774-5	0.10	3.5	0.0023	
M774-1	0.08	4.8	0.0017	
M774-1	0.07	6.6	0.0017	
N774-1	0.09	9.6	0.0034	
Sample #1	0.006	10	0.00049	[Mishima 1985] [a)]
DU5			0.0017	[Crist 1984] (samples burnt at different temperatures)
DU9			0.0032	
Industrial uranium compounds				
	f_r	**s_r [1/d]**	**s_s [1/d]**	**Reference**
Oxide area	0.15	0.0064	< 0.00023	[Metzger 2004] (airborne uranium in various process areas inside a uranium recycling plant)
Punch area	0.17	0.0077	0.0042	
Forming area	0.07	0.24	0.0029	
Shear area	0.06	0.046	< 0.00023	
Crucible area	0.14	0.030	0.0050	
UO_3	0.71	0.28	0.0011	[Ansoborlo 2002]
	0.92	1.4	0.0036	[Hodgson 2000] / [Stradling 1985]
U_3O_8	0.065	36	0.0037	[Pellow 2003]
	0.046	2.25	0.0012	[Ansoborlo 2002]
	0.03	2.07	0.00038	
	0.044	0.49	0.00035	[Hodgson 2000] / [Stradling 1987]
UO_2	0.03	1.25	0.0015	[Ansoborlo 2002]
	0.01	nd	0.00049	
	0.01	nd	0.00058	
UO_2 non-ceramic	0.011	0.95	0.00061	[Hodgson 2000] / [Stradling 1988]
UO_2 ceramic	0.008	1.3	0.00026	
WHO DU Default				
	f_r	**s_r [1/d]**	**s_s [1/d]**	**Reference**
DU Default	0.2	1	0.001	[WHO 2001]

[a)] own fit analysis
nd: not determined

Tab.3: ICRP Default Lung absorption types [ICRP 1994a] [ICRP1994b]

	f_r	s_r [1/d]	s_s [1/d]	**Uranium compounds**
Type F (fast)	1	100	-	Most hexavalent compounds, eg. UF_6, UO_2F_2 and $UO_2(NO_3)_2$
Type M (moderate)	0.1	100	0.005	Less soluble compounds, eg. UO_3, UF_4, UCl_4 and most other hexavalent compounds
Type S (slow)	0.001	100	0.0001	Highly insoluble compounds, eg. UO_2 and U_3O_8

It can be seen that the absorption parameters of uranium dust from various sources (penetrator impact tests, burn tests, and industrial compounds) in most cases reported are somewhere between ICRP's Type M and Type S. Remarkably, the dissolution rate of the slow component is faster than Type S for all values explicitly listed. To facilitate biokinetic modeling, WHO has proposed a default absorption parameter set for DU dust [WHO 2001].

For DU dust from penetrator impact tests, the absorption characteristics are plotted in Fig.4, in comparison to Type M and S, and to WHO's DU Default proposal. For times since exposure of up to approx. 3 years, the fraction retained tends to be closer to that for Type M for all materials, while later some materials come closer to Type S. Moreover, the relative differences are increasing considerably for the longer times.
For DU dust from burn tests, the plots are shown in Fig.5: they all are scattered between Type M and Type S. The plots for industrial uranium compounds are shown in Fig.6: while UO_2 and U_3O_8 again are in between Type M and Type S, the UO_3 samples dissolve considerably faster than Type M.

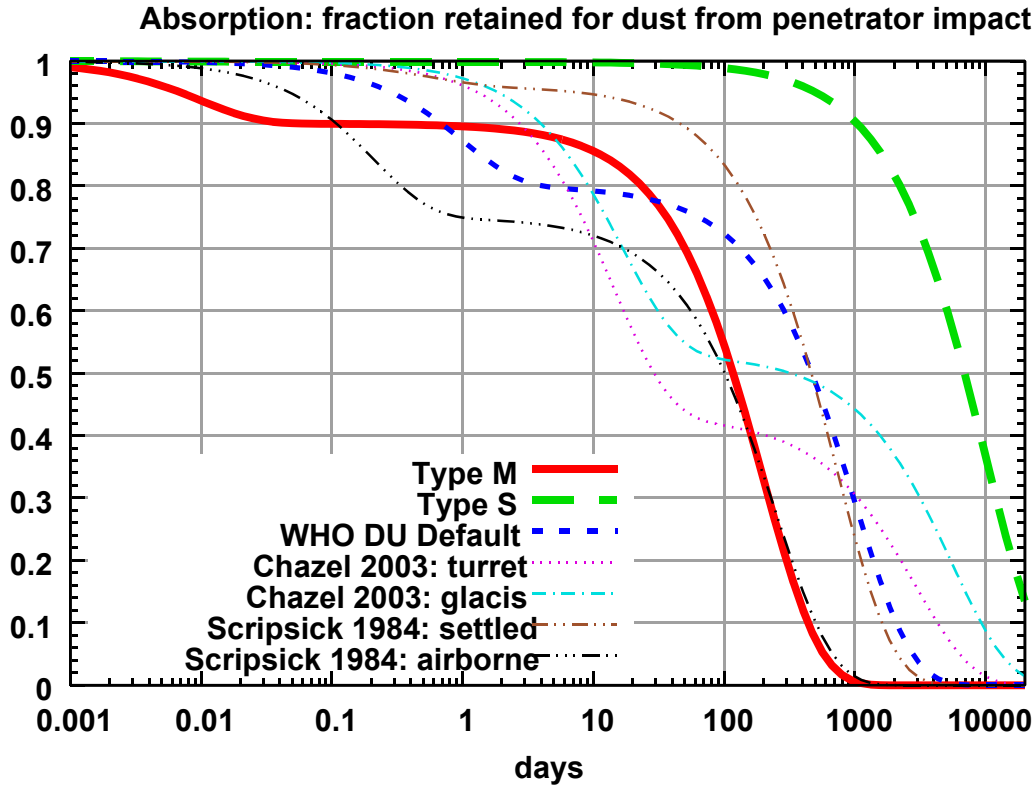


Fig.4

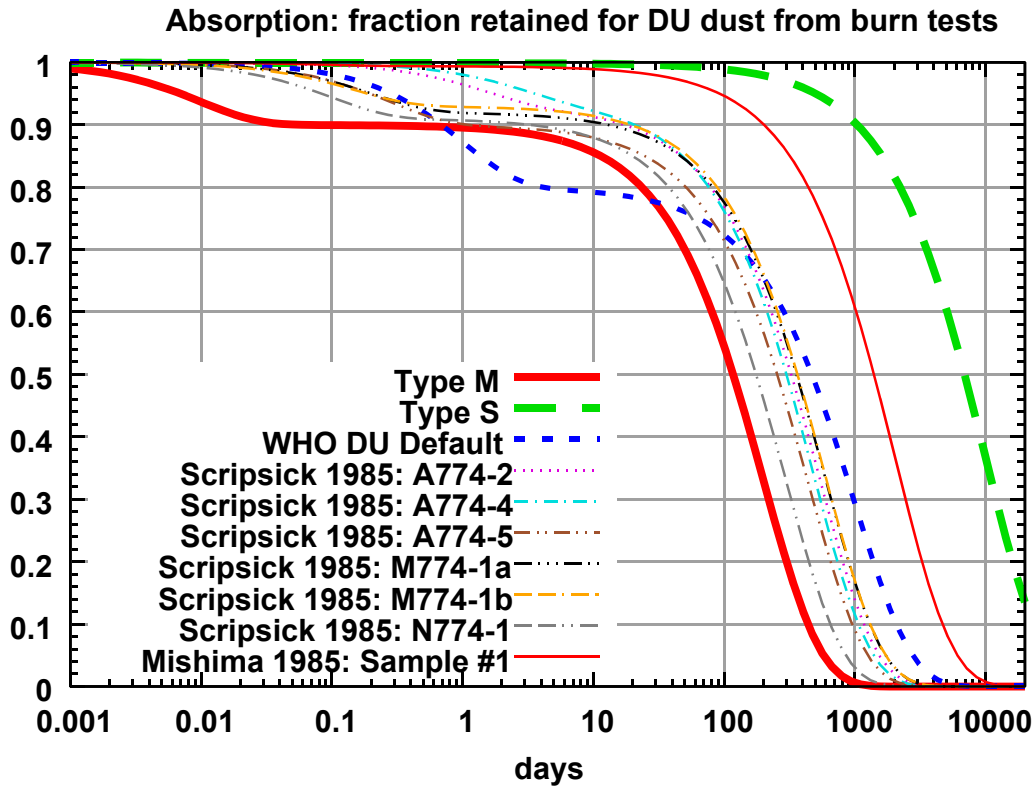

Absorption: fraction retained for DU dust from burn tests
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.001
0.01
0.1
1
10
100
1000
10000
days
Type M
Type S
WHO DU Default
Scripsick 1985: A774-2
Scripsick 1985: A774-4
Scripsick 1985: A774-5
Scripsick 1985: M774-1a
Scripsick 1985: M774-1b
Scripsick 1985: N774-1
Mishima 1985: Sample #1

