Evaluation of the Groundhog Synergy Beach Monitoring System for Detection of Alpha-rich Objects and Implications for the Health Risks to Beach Users

G Etherington, M J Youngman, J Brown and W Oatway

ABSTRACT

Since 2006 an intensive programme of monitoring for radioactive objects has been carried out on beaches in the vicinity of the Sellafield site in West Cumbria. Until August 2009, the Groundhog Evolution2™ beach monitoring system was used. At that time, a new beach monitoring system, Groundhog Synergy, was brought into operation. This system has a better detection capability for “alpha-rich” objects that contain alpha-emitting radionuclides such as americium-241 (^{241}Am). The Environment Agency (EA) first sought the advice of the Health Protection Agency (HPA) on the health implications of the findings of this beach monitoring in 2007. At the request of the Environment Agency (EA), HPA undertook an assessment of the health risks to people using the beaches, and this was published in early 2011. That assessment used only the data from the Groundhog Evolution2™ beach monitoring programme. The study presented in this report was carried out to evaluate the performance of the Synergy system, and to assess the implications of the results of the Synergy monitoring programme for the health risk assessment. Good evidence was found that the increased object find rate of Synergy can be attributed to its increased sensitivity, rather than to any real increase in the number of objects present on the beaches. New estimates were made of the health risks to beach users from the ingestion of alpha-rich objects and the changes in the estimated health risks were small and judged not to be significant. The conclusions of the original study therefore remain unchanged. That is, based on the currently available information, it may be concluded that the overall health risks to beach users are very low and significantly lower than other risks that people accept when using the beaches.

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This report from the HPA Centre for Radiation, Chemical and Environmental Hazards reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

The following amendments have been made to this report since its first publication (August 2012).

October 2012

Table 8. The estimated total number of particles per hectare present on Braystones beach has been amended to read 6.

The format of some of the references have been corrected.

EXECUTIVE SUMMARY

Since 2006 an intensive programme of monitoring for radioactive objects has been carried out on beaches in the vicinity of the Sellafield site in West Cumbria. These objects comprise particles with sizes smaller than or similar to grains of sand (less than 2 mm) and contaminated pebbles and stones. Until August 2009, the Groundhog Evolution2™ beach monitoring system was used, and by the end of the summer of 2009, over 650 radioactive objects had been identified and removed. In August 2009 a new beach monitoring system, Groundhog Synergy, was brought into operation as a replacement for the Groundhog Evolution2™ system. This system has better detection capabilities for “alpha-rich” objects that contain alpha-emitting radionuclides which emit low energy photons, such as americium-241 (^{241}Am). By the end of March 2012, the total number of objects detected had increased to approximately 1500. Of these, approximately 650 are alpha-rich objects detected between August 2009 and March 2012 using the Synergy system.

The Environment Agency (EA) first sought the advice of the Health Protection Agency (HPA) on the health implications of the findings of this beach monitoring in 2007. In May 2008, EA asked HPA to undertake an assessment of the health risks to people using the beaches along the Cumbrian coast from contaminated objects on the beaches. The results of the assessment were published in early 2011 and only used the data from the Groundhog Evolution2™ beach monitoring programme.

The study presented in this report was carried out to evaluate the performance of the Synergy system, and to assess the implications of the results of the Synergy monitoring programme for the health risk assessment. Qualitative comparisons of the activity distributions of objects found by the two systems were made to determine whether the increased alpha-rich object find rate can be attributed in whole or in part to Synergy’s increased sensitivity. This comparison provided good evidence that the increased object find rate of Synergy can be attributed to its increased sensitivity, rather than to any real increase in the number of objects on the beaches. The Synergy monitoring data show clearly that the numbers of detected alpha-rich objects at lower activity levels (3 – 30 kBq ^{241}Am) are significantly greater than those for higher activity objects, a finding that was not clearly seen in the results of the Evolution2™ monitoring programme.

A quantitative analysis was then performed with the same methodology used in the earlier HPA study to provide new estimates of the population of alpha-rich objects on the beaches. The results indicate a small increase in the estimated lifetime risk of radiation-induced fatal cancer for an adult beach user from $8\ 10^{-13}$ to $2\ 10^{-12}$, and a small decrease for young children using the beaches from $1\ 10^{-11}$ to $8\ 10^{-12}$. Given the uncertainties associated with assessments of this type, it is judged that these changes are not significant. The fact that the estimated overall risks associated with the ingestion of alpha-rich objects are very similar provides confidence in the findings of the earlier study.

