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Human Health Risk Assessment at a Depleted Uranium Site

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Human health risk assessments for depleted uranium are common for Department of Defense (DOD) sites since the metal has various military uses. At a training and experimental site, DU was evaluated in soil in order to make decisions regarding cleanup and future use of the site. At this site, concentrations were found to be protective of human health; DU is less toxic than uranium. Other data important to this decision were the type of receptors likely to be exposed, the amount of time spent by the receptor on-site, the acceptable yearly radiation dose, and other non-radiation associated effects to the kidney. Total uranium concentrations in soil were calculated for the 90th percentile and the 50th percentile. The highest soil concentration used as an exposure point was 3500 ug/g (90th percentile). Short exposure timeframes contributed to the risk results.

Keywords Depleted uranium, soil exposures to radioactivity, risk assessment.

Evaluation of the site was done according to EPA protocol as required by DOD. Other methodologies were investigated but not described in this paper. Use of these other protocols also concluded that the site was safe for future land use (workers, trespassers and archaeologists). The latter group was assigned highest risk because of their intense contact with soil.

Site Description

A human health risk assessment was completed at the request of the US Navy in select areas of a site operated by the Navy. The site is used for military training. The areas of the site that were evaluated in the risk assessment contained depleted uranium (DU). The Navy was interested in whether concentrations of DU in the soil were acceptable for current human receptors known to be in the vicinity of the areas containing DU and to those future receptors who might be in these areas. The objective of this risk assessment is to address the concerns of the US Navy.

The site is located in a high desert area in the continental US. The closest population center is approximately 14 miles away.

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Some groundcover exists at the site. The military have developed or tested multiple airborne weapon systems in the past five decades here. Currently, about 4400 civilian employees and about 1000 military personnel work at the site. Land use, therefore, has been for training of military personnel and testing purposes. This use is not expected to change in the future.

Potential human receptors based on this land use and discussions with the Navy include:

- Range workers
- Trespassers
- Archaeologists

Civilian range workers are present on site and their time and exposure is greater than that of military personnel. This difference in exposure time is because military personnel are on site generally for training purposes, a shorter timeframe than for range workers. In addition, trespassers have been observed at the site and may come into the areas of the site with DU for short periods of time. Archaeologists may also be potential future receptors since artifacts have occasionally been observed in the soil. However, no archaeologists are currently on site or have ever excavated for artifacts at the site.

Climate conditions and geography are typical of the desert regions of the Southwest. The weather is clear with almost unlimited visibility throughout the year; precipitation is low. The land consists mainly of flat dry lake beds, dry washes, alluvial fans and mountains. Prevailing wind is from the south.

Although the site is a large military complex, this human health risk assessment focuses on the two areas where live fire testing occurred using DU penetrators. These areas have been designated Area 1 and Area 2.

Comparison of Two EPA Methods

As proposed by the US Environmental Protection Agency (EPA), the acceptability of soil concentrations of radioactive isotopes can be calculated in two ways. First, risk can be estimated using the traditional Risk Assessment Guidance for Superfund (RAGS) approach, which multiplies exposure and toxicity to determine *cancer risk*. The second approach estimates dose in rems or mrems. This value can be calculated to determine whether (in this case) the mrem per year exposure exceeds an acceptable 25 mrem (25 rad). We employed both approaches in the human health risk assessment for the two areas of the site. Since DU is not known to be a potent radioactive material, it was not surprising to find that unacceptable risk was not identified by either method. Results from the second method are described in this paper.

In addition, non-cancer effects to the kidney were also investigated. This process uses the calculation of a hazard index for the non-cancer endpoint. The hazard index is the ratio of the dose from the site to an acceptable dose defined by EPA. Therefore, if the ratio is less than one, risk is acceptable. These kidney effects were found to subsume the potential risk from radiation in the case of DU but were also found to be acceptable for the two areas of the site.

Risk Assessment Methodology

The procedures for the assessment of radiation risk are located in US EPA 1993 Federal Guidance Reports No. 11 and 12 and other noted sources that address radiologic risk. The risk assessment for the site was performed in accordance with these guidance procedures and in a manner consistent with scientifically acceptable risk assessment practices established by federal agencies, including the Navy. The purpose of this risk assessment is to determine whether DU detected in two areas of the site poses an unacceptable risk of harm to human health. Figure 1 is a flow diagram of the methodology used. In this figure, CTE and RME represent the central tendency estimate (lower bound, less conservative values used) and the reasonable maximum exposure (upper bound, more conservative values used).