Fig.5

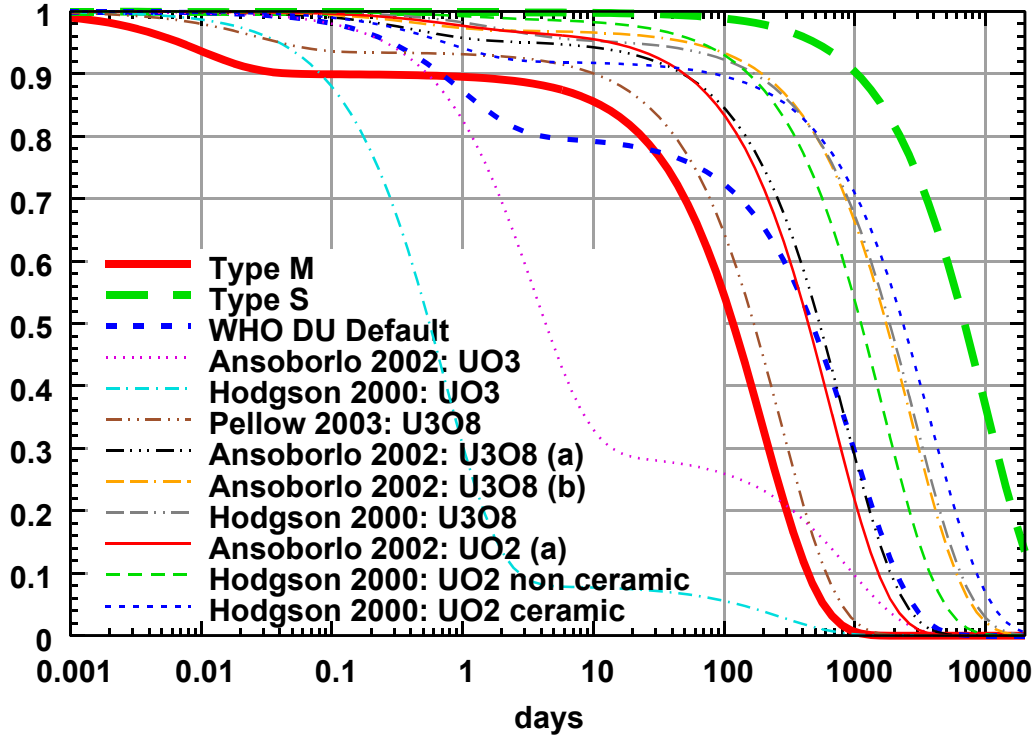

Absorption: fraction retained for industrial uranium compounds
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.001
0.01
0.1
1
10
100
1000
10000
days
Type M
Type S
WHO DU Default
Ansoborlo 2002: UO3
Hodgson 2000: UO3
Pellow 2003: U3O8
Ansoborlo 2002: U3O8 (a)
Ansoborlo 2002: U3O8 (b)
Hodgson 2000: U3O8
Ansoborlo 2002: UO2 (a)
Hodgson 2000: UO2 non ceramic
Hodgson 2000: UO2 ceramic

Fig.6

The impact of the absorption parameter variations on the uranium concentration in urine after a single inhalation event is shown in Fig.7, for the dust from penetrator impact.

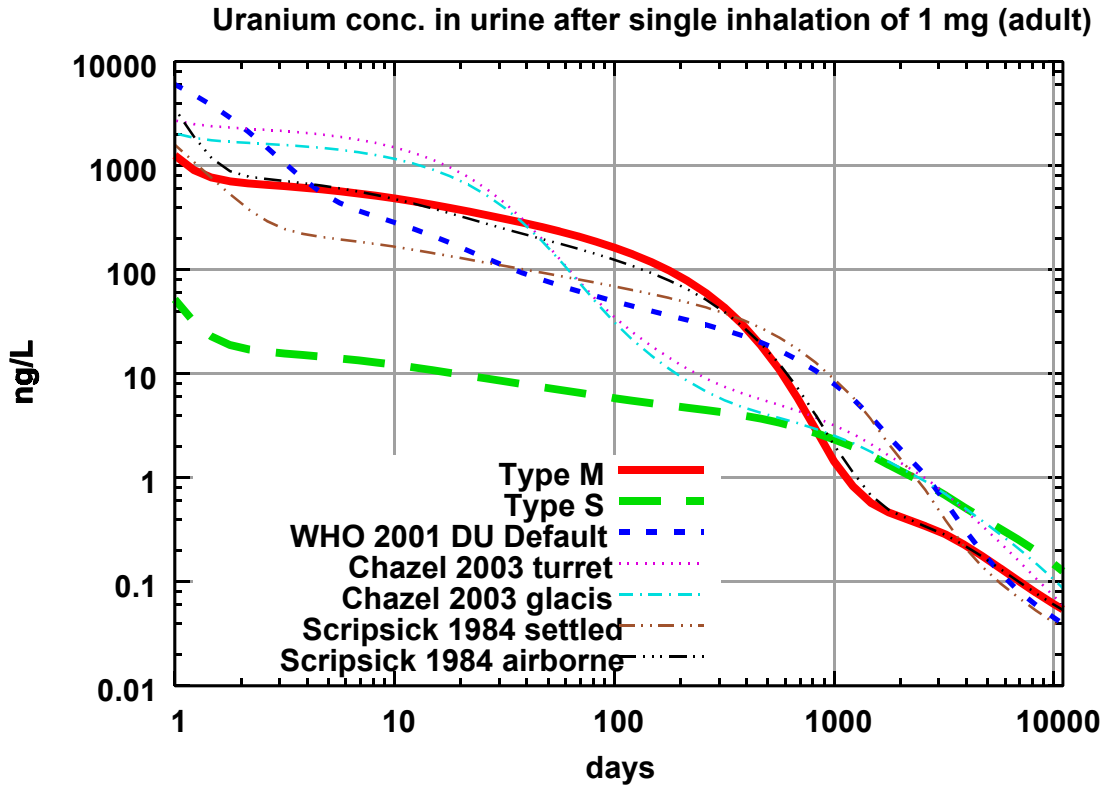


Fig.7

Here, it can be seen that, also for the effects on uranium concentrations in urine, all materials behave more like Type M for times since exposure up to approx. 3 years, while the span between the materials now decreases for longer times, though the span between the absorption characteristics increased for longer times, as seen in Fig.4. This shows that the variations in the absorption characteristics of the various DU dust materials have little impact on DU concentrations in urine for times since exposure of more than approx. 3 years.

The question is now, which values to use for an assessment of the hazards from DU dust in the battlefield. As has been shown, the variations are comparatively high, whether one takes the data obtained from DU impact tests or burn tests, or whether the data for industrial uranium compounds is used in conjunction with the data obtained for the compound composition of DU impact tests. Moreover, the dust is never composed of one material type only, but from a mixture of two or more components of different solubility. Therefore, for the purposes of this paper, no single parameter set for DU dust is used, but both values for Type M and Type S are computed in parallel to be better in the position to assess the range of possible effects.

Ingestion

The case of uranium ingestion is covered here for comparison only; there is no such relevant exposure pathway for soldiers in war theaters.

Continuous ingestion of uranium at a constant rate (e.g. with drinking water), see Fig.8 (stacked diagram): excretion occurs via faeces, and, to a small degree, via urine (only excerpt shown in graph).

A constant amount is contained in the gastrointestinal tract, while deposits are slowly accumulating with time, mainly in bones, but also in kidneys and other soft tissue.

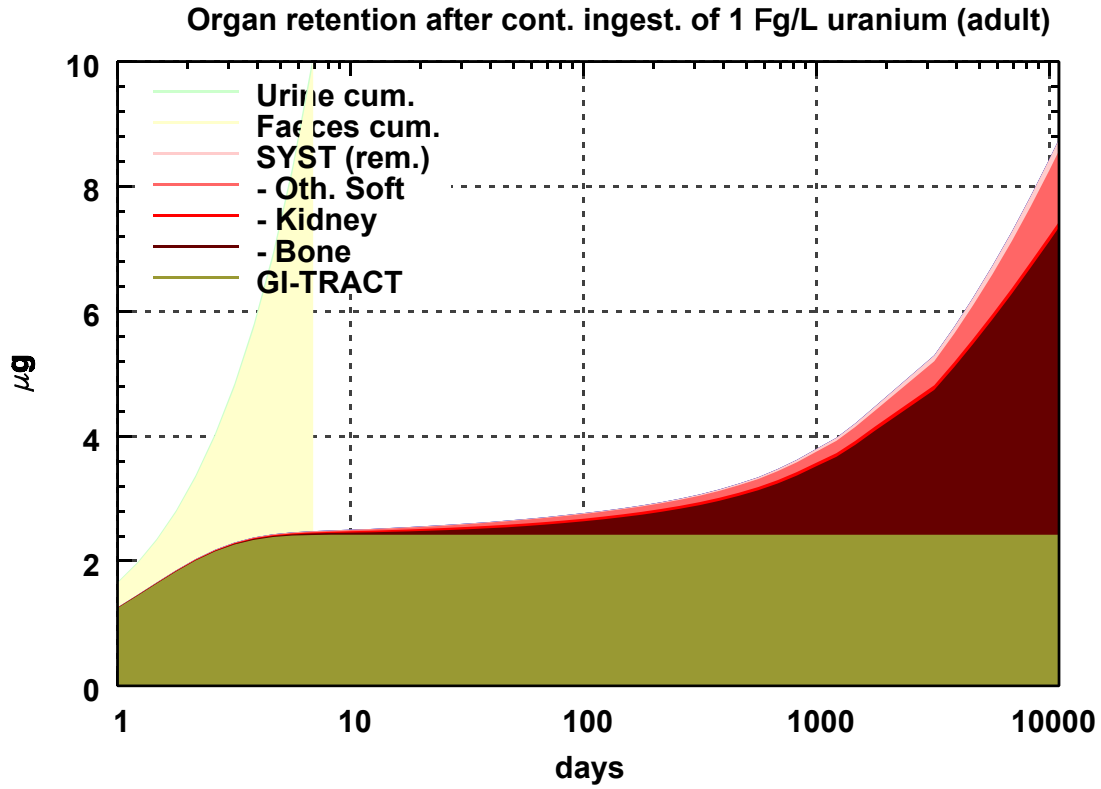


Fig.8

Fig.9 shows the uranium concentration in urine for continuous ingestion of uranium in drinking water at a concentration of 1 µg/L and a daily consumption of 1.4 litres, for the time since begin of exposure.

Embedded shrapnel

Some soldiers have embedded DU shrapnel from so-called „friendly fire“ incidents.

Continuous exposure to embedded DU shrapnel, see Fig.10 (stacked diagram): The shrapnel, mostly located in soft tissue, such as muscles, dissolves at a constant rate into blood (the biokinetic model handles this as „injection“). The vast majority of the amount dissolved is excreted via urine and, to a small degree, via faeces (only excerpt shown in graph). Deposits are slowly accumulating with time, mainly in bones, but also in kidneys and other soft tissue.
Other than with ingestion, the role of urine and faeces for excretion is inverse, and there is nearly no deposit in the gastrointestinal tract (for obvious reasons).
Fig.10 is scaled with the average data reported for a cohort of 1991 Gulf War veterans carrying embedded DU shrapnel, tested in 1995 [Hooper 1999].

