**Beresford, N.A.**; Gaschak, S.; **Barnett, C.L.**; **Howard, B.J.**; Chizhevsky, I.; Stromman, G.; Oughton, D.H.; **Wright, S.M.**; Maksimenko, A.; Copplestone, D.. 2008 Estimating the exposure of small mammals at three sites within the Chernobyl exclusion zone – a test application of the ERICA Tool. *Journal of Environmental Radioactivity*, 99. 1496-1502. doi: 10.1016/j.jenvrad.2008.03.002

**Estimating the exposure of small mammals at three sites within the Chernobyl exclusion zone – a test application of the ERICA-Tool**

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**Abstract**

An essential step in the development of any modelling tool is the validation of its predictions. This paper describes a study conducted within the Chernobyl exclusion zone to acquire data to conduct an independent test of the predictions of the ERICA-Tool which is designed for use in assessments of radiological risk to the environment. Small mammals were repeatedly trapped at three woodland sites between early July and mid-August 2005. Thermoluminescent dosimeters mounted on collars were fitted to *Apodemus flavicollis*, *Clethrionomys glareolus* and *Microtus spp*. to provide measurements of external dose rate. A total of 85 TLDs were recovered. All animals from which TLDs were recovered were live-monitored to determine $^{90}$Sr and $^{137}$Cs whole-body activity concentrations. A limited number of animals were also analysed to determine $^{239,240}$Pu activity concentrations. Measurements of whole-body activity concentrations and dose rates recorded by the TLDs were compared to predictions of the ERICA-Tool. The predicted $^{90}$Sr and $^{137}$Cs mean activity concentrations were within an order of magnitude of the observed data means. Whilst there was some variation between sites in the agreement between measurements and predictions this was consistent with what would be expected from the differences in soil types at the sites. Given the uncertainties of conducting a study such as this the agreement observed between the TLD results and the predicted external dose rates gives confidence to the predictions of the ERICA-Tool.

**Keywords:** Thermoluminescent dosimeter, external dose rate, ERICA, plutonium, caesium, strontium, small mammals, Chernobyl

## 1 Introduction

There are now a number of models and approaches available for the assessment of radiological risk to the environment (Beresford et al. in press). An essential step in the development of such approaches is the validation of their predictions. The ERICA Integrated Approach (Beresford et al. 2007a; Larson et al. 2008) was applied to a number of case studies to test various of its elements (from user friendliness of documentation to comparison of predictions to measurements in a range of ecosystems) during the course of its development (Beresford et al. 2007b; Wood et al. in 2008). This paper describes the results of one of these case study assessments.

### *1.1 The ERICA-Tool*

The ERICA-Tool (Brown et al. in 2008) is the software implementing the ERICA Integrated Approach (Beresford et al. 2007a; Larsson et al. 2008). The assessment element of the ERICA Integrated Approach is organised in three separate tiers. The first of these (Tier 1) is a simple, conservative screening tier which compares input media (water, sediment, soil or air) activity concentrations to predefined environmental media concentration limits (the concentration which would result in a dose-rate to the most exposed organism equal to the screening dose-rate). Tier 2 allows the user to be more interactive, for instance, user defined organisms can be created and default transfer parameters changed. Outputs of a Tier 2 analysis include biota whole-body activity concentrations and dose rates (internal, external and total). Tier 3 allows the user to additionally run the assessment probabilistically. In both Tiers 2 and 3 the user can select a default concentration ratio (CR) database to estimate biota whole-body activity concentrations from input media activity concentrations (the CR databases are described within Beresford et al. (2008) and Hosseini et al. (2008)); Tier 3 also contains default probability distribution functions for each CR. For the purposes of this paper the CR for terrestrial ecosystems is defined as:

$$CR = \frac{\text{Activity concentration in biota whole - body (Bq kg}^{-1}\text{ fresh weight)}}{\text{Activity concentration in soil (Bq kg}^{-1}\text{ dry weight)}}$$

Both Tiers 2 and 3 also allow the user to input biota whole-body activity concentrations if they are available.

The relationship between the activity concentration of an organism or media and internal or external absorbed dose rates is described by the dose conversion coefficient (DCC; μGy $h^{-1}$ per Bq $kg^{-1}$ fresh weight). The methodology used to derive DCC values within the ERICA-Tool is described by Ulanovsky et al. (2008).

Tier 2 predicts both 'best estimate' and 'conservative' dose rates. The best estimate is derived from user input data and mean transfer parameter values (if the default database is used). The conservative dose rate is defined as being equivalent to a specified percentile of the dose rate. This is calculated by applying a default uncertainty factor of three (for 95$^{th}$ percentile) or five (for 99$^{th}$ percentile) to the calculated best estimate value (see Brown et al. (2008) for a more complete description).

*1.2 Objectives of the Chernobyl small mammal case study*

The work described here tested elements of Tiers 2 and 3 of the ERICA-Tool. In particular the objectives were to:

- test the predictions of the activity concentrations from the ERICA-Tool against field based measurements; and
- compare absorbed dose rate predictions with measured dose rates.

To achieve this, a field study was specifically undertaken to provide measurements of external dose rates received by animals within contaminated environments as such dose rate validation data are sparse in the scientific literature.

## 2 Materials and Methods

*2.1 Study sites and determination of soil activity concentrations*

Three forest sites, anticipated to have differing soil radionuclide activity concentrations, were selected in the Chernobyl exclusion zone. The sites will be referred to throughout as *Low*, *Medium* and *High* on the basis of their anticipated soil activity concentrations. At each site a 100 m x 100 m study area was marked out using posts at 10 m intervals. These were subsequently used as the location of small animal traps.