Evaluate DU Data

Specific DU radionuclides were chosen for further evaluation based on whether the maximum DU concentration detected was above the adult criterion for exposure. This criterion was found in the "Radionuclide Toxicity and Preliminary Remediation Goals for Superfund" (EPA, 2002). Other documents utilized were:

- USEPA, Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors, Federal Guidance Report No. 11.1988;
- USEPA, External Exposure to Radionuclides in Air, Water and Soil;
- USEPA, External Exposure to Radionuclides in Air, Water, and Soil. Federal Guidance Report No. 12. 1993.

The detected radionuclides in either of the two areas of concern (AOCs) of the site are found in Table 1 and the concentrations in Table 1a. Because of the highly discrete distribution

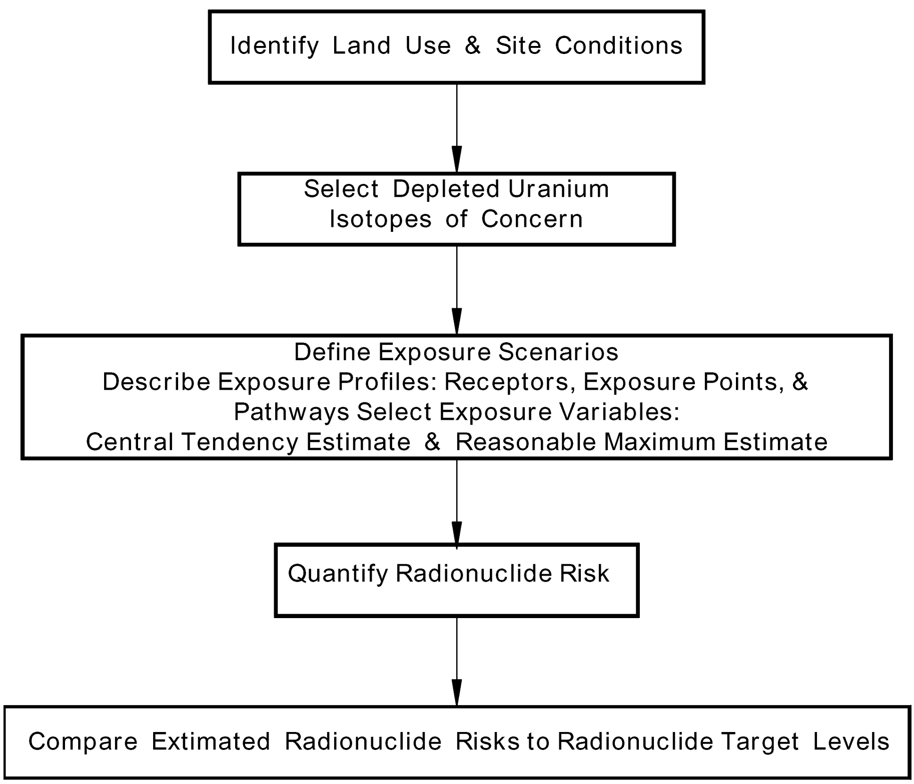

Figure 1. Methodology.

Table 1
Selection of radionuclides

Radionuclide detected on-site	Preliminary remediation goal–soil for adult ug/g	Is concentration greater than PRG?
U-238	1.12×10^{2}	Yes
U-235	1.91×10^{-1}	Yes
U-234	5.31×10^{-3}	Yes

*For external radiation, daughter products were included.

and the large variation in concentrations over very short distances, the average DU soil concentration for any sampling area would be dominantly influenced by the very high DU concentrations at penetrator locations, though these areas constitute only a very small fraction of the total sampling area. However, if the very high DU concentrations are considered as outliers and excluded from exposure point concentration (EPC) consideration, the resultant EPC would only slightly exceed the background levels of natural uranium. Therefore, it was determined that the EPCs would be best represented by the percentile values (Table 1a) rather than the maximum and mean values of the sampling data.