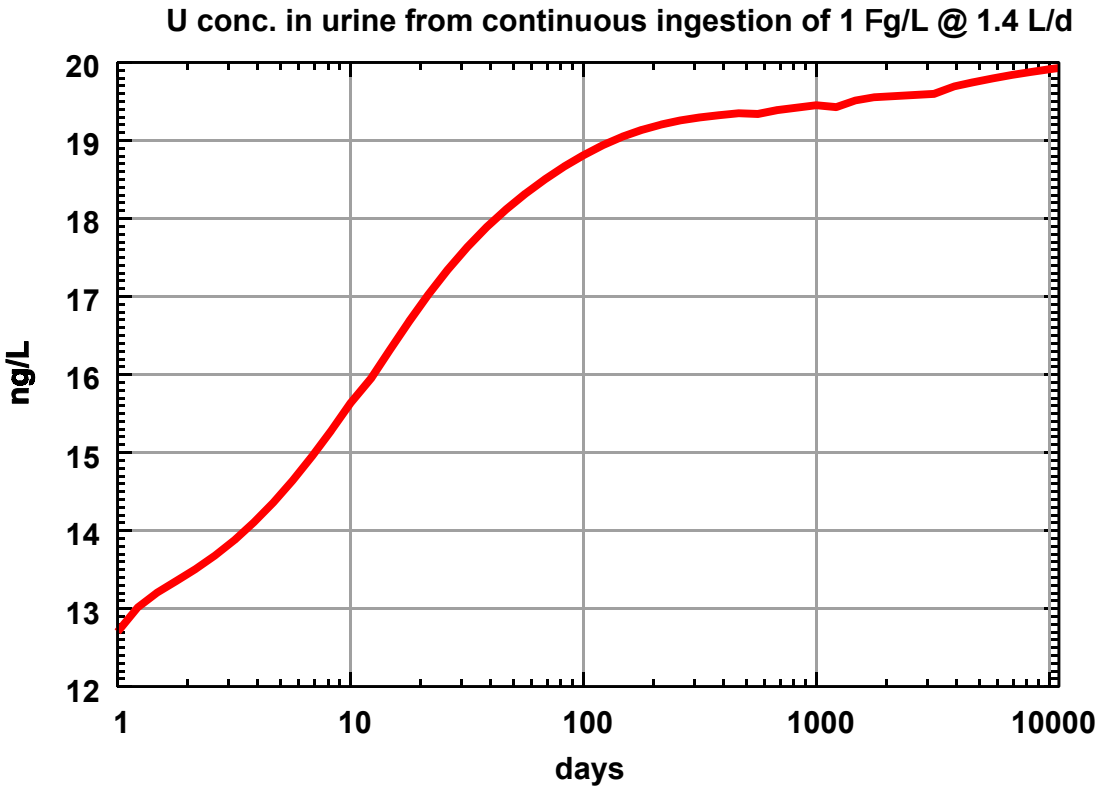

U conc. in urine from continuous ingestion of 1 Fg/L @ 1.4 L/d
ng/L
20
19
18
17
16
15
14
13
12
1
10
100
1000
10000
days

Fig.9

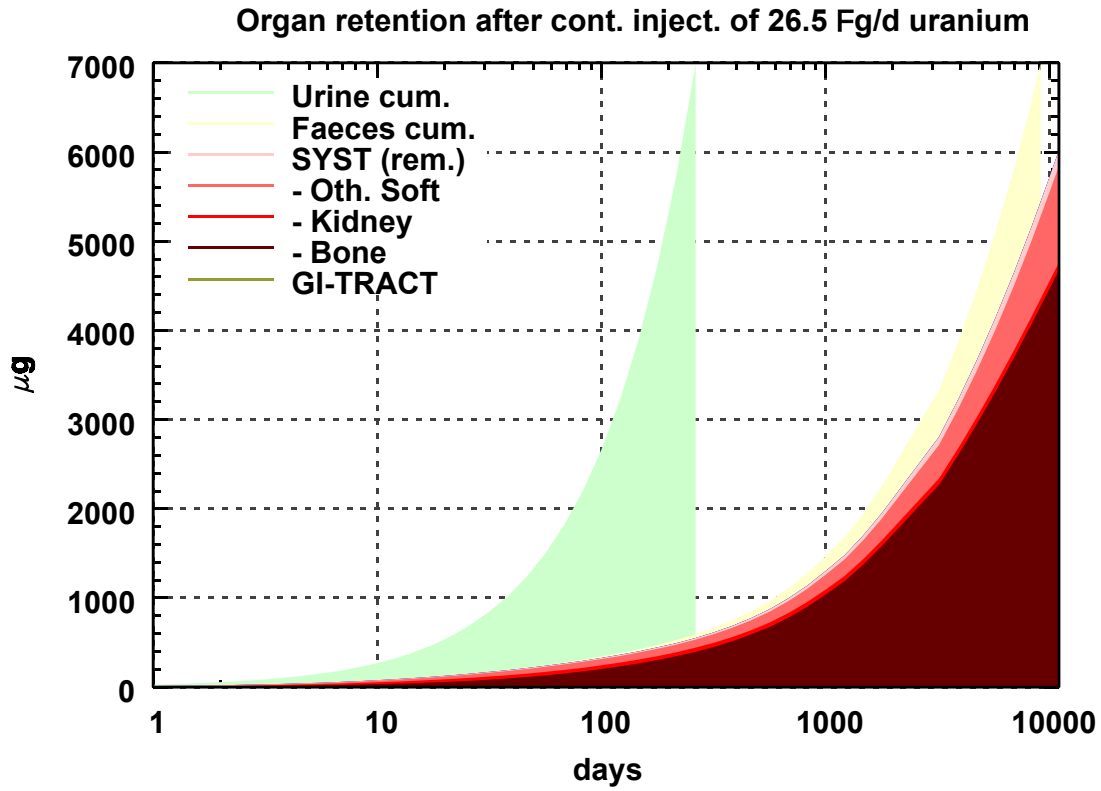

Organ retention after cont. inject. of 26.5 Fg/d uranium
µg
7000
6000
5000
4000
3000
2000
1000
0
Urine cum.
Faeces cum.
SYST (rem.)
- Oth. Soft
- Kidney
- Bone
GI-TRACT
1
10
100
1000
10000
days

Fig.10

● Is DU less hazardous than natural uranium, since it is depleted?

Yes, somewhat: the alpha activity (relevant for radiation exposure from intake) is approx. 40% less than in natural uranium, while the beta activity (from short-lived decay products) is only slightly reduced. The chemical behavior of depleted uranium is the same as for natural uranium, therefore its biokinetic behavior and its toxicity is unchanged.
Note: natural uranium stands here for chemically separated uranium, including its short-lived decay products. Before chemical separation however, such as in uranium ore, uranium is accompanied by more decay products presenting additional radiation hazards.

● Is DU more hazardous than natural uranium, since it contains contaminants such as uranium-236, plutonium-239, etc.?

No. Depleted uranium used for bullets has been found to contain trace amounts of artificial radionuclides, such as uranium-236, neptunium-237, and plutonium-239. The presence of these radionuclides can be explained by contamination from recycling of spent fuel introduced in the manufacturing process; for details, see [Diehl 2002]. The radiation dose from exposure to such contaminated DU is only a fraction of a percent higher than from pure DU - and thus still is lower than from natural uranium; for details, see [Diehl 2001].

● Is ceramic DU oxide more hazardous than other DU oxide?

No, not really. The lung retention times of ceramic and non-ceramic UO_2 differ only slightly [Stradling 1988]. Therefore, the radiation doses from the uranium retained in the lung should be comparable - and the lung dose represents the major radiation hazard for slowly soluble inhaled material.
There is, however, one important difference: according to [Stradling 1988], ceramic uranium oxide dissolves approx. twice slower in the lung fluid, so less uranium reaches the blood and eventually the urine, at least during the first few years following exposure. This has to be taken into account, if the concentration of uranium in urine is to be used to determine a prior inhalation intake of uranium dust. But, on the other hand, even the dissolution of this ceramic UO_2 is faster still than ICRP Type S (see graph). And, in dust obtained from DU penetrator impact tests, there never was found the slowly soluble UO_2 (whether ceramic or not) alone: there always was observed a mix with U_3O_8, and possibly other oxides, - components which often have higher solubility rates.

Fig.11 shows the absorption characteristics of ceramic and non-ceramic UO_2 dust, in comparison to Type M and S. The ceramic material dissolves slower than the non-ceramic one, but it still dissolves faster than Type S.

Fig.12 shows the uranium concentration in urine after single inhalation of such ceramic and non-ceramic UO_2, once again in comparison to Type M and S.