The *Low* site was located approximately 8.5 km south-east of the Chernobyl reactor number 4 (Figure 1). The dominant tree species at this site was *Pinus sylvestris* (Scots pine) with few deciduous trees. Most of the 10 000 $m^2$ study area had sparse understorey vegetation although the eastern part had complete ground cover dominated by graminaceous species. The soils at this site was primarily soddy pseudopodzolic with some podzolic-sandy and loamy sand gleys on fluvio-glacial deposits. The *High* and *Medium* sites were approximately 5 km and 8 km respectively to the west of the Chernobyl power plant complex (Figure 1). The *Medium* site consisted of mainly *P. sylvestris* and *Quercus robur* (Oak) with some *Sorbus aucuparia* (Rowan) and *Tilia platyphyllos* (Large leaved lime), the sparse understorey vegetation included *Pteridium aquilinum* (Bracken). The site had soddy pseudopodzolic sandy and boggy soils on modern alluvial deposits. The *High* site was dominated by *Betula* spp., with few coniferous trees present (this area was a young coniferous plantation at the time of the Chernobyl accident and the majority of coniferous trees were killed). The site had a ground cover consisting predominantly of graminaceous species throughout, although ericaceous species, such as *Calluna vulgaris* (Heather), were also present. Bog peat and soddy pseudopodzolic sandy soil predominated at the *High* site.

Gamma-kerma rates were determined at 5 cm above ground surface at each trapping point using a MKS–01R–01 dose rate meter with a BDKB-01R detector. A stand was used to achieve the same height at each point and the mean of three 10s measurements was recorded. The location of each trapping point was determined using a handheld GPS.

Using a random sampling scheme, 23 soil samples were collected from each site. Samples were taken to a depth of 10 cm and sampling locations recorded using a handheld GPS. The soil sampling area was extended to 50 m beyond the trapping area

to encompass the likely home ranges of the species being trapped (The Mammal Society, 2007). Samples were subsequently, dried and homogenised. Sub-samples were analysed on hyper-pure (Canberra-Packard) germanium detectors to determine the activity concentration of gamma-emitting radionuclides, spectra were analysed using the Canberra-Packard Genie-2000 software package. Count times were such that an error of <20 % on the $^{40}$K estimate was achieved. For samples from the *Medium* and *Low* sites the mass analysed was approximately 750 g dry weight (DW) per sample whilst that for the *High* site was approximately 130 g DW per sample.

The $^{238,239,240}$Pu activity concentrations soils were determined in 10 g DW sub-samples using the method described by Bondarkov et al. (2002a). This method is based on measurement of the $L_x$ - radiation (13-23 keV) emitted from excited uranium daughter isotopes following the α-decay of $^{238\text{-}240}$Pu. The method includes an absorption correction based on the self-absorption of $K_x$ -radiation of Barium (32-37 keV) which is a daughter isotope of $^{137}$Cs. Previous studies have shown good correlation between the $L_x$ method and measurements using standard radiochemistry, and a detection limit of 3-5 Bq Bondarkov et al. (2002a). The accuracy of the method is 10-15%.

Strontium-90 activity concentrations in soils were determined in 10 g DW sub-samples via the measurement of $^{90}$Y activity concentrations using a thin-film (1 mm) NaI scintillation detector as described by Bondarkov et al. (2002b; 2002c); calibration of the method for soil samples is presented by Bondarkov et al. (2002c).

*2.2 Small mammal trapping, whole-body counting and TLDs*

Trapping was conducted on 14 occasions from early July to mid-August 2005. One hundred Sherman humane traps were placed over each sampling area (at the marker posts described above) and baited with rolled oats in the late evening. Traps were revisited early the following day and any animals caught were transported to a laboratory in the town of Chernobyl. The trapping location of each animal was recorded. Only *Apodemus flavicollis* (Yellow-necked mouse), *Clethrionomys glareolus* (Bank vole) and *Microtus spp*. (Vole species) were processed for this study.

The first time an animal was caught it was fitted with a numbered collar to which a LiF-100 thermoluminescent dosimeter (TLD) (Global Dosimetry Solutions Inc., California) had been attached. The collar comprised a 4 mm wide cable-tie; the TLD was attached to this using electrician's tape having first been covered in a single layer of 200 gauge polythene. The live-weight of the animal was recorded and its whole-body $^{137}$Cs and $^{90}$Sr content determined using the method described by Bondarkov et al. (2002b; 2002d). The animals were placed in a small, disposable, cardboard box (70x40x40 mm) the upper side of which was made from <0.1 mm thick polyethylene prior to whole-body counting. The box was then placed inside a lead shielded counting container. The detectors comprised a hyper-pure germanium detector and thin-film (1 mm) NaI scintillation detector to measure $^{137}$Cs and $^{90}$Sr respectively. The $^{137}$Cs spectra were analysed using the Genie-2000 software package. The activity concentration of $^{90}$Sr was determined from that of its daughter nuclide, $^{90}$Y. The method has previously been calibrated against phantoms containing $^{137}$Cs and $^{90}$Sr, and $^{90}$Sr results also validated against traditional radiochemical extraction and analyses methodology (Bondarkov et al., 2002b). The duration of count times varied from 150 to 1200 seconds depending upon the radioactivity in the animal.