The isotopes were defined (second step in Figure 1) at the site as DU (^{238}U, ^{234}U and ^{235}U) in soil. The next steps in the risk assessment used existing criteria and standards to compare to the calculated 50th percentile and 90th percentile soil concentration limits, in order to make quantitative and qualitative evaluations of risk to potential human receptors at the two areas of concern (AOCs).

Dose-Response Assessment

Uranium is a product of various isotopes that are radioactive. Generally speaking, DU is greater than 99% U-238; the remaining (less than 1%) is U-234 and U-235. All three of these isotopes are alpha emitters. The alpha particle is a helium nucleus so that a new element is formed on emission.

Table 1a
Representative uranium concentrations from areas 1 and 2

Area and U concentration	Total uranium ug/g	U-238 Bq/g	U-235 Bq/g	U-234 Bq/g
Area 1				
Maximum	101,000	1241	19	1429
90th percentile	3500	43	0.7	50
50th percentile	57	0.71	0.01	0.81
Minimum	8.7	0.11	0.002	0.12
Area 2				
Maximum	805	909	0.35	10.8
90th percentile	440	5.5	0.2	6.0
50th percentile	15.3	0.2	0.01	0.2
Minimum	4.2	0.05	0.002	0.06

Uranium is measured in units of mass or radioactivity (Curies or Becquerels). The Becquerel (Bq) is a newer international unit and the Curie (Ci) is a traditional unit. The Bq is the amount of radioactive material in which 1 billion atoms transform every second, and a Ci is the amount of radioactive material in which 37 billion atoms transform every second (ATSDR, 1999).

The Nuclear Regulatory Commission defines the specific activity of depleted uranium as 0.36 uCi/g (10 CFR 20), less than natural uranium. All radiation exposure is considered carcinogenic by USEPA. However, based on the cancer slope factors assigned to the various isotopes, depleted uranium is a weak carcinogen. In addition, there is increasing evidence that a threshold exists for radiation-induced carcinogenicity (Clark, 1999). The bone is the target organ for uranium-induced cancer (ATSDR, 1999). The kidney is the target organ for chemical effects.

There exists no limit for uranium in air set by USEPA; however, the agency has set a goal of *no* uranium in drinking water. This value is called the Maximum Contaminant Level Goal (MCLG). Currently, there is no practical way to meet such a goal. Therefore an MCL (Maximum Contaminant Level) has been set at 20 ug/L based on possible carcinogenic effect.

Dose Conversion Factors (DCFS) were utilized in the calculations to define radiation risk at the site. DCFs used in these calculations were taken from Federal Guidance Reports Nos. 11 (1988) and 12 (EPA, 1993). Dose Coefficients for Exposure to a contaminated soil depth of 15 cm were employed. The units of these coefficients are in Sv per Bq s m^{-3}. The coefficients are specific to the nuclides and their decay products. For ingestion and inhalation pathways, U-234, U-235 and U-238 were considered. The coefficient for U-238 + D was employed for U-238 *and* daughter products. For external radiation hazard calculation, daughter products were included and calculated separately to be more conservative in the assessment (Table 4).

Exposure Assessment

Exposure assessment identifies current and potential future receptors, and characterizes the nature of their contact with an isotope, in this case DU. It is a critical component in risk assessment (third box in Figure 1) as it describes, both qualitatively and quantitatively, the contact between DU and the potential receptors who may be affected by exposure to DU. Consistent with risk assessment guidance, the exposure assessment must incorporate site conditions associated with current land use and identified reasonable foreseeable uses of the site and surrounding environment. The two important components of the exposure assessment process are:

1) exposure profiles,
2) quantitative estimates of exposure.

Development of Exposure Profiles

Exposure profiles provide the narrative description of how exposure may occur to compounds of concern at a site. These profiles are developed for each of the previously identified receptors for all current and foreseeable future uses of the site to assist in proposing values for exposure variables. Potential exposure variables such as the route from the exposure point are discussed in terms of realistic site-specific conditions for current and reasonable foreseeable future uses of the site.