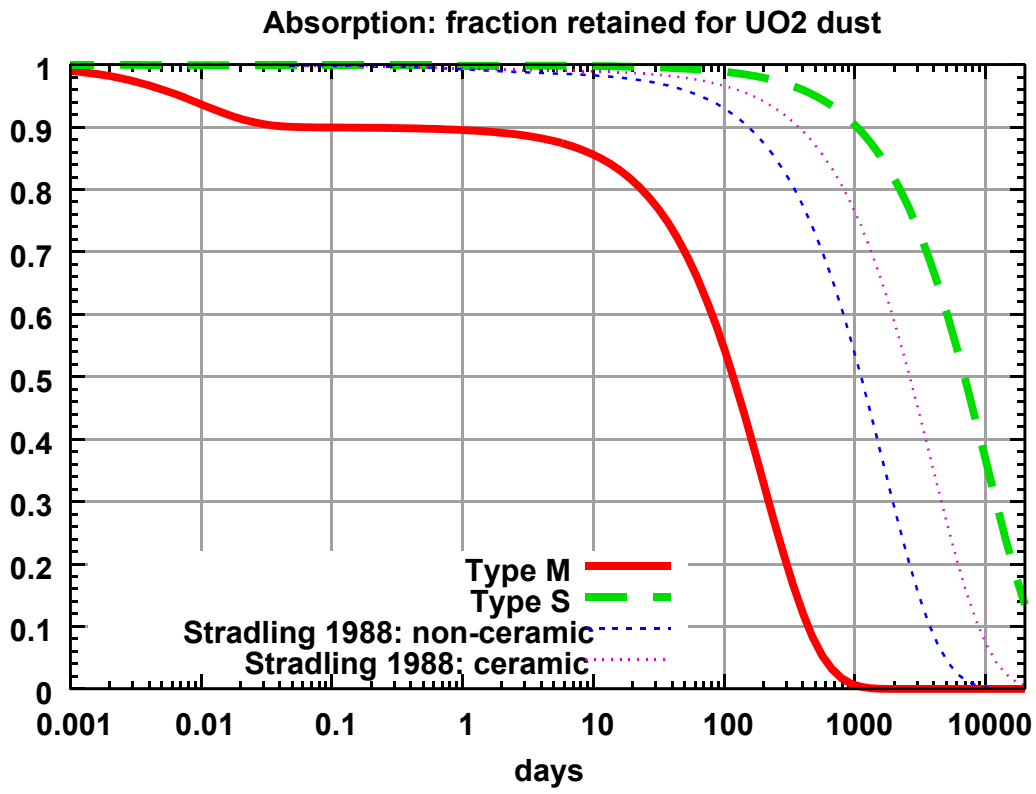

Absorption: fraction retained for UO2 dust
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.001
0.01
0.1
1
10
100
1000
10000
days
Type M
Type S
Stradling 1988: non-ceramic
Stradling 1988: ceramic

Fig.11

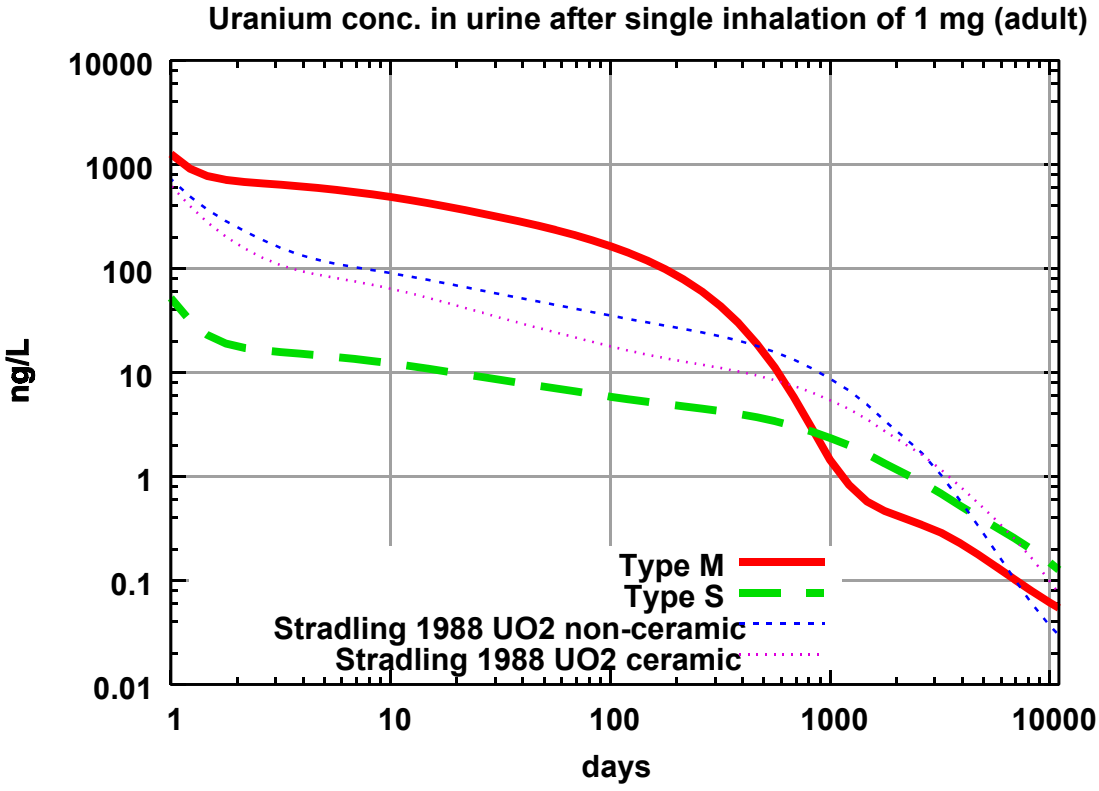

Uranium conc. in urine after single inhalation of 1 mg (adult)
10000
1000
100
10
1
0.1
0.01
ng/L
1
10
100
1000
10000
days
Type M
Type S
Stradling 1988 UO2 non-ceramic
Stradling 1988 UO2 ceramic

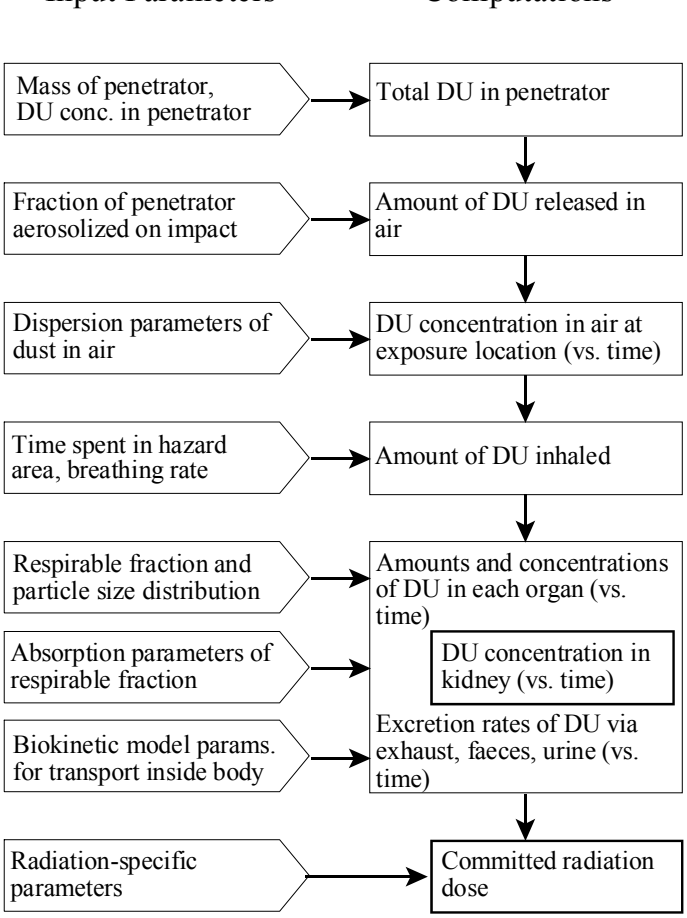
Fig.12

How can the hazard from a DU exposure be assessed?

Inhalation hazard from penetrator impact

Since no live monitoring has been done yet in war situations, modeling is required.

Fig.13: Forward Modeling Approach



However, quite a number of input parameters are required, many of which are difficult to determine (see Fig.13). The only information easily obtainable is the mass and DU content of the penetrator. For some parameters, such as fraction of penetrator aerosolized on impact, respirable fraction, and lung absorption characteristics, live penetrator tests have been performed, with results varying widely. Other tests only comprised burn tests with DU material.
As an alternative to direct tests of the absorption parameters, also a different approach has been used: determination of the compound composition of the dust and the use of the respective absorption parameters determined for such compounds in the nuclear fuel industry. But, once again, the absorption parameters determined for each uranium compound in the nuclear fuel industry vary widely.

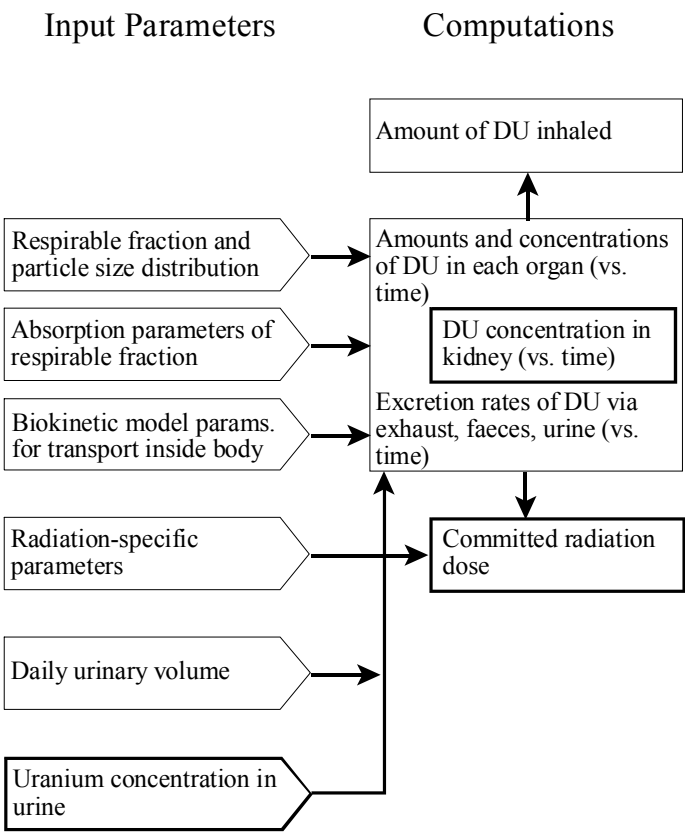
With all information available, the amount of uranium taken in by inhalation can be calculated, and the distribution of the DU inside the body can be modeled with ICRP's biokinetic model for uranium for any time after exposure.
The value obtained for the uranium concentration in the kidney can be used to assess the *chemical toxicity* aspect of the exposure. Since the 1950's, a toxicity standard of 3 µg/g has been in use for the uranium concentration in the kidney, while researchers continually have been urging for a reduction of this value to 0.3 µg/g for more than a decade now, see [Leggett 1989], [Stradling 1997], [Stradling 2002].
For the determination of the *radiation dose* caused from the DU intake, committed doses can be calculated for each organ, based on the biokinetic modeling results, the isotopic composition of DU, and the radiation characteristics of the uranium isotopes. The term „committed" indicates that the dose is meant that the radiation present in an organ will have in the long-term (50 years), not only the effect it actually has had until the time of monitoring. According to ICRP's approach, a „committed equivalent dose" can then be determined for each organ, based on its specific radiation sensitivity. These organ doses can then be combined into a single figure for the whole body, the „committed effective dose", using weighting factors for each organ. This figure can be used for comparison to reference values, such as ICRP's current annual dose limits for members of the public (1 mSv), or for workers (20 mSv average, less than 50 mSv in any single year), for example. The committed effective dose can be translated into a health risk; ICRP uses a risk factor of 0.05 per Sv for the general public. Thus, the risk to die from a radiation exposure, would be 1:20000 from a single 1 mSv dose, 1:1000

from a single 20 mSv dose, or 1:286 for a continuous dose rate of 1 mSv/a (for 70 years), for example. Such dose and risk calculation results should, of course, be used with caution, as all modeling simplifies the real world.
Note: In this paper, the term „radiation dose“ is used as a synonym for the committed effective dose.

