Depleted Uranium Survey Report: Kirkcudbright Training Area 2011 Part 2 Marine Environment

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Executive Summary

Depleted uranium (DU) ammunition has been test fired at the Kirkcudbright Training Area (KTA) since 1982. Routine environmental monitoring has been carried out at KTA since 1980 to assess the extent of any radiological impact of the firings on the terrestrial and marine environments and any associated risk to humans.

This report presents the findings of the marine survey undertaken in the areas surrounding KTA during 2011; the terrestrial survey is reported separately in Part 1. The survey was undertaken to monitor the levels of any depleted uranium in the marine environment resulting from operations on the site and to identify the extent of any environmental transfer processes.

The measured levels of uranium were found to be consistent with natural background levels. None of the samples analysed were radioactive within the meaning of the Radioactive Substances Act 1993, nor did they exceed a very small fraction of the Generalised Derived Limits advised by the Health Protection Agency (formerly the National Radiological Protection Board).

The results of the 2011 survey are consistent with historical survey findings. There is no evidence to indicate that members of the public are exposed to a radiological hazard from the marine environment as a result of test firing DU ammunition at Kirkcudbright.

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1 Introduction

Depleted uranium (DU) ammunition has been test fired at the Kirkcudbright Training Area (KTA) since 1982. Routine environmental monitoring has been carried out at KTA since 1980 to assess the extent of any environmental impact of the firings on the terrestrial and marine environments and any associated radiological risk [1 to 15].

This report presents the findings of the marine survey undertaken in the areas surrounding KTA during 2011; the terrestrial survey is reported separately in Part 1 [15]. The survey was undertaken to monitor the levels of any uranium in the marine environment resulting from operations on the range and to identify the extent of any environmental transfer processes.

Since its inception in 1980, the monitoring programme has evolved to incorporate changes in best practice and increased knowledge of the local environment. The changes to sampling protocols over the years were fully explained in the marine report for 2005 [9]. Since 1996, the survey methodology has remained consistent and involves the annual sampling of inter-tidal sediment and biota, together with the measurement of environmental gamma dose rates along the Dumfries coastline. Underwater sediment and locally caught seafood are also sampled.

2 Background

The KTA range is located on the coast of Dumfries and Galloway, near Castle Douglas. In April 2006, the range became part of the Defence Training Estate (DTE).

DU has been released into the environment at KTA as a consequence of the test firing of DU ammunition during design and accuracy assessment trials. DU projectiles are fired through soft vertical targets and continue their trajectory, coming to rest in the Solway Firth.

There was no DU firing at KTA between 2003 and 2007. A total of 20 rounds was fired in 2008 as part of a routine surveillance programme to ensure the safety and serviceability of the ammunition. No firing has taken place since 2008 (see Figure 3 in Annex B Historical Data).

Testing of projectiles has historically taken place at five locations at KTA. Each battery location had a designated target and line of fire and hence a predictable area of impact ranging from several hundred metres to approximately 7 kilometres offshore. Although a small number of the DU rounds malfunctioned and impacted on land, the vast majority entered the Solway Firth.

3 Depleted Uranium (DU)

Uranium is a naturally occurring radioactive material which exists as three isotopes: uranium-238 (^{238}U), uranium-235 (^{235}U) and uranium-234 (^{234}U). The typical mass composition of these isotopes is shown in Table 1. In the environment, natural uranium isotopes, ^{238}U and ^{235}U, are in approximate radioactive equilibrium with the daughter products[1]. Together these isotopes emit a range of alpha and beta particles along with gamma radiation. Being a heavy metal, the chemical toxicity of uranium is approximately equal to that of lead.

Uranium in an 'enriched' form is used as fuel in nuclear reactors. The enrichment process increases the concentration of ^{235}U (above 0.72%) in comparison to the natural form. The by-

[1] A radioactive decay series occurs when a heavy radionuclide decays into successively lighter radionuclides known as daughter products. For example, ^{238}U decays to ^{234}Th, then ^{234m}Pa, then ^{234}U and so on until a stable element is reached (^{206}Pb).

product of this process is 'depleted' uranium (DU), which has a reduced concentration of ^{235}U. Uranium-234 is also removed in the depletion process, meaning that DU is consequently less radioactive than natural uranium (the specific alpha activity of the DU alloy used at Kirkcudbright is approximately 1.4×10^7 milli becquerels per gram (mBq/g), compared to around 2.5×10^7 mBq/g for natural uranium). The mass compositions of DU and natural uranium are presented in Table 1 below.

Form of Uranium	^{238}U	^{235}U	^{234}U
Natural uranium	99.274%	0.72%	0.00554%
The DU used at Kirkcudbright	99.8%	0.20%	0.0008%

Table 1. Typical mass composition of uranium isotopes in natural and depleted uranium.

As discussed in paragraph 3.1, ^{234}U normally exists in approximate equilibrium with ^{238}U in the natural environment. In comparison, DU exhibits a $^{238}U/^{234}U$ activity ratio of between 7:1 and 8:1, dependent on the degree of depletion achievable by different methods of processing. This distinction is important in differentiating DU contamination from naturally occurring uranium in the environment (see Section 4). For the remainder of this report, isotopic ratios will be stated in terms of activity rather than mass and as a single value representing the ratio of becquerels of ^{238}U to 1 becquerel of ^{234}U (i.e. a $^{238}U/^{234}U$ ratio of 7 rather than 7:1).

4 Differentiating DU from Natural Uranium

The fundamental requirement of the DU environmental monitoring programme is to quantify the impact of DU firing. This is achieved partly by measuring the amount of total uranium in environmental materials and using this figure as an upper bound of DU contamination levels. However, as uranium is present at detectable levels in most environmental materials, this overestimates the risk. More sophisticated analyses involve the specific measurement of ^{238}U and ^{234}U isotopes (by activity and/or mass). Although isotope measurements are used in this survey, references to total uranium measurements are included for consistency with historic reports. The limitations of using total uranium concentrations are discussed further in Annex C.

A convenient fingerprint marker for DU contamination is the $^{238}U/^{234}U$ activity ratio. The DU fired at KTA has a $^{238}U/^{234}U$ activity ratio of approximately 7, whereas natural uranium in the environment has an activity ratio close to unity. Environmental samples are therefore analysed for isotopes of ^{238}U and ^{234}U to determine activity ratios and hence identify the origin of the uranium.

Samples are considered to contain detectable levels of DU contamination if the $^{238}U/^{234}U$ ratio is above 1.0 following the subtraction of the associated uncertainty (i.e. if there is 95% confidence that the true mean is greater than 1.0). This quantitative calculation can only be made when ^{238}U and ^{234}U are present at levels above the limit of detection for the analytical technique; no ratio can be calculated when both isotopes are below the limits of detection. However, qualitative information can be obtained when ^{238}U is detectable and ^{234}U is not, assuming that ^{234}U is present at a level equal to the limit of detection. Therefore, in some cases where the ratio is shown as “N/A” on the tables in Annex A, it has been possible to infer rather than definitely prove the presence of DU. This represents a pessimistic interpretation of the data.

Substantial deposition of DU in the environment (in addition to an existing natural uranium background) is required before the $^{238}U/^{234}U$ activity ratio diverges significantly from its natural ratio. An illustration of the impact of DU contamination on the isotopic ratio is given in Annex D. For the ratio to approach 7 in an analytical sample, the mass of DU would have to be approximately one hundred times the mass of the uranium that is naturally present. Hence, the lower the natural uranium background, the lower the levels of DU contamination that may be detected by isotopic analysis.

Isotopic quantification is achieved by techniques such as Alpha Spectrometry and Mass Spectrometry. The alpha spectrometry system utilised by Dstl can detect ^{238}U at a limit of detection of 0.5 mBq kg^{-1}, or to lower levels if count times are increased. Mass spectrometry is more sensitive, but the lower levels detectable are of no recognised health significance. The analysis method used for the environmental monitoring at Kirkcudbright is alpha spectrometry.

5 Reference Levels

The Depleted Uranium Firing Environmental Review Committee (DUFERC), on which the MOD is represented, has agreed investigation/action levels for levels of DU in the terrestrial environment. Reference levels for the marine environment are taken directly from legislation and guidance, as discussed below.

For uranium in sediment, the activity concentration can be compared to the Schedule 1 limit defined in the Radioactive Substances Act 1993 (RSA93) [16] and Generalised Derived Limits (GDLs) advised by the Health Protection Agency (formerly the National Radiological Protection Board) [17]. GDLs for uranium were last updated in 2000 and were referred to by the Royal Society in their studies of the potential health effects of using DU munitions [18]. They are based on a 1 milli-sievert (mSv) potential exposure to a member of the public: the dose limit set by the International Commission on Radiological Protection (ICRP) and incorporated into UK law [19].