Potential Human Receptors

As described, three receptors were identified (Figure 2) with respect to characteristics that influence exposure, such as location relative to the 2 AOCs of the site, activity patterns and the presence of sensitive subpopulations. Consideration is given to the characteristics of

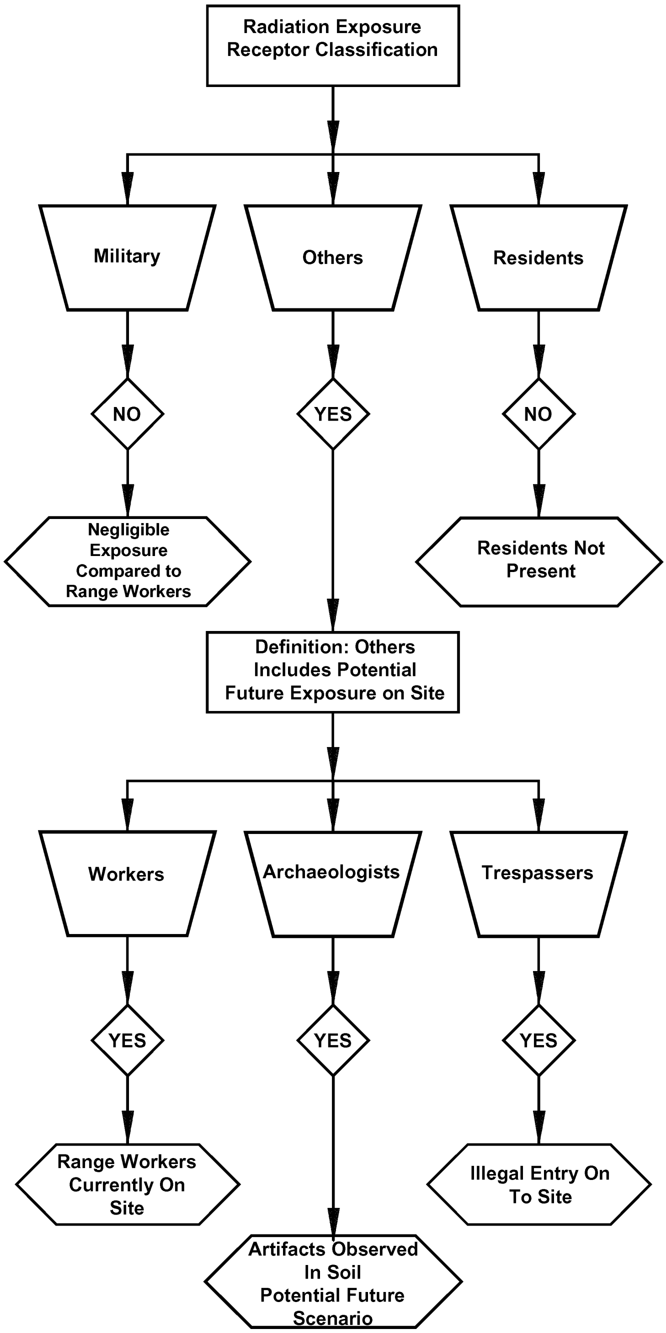

Figure 2. Receptor decision tree.

the current populations, as well as those of any potential future populations that may differ under any reasonable foreseeable future site activities and uses.

The human receptors are described as subpopulations (subsets of the more diverse overall population) rather than specific individuals, so that results of the risk characterization can be generalized. Receptor groups are described in terms that highlight their relationship to the site and the unique characteristics of the subpopulation. Special attention is given to the most sensitive subpopulations based on site conditions. Young children and women of childbearing age are often chosen as receptors of concern in residential locations. However, at other sites such as large military complexes, receptors are more often adults who work at the site or trespassers. These two receptors are more likely to be the most susceptible or sensitive receptors. At this site, artifacts were identified in soil, thus an archaeological dig may occur in the future. Off-site residents are not considered potential receptors for the two areas investigated because of their distance from the areas of concern. Therefore, as shown in the decision tree, Figure 2, the receptors chosen were:

- range workers;
- trespassers;
- archaeologists.

Based on site conditions and the exposure point concentration of DU in soil, Table 2 summarizes potential exposure routes and pathways quantified in the risk assessment.

The primary exposure variables (by receptor) used to quantify exposure are presented below. This provides both a central tendency estimate (CTE) and a reasonable maximum exposure (RME).