Following live-monitoring, the animals were each returned to the individual trapping point from which they were caught and released. If an animal was recaptured more than 14 d after being fitted with a TLD-collar the TLD was removed, the animal reweighed and its whole-body $^{90}Sr$ and $^{137}Cs$ activity concentrations determined again. If it was recaptured less than 14 d after having the collar fitted, the trapping location was recorded and it was released (on some instances additional whole-body Cs measurements were made). In the last two weeks of the study TLDs were removed if an animal was recaptured within 6 days of the TLD having been fitted. A total of 230 TLD-collars were fitted to animals of which 85 were recovered; the time recovered TLDs had been on the animals ranged from 6 to 36 days. Seven TLDs mounted on collars were transported from the UK to the Chernobyl laboratory and left there for the duration of the study as controls.

At four randomly selected trapping points within each sampling site, TLDs were placed 5 cm above ground level, at ground level and 10 cm deep within the soil. In each position, one TLD was prepared in the same manner as those attached to the collars and a second was additionally encapsulated within a 2x2x2 cm cube of Perspex. These were left at the study sites for the duration of the experiment when 25 of the possible 36 paired TLDs were recovered (the remainder having been lost).

The TLDs recovered from small mammals and the study sites were returned to the supplier for analysis together with the control TLDs.

*2.3 Determination of Pu-isotope activity concentrations in small mammal samples*

Pu-isotope activity concentrations have been determined in samples from six animals sacrificed at the end of the study and stored frozen prior to analysis. The animals were: two *A. flavicollis* from the *Medium* site; two *C. glareolus* from the *Medium* site; and two *Microtus spp*. from the *High* site. The carcass was washed prior to freezing, after defrosting the gastrointestinal tract was removed and disposed of. The liver and a bone sample, consisting of a hind-leg and tail, were removed for separate analyses. Samples (bone, liver and remaining carcass) were weighed and transferred to Teflon digestion vessels (120 ml capacity) for a microwave autoclave (UltraClave). Up to 30 ml nitric acid was added to each the vessel depending on the size of the samples. The system was closed, loaded with nitrogen to $1.2x10^7$ Pa, and the mixture was heated to 240º C for 30 minutes. The digested samples were then transferred to glass beakers, evaporated at 120º C and taken up in 7M $HNO_3$ prior to radiochemical separation and analyses using accelerator mass spectrometry (AMS).

High purity $^{242}Pu$ (National Physical Laboratory, USA, E3347) was used as a yield monitor, with certified $^{239}Pu$ and $^{240}Pu$ concentrations of less than $10^{-5}$ Bq per Bq $^{242}Pu$ (these were confirmed by AMS measurement of the tracer). Samples were then subjected to simple radiochemical separation using ion exchange chromatography to extract Pu from the sample matrix. Iron(III)nitrate solution was added to the final eluates, samples taken to dryness, then ashed at 500°C to give the final material for AMS measurements as $Fe_2O_3$ (2 mg Fe), with $^{242}Pu$:Fe atom ratio of $1.2x10^{-8}$.

Accelerator mass spectrometry measurements were carried out using the compact AMS facility at PSI Villigen / ETH Zurich (Switzerland) full details of the analytical technique can be found in Wacker et al. (2005). The three plutonium isotopes (mass 242, 240 and 239) were counted sequentially using repeat cycles for each sample. Analytical blanks, in house standards and certified reference material for Pu and Pu isotope ratios (UKAEA No. UK Pu 5/92138) were determined for each run. Plutonium-239+240 activities in the samples were calculated from the measured

239/242 and 240/242 atom ratios. The detection limit for $^{239}$Pu was 10 μBq, with errors of 5-20 % for the individual samples, largely attributable to counting errors.

## 3 Results

### *3.1 Experimental data*

Soil activity concentrations of $^{90}$Sr, $^{238,239,240}$Pu and detectable gamma-emitting radionuclides are summarised in Table 1 (arithmetic means are presented on this and subsequent tables). When minimum activity concentrations were below the detection limit a value of half the detection limit was used to derive the mean estimate. The mean percentage dry matter contents of the soils were 97 %, 88 % and 87 % at the *Low*, *Medium* and *High* sites respectively.

The trapping success varied across the three sites, Table 2 presents the numbers and species of animals from which TLDs were recovered at each of the sites. The predominant species differed at each site reflecting the different habitats. Trapping success at the *Low* site was reduced because of repeated interference with the traps by wild boar (*Sus scrofa*).

Whole-body $^{137}$Cs and $^{90}$Sr activity concentrations determined in animals from which TLDs were recovered are summarised by species in Table 2; the mean of measurements made for individual animals (each animal being live-monitored at least twice) were used to estimate the summary values.

Concentrations of $^{239+240}$Pu in the bone, liver and remaining carcass of the six animals analysed are presented in Table 3; whole-body (without the gastrointestinal tract) activity concentrations estimated from these results are also shown.

Dose rates determined from the TLDs recovered from trapped animals are presented in Table 4 together with the gamma-kerma rates determined for each site. No measurable dose rates were recorded on any of the control TLDs. The mean ratio of dose rates between the TLDs without and with a 2x2x2 cm Perspex covering placed at various heights above, and depths below, the soil surface at 12 sampling locations was 1.95±0.75 (n=25). There was no trend in this ratio either between study areas or with position above/ below the soil surface.