Uranium levels in foodstuffs such as fish, crustaceans and molluscs can be compared against the relevant GDL (expressed as fresh mass of the edible fraction). For biota such as seaweed, the European Council Food Intervention Level (CFIL) for 'other foodstuff' is considered a useful value although is predominantly used in the event of a radiological emergency. [20].

Since April 2011, there have been significant changes to the legislation concerning the control of radioactive substances [16] now include revised regulatory thresholds for material containing uranium. As such, DUFERC investigation/action levels are currently being reviewed in line with these changes. For the purpose of this report, the levels in Table 2 have been used.

Reference levels relevant to the Kirkcudbright marine survey are provided in Table 2.

Source	Reference Level	Activity concentration (mBq/g)
RSA 93	Schedule 1 limit - level at which regulatory control is required.	11,100
NRPB (2000)	Generalised Derived Limit: Marine sediment (dry weight)	100,000
	^{238}U in marine fish (fresh weight)	200
	^{238}U in crustaceans (fresh weight)	1,000
	^{238}U in molluscs (fresh weight)	1,000
CEC Regulation (Euratom) 2218/89	European Council Food Intervention Level (CFIL) for 'other foodstuff'	1,250

Table 2. Reference levels relevant to the Kirkcudbright marine survey.

In addition to these reference values, it is also possible to compare the results with those of similar surveys carried out in the UK. The Radioactivity in Food and the Environment (RIFE) [20] reports present the findings of an annual independent survey carried out by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) on behalf of the environment agencies and the Food Standards Agency. Where possible, monitoring results are compared against those of the RIFE reports and other relevant surveys [21]. The latter includes monitoring data for Sandyhills Bay (also monitored by Dstl); which is sufficiently close to KTA to be similar in geology, but sufficiently far away to be considered unaffected by activities at the range.

6 Methodology

The survey methodology comprises the sampling of inter-tidal sediment and biota, together with the measurement of environmental gamma dose rates along the Dumfries coastline. Underwater sediment and locally caught seafood are also sampled.

Inter-tidal zone sampling

Sampling and dose rate measurements were carried out at 11 locations as shown at Figure 1. These locations have been chosen to provide a suitable distribution of sampling points spanning the areas likely to be affected by the DU firing at KTA. It should be noted that sampling location 5 was re-positioned approximately 2 km to the North-East (Balcary Bay) in 2007 due to ongoing problems with safe access to the area.

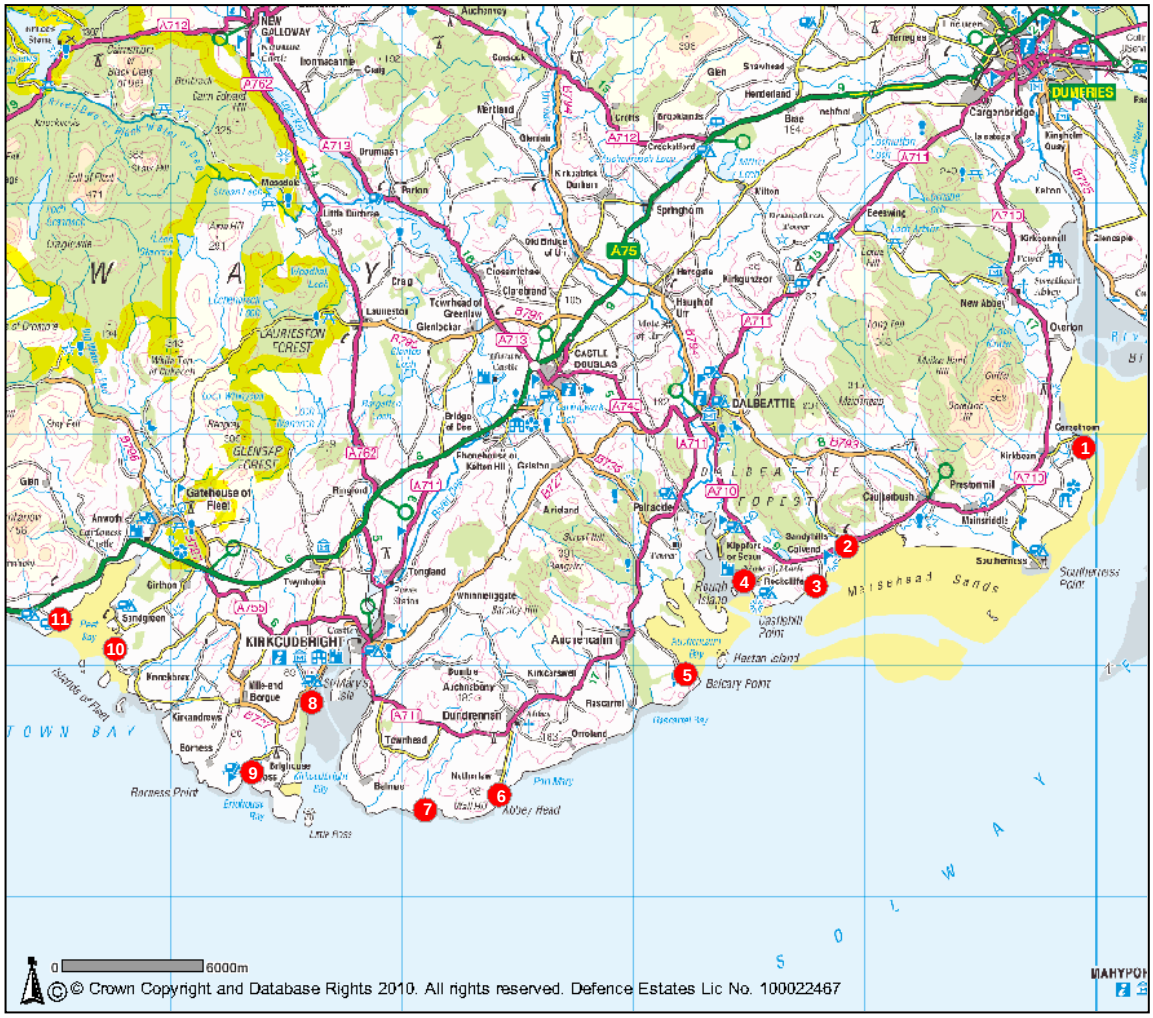

Figure 1. Kirkcudbright inter-tidal sampling locations 2011.

The Ordnance Survey of Great Britain grid references for the sampling locations in 2011 are given below:

1. South Carse NX 99333 59800
2. Sandyhills Bay NX 89553 55298
3. Port o'Warren Bay NX 87892 53427

4.	Port Donnel	NX 84800 53400
5.	Balcarry Bay	NX 82182 49544
6.	Abbey Burn Foot	NX 74276 44391
7.	Mullock Bay	NX 70996 43765
8.	Lower Nunton Bay	NX 65868 48605
9.	Brighouse Bay	NX 63469 45708
10.	Carrick Point	NX 57459 50502
11.	Mossyard Bay	NX 55195 51777

Inter-tidal sediment was collected from each sampling location for analysis by alpha spectrometry. The sediment was collected as close to the low water mark as possible, giving due consideration for the safety of the survey team. Due to the abundance of available inter-tidal sediment, composite samples were collected by taking the top few millimetres of sediment from a number of locations until enough material was collected to fill a 0.8 litre container. Shells, stones and other unwanted debris were removed from samples and any excess water was drained off.

Seaweed samples were collected where available from sampling locations for analysis by alpha spectrometry. The most recent growth of seaweed was collected by cutting the top 5cm of fronds from a number of locations and combining the material to form a composite sample (approximately 1.8 litre sample volume). The collected samples, which consisted of a single species (*Fucus vesiculosus*), were washed in sea-water to remove any sediment.

Mollusc samples were collected from each sampling location where found in sufficient amounts. A composite sample was collected in a 1.8 litre sample container and washed in sea-water to remove any sediment. The samples were washed a second time and boiled on the day of collection to prevent decomposition before analysis. The samples were placed in a re-sealable bag and frozen prior to transport to the laboratory for analysis by alpha spectrometry.

Environmental gamma dose rates were recorded at each sampling location using the Mini Instruments 6-80/81 fitted with an MC71 compensated Geiger-Muller tube. The instrument was allowed to record over a period of 300 seconds at three points along the low water mark and at one point at the high water mark (at one metre above the ground). The recorded count rates were converted to an environmental gamma dose rate using the methodology described in Reference 22.

A summary of samples collected and dose rate measurements taken from the inter-tidal zone is provided in Table 3.

Sample area number	Sample type and number of samples			Environmental dose rates	
	Sediment	Seaweed	Edible mollusc	LWM @ 1m height	HWM @ 1m height
1	✓	x	✓	✓	✓
2	✓	✓	✓	✓	✓
3	✓	✓	✓	✓	✓
4	✓	✓	✓	✓	✓
5	✓	✓	✓	✓	✓
6	✓	✓	x	✓	✓
7	✓	✓	x	✓	✓
8	✓	✓	✓	✓	✓
9	✓	✓	x	✓	✓
10	✓	✓	✓	✓	✓
11	✓	✓	x	✓	✓

Table 3. Summary of inter-tidal sample collection and measurements 2011.