Range Workers of ages >18 years are identified as having the potential for the longest timeframe exposure to the two AOCs. Exposure of these range workers subsumes exposure of military personnel who are likely to be training at the site for shorter periods of time. Therefore, if risk to the range workers is acceptable, military personnel will also be protected. Based on a survey at the site in the summer of 2002, range workers are likely to be present infrequently at either of the two AOCs with an estimate of 19.19 days/year (Roncase, 2002). This surveyed value was doubled to 38.44 days/year for estimating exposure to future range workers. Soil ingestion rates were based on 50 or 100 mg/day as proposed by USEPA (1997). Because α particles do not pass through human skin, the dermal route was eliminated for radiation risk. Inhalation was also calculated and inhalation rates were 13 and 20 m^3/day (range, USEPA, 1997).

Trespassers were defined as individuals ages 12 to 18 years old from the surrounding areas who may like to intrude on an area of military significance. This age group is considered to be a more sensitive receptor than an older adult trespasser. Children less than 12 years of age were not considered frequent trespassers on the site because they remain closer to home

Table 2
Exposure routes

Receptor	Inhalation	Dermal	Ingestion	External
Range worker	√	*	√	√
Trespasser	√	*	√	√
Archaeologist	√	*	√	√

*Eliminated during evaluation as insignificant.

under adult supervision. The trespasser soil ingestion rates were either 100 or 200 mg/day; their breathing rates were 8.7 and 12 m^3/day. Both of these rates are based on EPA guidance (upper and lower bound). They were assumed to be on-site for 1 or 12 days/year based on observations from workers on the site.

Archaeologists were investigated since the potential exists in the future for an archaeological dig. If, for example, the site is a Paleo-Indian mammoth kill site, buried in an ancient arroyo or under a sand dune, then this could be the site of a major archaeological excavation. In that case, a university–based archaeologist might conduct field studies at the site for a number of years, even up to 10 years.

Each year, the professor and 10–15 students and 2–3 graduate students might dig for 6–8 weeks, 5–6 days per week, 8 hours per day. In the most extreme case, they would excavate very slowly and carefully and only excavate between 15 and 30 square meters per year (estimated on the basis that each student would excavate between 1 and 2 square meters per year). The students and graduate students would excavate in the soil and/or screen the excavated soil. During the excavation and screening, archaeologists do get dirty and dust-covered. Screened dirt especially collects in socks and boots. Archaeologists also now generally wear hats, long-sleeved shirts and long pants, although in some cases, especially field schools, the students might wear shorts and male students are shirtless, with female students in tank tops (this is less common today with the evidence of skin cancer) (Chiarulli, 2002).

While no archaeologists have ever excavated on this site (and future potential may be low), the fact that such receptors are *possible* because of observed artifacts and such receptors are more intensely exposed to soil contributed to the choice of this subgroup for study. During the digging process, the archaeologist tends to be more exposed to both surface and sub-surface soils. Indeed, the potential for exposure to the archaeologist did drive risk when the calculations were completed.

Because such persons may have close contact with soil, the central tendency of 50 mg soil ingestion/day was assumed but for the reasonable maximum, four times higher, 200 mg soil ingestion/day was assumed. Inhalation rates are the same as for range workers.

Currently, there is no exposure to area residents as isotopes have not been shown to migrate downgradient from the areas of concern. Measurements of depleted uranium at other sites where depleted uranium munitions were used have indicated only localized contamination at the ground surface (WHO, 2002). This finding was also supported at this site where soils in areas of concern (identified because they were utilized in the shelling process) were found to contain concentrations of depleted uranium whereas adjacent areas were at background levels i.e. <1 pCi/g. This contamination line appeared to be sharply drawn, suggesting little migration of the metal to other areas of the site. Vertical migration was limited as well.

Assessment Methodology

The DU dose was calculated as described in the previous section and converted to mrems as shown in Table 3.

For external radiation, DU dose was calculated using appropriate exposure parameters for each receptor and the following Dose Conversion Factors (DCFs) were applied.