Modeling using this „forward approach“ has been done for first assessments in early studies such as [UNEP 1999] and [RoySoc 2001], before actual data from war theaters became available.

An alternative is the „reverse approach“ that models past exposure to DU from bioassay samples such as urine: Since some of the uranium taken in is deposited in various organs in the body, and the deposited uranium then slowly returns into blood, small quantities of uranium are excreted with urine even years after the exposure actually has occurred.

Fig.14: Reverse Modeling Approach



If the time since exposure and the exposure situation, as well as the absorption characteristics and the biokinetics of the uranium, are known, a monitored uranium concentration in urine can - in principle - be used to determine the amount of uranium taken in in the past. Then, the radiation dose and the max. uranium concentration in the kidneys can be calculated that this amount of uranium must have caused (see Fig.14). One advantage of this „reverse approach“ is that it avoids several input parameters that are hard to evaluate and usually vary over a wide range. Moreover, it allows for an otherwise impossible individual health hazard assessment.
However, a number of caveats apply also to this approach: In addition to the problem of widely varying parameter values, another new problem arises, since uranium is present in urine also from natural sources. The uranium concentrations in urine caused from ingestion in food and drinking water (in particular some mineral waters) may easily exceed by far those caused from past inhalation of DU dust. Nevertheless, the health hazard from past inhalation cannot simply be discarded, since a certain uranium concentration in urine may indicate a much higher health hazard, if caused from inhalation rather than from ingestion (see below).
An important indicator for the source of a uranium level found in urine may be its isotopic composition, since this is the only difference between natural uranium (such as normally found in drinking water and food), and depleted uranium. New variants of mass spectroscopy now allow for the determination of isotopic ratios of uranium also at concentrations as low as found in urine.

Embedded shrapnel

Embedded shrapnel produces excessive uranium concentrations in urine. These are 100 - 1000 times

higher than normal values and can in most cases easily be detected.
Kidney toxicity can be assessed using ICRP's biokinetic model, since it is also - more or less - applicable to embedded shrapnel, according to [Leggett 2003]. No attempt is made here for an assessment of the radiation dose to the tissue surrounding the shrapnel; reported values are approx. 0.1 mSv/a [Bleise 2003].

● Is monitoring of total uranium in urine sufficient, or is an isotopic analysis required?

It depends. [Gwiazda 2004] has found that 1991 Gulf War veterans showing DU in urine - even with no embedded DU shrapnel - tend to have slightly higher total uranium in urine, but their total uranium in urine still is in the range found in non-exposed individuals. So, an analysis of total uranium is insufficient and an isotopic analysis is mandatory, in case unequivocal knowledge about the presence or absence of DU is wanted. From the isotopic ratio of U-238 and U-235, the percentage of DU can be calculated, assuming some reference U-235 concentration for the DU used in penetrators. The DU used by the U.S. Forces has a rather constant fraction of 0.2 weight-% of U-235, though this fraction is in no way guaranteed. It has to be kept in mind, however, that an isotopic analysis at ng/L-levels is a challenging and expensive procedure and is not widely available.

The requirement for an isotopic analysis may be relaxed somewhat, if one only wants to know, whether an *excessive* radiation or toxicity hazard from inhaled DU may exist. In this case, a limit for total uranium in urine may be defined, depending on time since exposure, for which the radiation dose and the max. uranium concentration in the kidneys from past inhalation of DU would be below some given standard, even if all of the uranium found in urine were assumed to be DU. An isotopic analysis would then only be required, if the selected total uranium limit is exceeded.
One study performed on veterans [McDiarmid 2004] explicitly has used such a limit already, though not based on the possible hazard, but on other considerations: 50 ng/g creatinine (corresponding to a total uranium concentration in urine of approx. 70 ng/L). Other studies, such as [Roth 2001], [DPRSN 2001] and [May 2004], did not have the technical capabilities to do an isotopic analysis for the samples with lower total uranium values, and thus implicitly also used such a limit. See Tab.5 and Tab.6 below.

Extremely high uranium concentrations in urine, such as several micrograms per litre, are indicative of embedded shrapnel and don't require an isotopic analysis, except in the rare case when the water consumed is exceeding uranium standards for drinking water by an order of magnitude. In addition, isotopic analysis is much easier at such high levels.

● Can uranium-236 be used as an indicator for DU exposure?

Not really recommendable. The depleted uranium used by the U.S. Forces shows a rather constant concentration in U-236 of 0.003% by weight. This U-236 was introduced into the manufacturing process by recycling of spent fuel from plutonium-production reactors in the U.S. nuclear weapons industry; for details, see [Diehl 2002].
The presence of U-236 in DU thus is not mandatory, but the uranium used for the U.S. DU weapons

just happens to contain this by-product. This could make it a candidate for an indicator for the presence of such DU. However, the concentrations of U-236 in urine are very small, and samples may easily get contaminated in laboratories, since those use this isotope as a marker for other measurements. In addition, little data is available on environmental concentrations of U-236 from possible sources such as nuclear weapons fallout, or the nuclear industry. So, if an isotopic analysis is required, then preferably the U-238/U-235 ratio should be determined, rather than looking for U-236.
Note 1: Other contaminants contained in DU used by the U.S. Forces, such as plutonium-239, have much lower concentrations and thus are even less useful as indicator for DU than U-236.
Note 2: The health hazard from the presence of U-236 in depleted uranium (in the given concentration) is negligible, compared to that of the DU alone, see [Diehl 2001].

● What about monitoring methods other than uranium in urine?

Uranium in faeces:
Suitable for short-term monitoring only (within days from exposure)

Uranium in hair
Suitable in principle, but has several limitations. Isotopic assays were performed on hair samples from 19 Canadian 1991 Gulf War and Kosovo veterans. The isotopic hair assays were scattered around the natural U-238:U-235 ratio [Ough 2002].

Lung count
Counting of the gamma radiation emitted from uranium deposited in the lung is „only applicable if the amount of DU in the lungs is more than a few milligrams“ [Bleise 2003]. Such amounts are hardly possible, since only up to approx. 13% of the amount inhaled is deposited in the lung (based on AMAD 1).

Uranium in bone or other tissue
For obvious reasons not widely applicable. A single bone sample (vertebrate bone marrow) from a deceased member of the Canadian Forces was analyzed for total uranium content and isotopic ratio by ICP-MS. The sample was shown to have 16 µg/kg uranium by dry weight and a U-238:U-235 isotopic ratio consistent with natural uranium. [Ough 2002]

● How reliable is all this biokinetic modeling and radiation dose assessment?

To make it short: it‘s not exact, but it gives some idea, at least.
A biokinetic model describes transport of a contaminant inside the human body. ICRP‘s biokinetic model for uranium is based on animal data and on experience gained in the nuclear fuel industry. A more controversial issue is the calculation of the radiation doses resulting from radioactive material deposited in the body.
Modeling produces results only for typical situations, while results for individuals may scatter. The quality of the modeling results is depending on the applicability of the mathematical models used, and on the quality of the input data and parameters. Most parameters have been obtained from short-term experiments only and thus are becoming increasingly unreliable for the modeling of longer periods.

Many parameters are subject to wide variations, as seen above for the lung absorption parameters of DU dust, for example. And, parameters are subject to change: recent changes in the biokinetic model and dose assessment parameters (from ICRP 60 to ICRP 72 dose factors) led to a reduction by a factor of approx. 4 in the radiation doses calculated for inhalation of slowly soluble uranium, while the inhalation doses calculated for moderately soluble uranium increased by a factor of approx. 2.
Furthermore, models can only simulate transfers for which a function was defined. New research by [Lemercier 2003] for example, suggests that there possibly might also get some uranium across the blood-brain barrier - a pathway that is not covered by ICRP‘s biokinetic model (yet).

For the biokinetic modeling purposes of this paper, WISE Uranium Project‘s online „Uranium Biokinetics Calculator“ has been used. This applies ICRP‘s full human respiratory tract and systemic models for uranium. For the initial dust deposition in the lung, it only offers a choice of ICRP‘s activity median aerodynamic diameter (AMAD) parameter sets; individual particle size distributions could therefore not be assessed. All calculations have been made for an adult member of the public and an AMAD of 1.
For the computation of radiation doses, WISE Uranium Project‘s online „Uranium Radiation Individual Dose Calculator“ has been used. It determines the radiation doses from all relevant uranium isotopes and any ingrowing decay products. Unlike the Biokinetics Calculator, the Radiation Dose Calculator does not allow for the entry of individual absorption parameters and only works for ICRP‘s Type F/M/S standard parameter sets. Again, all calculations have been made for an adult member of the public (ICRP 72, AMAD 1).
For the „reverse modeling approach“ (see Fig.14), the following procedure has been used (since the Biokinetics Calculator does not calculate radiation doses): first, the Biokinetics Calculator was used to determine the amount of uranium inhaled based on the uranium concentration monitored in urine, and then the corresponding radiation dose was determined with the Uranium Dose Calculator using the same set of parameters.
It has to be kept in mind, that all results obtained with these calculators are subject to uncertainties and parameter variations, while only a single figure is presented as a result.