Notes: LWM: low water mark, HWM: high water mark, ×: sample not collected.

Underwater sediment sampling

Underwater sediment samples were collected from 24 of the 25 planned locations by use of a scooping device with a rubberised bag which was lowered to the sea bed at each sampling point (no sample was collected from location 8 in 2011 due to hard ground). The sample locations are shown in Figure 4 and the co-ordinates (latitude and longitude) are provided below:

1. N 54 45 078 W 03 59 782
2. N 54 45 600 W 03 59 808
3. N 54 44 527 W 03 59 746
4. N 54 45 569 W 04 02 577
5. N 54 45 032 W 04 02 541
6. N 54 44 479 W 04 02 522
7. N 54 45 211 W 04 01 174
8. N 54 45 083 W 04 01 243
9. N 54 44 827 W 04 01 391
10. N 54 44 684 W 04 01 477
11. N 54 44 991 W 03 58 807
12. N 54 44 856 W 03 58 758
13. N 54 45 484 W 03 57 969
14. N 54 45 375 W 03 57 744
15. N 54 45 673 W 03 57 125
16. N 54 44 136 W 03 57 108
17. N 54 44 575 W 03 57 081
18. N 54 42 874 W 04 01 311
19. N 54 42 750 W 04 01 290
20. N 54 43 235 W 04 02 493
21. N 54 42 732 W 04 02 476
22. N 54 42 225 W 04 02 451
23. N 54 43 292 W 04 00 243
24. N 54 42 785 W 04 00 226
25. N 54 42 258 W 04 00 192

The sampling locations may vary slightly due to the effect of underwater currents on the sampling rig which was dragged along the sea bed for distances ranging from 50 to 100 metres. The co-

ordinates given in paragraph 6.9 should therefore be considered as the approximate centre point of sampling areas of approximately 100 metres in radius.

Sediment collected from the sea-bed was screened for the presence of DU fragments by monitoring using a Mini Monitor and 44B probe. A portion of the sediment (approximately 0.8 litres) was collected for analysis by alpha spectrometry.

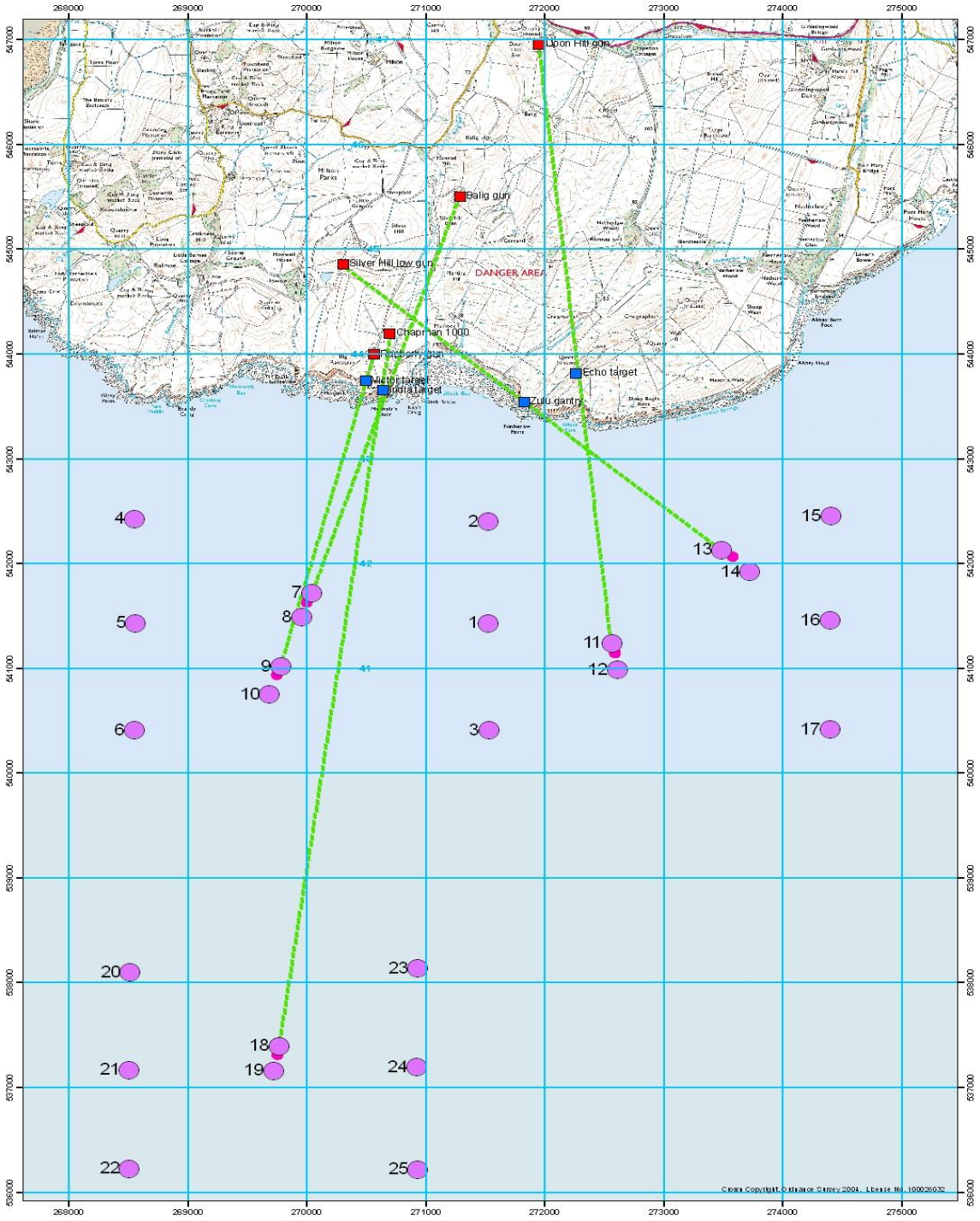

Figure 2. Approximate underwater sampling locations 2011 (showing line of fire for each battery).

Locally sourced seafood

Locally sourced seafood is sampled as part of the Kirkcudbright marine survey to determine the extent of any potential transfer of uranium through the food chain. In 2011, a total of 3 lobsters (*H. gammarus*), 3 crabs (*C. pagurus*), 5 mussels (*M. edulis)* and 2 whelks *(B.undatum)* were obtained for analysis by alpha spectrometry. The samples were boiled on the day of collection before being frozen and transported to the laboratory.

Sample descriptors

Each sample was given a unique sample descriptor. For inter-tidal and underwater sediment, seaweed and mussel samples, the descriptor is followed by a number which relates to the specific sample point. For samples which do not come from a defined sample point (e.g. locally sourced lobster), no sample point is given. In this case, samples are given a one letter suffix to distinguish between them. Some examples of typical sample descriptors are provided below:

I/T 4: Inter-tidal sediment sample from sample point 4

U/W 8: Underwater sediment sample from sample point 8

Mussel 9: Mussel sample from sample point 9

Crab a: Locally sourced crab sample (sample a)

Sample preparation and laboratory analysis

Sample preparation took place either at the time of collection or at the Dstl UKAS accredited radiochemistry laboratory. Samples were analysed by alpha spectrometry with uranium concentration reported in mBq/g (equivalent to Bq/kg) of dry weight. An outline of the analysis procedure is provided below.

Mussel, whelk, crab and lobster samples were boiled prior to analysis and any shells were removed. The brown and white crab meat was used for analysis, but the digestive tracts were discarded. Mussels and whelks were analysed as composite samples. The crab and lobster samples were analysed individually.

All samples were weighed before drying to remove moisture and then weighed again (with results being reported as dry weight). The samples were ashed to remove organic material and homogenised by hand. During this process the quantity of uranium in each of the samples does not alter significantly. The ashed samples were boiled in concentrated mineral acid (nitric acid and hydrochloric acid) to remove the ‘loose’ and leachable uranium from the sample. Recalcitrant matrices such as mineral grains are not broken down by the process and hence the natural uranium within them was not extracted. The samples were filtered to remove solids.

Uranium separation was carried out by extraction chromatography. Each eluted sample was electro-deposited onto a stainless steel planchette and the activity of each planchette was counted in a low background alpha spectrometer with a silicon surface barrier.

7 Results and Interpretation

A summary of the results for all marine samples collected in 2011 is given below in Table 4. The full marine monitoring results are provided in Tables 5 to 9 in Annex A. Historical monitoring results for the Kirkcudbright marine survey for the years 1998 to 2011 are presented in Annex B.