### *3.2 Predictions using the ERICA-Tool*

An organism geometry to represent each of the three study species was generated within the ERICA-Tool. The live-weights of the three species, as determined during the study, were similar. Therefore, the overall average live-weight of 30 g was used for all species together with dimensions of 8 cm long, 3.5 cm high and 3.5 cm wide (based on measurements made from animals trapped in the area previously by the Ukrainian co-authors of this paper) to create a geometry for which the Tool could estimate DCC values. It was assumed that both *C. glareolus* and *Microtus* spp. spend 30 % of their time on the soil surface and 70 % underground (The Mammal Society, 2006); *A. flavicollis* were assumed to spend equal amounts of time above and below ground (The Mammal Society, 2006). The default ERICA CR values (and associated probability distribution functions) for terrestrial mammals[1]

[1] The ERICA terrestrial mammal CRs are based on available data for all terrestrial mammal with the exception of reindeer (see Beresford et al. this issue).

were assumed to be applicable to each of the species for all radionuclides measured in soil (with the exception of $^{40}$K which is not included within the ERICA-Tool).

3.2.1 Predicted whole-body activity concentrations

Whole-body $^{137}$Cs and $^{90}$Sr activity concentrations were estimated probabilistically using Tier 3 of the ERICA-Tool and assuming that the soil activity concentrations (as presented in Table 1) were log-normally distributed. The relative activity concentrations of $^{239:240}$Pu in soil were assumed to be the same as those determined in the rodent samples by AMS (mean activity ratio $^{239:240}$Pu = 0.64); the $^{238:239}$Pu ratio was assumed to be unity based upon relative releases of the two isotopes from the Chernobyl reactor (from Smith and Beresford 2005) with correction for decay.

Predicted whole-body activity $^{137}$Cs and $^{90}$Sr concentrations are compared to live-monitoring measurements in Table 2; predictions are similar for all three species because the same CR values were used. For most comparisons the measured values are within the range of the predicted 5$^{th}$ and 95$^{th}$ percentiles. Exceptions are: (i) all $^{137}$Cs activity concentrations measured in *C. glareolus* (n=2) from the *High* site are in excess of the predicted 95$^{th}$ percentile value; (ii) the maximum measured $^{137}$Cs activity concentration for *Microtus* spp. at the *High* site is in excess of the predicted 95$^{th}$ percentile; (iii) the maximum measured $^{90}$Sr for *A. flavicollis* at the *Low* site is in excess of the 95$^{th}$ percentile prediction. However, all measured (maximum) values are below the maximum predicted values (not presented here). Mean predicted $^{90}$Sr whole-body activity concentrations are all within 50 % of the observed mean. In the case of $^{137}$Cs mean predicted whole-body concentrations range from an under-prediction by nearly an order of magnitude (*C. glareolus* - *High* site) to an over-prediction of approximately sevenfold (*A. flavicollis* - *Low* site).

Predicted whole-body $^{239+240}$Pu activity concentrations are compared to the measured values in Table 3. Although measurements tend to be within (or close to) the predicted ranges they are all at the low end of predictions. The predicted means (*circa* 20 Bq kg$^{-1}$ (FW) at the *Medium* site and 33 Bq kg$^{-1}$ (FW) at the *High* site) are all more than an order of magnitude greater than the highest measured values.

3.2.2 Predicted external dose rates and a comparison with the TLD results

For comparison with the dose rate estimates reported for the TLDs attached to animals at the study sites, external dose rates have been estimated using: (i) predictions made for each individual animal for which a TLD result was available using Tier 2 of the ERICA-Tool; (ii) probabilistic estimations using Tier 3 of the ERICA-Tool.

To derive individual animal specific soil activity concentration inputs for the comparison using Tier 2, spatial interpolations of the data were attempted using block kriging (Karssenberg and Burrough, 1996). However, whilst variable, the data demonstrated no significant spatial trend at any of the three sites. Therefore, the average activity concentration was determined for all soil samples falling within a 30 m radius of each trapping location (a 30 m radius was considered as representative of likely home ranges of the three species (The Mammal Society, 2007)). If an animal had been caught in more than one trap, a weighted soil activity concentration was derived.

Whilst $^{40}$K is not considered within the ERICA-Tool, DCC values have been derived using the same methodology (Ulanovsky pers com; some of these are

presented in Beresford et al. 2007c)[2]. Those for the default rat geometry were used to estimate external dose rates due to $^{40}$K. From the Tier 2 analyses caesium-137 was estimated to contribute ≥99 % of the total external dose rate at all three sites; $^{40}$K was estimated to contribute from 0.02 % at the *High* site to 0.8 % at the *Low* site. The contribution to the total dose due to time spent underground was approximately 86 % for both vole species and 72 % for *A. flavicollis*. Comparison of individual TLD measurements and Tier 2 predictions is presented after the discussion of the Tier 3 predictions.

Unfortunately, Tier 3 of the ERICA-Tool does not report a result for total external dose rate; instead results are presented for each radionuclide. However, as $^{137}$Cs dominated the estimated external dose using Tier 2, it can be assumed that the predicted external dose rate due to $^{137}$Cs at Tier 3 can be used as a comparison to the TLD results (Table 4). The predicted external dose rates are consistently lower than the results of the TLD derived dose rates with the predicted 95$^{th}$ percentile being less than the minimum dose rate recorded on the TLDs for four of the seven comparisons. The predicted dose rates tend to be in better agreement with the gamma-kerma rates measured at 5cm above the soil surface (Table 4).