● What levels of total uranium are normally found in urine?

Total concentrations of uranium normally found in urine are mainly depending on the concentrations of uranium in food and drinking water. The concentrations in drinking water, in particular, can vary widely over several orders of magnitude between one location and another, and may completely dominate the uranium concentrations in urine. Here some examples for illustration purposes:

According to ICRP‘s biokinetic model for uranium, the continuous uranium uptake with drinking water of 1 µg/L at a consumption rate of 1.4 L/d results in an ultimate uranium level in urine of approx. 20 ng/L for adults (see Fig.9).

[UNSCEAR 2000] uses a reference value for uranium in drinking water of 1 mBq U-238 per kg, that is 81 ng U_{nat}/L and results in a uranium level in urine of approx. 1.6 ng/L, according to the biokinetic model for adults.
[Roth 2001] summarizes age-dependant values reported for uranium in urine in residents of Germany: averages are 11 ng/L at age 20 y, and 21 ng/L at age 50 y; upper reference range values are: 21 ng/L at age 20 y, and 50 ng/L at age 50 y (values converted from ng/d with 1.4 L/d).
In a study on European bottled mineral waters, 20% of the samples exceeded WHO‘s former 2 µg/L recommendation for drinking water, with the highest uranium concentration found at 232 µg/L [FAL

2003]. This maximum value observed would lead to a uranium concentration in urine of up to 4640 ng/L, based on ICRP's biokinetic model.

What levels of uranium in urine are dangerous?

The figure for the uranium concentration in urine obtained from a laboratory is not itself sufficient to assess the associated hazard. The health hazard varies widely depending on the exposure situation that resulted in such a value.
For a first assessment, existing standards for the various exposure pathways can be helpful.

Ingestion

Uranium in drinking water has not been regulated for long times; only recently activities are increasing to elaborate and enforce standards; and where they already exist, they are being changed quite often. Tab.4 shows some examples of current drinking water standards.

Tab.4: Standards for uranium in drinking water

Standard		Effects after continuous long-term exposure			
	U conc. in drinking water	**U conc. in urine** [a)]	**U conc. in kidneys** [a)]	**Annual radiation dose for Unat** [b)]	**Annual radiation dose for Udep** [b)]
[US EPA 2000] Standard	30 µg/L	600 ng/L	0.0089 µg/g	0.018 mSv/a	0.011 mSv/a
[WHO 2004] provisional guideline	15 µg/L	300 ng/L	0.0045 µg/g	0.009 mSv/a	0.0055 mSv/a

[a)] using ICRP biokinetic model for uranium, assuming consumption of 500 L/a for 30 years
[b)] using ICRP 72 dose factors for adults, assuming consumption of 500 L/a
Unat = uranium of natural isotope composition (0.71 wt_% U-235)
Udep = depleted uranium (0.2 wt_% U-235)

These drinking water standards are based on chemical toxicity and are intended to protect the kidneys, taking some safety factors into account. The max. uranium concentration obtained in the kidney after 30 years of continuous exposure at EPA's 30 µg/L drinking water standard is still a factor of 30 lower than the proposed 0.3 µg/g kidney standard, and the annual radiation dose is more than a factor of 50 lower than ICRP's 1 mSv/a standard for the public.

Inhalation

Radiation dose

Fig.15 shows the radiation dose (in µSv) that results from single inhalation of that amount of DU that leads to a DU concentration in urine of 1 ng/L, depending on time since exposure (DU with 0.2% U-235, ICRP 72 for adult, AMAD 1). So, for a given DU concentration in urine, one only has to multiply the ng/L figure obtained from the laboratory by the radiation dose obtained from the graph, to obtain the corresponding radiation dose.
It can be seen that, for this radiation dose-based assessment, the DU concentration in urine varies over

two orders of magnitude depending on absorption Type M or S during the first few years after exposure, but it is rather independent of the absorption type for times later than approx. 3 years after exposure. Thus, the effect of decreasing sensitivity with time of uranium concentrations in urine to solubility variations of the dust inhaled, as already observed in Fig.7, now has evolved into a near independence, when considering the radiation doses. This facilitates assessments for the later periods enormously. It has to be kept in mind, however, that the elements of uncertainty with any such modeling are increasing with time.

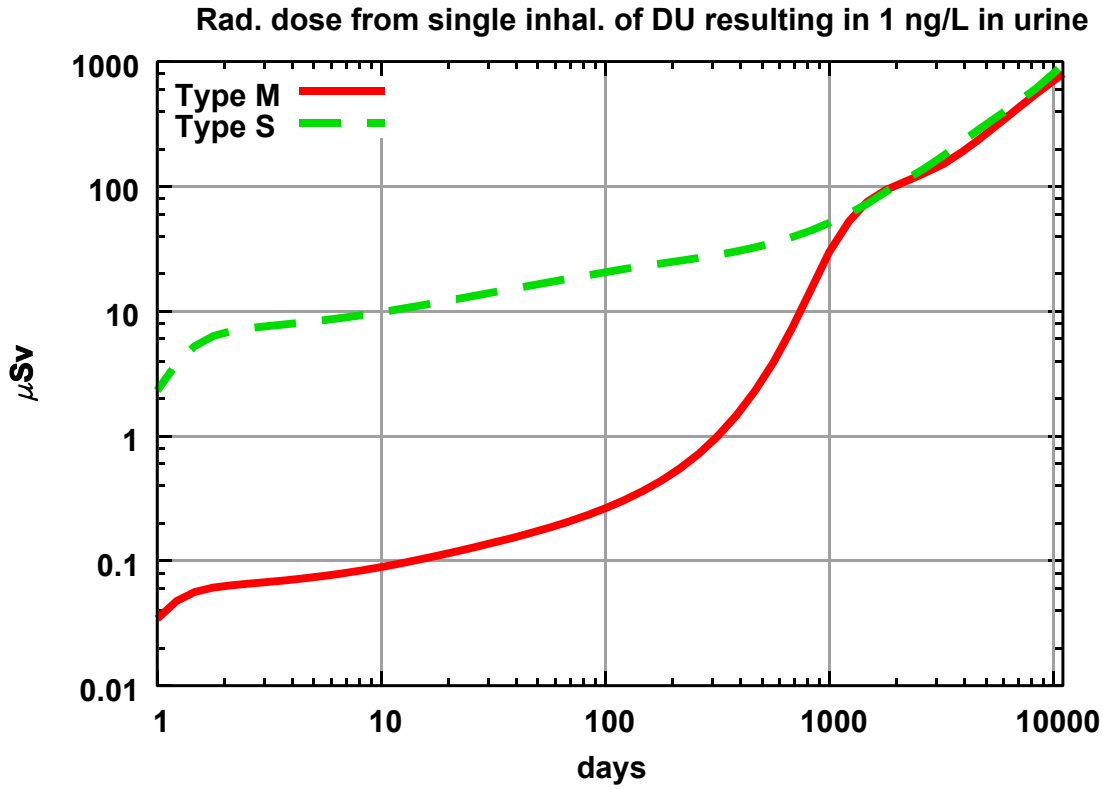


Fig.15

For some situations, it may be convenient to compare a given uranium concentration in urine to some standard at a single glance, without having to perform any calculations. This can be accomplished with Fig.16, which shows the same data in a different form. This form is also better suitable for a direct comparison of the hazards from radiation and from chemical toxicity, see below.

Toxicity

Fig. 17 shows the permissible uranium or DU concentration in urine from single inhalation to meet the proposed toxicity standard of 0.3 µg/g uranium concentration in kidney, vs. days since exposure, for two lung absorption types (adult, AMAD 1)
For times up to approx. 1 month after exposure, the permissible uranium or DU concentration in urine is rather independent of the absorption type, but for longer times, just opposite than with radiation, the span between Type M and S spreads, and the values for Type M are getting more restrictive.
It can, moreover, be seen that the radiation-based 1 mSv standard also covers the toxicity standard for both Type M and S material, though with a rather small safety margin only.

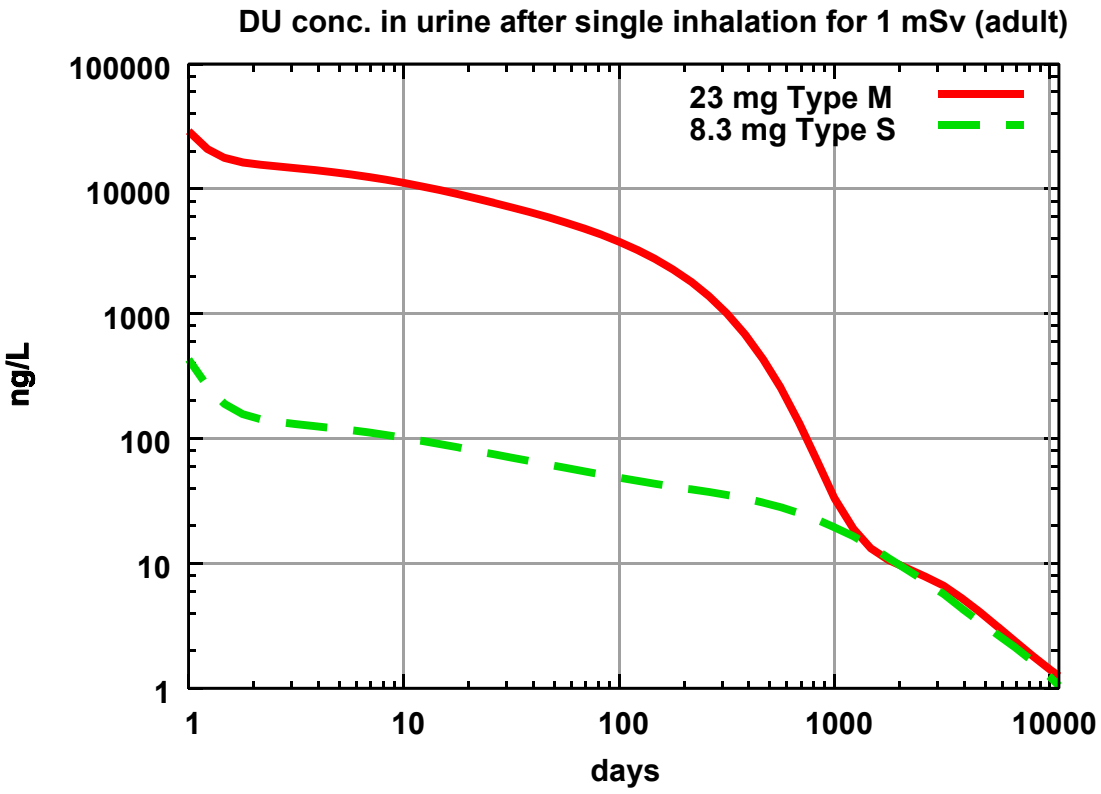

DU conc. in urine after single inhalation for 1 mSv (adult)
23 mg Type M
8.3 mg Type S
ng/L
days
100000
10000
1000
100
10
1
1
10
100
1000
10000