Sample Type	Number of Samples	No. of samples possibly containing detectable DU[2]	Total uranium concentration (mBq/g)			
			Mean	Standard deviation of the mean	Minimum	Maximum
Inter-tidal Sediment	11	0	19.36	7.17	9.41	35.89
Seaweed	10	0	13.98	2.96	9.18	19.24
Mussels	5	0	7.52	0.98	6.21	8.66
Whelks	2	0	0.63	0.09	0.56	0.69
Lobsters	3	0	0.12	0.06	0.08	0.19
Crabs	3	0	0.64	0.19	0.44	0.81
Underwater Sediment	24	10	21.41	5.09	17.69	27.26

Table 4. Summary of sample analyses - KTA 2011.

Inter-tidal zone and biota sampling

Environmental gamma dose rate measurements for the inter-tidal monitoring locations are provided in Table 5. Measurements ranged from 0.066 to 0.109 micro grays per hour (µGy/h). These results are consistent with those recorded in previous surveys [1-14], indicating that they are due to natural background radiation. Measurements recorded over salt marsh at Kirkcudbright and reported in the most recent RIFE report [20] are consistent with these measurements (average of 0.082 µGy/h), although it should be noted that no specific measurements of the inter-tidal area were carried out as part of the RIFE survey.

Alpha spectrometry analysis results for inter-tidal sediment samples are provided in Table 6. No sample was radioactive within the meaning of RSA93, nor did they exceed the GDL for marine sediment. The level of total uranium ranged from 9.41 ± 1.92 to 35.89 ± 3.8 mBq/g, which is

[2] It is assumed that an underwater sediment sample may possibly contain DU if it has a $^{238}U/^{234}U$ isotopic ratio greater than 0.8 at the 95% confidence level (i.e. after subtraction of the measurement uncertainty). However, ratios of around 1.0 were recorded even before DU firings began; further information is provided in Annexes C and D. For inter-tidal sediment and biota, samples are assumed to contain a degree of depletion if the isotopic ratio exceeds 1.0 (following subtraction of measurement uncertainty).

consistent with the typical background levels reported in the literature for the UK[3] and with the results of previous surveys. The results also compare favourably with the level of ^{238}U found at Sandyhills Bay in an independent study (14 mBq/g dry weight) [21] and those values reported by CEFAS in 2007 (see Annex F); both of which can be seen as good indicators of background uranium levels.

Following subtraction of the associated uncertainty values, the isotopic ratios of all inter-tidal sediment samples are found to be below a value of 1.0, indicating that any uranium present is of natural origin.

Analysis results for the 10 inter-tidal seaweed samples (*F. vesiculosus*) are provided in Table 7. The levels of total uranium detected ranged from 9.18 ± 0.99 to 19.24 ± 2.06 mBq/g. Although the maximum value lies slightly outside the typical UK range reported in the literature (3.8 to 18.6 mBq/g, see Annex F), it is emphasised that the levels represent less than 2% of the CFIL for 'other foodstuffs' and that the isotopic ratios are indicative of natural uranium.

Alpha spectrometry analysis results for biota samples collected in 2011 are presented in Table 8. It should be noted that GDLs and biota results reported by CEFAS [20] are expressed as activity per *fresh* mass. In contrast, Dstl results are expressed as activity per *dry* mass; resulting in higher activity concentrations. In order to directly compare the results, it is necessary to convert the reported result to fresh mass activity concentrations using the recorded wet:dry ratio (the preparatory drying stage leads to a reduction in mass of approximately 70%). The biota results are discussed further in the following paragraphs.

A total of five mussel (*M. edulis*) samples were analysed in 2011. The total uranium content ranged from 6.21 ± 0.76 to 8.66 ± 0.87 mBq/g (dry weight). Even before converting these values to the lower fresh weight equivalent, they represent less than 1% of the GDL for molluscs (1000 mBq/g). Although the results are slightly higher than those reported from Sandyhills Bay in an independent study [21], they are consistent with the results of previous surveys [1 to 15]. Furthermore, isotopic ratios suggest that any uranium present is natural in origin.

The results from the lobster, crab and whelk samples indicate that, where an isotope ratio could be calculated or inferred, the uranium is of natural origin.

Underwater sediment sampling

A total of 24 underwater sediment samples were collected in 2011. Screening of these samples with a Mini Monitor and 44B probe did not indicate the presence of any gross contamination or fragments of DU. Alpha spectrometry analysis results are shown in Table 9. No sample was radioactive within the meaning of RSA93 nor did it exceed 0.04% of the GDL for marine sediment. The measured levels of ^{238}U (17.69 ± 2.51 to 27.26 ± 3.39 mBq/g) lie within the typical UK coastal sediment range of 3.6 to 32.3 mBq/g (see Annex F). The levels of total uranium present are consistent with those found during previous surveys.

Ten of the twenty-four underwater sediment samples exhibited isotopic ratios which were greater than 0.8 at a confidence level of 95% or higher (maximum value 1.43 ± 0.41). Whilst this can be seen as an indication of low level DU contamination in marine sediments (see Annex E), it should be noted that ratios of around 1.0 have been recorded in sediments around KTA even before DU munitions testing began. However, these results are of no radiological concern as the levels of ^{238}U represent less than 0.04% of the relevant GDL.

[3] Minerals containing uranium are widely distributed throughout the Earth's crust and the concentrations of natural uranium found locally can vary significantly due to the nature of the underlying geology. Consequently, there is no definitive reference level for uranium in soils and sediments, although there is broad agreement in the typical range of values published in the literature. Typical values in UK coastal sediment range from 3.6 to 32.3 mBq/g (dry weight) [see Annex F], but values exceeding 100 times this typical range can be found locally.

8 Evaluation of Potential Exposure Pathways

Any contamination of the marine environment with DU could result in three potential exposure pathways for humans, as described below:

- External radiation exposure from contaminated sediment or seaweed;
- Inhalation of re-suspended DU contamination; and
- Ingestion of seaweed or seafood products contaminated with DU.

External radiation exposure

The measured radiation levels on the inter-tidal zone are consistent with natural background levels. Furthermore, only background levels of uranium isotopes have been identified by alpha spectrometry of inter-tidal sediment samples. The measurements carried out are sensitive enough to detect radiation at levels far below anything which could be considered as a health risk; it is therefore concluded that there is no external dose risk associated with the firing of DU munitions at Kirkcudbright.

Inhalation of re-suspended DU

DU which has been deposited on sediment may become re-suspended in the air especially if it is attached to items which are subject to disturbance (e.g. fisherman's netting). Once the DU has been re-suspended in the air, it is then free to be inhaled by persons in close proximity. However, the levels of uranium identified in this report are consistent with those expected due to natural background radioactivity; the amount of ^{238}U representing a very small fraction of relevant GDLs. It is concluded that the risk from potential inhalation of re-suspended DU is indistinguishable from the risk due to natural background exposure.

Ingestion of DU contaminated foodstuffs

The levels of uranium isotopes found in biota samples were consistent with those expected due to natural background radioactivity and represented a very small fraction of the relevant GDLs. This indicates that, in terms of potential DU contamination, there is no risk associated with the consumption of food stuffs in the Kirkcudbright area.

Although the inadvertent consumption of seawater by members of the public is possible, it was recommended by SEPA in 2001 to discontinue seawater sampling. The basis of this recommendation was that the immense dilution of the Solway would never give rise to detectable levels of DU or to any significant radiation exposures.

9 Conclusions

The 2011 annual Kirkcudbright marine monitoring programme was undertaken to assess the levels of any DU in the environment resulting from firing of DU munitions. The monitoring programme involved the sampling of inter-tidal sediment and biota, together with the measurement of environmental gamma dose rates along the Dumfries coastline. Underwater sediment and locally caught seafood were also sampled.

The findings of the survey indicate that the levels of uranium present in the marine environment are indistinguishable from natural background levels. None of the samples were radioactive within the meaning of the Radioactive Substances Act 1993; nor did they exceed a very small fraction of the Generalised Derived Limits advised by the Health Protection Agency.

The results of the 2011 survey are consistent with historical survey findings. There is no evidence to indicate that members of the public are exposed to any radiological hazard from the marine environment as a result of the test firing of DU ammunition at Kirkcudbright.

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ANNEX A KTA Marine Survey Results

Station number	Location	Mean dose rate (µGy/h) (n = 4)
1	South Carse	0.086
2	Sandyhills Bay	0.082
3	Port o'Warren Bay	0.100
4	Port Donnel	0.092
5	Balcarry Bay	0.100
6	Abbey Burn Foot	0.090
7	Mullock Bay	0.109
8	Lower Nunton Bay	0.078
9	Brighouse Bay	0.073
10	Carrick Point	0.082
11	Mossyard Bay	0.066

Table 5. Inter-tidal environmental gamma dose rates - KTA 2011.