However, as reported above, the dose rates recorded by TLDs prepared in the same manner as those attached to the study animals and placed at various heights above and below the soil surface were on average 1.95 times higher than the dose rates recorded by TLDs situated in the same location but shielded by 2 cm of Perspex. If we assume that this additional dose is the result of exposure to beta radiation (excluded by the Perspex) and that it is representative of beta dose rates recorded by the TLDs on the animal collars then we can correct the results from the TLDs attached to the collars (i.e. dividing by 1.95) to derive the external gamma dose rate. The resultant 'corrected' TLD results are presented in Table 4. Comparison between the 'corrected' TLD dose rates and predicted external dose rates are improved, especially for both species from the *Low* site and *C. glareolus* at the *Medium* sites. Mean predicted external dose rates ranged from 70 % to 99 % of the 'corrected' TLD measurement for these animals. For the remaining animals predictions were 31 to 47 % of the 'corrected' TLD measurement.

Whilst the mean predictions of dose rate are in reasonable agreement with the 'corrected' TLD measurements, individual dose rates (estimated using Tier 2) are not well predicted as demonstrated in Figure 2 for the *Medium* site.

3.2.3 Total dose rate predictions – a comparison of Tier 2 and 3

As discussed above, within Tier 2 of the ERICA-Tool the user can select uncertainty factors within their assessment to determine the estimated 'conservative' absorbed dose rate and risk quotient. An uncertainty factor of three is suggested for use to give a conservative estimate of absorbed dose rate equivalent to the 95$^{th}$ percentile value (see Brown et al. 2008). To test this assumption, total (internal plus external) absorbed dose rates have been predicted using Tiers 2 and 3. Table 5 compares the resultant conservative dose rate estimates from Tier 2 with the predicted 95$^{th}$ percentile values from Tier 3. For both tiers, calculations were performed using soil activity concentrations as the input, and again, using soil and available whole-body $^{137}$Cs and $^{90}$Sr activity concentrations as inputs. Within Tier 3, default CR values

[2] Note the version of the ERICA-Tool to be released early 2008 should include $^{40}$K as a default radionuclide.

with associated probability distributions functions were used (when whole-body activity concentrations were not used/available) and calculations were performed assuming input data were log-normally distributed. In all instances, the 95$^{th}$ percentile value predicted using Tier 3 of the Tool was similar to, or lower than, the conservative estimate output by Tier 2 (Table 5). Generally, the inclusion of measured whole-body activity concentrations as input data reduced the Tier 2 conservative dose rate and the Tier 3 95$^{th}$ percentile prediction; exceptions were observed for some species at the *High* site in the results for both tiers.

## 4 Discussion

The default ERICA CR values for $^{90}$Sr, $^{137}$Cs and $^{239/240}$Pu generally predicted ranges (5$^{th}$ and 95$^{th}$ percentiles) in whole-body activity concentrations which encompassed the measured data. Predicted $^{90}$Sr activity concentrations showed the best agreement with the measured data; mean predictions being within a factor of two of the observed data means. Whilst predictions of $^{137}$Cs whole-body activity concentrations for *C. glareolus* at the *High* site appear poor (Table 2) there were only two samples for this species at this site and the species was adequately predicted at the other two sites. Observed whole-body activity concentrations of $^{239+240}$Pu for the few (n=6) animals analysed were generally close to the predicted 5$^{th}$ percentile value (Table 3). This is consistent with the finding of an international comparison exercise which found that the default mammal CR value for Pu used by the ERICA-Tool is one to two orders of magnitude higher than that used by other approaches (see Beresford et al. in press).

There is considerable variation in environmental transfer of radionuclides to biota; the CR databases used to compile the ERICA CR values show three to four orders of magnitude variation in transfer to mammals for Cs, Sr and Pu. It is possible that the differing agreement between predictions and observations at the three study sites was a consequence of site specific factors such as soil characteristics and the contribution of 'hot particles' to the radionuclide deposit (potentially significant and variable within the exclusion zone). In terms of the possible influence of soil type, the variation in comparative transfer of $^{137}$Cs (lowest at the *Low* site and highest at the *High* site) and $^{90}$Sr (lowest at the *High* site and highest at the *Low* site) at the three sites is in agreement with differences in soil to plant transfer observed within the exclusion zone (Sobotovich et al. 2003). Since the prediction of all $^{90}$Sr and $^{137}$Cs mean activity concentrations are within an order of magnitude of the observed data means, the predicted whole-body activity concentrations for all three radionuclides can be considered acceptable. This study can be considered an independent test of the ERICA-Tool CR values, the default CR database for mammals contains few measurements of rodents within the Chernobyl exclusion zone (being limited to one data entry for each of Pu and Sr).

The mean predicted external ($^{137}$Cs) dose rates were within a factor of three of measured ('corrected' TLD) values for all site-species combinations. As for predictions of whole-body $^{137}$Cs activity concentrations, agreement was poorest for *Microtus* spp. and *C. glareolus* at the *High* site. Whilst most external dose rate predictions were within 50 percent of the measured values all predicted means were below the mean observed values. However, this may be due, at least in part, to the

interpretation of what the corrected TLD measurements represent. At the *Medium* and *High* sites the mean whole-body $^{137}Cs$ activity concentration of the animals was greater than the mean fresh weight soil activity concentration (up to 20 times at the *High* site). It is, therefore, highly likely that the TLDs recorded 'external dose' included a contribution from the animal itself.

There was poor agreement between individual TLD measurements and predicted external dose rates (see Figure 2). This may be because the numbers of soil samples taken in the study were insufficient to adequately describe the spatial variation in contamination of soil making individual predictions unreliable (no spatial trends were evident in soil activity concentrations).