DCFs were obtained from EPA Federal Guidance Reports No. 11 and No. 12. They represent conservative values associated with the radionuclides; 15 cm is a practical maximum. The dose is for a height of one meter above the ground. For U-238, the values include contributions from short-lived progeny (except for external calculations where progeny

Table 3
Conversion factors for internal radiation

Isotope	Ingestion	Inhalation
U-234	2.83×10^{-4} mrem/pCi	0.32×10^{-1} mrem/pCi
U-235	2.67×10^{-4} mrem/pCi	1.23×10^{-1} mrem/pCi
U-238 + D	2.69×10^{-4} mrem/pCi	0.18×10^{-1}mrem/pCi

Values calculated from Dose Equivalent per unit intake in EPA FGR No. 11.

are calculated separately). Subsequently, the mrem dose was compared to an acceptable 25 mrem/year.

Soil Exposure Point Concentrations

USEPA recommends that the determination or estimation of exposure point concentrations be representative of actual and foreseeable exposures and compatible with the dose-response values used in the risk characterization. The development of exposure point concentrations often involves statistical analysis of the data; for example the use of the 50th percentile concentration is appropriate to evaluate the Central Tendency Exposure (CTE) and the 90th percentile concentration used for a Reasonable Maximum Exposure (RME). Soil exposure point concentrations are those concentrations that provide a conservative estimate of the concentrations to which a potential receptor may be exposed.

Chemical exposure via each of these pathways was quantified using equations which include the variables discussed above as well as other standard EPA variables for exposure duration, receptor weight, and averaging period.

Evaluation of Risk to Human Health

Evaluation of risk to human health is the estimation of the incidence and severity of the adverse effects likely to occur in a human population due to chemical and/or radiation exposures, which are expressed as risk estimations. Under the EPA framework, risk estimations are based on the comparison of the results between the exposure assessment and the dose-response assessment. This comparison produces estimates that are indicative of the likelihood that adverse effects will occur. The purpose of this risk characterization is to

Table 4
Dose conversion factors for external radiation

Isotope	Dose conversion factor per Bq s m^{-3}
U-234	2.14E-21
U-235	3.75E-18
Th-231	1.94E-19
U-238	5.52E-22
Pa-234m	4.42E-19
Th-230	1.29E-19

Dose coefficients from federal guidance report #12.

present numerical estimates of risk in a context that can be used to make decisions about remediation.

Specifically, this section describes the methods for characterizing cancer risks associated with individual isotopes in soil with cumulative risks for each receptor by exposure pathway. The cumulative risks are then compared with specific risk management criteria that include cumulative receptor risk limits. The result of these comparisons determines whether a condition of no significant risk of harm to human health exists or has been achieved at the site.

Internal Radiological Dose from Soil Ingestion

The primary guide for the annual assessed dose is as follows:

$$H_E + H_{Eext} < 25 \text{ mrem} \quad \text{(for stochastic effects)}$$

where H_E is the annual effective dose from ingestion/inhalation and H_{Eext} is the annual effective external dose.

The internal dose resulting from the incidental ingestion of soil was estimated for the receptors defined using the 90th percentile and 50th percentile radionuclide concentrations for each area. The doses from the ingestion of soil containing DU-associated radionuclides were calculated using the equation:

$$\text{Dose} = \text{Cs} \times \text{IR} \times \text{CF} \times \text{EF} \times \text{DCF}$$

Where:

Dose = effective dose equivalent (mrem per year)
Cs = radionuclide concentation in soil (pCi per g of soil)
IR = soil ingestion rate (mg soil per day)
CF = unit conversion factor (g per mg) = 0.001
EF = exposure frequency (days per year)
DCF = dose conversion factor (mrem per pCi)

Soil ingestion was assumed to occur incidentally during outdoor activities, which could occur year round at this site. For the range worker, incidental soil ingestion rates of 50 mg/day and 100 mg/day were used to represent CTE and RME exposures. For the trespasser, 100 mg/day, CTE, and 200 mg/day, RME ingestion rates were assumed. In archaeologist scenarios, soil ingestion rates were 50 mg/day (CTE) and 200 mg/day (RME); the higher rate reflecting potentially intensive exposure to the soil during digging.