Sample Descriptor	Wet weight (g)	Dry weight (g)	Ashed weight (g)	Measured Activity of Dry Sample (mBq/g)				Ratio of ^{238}U /^{234}U
				^{238}U	^{235}U	^{234}U	Total U	
IT1	28.1	12.1	10.9	14.26 ± 2.46	0.64 ± 0.4	12.7 ± 2.27	27.6 ± 3.37	1.12 ± 0.28
IT2	47.6	34.6	33.7	18.23 ± 2.76	0.64 ± 0.35	17.02 ± 2.62	35.89 ± 3.82	1.07 ± 0.23
IT3	56.7	43.7	43.1	4.92 ± 1.40	<0.71	4.32 ± 1.3	9.41 ± 1.92	1.14 ± 0.47
IT4	49.9	38.5	37.7	9.14 ± 1.74	<0.45	7.86 ± 1.57	17.11 ± 2.34	1.16 ± 0.32
IT5	42.2	27.5	26.4	9.76 ± 1.91	<0.54	9.47 ± 1.87	19.35 ± 2.67	1.03 ± 0.29
IT6	74.1	56.2	54.7	9.47 ± 1.97	<0.64	10.27 ± 2.08	19.97 ± 2.88	0.92 ± 0.27
IT7	61.7	46.8	45.4	9.36 ± 1.91	<0.59	10.84 ± 2.11	20.64 ± 2.87	0.86 ± 0.24
IT8	75.1	54.9	53.2	9.03 ± 1.68	<0.43	9.23 ± 1.71	18.36 ± 2.4	0.98 ± 0.26
IT9	101.4	76.9	75.4	7.22 ± 1.48	<0.44	6.51 ± 1.38	13.95 ± 2.03	1.11 ± 0.33
IT10	69.6	51.5	50.5	7.17 ± 1.66	<0.62	6.69 ± 1.59	14.01 ± 2.3	1.07 ± 0.35
IT11	64.7	47.1	46.0	9.31 ± 1.70	<0.42	6.99 ± 1.4	16.63 ± 2.22	1.33 ± 0.36

Table 6. Inter-tidal sediment: alpha spectrometry analysis results showing total uranium and isotopic ratios - KTA 2011.

Sample Descriptor	Wet weigh t (g)	Dry weight (g)	Ashed weight (g)	Measured Activity of Dry Sample (mBq/g)				Ratio of ^{238}U /^{234}U
				^{238}U	^{235}U	^{234}U	Total U	
Seaweed 2	51.1	12.0	2.9	5.68 ± 1	0.35 ± 0.19	6.93 ± 1.16	12.96 ± 1.55	0.82 ± 0.2
Seaweed 3	50.9	10.6	2.3	4.58 ± 0.8	<0.17	5.4 ± 0.9	10.09 ± 1.21	0.85 ± 0.21
Seaweed 4	48.5	15.0	2.6	7.22 ± 1.09	0.34 ± 0.15	8.25 ± 1.21	15.8 ± 1.63	0.88 ± 0.18
Seaweed 5	51.6	14.2	3.5	8.46 ± 1.32	0.26 ± 0.15	10.52 ± 1.57	19.24 ± 2.06	0.8 ± 0.17
Seaweed 6	73.5	10.1	2.0	7.57 ± 1.07	0.39 ± 0.15	8.33 ± 1.16	16.29 ± 1.59	0.91 ± 0.18
Seaweed 7	52.0	15.2	2.4	6.23 ± 0.92	0.3 ± 0.13	7.1 ± 1.03	13.63 ± 1.39	0.88 ± 0.18
Seaweed 8	61.1	15.6	3.0	4.26 ± 0.67	0.29 ± 0.12	4.63 ± 0.72	9.18 ± 0.99	0.92 ± 0.2
Seaweed 9	61.6	14.4	2.2	6.2 ± 0.9	0.18 ± 0.09	7.48 ± 1.05	13.86 ± 1.39	0.83 ± 0.17
Seaweed 10	53.4	12.4	2.2	7.43 ± 1.08	0.24 ± 0.12	7.91 ± 1.13	15.58 ± 1.57	0.94 ± 0.19
Seaweed 11	52.9	12.9	2.0	5.76 ± 0.81	0.33 ± 0.12	7.09 ± 0.96	13.17 ± 1.26	0.81 ± 0.16

Table 7. Seaweed samples: alpha spectrometry analysis results showing total uranium and isotopic ratios – KTA 2011

Sample Descriptor	Wet weight (g)	Dry weight (g)	Ashed weight (g)	Measured Activity of Dry Sample (mBq/g)				Ratio of ^{238}U/^{234}U
				^{238}U	^{235}U	^{234}U	Total U	
Mussel 3	91.1	23.1	4.1	3.53 ± 0.57	0.15 ± 0.08	4.01 ± 0.62	7.69 ± 0.85	0.88 ± 0.2
Mussel 4	115.2	29.0	4.2	3.76 ± 0.56	0.13 ± 0.07	4.28 ± 0.63	8.17 ± 0.85	0.88 ± 0.18
Mussel 5	116.5	32.5	7.2	2.82 ± 0.51	<0.12	3.29 ± 0.57	6.21 ± 0.76	0.86 ± 0.21
Mussel 8	86.1	20.6	2.7	3.9 ± 0.57	0.14 ± 0.07	4.62 ± 0.65	8.66 ± 0.87	0.85 ± 0.17
Mussel 10	135.1	33.7	4.1	3.04 ± 0.46	0.12 ± 0.06	3.72 ± 0.54	6.89 ± 0.71	0.82 ± 0.17
Crab a	150.9	44.6	4.9	<1.07	<1.07	<1.07 ±	0.81 ± 0.66	N/A
Crab b	120.5	31.6	3.2	0.23 ± 0.09	<0.08	0.19 ± 0.09	0.44 ± 0.13	1.2 ± 0.74
Crab c	117.7	29.4	4.4	0.24 ± 0.11	<0.09	0.4 ± 0.14	0.67 ± 0.18	0.61 ± 0.34
Lobster 1	188.6	50.6	3.8	<0.07	<0.07	<0.07	0.08 ± 0.05	N/A
Lobster 2	163.6	44.1	3.2	<0.06	<0.06	0.12 ± 0.06	0.19 ± 0.08	N/A
Lobster 3	115.2	26.6	2.9	<0.14	<0.14	<0.14	0.1 ± 0.08	N/A
Whelk 1	113.3	26.8	1.9	0.33 ± 0.11	<0.09	0.34 ± 0.11	0.69 ± 0.16	0.96 ± 0.45
Whelk 2	105.3	24.2	1.7	0.29 ± 0.1	<0.10	0.25 ± 0.1	0.56 ± 0.14	1.14 ± 0.6

Table 8. Biota samples: alpha spectrometry analysis results showing total uranium and isotopic ratios - KTA 2011.