Fig.16

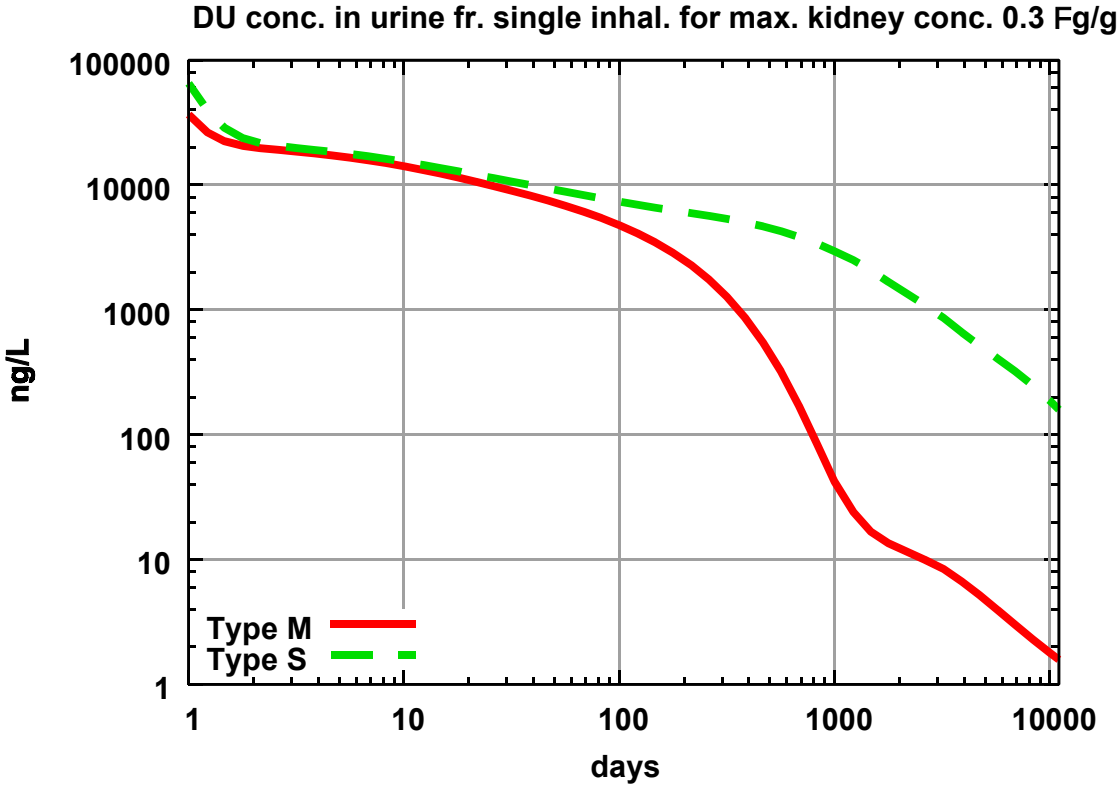

DU conc. in urine fr. single inhal. for max. kidney conc. 0.3 Fg/g
Type M
Type S
ng/L
days
100000
10000
1000
100
10
1
1
10
100
1000
10000

Fig.17

Embedded shrapnel

Fig.18 shows the permissible uranium concentration in urine from embedded DU shrapnel to ensure that the proposed 0.3 µg/g toxicity standard of uranium concentration in the kidneys is met, vs. days since begin of exposure (note unit µg/L rather than ng/L!). Two cases are shown, since the uranium concentration in urine may still be on the increase at sampling time:
- the actual kidney concentration meets the toxicity standard (and thus has been met in the past),
- the toxicity standard has been met in the past and will be met even in the future.

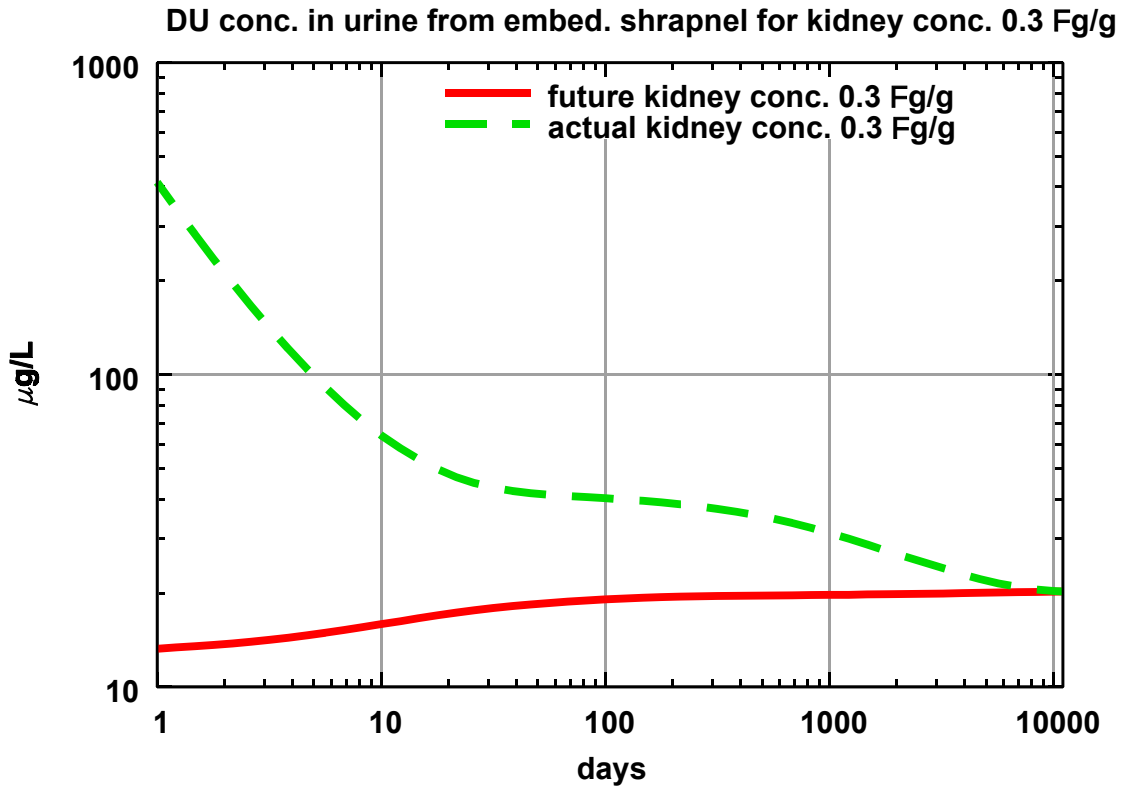


Fig.18

Summary of exposure situations

Fig.19 combines the information from Fig.16 - Fig.18. and gives a comparison of permissible uranium and/or depleted uranium concentrations in urine for exposure from different pathways for a kidney toxicity standard of 0.3 µg/g and/or a radiation dose standard of 1 mSv vs. time since exposure (respectively begin of exposure):
- single inhalation of Type S and M (toxicity and DU radiation dose)
- embedded shrapnel (actual toxicity and future toxicity)
Note: the embedded shrapnel curves can also be used for exposure from continuous drinking water consumption

This figure contains all information required for a first assessment of the hazard presented by a certain uranium concentration in urine, and one can obtain hints, whether a further investigation into the sources of an exposure is warranted, and whether an isotopic analysis should be considered to separate possible sources of exposure, etc.

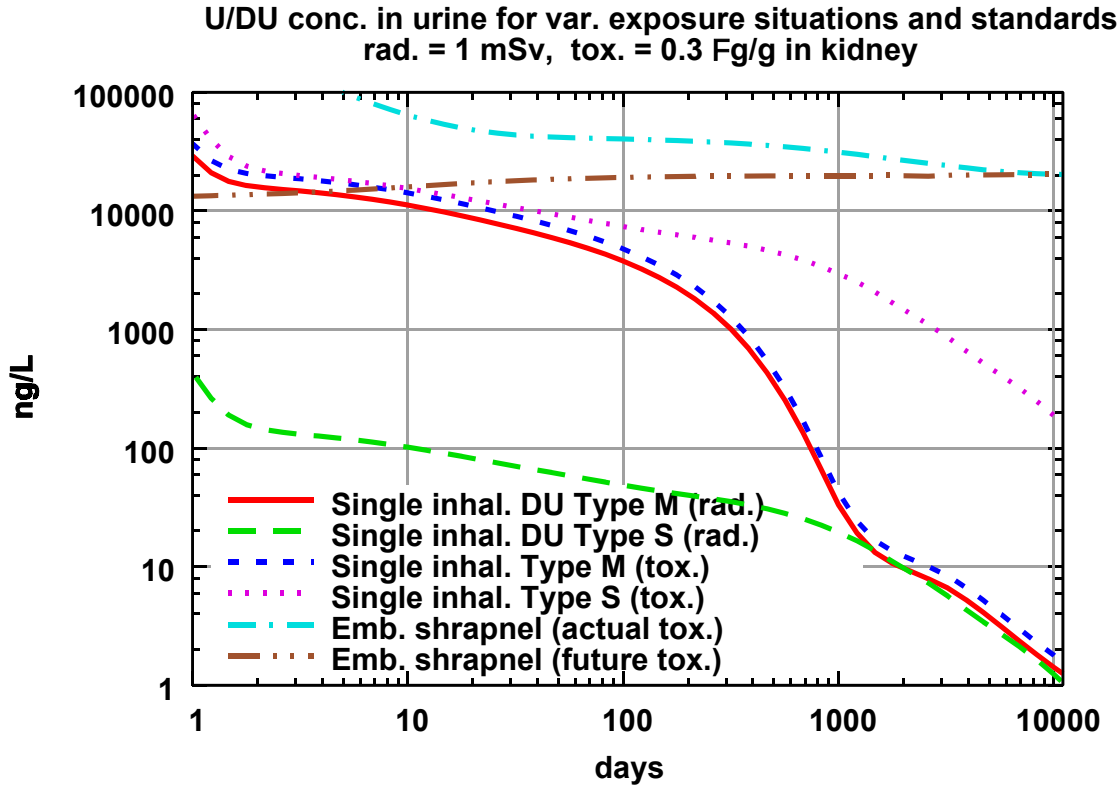


Fig.19

It can be seen that the permissible concentration of uranium and/or DU in urine at a given time after exposure (respectively from begin of exposure) can vary over a range of up to four orders of magnitude, depending on the exposure situation! This emphasizes the necessity to perform a thorough assessment of the exposure situation, before any conclusions are drawn from the uranium concentration found in an urine sample.