Given the uncertainties of conducting a study such as this we consider that the agreement observed between the TLD results and the predicted external dose rates gives confidence to the predictions of the ERICA-Tool.

## Acknowledgements

This work was partially supported by the EC-EURATOM 6th Framework Programme (2002-2006) as part of the ERICA (*Environmental Risk from Ionising Contaminants: Assessment and Management*) project (contract FI6R-CT-2003-508847). The financial support of the EC is gratefully acknowledged. CEH and IRL also acknowledge the funding provided by the England and Wales Environment Agency and the Centre for Ecology & Hydrology. The work at UMB was also supported by the Norwegian Research Council (project 166947). We thank Lucas Wacker at ETH, Zurich for his invaluable help in the AMS determination of plutonium. The ERICA-Tool is freely available from: http://www.project.facilia.se/erica/_download.html.

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Table 1**. Activity concentrations determined in soil samples collected over each sampling area (n=23 from each sampling site).**

| | Soil activity concentrations (kBq kg$^{-1}$ DW) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Site** | **$^{134}$Cs** | **$^{137}$Cs** | **$^{90}$Sr** | **$^{40}$K** | **$^{60}$Co** | **$^{241}$Am** | **$^{154}$Eu** | **$^{155}$Eu** | **$^{238,239,240}$Pu** |
| **Low** | | | | | | | | | |
| Mean | 0.007 | 7.37 | 2.20 | 0.19 | <0.004 | 0.21 | 0.04 | 0.02 | 0.13 |
| SD | 0.005 | 4.21 | 1.10 | 0.05 | | 0.15 | 0.02 | 0.005 | 0.14 |
| Min. | <0.004 | 1.70 | 0.85 | 0.14 | | 0.04 | <0.05 | <0.03 | <0.02 |
| Max. | 0.02 | 23.7 | 5.99 | 0.33 | | 0.65 | 0.12 | 0.03 | 0.68 |
| **Medium** | | | | | | | | | |
| Mean | 0.09 | 43.3 | 18.6 | 0.09 | 0.02 | 1.47 | 0.19 | 0.06 | 0.83 |
| SD | 0.21 | 25.7 | 14.9 | 0.05 | 0.02 | 2.48 | 0.16 | 0.07 | 1.49 |
| Min. | 0.0005 | 12.6 | 1.84 | 0.00 | <0.004 | 0.01 | <0.05 | <0.03 | <0.02 |
| Max. | 1.05 | 115 | 61.1 | 0.20 | 0.09 | 11.7 | 0.56 | 0.26 | 7.4 |
| **High** | | | | | | | | | |
| Mean | 0.10 | 97.7 | 56.5 | 0.08 | 0.07 | 3.20 | 0.52 | 0.20 | 1.47 |
| SD | 0.05 | 41.8 | 39.0 | 0.02 | 0.08 | 4.59 | 0.63 | 0.24 | 2.02 |
| Min. | 0.001 | 27.5 | 7.43 | 0.04 | <0.004 | 0.03 | <0.05 | <0.03 | 0.08 |
| Max. | 0.22 | 208 | 165 | 0.15 | 0.39 | 19.21 | 3.20 | 1.17 | 9.79 |

**Table 2**. A comparison of measured $^{90}Sr$ and $^{137}Cs$ whole-body activity concentrations with those predicted using Tier 3 of the ERICA-Tool. The number of each species trapped at the three sites is also indicated.

| Radionuclide/ site/species | n | Measured whole-body activity concentration (kBq kg$^{-1}$ FW) Mean±SD | Range | Predicted whole-body activity concentration (kBq kg$^{-1}$ FW) Mean | 5$^{th}$ percentile | 95$^{th}$ percentile |
|---|---|---|---|---|---|---|
| **$^{137}Cs$** | | | | | | |
| **Low** | | | | | | |
| *C. glareolus* | 3 | 3.8±0.8 | 3.1-4.7 | 21.1 | 1.4 | 73.4 |
| *A. flavicollis* | 18 | 3.1±2.0 | 1.3-9.8 | 21.2 | 1.4 | 76.6 |
| **Medium** | | | | | | |
| *C. glareolus* | 39 | 70.5±46.3 | 17.0-252 | 123 | 8.0 | 437 |
| *A. flavicollis* | 10 | 59.7±37.1 | 24.1-143 | 124 | 8.1 | 421 |
| **High** | | | | | | |
| *C. glareolus* | 2 | 2260±1290 | 1350-3180 | 273 | 22.6 | 931 |
| *Microtus spp.* | 11 | 611±282 | 252-1140 | 279 | 21.0 | 976 |
| *A. flavicollis* | 2 | 145±53.3 | 108-183 | 274 | 22.3 | 959 |
| **$^{90}Sr$** | | | | | | |
| **Low** | | | | | | |
| *C. glareolus* | 3 | 7.7±4.1 | 3.1-10.3 | 3.9 | 0.3 | 13.5 |
| *A. flavicollis* | 18 | 7.4±5.2 | 1.4-21.1 | 3.8 | 0.3 | 12.7 |
| **Medium** | | | | | | |
| *C. glareolus* | 39 | 19.5±7.4 | 4.3-36.0 | 32.8 | 1.9 | 117 |
| *A. flavicollis* | 10 | 24.7±6.1 | 16.0-34.0 | 32.7 | 1.9 | 121 |
| **High** | | | | | | |
| *C. glareolus* | 2 | 81.3±22.1 | 65.6-96.9 | 99.4 | 6.7 | 362 |
| *Microtus spp.* | 11 | 107±35.0 | 38.1-167 | 100 | 6.7 | 352 |
| *A. flavicollis* | 2 | 66.6±28.3 | 46.6-86.7 | 99.3 | 6.6 | 353 |