Internal Radiological Dose from Inhalation of Fugitive Dust

The internal dose to each of the human receptor categories from inhalation of fugitive dust was calculated using the following equation:

$$\text{Dose} = \text{Cs} \times \text{InhR} \times (1/\text{PEF}) \times \text{CF} \times \text{EF} \times \text{ED} \times \text{DCF}$$

where

Dose = committed effective dose equivalent (mrem per year)
Cs = radionuclide concentration in soil (pCi per g of soil)
InhR = inhalation rate (m^3 per day)
PEF = particulate emission factor (m^3 per kg of soil)

CF = unit conversion factor (g per kg) = 1000
Ef = exposure frequency (days per year)
ED = exposure duration (years)
DCF = dose conversion factor (mrem per pCi)

CTE and RME inhalation rates used for current and future range workers and archaeologists were 13.25 and 20 m^3 per day; these values are the average and upper-bound inhalation rates identified for adults by USEPA (1997). Inhalation rates for the supposed trespassers were 8.7 and 12 m^3 per day, based on the average and upper-bound rates for 12 to 18 year olds (USEPA, 1997).

The PEF was calculated from data retrieved from the closest airfield from their climate dataset.

External Dose Estimation

The external dose resulting from radiation emitted directly form the soil surface was estimated at a height of one meter above the ground surface. The equation was:

$$\text{Dose} = \text{Cs} \times \text{CF}_1 \times \text{SD} \times \text{T} \times \text{CF}_2 \times \text{DCF}$$

where

Dose = annual external dose (mrem per year)
DCF = external dose conversion factor ([Sv * m^3] per [Bq-s])
Cs = radionuclide soil concentration (Bq per g)
CF_1 = unit conversion factor 1 (g per kg) = 1000
CF_2 = unit conversion factor 2 (mrem per Sv) = 10,000
SD = soil density (kg/m^3) = 1.60×10^3
T = exposure time (sec/year)

Findings

In August of 2002, the University of Massachusetts assessed human health risk in two areas at a military complex using current risk assessment methodology proposed by the USEPA for radiation risk. Risks were calculated for three receptors: range workers, trespassers and archaeologists. The results of the human health risk assessment as shown in Tables 5 and 6

Table 5
Area 1 ingestion/inhalation/external dose Mrem/ year

Receptor	Sum ingestion/inhalation/ external CTE	Sum ingestion/inhalation/ external RME	Exceeds limits?
Range worker carcinogenic	1.4×10^{-2}	3.4	No
Future archeologist carcinogenic	7.8×10^{-3}	13.1	No
Youth trespasser carcinogenic	1.3×10^{-3}	1.9	No

CTE = Central Tendency Estimate.
RME = Reasonable Maximum Exposure.

Table 6
Area 2 ingestion/inhalation/external dose Mrem/year

Receptor	Total risk CTE	Total risk RME	Exceeds limits?
Range worker carcinogenic	4.0×10^{-3}	0.45	No
Youth trespasser carcinogenic	3.6×10^{-4}	0.25	No

CTE = Central Tendency Estimate.
RME = Reasonable Maximum Exposure.

indicated that risks posed to these receptors were below acceptable limits defined by not exceeding 25 mrem on an annual basis for either the CTE or the RME.

Therefore, the future archaeologist is at most risk for carcinogenic effects with a RME mrem annual rate of >13. However, even this highest exposure value does not exceed the acceptable 25 mrem per year. The fact that this exposure is greater than the range worker reflects the intense contact to soil during an archaeological dig.

Conclusions

The calculations revealed that ingestion of soil and external radiation are the predominant exposure pathways in contributing to overall risk. In other assessments—for example in the instance of military personnel exposed in battle—inhalation plays a more important role. This phenomenon is due to the large amounts of DU present as particulate (and even aerosolized) immediately (and for some time) after the penetration of a shell. In the case of this site, the particulate is from a soil source influenced only by climate at this time. Thus, ingestion plays a larger role. This larger role is consistent with the results of Preliminary Risk Guidelines (PRG equations (EPA, 2000)), which show a similar pattern of risk via the two different routes.

Other items investigated during this risk assessment were the chemical effects of DU to the kidney. This calculation employed comparison to the EPA Reference Dose. The results of this evaluation indicated that all hazard indices for the three identified receptors were less than one (<1.0). Other calculations showed that using the Superfund Cancer Slope Factor (CSF) to estimate potential cancer risk resulted in risk estimates within EPA's acceptable target cancer risk levels (1×10^{-4} to 1×10^{-6}) for each receptor. Comparisons of this methodology with the methods described in this paper will be the goal of a future publication.

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