Sample descriptor	Wet weight (g)	Dry weight (g)	Ashed weight (g)	Measured Activity of Dry Sample (mBq/g)				Ratio of ^{238}U /^{234}U
				^{238}U	^{235}U	^{234}U	Total U	
UW1	71.4	49.4	47.0	10.86 ± 1.93	<0.44	9.54 ± 1.76	20.67 ± 2.62	1.14 ± 0.29
UW2	72.8	50.2	47.8	11.50 ± 2.04	0.67 ± 0.38	11.73 ± 2.07	23.9 ± 2.93	0.98 ± 0.25
UW3	66.1	45.7	43.3	12.18 ± 2.33	<0.61	10.83 ± 2.15	23.32 ± 3.19	1.13 ± 0.31
UW4	83.0	52.9	50.1	10.52 ± 1.91	<0.45	10.24 ± 1.87	21 ± 2.68	1.03 ± 0.26
UW5	104.2	73.4	70.2	11.49 ± 2.21	<0.58	10.37 ± 2.06	22.29 ± 3.04	1.11 ± 0.31
UW6	101.0	72.9	69.9	12.18 ± 2.32	<0.59	8.53 ± 1.82	20.92 ± 2.96	1.43 ± 0.41
UW7	93.7	65.1	62.7	9.27 ± 1.67	<0.39	8.45 ± 1.57	18.11 ± 2.31	1.1 ± 0.28
UW9	70.5	50.7	48.5	10.50 ± 1.87	0.54 ± 0.33	10.67 ± 1.89	21.7 ± 2.68	0.98 ± 0.25
UW10	95.3	68.0	65.0	11.46 ± 1.97	<0.42	8.21 ± 1.56	19.98 ± 2.53	1.4 ± 0.36
UW11	76.9	52.8	50.9	10.32 ± 1.93	0.59 ± 0.37	10.49 ± 1.96	21.4 ± 2.77	0.98 ± 0.26
UW12	85.9	59.4	57.1	11.16 ± 1.97	<0.43	10.72 ± 1.91	22.31 ± 2.76	1.04 ± 0.26
UW13	84.7	56.5	54.6	9.62 ± 1.94	<0.58	8.55 ± 1.79	18.3 ± 2.65	1.13 ± 0.33
UW14	71.1	50.6	48.8	9.92 ± 1.97	<0.55	9.92 ± 1.97	19.97 ± 2.79	1 ± 0.28
UW15	81.4	55.5	53.1	11.13 ± 1.91	0.75 ± 0.38	10.83 ± 1.87	22.71 ± 2.7	1.03 ± 0.25
UW16	80.3	57.4	55.4	11.94 ± 2.04	0.61 ± 0.35	10.94 ± 1.91	23.5 ± 2.82	1.09 ± 0.27
UW17	78.9	57.1	55.0	9.60 ± 1.88	<0.52	7.78 ± 1.63	17.69 ± 2.51	1.23 ± 0.35
UW18	62.8	45.6	43.8	12.32 ± 2.30	<0.59	11.82 ± 2.24	24.58 ± 3.23	1.04 ± 0.28
UW19	78.0	56.0	53.7	11.79 ± 2.22	<0.58	10.21 ± 2.01	22.55 ± 3.02	1.15 ± 0.31
UW20	76.5	54.6	52.1	12.58 ± 2.27	<0.52	14.35 ± 2.5	27.26 ± 3.39	0.88 ± 0.22
UW21	51.0	37.0	35.4	14.09 ± 2.47	<0.56	11.45 ± 2.14	25.95 ± 3.28	1.23 ± 0.32
UW22	68.0	47.1	45.0	13.15 ± 2.21	0.64 ± 0.37	12.23 ± 2.1	26.02 ± 3.08	1.08 ± 0.26
UW23	73.4	50.6	48.6	13.02 ± 2.35	<0.54	12.02 ± 2.22	25.3 ± 3.24	1.08 ± 0.28
UW24	83.6	58.3	56.1	10.96 ± 2.04	<0.52	11.64 ± 2.13	22.99 ± 2.96	0.94 ± 0.25
UW25	102.0	70.8	68.0	11.24 ± 2.15	<0.59	11.17 ± 2.14	22.84 ± 3.06	1.01 ± 0.27

Table 9. Underwater sediment: alpha spectrometry analysis results showing total uranium and isotopic ratios – KTA 2011 (No sample was able to be taken from Point No.8).

Note (for tables 6 to 9): Activity results have been rounded to two decimal places. All uncertainties are stated at a 95% confidence level. Limits of Detection (LoD) are calculated by a 'modified Currie formula' at 95% (Hurtgen C., Jerome S. & Woods M. (2000) 'Revisiting Currie – how low can you go?' *Applied radiation and Isotopes* 53 pp 45-50). The total activity is calculated from the sum of the actual activities for each isotope, regardless of the quoted LoD. Therefore, in Tables 6 to 9, where activities are reported as less than LoD for any of the uranium isotopes, the total uranium value may not be equal to the sum of the individual isotopic values.

ANNEX B Historical Data

To allow historical comparison, data from KTA marine surveys from 2000 to 2011 are presented in Table 10. This includes inter-tidal sediment, underwater and biota samples. Figure 3 shows the number of DU projectiles fired at KTA between 1982 and 2010. There have been no firings since 2008.

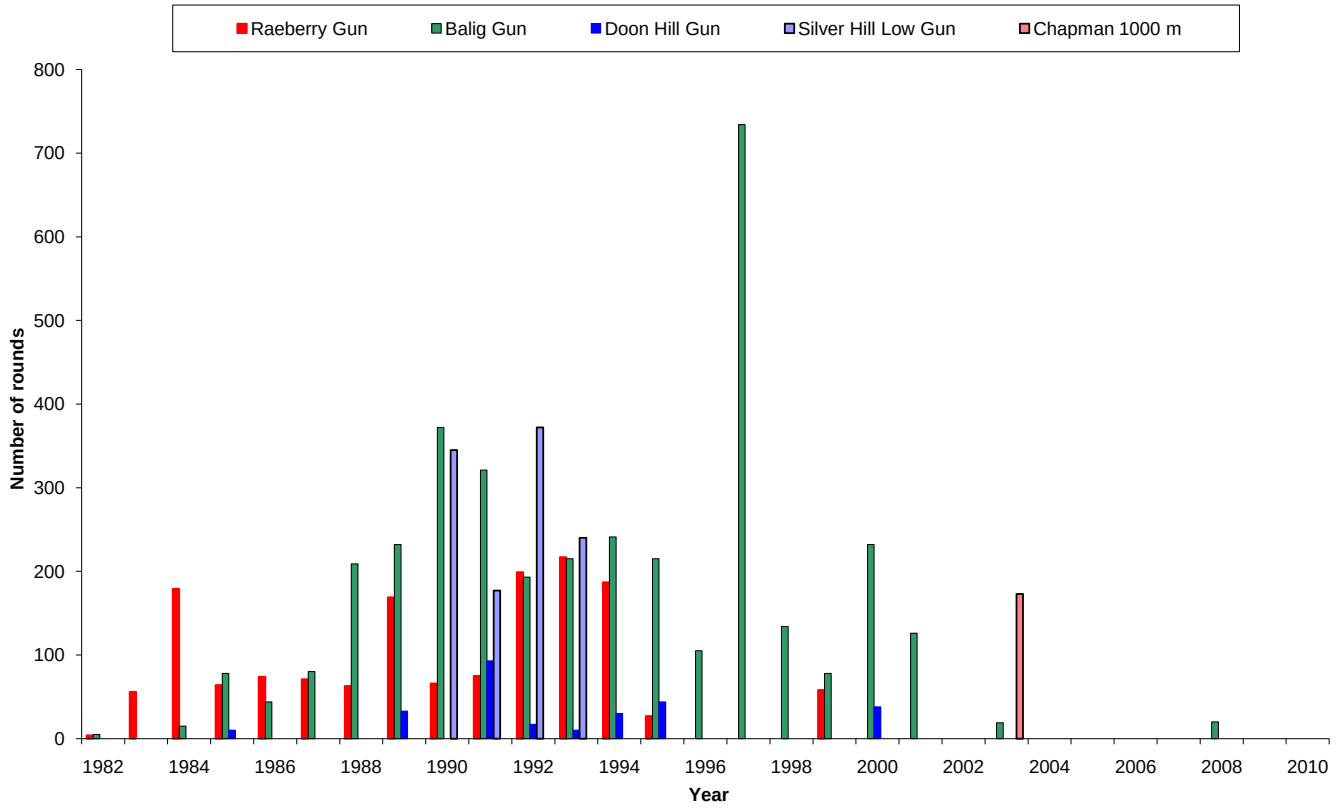

Figure 3. The number of projectiles fired at KTA between 1982 and 2010.