**Table 3.** $^{239+240}$Pu activity concentrations in selected small mammals from the *Medium* and *High* sampling sites (two animals were analysed for each species type; results presented as range of these two measurements); measured whole-body activity concentrations are compared with predictions using the ERICA-Tool.

| | $^{239+240}$Pu (Bq kg$^{-1}$ FW) | | | | |
|---|---|---|---|---|---|
| **Species/site** | **Bone** | **Liver** | **Remaining carcass** | **Whole-body** | **Predicted whole-body**[+] |
| **Medium** | | | | | |
| *C. glareolus* | 0.30-0.94 | 0.10-0.68 | 0.22-1.85 | 0.21-1.71 | 0.10-72 |
| *A. flavicollis* | 0.34-0.51 | 0.49-0.56 | 0.34-1.09 | 0.35-1.04 | 0.10-74 |
| **High** | | | | | |
| *Microtus spp.* | 0.24-1.10 | <0.07-0.52 | 0.17-0.52 | 0.17-0.52 | 0.24-134 |

[+]Predicted 5$^{th}$ and 95$^{th}$ percentiles are presented for comparison with measured range.

**Table 4**. A comparison of dose rates recorded by TLDs compared with external dose rates predicted using Tier 3 of the ERICA-Tool; gamma-kerma rates determined 5 cm above the soil surface are also presented.

| | | TLD dose rate µGy $h^{-1}$ | | | | TLD dose rate 'corrected' µGy $h^{-1}$ | | | | External dose rate Predicted[+] µGy $h^{-1}$ | | | Gamma-kerma (µGy $h^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Species/site** | **n[*]** | **Mean** | **SD** | **Min.** | **Max.** | **Mean** | **SD** | **Min.** | **Max.** | **Mean** | **5th percentile** | **95th percentile** | **Mean** | **SD** | **Min.** | **Max.** |
| **Low** | | | | | | | | | | | | | 1.96 | 0.42 | 0.66 | 3.38 |
| *C. glareolus* | 3 | 4.11 | 1.21 | 2.78 | 5.14 | 2.11 | 0.62 | 1.43 | 2.64 | 1.75 | 0.63 | 3.71 | | | | |
| *A. flavicollis* | 18 | 2.90 | 1.16 | 0.90 | 5.00 | 1.49 | 0.60 | 0.46 | 2.57 | 1.48 | 0.54 | 3.15 | | | | |
| **Medium** | | | | | | | | | | | | | 11.5 | 3.2 | 5.8 | 20.1 |
| *C. glareolus* | 39 | 25.5 | 12.1 | 9.04 | 74.1 | 13.1 | 6.21 | 4.65 | 38.1 | 9.21 | 3.22 | 19.1 | | | | |
| *A. flavicollis* | 10 | 33.4 | 24.4 | 17.3 | 100 | 17.2 | 12.6 | 8.87 | 51.4 | 7.80 | 2.73 | 16.2 | | | | |
| **High** | | | | | | | | | | | | | 31.4 | 7.9 | 5.7 | 52.3 |
| *C. glareolus* | 2 | 129 | 82.3 | 71.1 | 188 | 66.5 | 42.3 | 36.5 | 96.4 | 20.7 | 9.61 | 37.2 | | | | |
| *Microtus spp.* | 11 | 84.9 | 28.7 | 46.5 | 151 | 43.7 | 14.7 | 23.9 | 77.6 | 20.7 | 9.61 | 37.2 | | | | |
| *A. flavicollis* | 2 | 84.1 | 0.58 | 83.7 | 84.5 | 43.2 | 0.30 | 43.0 | 43.4 | 17.6 | 8.15 | 31.5 | | | | |

*Number of TLD measurements.

[+]Estimated from $^{137}Cs$ soil activity concentrations.

**Table 5**. Comparison of total absorbed dose rates predicted using Tier 2 (conservative prediction assuming an uncertainty factor of 3) with the output from Tier 3 (predicted 95$^{th}$ percentile value).

| | **Total absorbed dose rate (μGy h$^{-1}$)** | | | |
|---|---|---|---|---|
| | **Tier 2 Input data** | | **Tier 3 Input data** | |
| **Site/Species** | **Soil** | **Soil & whole-body** | **Soil** | **Soil & whole-body** |
| **Low** | | | | |
| *C. glareolus* | 23.2 | 22.0 | 19.2 | 12.2 |
| *A. flavicollis* | 22.3 | 20.3 | 19.2 | 12.9 |
| **Medium** | | | | |
| *C. glareolus* | 149 | 101 | 134 | 54.6 |
| *A. flavicollis* | 145 | 101 | 130 | 52.1 |
| **High** | | | | |
| *C. glareolus* | 383 | 1270 | 336 | 808 |
| *Microtus spp.* | 383 | 551 | 336 | 277 |
| *A. flavicollis* | 373 | 254 | 329 | 125 |