● What DU levels have been found in soldiers and/or residents of past war theaters?

Since the first reported battlefield-use of DU weapons in the 1991 Gulf War, a number of studies have been performed with soldiers and veterans of this and later wars in Bosnia (1994/1995), Kosovo/Serbia/Montenegro (1999), Afghanistan (2001/2002), and in the 2003 Gulf War. The sensitivities of the analysis methods used varied very much between studies, and many studies only tested total uranium, while others also did at least some isotopic analysis to determine the percentage of DU contained. Tab.5 compiles the results for soldiers with no shrapnel, Tab.6 for those with embedded DU shrapnel.

Thus, the highest DU concentration in urine from soldiers that have no embedded shrapnel, is reported as approx. 266 ng/L in [Gwiazda 2004]. Further analysis of this reference shows that there exists one more - somewhat lower - similar value, while all other values are approx. one order of magnitude lower. So, seen over all studies, the subsequent values in descending order would be 107 ng/L [Durakovic 2003b], followed by a non-DU-exposed case of approx. 106 ng/L in the reference group of [Gwiazda 2004].

Tab.5: Uranium in urine (no embedded DU shrapnel)

	Date sampled	**No. of per-sons**	**total U range, average [ng/L]**	**DU range [ng/L], (DU fraction)**	**Reference**
US soldiers in Iraq	Sep. 2003	9	1.6 - 6.2 avg. 3.6	**DU found** in 4 cases: 0.12 - 0.87 (4.2% - 22.8%)	[Durakovic 2004]
US soldiers in Iraq, Iraqi civilians	Sep. 2003		1.1 - 65.3	**DU found** (0.2% - ~ 10%)	[Goethe 2004]
British soldiers in Iraq	2003	275		No DU found	[Glasgow Herald 2004]
Australian soldiers in Afghanistan and Iraq	2003		< 50	na	[TheAge 2003]
„symptomatic civilians“ from Eastern Afghanistan	2002	8	88.52 - 477.88 avg. 275.04	No DU found	[Durakovic 2003a]
Swedish soldiers in Kosovo	March 2001	200	avg. 9.9 [b)]	na	[FOI 2002]
-- control (in Sweden)		200	avg. 38.3 [b)]	na	
Canadian soldiers in 1991 Gulf War and Kosovo	2002	103	0.5 - 49.5 avg. 4.5 (ICP-MS); 1 - 81 avg. 17 (INAA)	na	[Ough 2002]
German soldiers in Kosovo	Sep./Oct. 2000	43	2.9 - 29 [a)] avg. 11.4	na	[Roth 2001]
-- control (same before service)	Apr./May 2000		2.9 - 29 [a)] avg. 12.6	na	
5 Portuguese soldiers and 10 local civilians in Kosovo	January 2001	15	32 - 411 avg. 115	possibly DU detected in 1 case	[DPRSN 2001]
Portuguese soldiers in Bosnia		12	14 - 682 avg. 36 [c)]	na	
Portuguese civilians after service in Balkans		9	7 - 204 avg. 78	na	
Portuguese soldiers after service in Balkans		17	7- 347 avg. 144	na	
-- control (in Portugal)		4	34 - 154 avg. 95	na	
US soldiers in Bosnia	Aug./Sep. 2002	46	avg. 3.651	No DU found	[May 2004]
– control (same before service)	Feb. 2002		avg. 1.369	na	
Residents of Bosnia and Herzegovina and Kosovo	2001	22	2.9 - 71.2 [a)]	**DU found** in all cases: 0.9 - 33.1 [a)] (8% - 51%)	[Priest 2001]
French veterans of 1991 Gulf	2002 - 2004	110	No „anomaly“	na	[Salamon

U.S. veterans of 1991 Gulf War (without shrapnel)	Aug. 1998 - Dec. 2002	440	1.4 - 618 [b] median 14	No DU found (DU tested only in 18 cases with total U > 71 ng/L)	[McDiarmid 2004]
U.S. veterans of 1991 Gulf War (DU-exposed, without shrapnel)	1997 / 1999	28	2.6 - 286 [b] median 94	**DU found** in 10 cases: ~3 - ~266 [b] [d] (~30% - ~93%)	[Gwiazda 2004]
U.S. veterans of 1991 Gulf War (not DU-exposed)	1997	12	1.7 - 126 [b] median 24	**DU found** in 1 case: ~106 [b] [d] (~84%)	
British, Canadian, and U.S. 1991 Gulf War veterans (DU-exposed)	1999 - 2000	11	0.0256 - 191 avg. 21.9 [a]	**DU found** in 5 cases: 0.08 - 107 avg. 23.4 [a] (8.52% - 55.86% avg. 36.08%)	[Durakovic 2003b]
U.S. 1991 Gulf War veterans (no shrapnel)	1993 / 1994	10	avg. 70	na	[Hooper 1999]
	1995	3	avg. 40	na	

[a] converted from ng/d using 1.4 L/d
[b] converted from ng/g creatinine using 2 g creatinine/d and 1.4 L/d
[c] excluding one value (682 ng/L)
[d] data extracted from graph
na = not analyzed

Tab.6: Uranium in urine (with embedded DU shrapnel)

	Date sampled	**No. of per-sons**	**total U range, average [ng/L]**	**DU range [ng/L], (DU fraction)**	**Reference**
U.S. veterans of 1991 Gulf War (with shrapnel)	Aug. 1998 - Dec. 2002	3	107 - 4140 [b]	**DU found** 95 - 4100 [b] (89% - 99%)	[McDiarmid 2004]
U.S. veterans of 1991 Gulf War (with shrapnel)	1997 / 1999	17	7 - 102,400 median 3730 [b]	**DU found** in 16 cases: [d] ~13 - ~ 97,000 [b] (~66% - ~99%)	[Gwiazda 2004]
U.S. 1991 Gulf War veterans (with shrapnel)	1993 / 1994	15	avg. 10,080	na	[Hooper 1999]
	1995	11	avg. 18,200	na	

[b] converted from ng/g creatinine using 2 g creatinine/d and 1.4 L/d
[d] data extracted from graph
na = not analyzed

● What is the health hazard from past exposure to DU, based on uranium data in urine analyzed so far?

Soldiers with no shrapnel:

Radiation dose from single inhalation event

The samples for the studies showing the highest DU concentrations in urine were taken around 8 years after exposure. So, if all DU in urine would come from a single exposure during the 1991 war, an inhalation dose of approx. 0.15 mSv per ng/L DU detected in urine would apply - independent of the solution characteristics of the DU, see Fig.15.

For the highest reported DU concentration in urine of 266 ng/L, this results in a committed radiation dose of **40 mSv**, twice ICRP's annual reference dose for workers, but below ICRP's recommended value of 50 mSv for maximum worker exposure in any single year. The corresponding amount of DU dust inhaled would have been 860 mg for Type M, or 360 mg for Type S. (Note: these appear to be rather unlikely amounts for single inhalation events and raise the question for other exposure sources and/or for the applicability of the assumptions made for the modeling.)

For the value of 107 ng/L, the radiation dose is 16 mSv. So, except for the two highest values reported, all other soldiers were exposed to less than ICRP's annual reference dose for workers of 20 mSv.

The dose for those soldiers with less than 7 ng/L DU in urine 8 years after exposure would even be lower than ICRP's annual reference dose for the public of 1 mSv.

Toxicity from single inhalation event

For the highest observed DU concentration in urine of 266 ng/L, the max. DU concentration in the kidney would be 0.085 µg/g for Type S material and 8.9 µg/g for Type M material. Thus, for the Type M material, the proposed 0.3 µg/g standard would have been **exceeded by a factor of approx. 30** immediately after exposure; and this exceeding would have continued for somewhat more than a year after exposure, until the concentration would have declined sufficiently.

Soldiers with embedded shrapnel:

The permissible DU concentration in urine 8 years after begin of exposure from embedded shrapnel for meeting the proposed 0.3 µg/g uranium concentration standard in the kidney at the time of sampling is 24.5 µg/L (24,500 ng/L). In case the toxicity standard is to be met also in the long term, then the permissible DU concentration 8 years after begin of exposure still is 20 µg/L (20,000 ng/L). These values were **exceeded up to 5-fold** in 4 veterans tested in [Gwiazda 2004].

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For the biokinetic and radiation dose calculations, the following WISE Uranium Project on-line calculators have been used:

- Uranium Biokinetics Calculator: http://www.wise-uranium.org/cubk.html
- Uranium Radiation Individ. Dose Calculator: http://www.wise-uranium.org/rdcu.html
- Depleted Uranium Fraction Calculator: http://www.wise-uranium.org/rcfdu.html

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