Sample Type	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Inter-tidal sediment	2.2- 44.7 **(10)** *(0.8-1.2)*	10.7-31.1 **(9)** *(0.9-1.4)*	12.0-31.9 **(10)** *(0.9-1.2)*	9.8-714.4 **(10)** *(0.8-1.3)*	4.2-35.0 **(11)** *(0.9-1.3)*	9.8-24.5 **(11)** *(0.8-1.3)*	7.5-29.9 **(11)** *(0.8-1.3)*	*6.9-27.6* **(11)** *(0.9-1.1)*	11.3–35.8 **(11)** *(0.8-1.3)*	8.5-26.2 **(11)** *(0.7-1.2)*	11.7-27.5 **(11)** *(0.9-1.2)*	9.41-35.89 **(11)** *(0.86-1.33)*
Seaweed	1.3 -5.1 **(9)** *(0.9 -1.1)*	6.8-12.1 **(7)** *(0.8-1.3)*	0.2-16.7 **(9)** *(0.7-1.2)*	7.2-34.2 **(9)** *(0.7-0.9)*	9.2-22.6 **(9)** *(0.8-1.0)*	4.9-18.2 **(10)** *(0.8-1.2)*	6.9-16.0 **(9)** *(0.8-1.0)*	10.7-25.6 **(10)** *(0.5-1.1)*	5.3-12.3 **(10)** *(0.8-1.0)*	9.1-33.6 **(10)** *(0.4-1.0)*	7.6-23.0 **(10)** *(0.8-1.1)*	9.18-19.24 **(10)** *(0.80-0.94*)
Mussels	3.6 -7.2 **(5)** *(0.8-0.9)*	2.9-11.6 **(7)** *(0.3-0.9)*	6.4-10.5 **(5)** *(0.9-1.0)*	5.6-7.4 **(5)** *(0.7-0.9)*	4.0-7.8 **(4)** *(0.8-0.9)*	5.1-10.7 **(4)** *(0.9-1.0)*	2.6-12.6 **(7)** *(0.9-1.1)*	4.8-12.0 (**5**) *(0.6-0.9)*	5.7-9.6 **(5)** *(0.8-1.0)*	6.2-13.7 **(5)** *(0.7-0.9)*	6.9-9.8 **(5)** *(0.8-0.9)*	6.21-8.66 (5) *(0.82-0.88)*
Whelks	0.6-1.3 **(5)** *(0.5-1.6)*	2.0-3.7 **(8)** *(0.5-1.4)*	1.1-39.4 **(8)** *(0.9±0.5)*	×	×	0.7-2.9 **(6)** *(0.8-1.6)*	0.1-0.1 **(4)** *(n/a)*	0.4-1.2 **(8)** *(0.9-1.1)*	0.8-1.4 **(6)** *(0.8-1.4)*	×	×	0.56-0.69 **(2)** *(0.96-1.14*)
Scallops		2.8-13.3 **(8)** *(0.7-1.6)*	×	1.5-33.0 **(6)** *(n/a)*	2.8-3.1 **(2)** *(0.9-9.9)*	2.8-13.3 **(3)** *(n/a)*	0.1-0.2 **(4)** *(n/a)*	×	×	×	×	X
Crabs	0.2-1.4 **(8)** *(0.1-3.7)*	1.2-2.3 **(2)** *(0.9-1.0)*	0.8-23.8 **(4)** *(0.9 0.5[a])*	0.1-2.3 **(3)** *(n/a)*	×	0.4-1.6 **(6)** *(n/a)*	0.1-0.6 **(5)** *(n/a)*	0.4-0.8 **(3)** *(1.6±0.8)*	0.2-0.5 **(5)** *(0.3-0.4)*	0.3-0.6 **(3)** *(1.2)*	0.5-1.5 **(3)** *(0.6-1.1)*	0.44-0.81 **(3)** *(n/a-1.20)*
Lobsters		2.4-3.2 **(4)** *(0.7-1.6)*	1.2-1.8 **(2)** *(n/a)*	0.3-3.4 **(3)** *(n/a)*	0.4 ± 0.1 **(3)** *(1.0* ± 0.4*)*	0.4-0.9 **(4)** *(n/a)*	0.1-0.1 **(2)** *(n/a)*	0.1-0.2 **(4)** *(n/a)*	0.1-0.3 **(3)** *(n/a)*	0.3-0.5 **(2)** *(n/a)*	0.1-0.3 **(3)** *(0.9-1.1)*	0.08-0.19 **(3)** *(n/a)*
Underwater sediment	0.2-12.8 **(6)** *(0.8-1.3)*	19.3-31.0 **(34)** *(0.8-1.3)*	15.2-30.4 **(33)** *(0.9-1.2)*	20.2-30.9 **(36)** *(0.9-1.2)*	17.0-33.2 **(64)** *(0.8-1.2)*	16.3-24.3 **(18)** *(0.9-1.3)*	16.6-26.6 **(25)** *(0.8-1.3)*	19.5-42.3 **(25)** *(0.8-1.3)*	23-31.9 **(25)** *(0.9-1.4)*	17-28.4 **(25)** *(0.9-1.6)*	18.4-32.1 **(25)** *(0.8-1.3)*	17.7-27.2 (24) (*0.88-1.43)*

Table 10. Historical summary of total uranium and isotopic ratios for sediment and biota samples 2000 to 2011.

Notes: Values provided on the top row show the range of total uranium values in mBq/g (e.g. 1.5 – 3.2). The value in bold shows the total number of samples collected (e.g. **(12)**). The values in the bottom row show the range of $^{238}U/^{234}U$ isotopic ratios (e.g. *(0.8 – 1.1)*). Measurement uncertainties can be found in the annual reports.

ANNEX C Issues to be considered when interpreting or comparing uranium data

C1 There are a number of issues that may give rise to uncertainties when interpreting or comparing uranium data as shown below. Further information is available from Reference [C1].

- Analytical technique;
- Statistical variation;
- Spatial variability;
- Temporal variability; and
- Species variation (for plant and animal samples).

Analytical approaches

C2 Sediment sample results may be reported as either dry weight or wet weight depending on whether the masses of the samples were obtained prior to, or after, drying. This will have implications for comparison of results between the surveys at Kirkcudbright, which are reported as dry weight and other UK uranium in sediment data, which may be reported as wet weight. Samples reported as dry weight will appear to have concentrations of uranium approximately 20% higher than those reported as wet weight (although this will depend on the moisture content).

C3 For analysis techniques such as inductively coupled plasma mass spectrometry (ICP-MS) or alpha spectrometry the uranium present in a sample may be extracted into solution by either leaching the soil samples, or totally dissolving them. Total dissolution will give rise to higher uranium results, because the analysis will include all uranium, including that which is contained within the mineral grains, whereas leached samples will only contain uranium that is either easily dissolved, or is fixed to the surfaces of mineral grains. This limitation is acceptable as the primary purpose of the environmental survey is to assess any levels of DU in addition to naturally occurring uranium. However, this limitation causes a conservative bias on the $^{238}U/^{234}U$ isotopic ratios for mineral samples and other recalcitrant matrices. Total sample analysis techniques such as gamma spectrometry will give results similar to those for total dissolution. Given the differences between the results for total analysis and leached analysis, care should be taken when comparing sets of data to ensure that either the same approach has been used, or differences are appropriately discussed.

C4 Uranium concentrations in seaweed may be affected by contamination of surfaces with sediment particles. Preparation of seaweed for analysis may or may not involve a washing stage; hence it is important to be aware of the preparation approaches that have been applied when comparing the results of different seaweed analyses.

C5 Seaweed and marine biota sample results may be reported as either dry weight or wet weight depending on whether the masses of the samples were obtained prior to, or after, drying. For marine biota, samples reported as dry weight will appear to have concentrations of uranium higher than those reported as wet weight. The relative increase in uranium concentration will depend on the moisture content, and can be as much as 300% for biota with high water content such as molluscs.

Statistical variations

C6 There is a statistical uncertainty associated with the result of a radiochemical analysis (identified in the counting statistics for the technique). However, this uncertainty is likely to be small in comparison with the overall variation in activity between environmental samples.

Spatial variations

C7 DU contamination will not be uniformly distributed within a sampling area, but will depend on factors such as water flow, tidal movements and sediment drift. Repeat sampling and analysis of sediments from within an area may therefore give rise to some degree of variation.

C8 In addition to DU contamination due to firing at the range, there may be variations in uranium concentrations due to local anthropogenic or natural discharges. For example, natural uranium concentrations may be enhanced by the local application of phosphate based fertiliser to agricultural land. Veins rich in uranium minerals occur naturally along the coast of the Solway Firth, such as uraninite found at Needle's Eye, Caulkerbush, approximately 24 km away from KTA on the north coast of the estuary. These features are thought to be present across the region [C2, C3], although this has not been studied specifically.

Temporal variations

C9 There will be natural temporal variations in the uranium concentration and the abundance of the various isotopes in the samples, due to seasonal variations in rainfall. Rainfall can impact on the dissolution of uranium and its migration in surface waters.

C10 The activities of samples from any particular sampling site may vary from year to year. This may relate to temporal changes in uranium concentration, but will also be affected by spatial variation (see above).

C11 Marine plant uptake of radionuclides is affected by the period in the plant growing cycle. This phenomenon also occurs in animal uptake of radionuclides within their life cycle.

Species variations

C12 Plant uptake of radionuclides is affected by the substrate characteristics (uranium concentration and speciation as well as other soil physico-chemical characteristics) and varies with plant species.

C13 Animal uptake of uranium is affected by their life habits, feeding patterns, physiology and the uranium concentration in their foodstuffs and the environment.

Annex C References

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ANNEX D Change in the $^{238}U/^{234}U$ activity ratio of a medium containing natural uranium with the addition of depleted uranium

Mass proportion of DU added*	Activity concentration (mBq/kg)**			Ratio of total activity natural uranium to total activity	$^{238}U/^{234}U$ activity ratio
	U-238	U-235	U-234		
0	3.7×10^4	1.7×10^3	3.8×10^4	1.0	1.0
1	7.4×10^4	2.2×10^3	4.3×10^4	1.6	1.7
2	1.1×10^5	2.7×10^3	4.8×10^4	2.1	2.3
3	1.5×10^5	3.2×10^3	5.3×10^4	2.6	2.8
4	1.9×10^5	3.7×10^3	5.8×10^4	3.2	3.2
5	2.2×10^5	4.1×10^3	6.3×10^4	3.8	3.6
6	2.6×10^5	4.6×10^3	6.8×10^4	4.3	3.9
7	3.0×10^5	5.1×10^3	7.2×10^4	4.9	4.1
8	3.4×10^5	5.6×10^3	7.7×10^4	5.4	4.3
9	3.7×10^5	6.0×10^3	8.2×10^4	6.0	4.5
10	4.1×10^5	6.5×10^3	8.7×10^4	6.5	4.7
20	7.8×10^5	1.1×10^4	1.4×10^5	12.0	5.8
60	2.3×10^6	3.1×10^4	3.3×10^5	34.1	6.9
80	3.0×10^6	4.0×10^4	4.3×10^5	45.1	7.1
100	3.8×10^6	5.0×10^4	5.2×10^5	56.1	7.2
200	7.5×10^6	9.8×10^4	1.0×10^6	111.0	7.4
600	2.2×10^7	2.9×10^5	3.0×10^6	332.0	7.6
800	3.0×10^7	$3..9 \times 10^5$	3.9×10^6	442.0	7.6
1000	3.73×10^7	4.8×10^5	4.9×10^6	552.0	7.6

Table reproduced from Volume 2 - Appendices, WS Atkins Environmental Assessment on DU Firings.