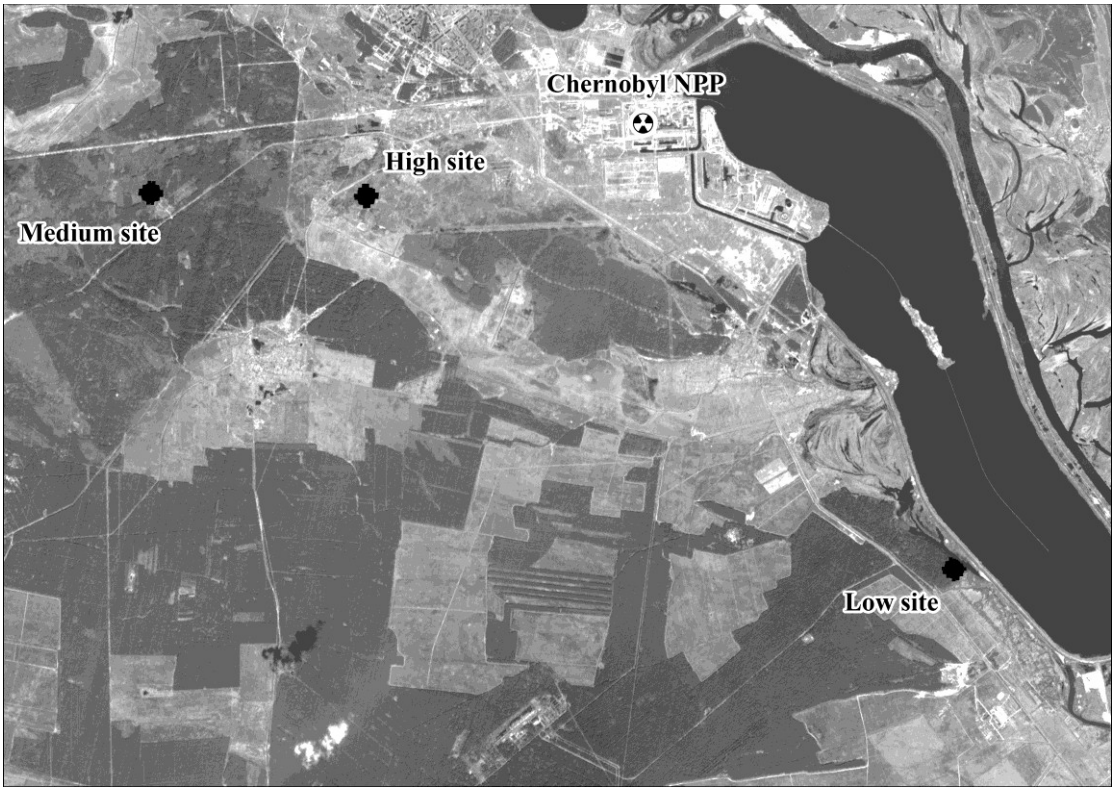


**Figure 1**. Location of the study sites relative to the Chernobyl nuclear power plant (NPP). Photograph from the original with the kind permission of Valery Kashparov of the Ukrainian Institute of Agricultural Radiology (UIAR, 2001).

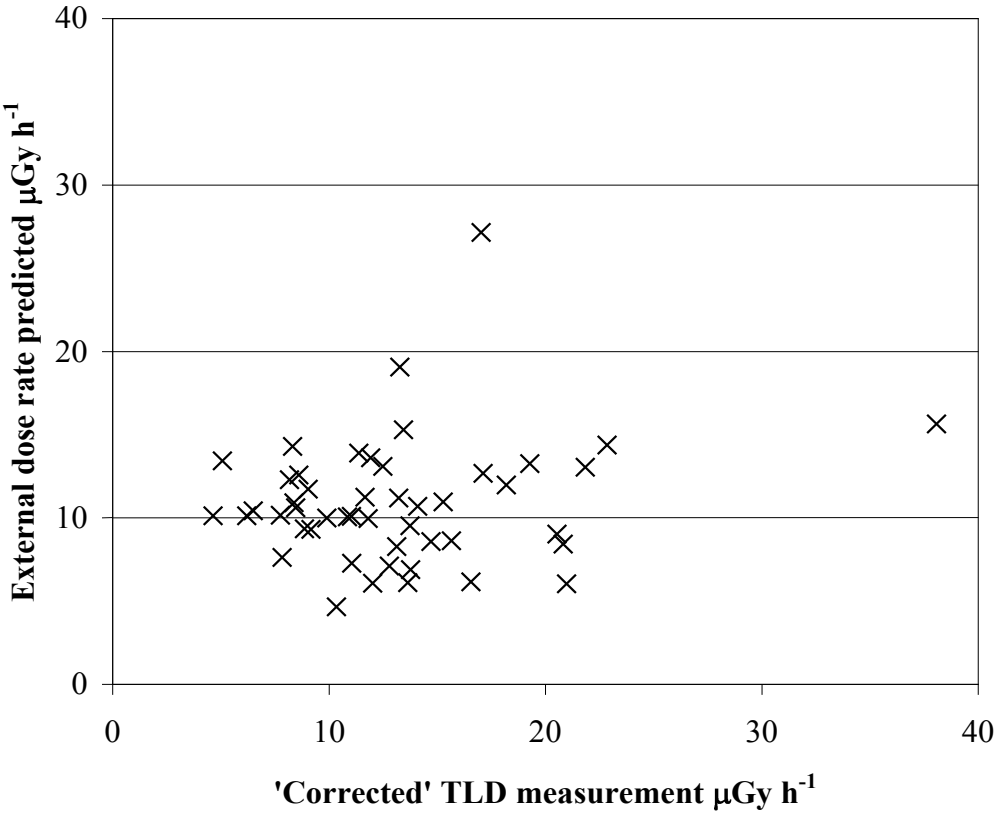


**Figure 2.** A comparison of predicted external dose rates with 'corrected' TLD measurements for animals at the *Medium* site.