* The value represents the additional mass of depleted uranium added (all radionuclides) relative to the original mass of natural uranium present (3 mg U/kg soil).

** Table assumes 3 mg U/kg of natural uranium present in soil in following proportion: ^{238}U (2.978 mg /kg); ^{235}U (0.022 mg /kg); ^{234}U (2e-04 mg /kg), prior to addition of DU.

ANNEX E Variability of uranium concentration and uranium isotopic ratios in marine environmental samples

E1 There are few specific examples that demonstrate the variability of uranium concentrations and isotopic ratios within marine environmental samples. In order to understand this variability, it is useful to consider the flux of uranium between the various components of the marine environment.

E2 Uranium occurs naturally in seawater and its concentration generally varies in proportion to salinity. It is present in open seawater at an average concentration of 82.5 ± 5 Bq/m^3, with a ^{238}U/^{234}U activity ratio of 0.88 ± 0.03 at a salinity of 35 %. The isotopic ratio of seawater is below unity as ^{234}U is preferentially mobilised from the soil during chemical weathering, thus enhancing its presence in seawater [C1 & C2]. The physical mixing of low uranium river water[1] and high uranium sea water in estuary environments generally results in a dilution of uranium in the estuarine waters. As a result, uranium concentrations in estuarine water are mostly lower than open ocean values and increase linearly with salinity [C2].

E3 Concentrations of uranium in marine sediment are variable (from 32.5 to 1,625 mBq/g dry weight) and vary primarily as a function of the geology of the area.

Sample Type	Uranium Concentration	Typical ^{238}U/^{234}U ratio
Sea water	82.5 Bq/m^3	0.88
Estuarine water	<82.5 Bq/m^3	<0.88
Marine sediment (^{238}U only)	32.5-1,625 mBq/g	0.81

E4 Levels of uranium also vary depending on the type of sediment present, as the physical and chemical characteristics of the sediment determine the amount of uranium which is concentrated from marine waters [E2 & E3]. Both low oxygenation[2] and low salinity[3] provide favourable conditions for uranium scavenging from the water column by a variety of processes. These include the precipitation of uranium rich colloids into the low salinity zone and the reduction of uranium into insoluble forms [E3 & E4].

Annex E References

[E1] Murphy, W M. Shock, E L. (1999) Environmental Aqueous Geochemistry of Actinides, in Uranium: Mineralogy, Geochemistry and the Environment, edited by Burns, P and Finch, R. Reviews in Mineralogy, Vol 38, The Mineralogical Society of America.

[E2] Cochran, J K. (1982) The Oceanic Chemistry of the U- and the Th-series Nuclides, in Uranium Series Disequilibrium: Applications to Environmental Problems, edited by Ivanovich, M and Harmon RS. Clarendon Press, Oxford.

[E3] Van den Berg, C M G. Huang, Z Q. (1984) Analytica Chemica Acta, 164, 209-222.

[1] Concentrations of uranium in rivers vary considerably, with carbonate and dissolved solids concentrations, with an average of 7.5-15 Bq/m^3, and an isotopic ^{238}U/^{234}U activity ratio of 0.77-0.83 as ^{234}U is preferentially mobilised during chemical weathering.

[2] Low oxygenation is found with increasing depth and increasing organic content.

[3] Salinity is dependent on river rate of flow, proximity to river outflow and depth of water.

[E4] Ragnarsdottir, V. Charlet, L. (2000) Uranium Behaviour in Natural Environments in: Environmental Mineralogy: Microbial Interactions, Anthropogenic Influences, Contaminated Land and Waste Management, Mineralogical Society Series Vol. 9, Mineralogical Society of Great Britain & Ireland.

ANNEX F Reference values for uranium in the Solway Firth and the UK

F1 For UK coastal sediment, ^{238}U concentrations generally range from 3.6 to 32.3 mBq/g of dry weight [F1]. Values reported for inter-tidal sediment uranium concentrations in the Solway Firth vary with location and the specific uranium rich geology of the area.

F2 Values for ^{238}U, ^{235}U and ^{234}U for sediment collected at Kirkcudbright in 2007 were reported by CEFAS as 10, 0.92 and 13 mBq/g of dry weight respectively [F2].

F3 Values reported for ^{238}U concentrations at Sandyhills Bay, in southwest Scotland, were lower than worldwide average values for seawater and sediment reported in ANNEX C. Seawater and sediment from Sandyhills Bay had ^{238}U concentrations of 40 $\pm$ 3 Bq/m and 14 $\pm$ 0.4 mBq/g dry weight, respectively [F3]. No other uranium isotopes were measured, so no indication of isotopic ratio could be provided.

F4 However, semi-quantitative analysis of shore sediment samples obtained from the mudflats offshore from the uraninite vein, located approximately 24 km east from KTA at Needle's Eye, yielded uranium values of up to several hundred parts per million. These activities were measured both around open, oxygenated root channels and in near surface peat material. This analysis has suggested that uranium disperses seawards and in ground waters, and is retarded in this by organic material in the sediment [F4].

Sample	Location	Activity per fresh weight (mBq/g)	Activity ^{238}U per dry weight (mBq/g)
Seaweed	[F3] Sandyhills Bay [F3] UK		3.8 ± 0.1 3.8 to 18.6
Mussel	[F3] Sandyhills Bay [F3] UK		1.1 ± 0.1 1.01 to 37.1
Mollusc	[F3] Sandyhills Bay(winkle) [F3] UK [F2] UK (mollusc & winkle) [F2] Parton (winkle)	 0.89 1.3	2.72 ± 0.01 1.36 to 18.9
Crab	[F2] UK [F2] Parton	0.046 0.052	
Lobster	[F2] UK [F2] Parton	0.035 0.028	

F5 Literature values reported for ^{238}U in seaweed and marine biota samples for the Solway Firth area are shown in the table above; also reported are estimated values of ^{238}U from natural sources in aquatic foodstuff for the UK given by CEFAS [F2, F3]. Analysis results from Parton (near Whitehaven) are also included, although it should be noted that the uranium inventory at Parton is dominated by historical anthropogenic input of natural uranium from a local phosphate processing plant.

Annex F References

[F1] Ragnarsdottir, V. Charlet, L. (2000) Uranium Behaviour in Natural Environments in: Environmental Mineralogy: Microbial Interactions, Anthropogenic Influences, Contaminated Land and Waste Management, Mineralogical Society Series Vol. 9, Mineralogical Society of Great Britain & Ireland.

[F2] Radioactivity in Food and the Environment 13 (2007) Centre for Environment, Fisheries and Aquaculture Science ISSN 1365-6414.

[F3] McDonald, P. Cook, G T. Baxter, M S. (1991) Natural and Artificial Radioactivity in Coastal Regions of UK. In: Radionuclides in the Study of Marine Processes, edited by Kershaw, P J and Woodhead, D S. Elsevier Applied Science, London.

[F4] Milodowski, A E. et al. (1990) Uranium-mineralised Micro-organisms Associated with Uraniferous Hydrocarbons in Southwest Scotland. Nature, 347, 465.

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13. Abstract (A brief (approximately 150 words) factual summary of the report)

Depleted uranium (DU) ammunition has been test fired at the Kirkcudbright Training Area (KTA) since 1982. Routine environmental monitoring has been carried out at KTA since 1980 to assess any radiological impact of the firings on the terrestrial and marine environments and any associated risk to humans. This report presents the findings of the marine survey undertaken at KTA during 2011; the terrestrial survey is reported separately in Part 1. None of the samples analysed were radioactive within the meaning of the Radioactive Substances Act 1993, nor did they exceed a very small fraction of the Generalised Derived Limits advised by the Health Protection Agency (formerly the National Radiological Protection Board). In fact, the measured levels of uranium were found to be consistent with natural background levels. The results of the 2011 survey are consistent with historical survey findings. There is no evidence to indicate that members of the public are exposed to a radiological hazard from the marine environment as a result of test firing DU ammunition at Kirkcudbright.

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