The conclusions of the earlier HPA study on health risks to members of the public from radioactive objects on the beaches remain unchanged. That is, based on the currently

available information, it may be concluded that the overall health risks to beach users are very low and significantly lower than other risks that people accept when using the beaches. The highest calculated lifetime risks of radiation-induced fatal cancer are of the order of one hundred thousand times smaller than the level of risk that the Health and Safety Executive considers to be the upper limit for an acceptable level of risk (1 in a million) for members of the public and workers. The conclusion that it is very unlikely that deterministic effects such as skin ulceration could occur from encountering an object also remains unchanged.

This study fulfils the recommendation HPA made to EA, following the assessment of health risks made in 2011, that an investigation should be carried out of the increases in the number of alpha-rich objects being found by the recently-introduced Groundhog Synergy beach monitoring system, and the implications for the assessment of overall risk considered. HPA continues to advise that continued regular monitoring of Sellafield beach and monitoring at one or two other beaches with high public occupancy will provide regulators and the public with continued reassurance that risks associated with radioactive objects in the environment remain very low.

CONTENTS

1 INTRODUCTION AND BACKGROUND

Since 2006 an intensive programme of monitoring for radioactive objects has been carried out on beaches in the vicinity of the Sellafield site in West Cumbria. This beach monitoring programme is carried out by Nuvia Ltd on behalf of Sellafield Ltd (SL); a description of the programme is given in Oatway *et al*. (2011). Until August 2009, the Groundhog Evolution2™ beach monitoring system was used. This system uses an array of five sodium iodide (NaI(Tl)) detectors mounted on the front of an eight-wheel drive vehicle. It is designed to detect objects containing the gamma-emitting radionuclides caesium-137 (^{137}Cs) and cobalt-60 (^{60}Co), the pure beta-emitting radionuclide strontium-90 and its radioactive daughter yttrium-90 ($^{90}Sr/^{90}Y$), and the alpha-emitting radionuclide americium-241 (^{241}Am).

Evolution2™ uses a portable computer to provide the operator with a display of the detector readings, real-time mapping information, and an alarm to indicate detection of an object. Global Positioning Systems (GPS) are used to provide location information. The active volume of each detector is 76 mm in diameter by 400 mm long. The detectors are arranged horizontally in a slightly staggered configuration, with their axes perpendicular to the direction of movement, providing a continuous monitoring width of 2.0 metres (Figure 1). The axial centre of each detector is less than 25 cm above the ground surface on level ground. The detectors are installed in a weatherproof instrument case, which also contains the counting electronics and multi-channel spectrometry ratemeters. The gamma radiation count rate measured by each detector in each of the defined energy regions is transmitted to a datalogging computer. The vehicle is driven over the survey area at a speed of approximately 1 m s^{-1}, with the GPS system providing information for a 'moving map' of the area surveyed. Successive passes across the beach are overlapped by some 0.3 metres to ensure that all areas are adequately covered. If, during the course of a survey, a particle alarm occurs, the vehicle is stopped and reversed slowly (0.5 ms^{-1}) for up to 5 metres, and then advanced slowly up to the original stopping point. If the particle alarm is again triggered during this process, the vehicle is stopped and a manual particle search and recovery process initiated. Further information on the Evolution2™ system, including a description of the detection algorithms, is given in Appendix A2 of Oatway *et al.* (2011).

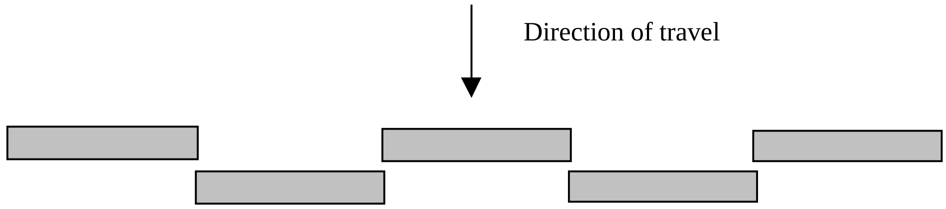

Figure 1. Groundhog Evolution2™ detector array

By August 2009, over 650 radioactive objects had been identified using Evolution2™ and then removed. These objects comprised particles with sizes smaller or similar to grains of sand (less than 2 mm) and contaminated pebbles and stones (known as “stones”) with sizes greater than 2 mm.

HPA performed an assessment of overall risk to the health of beach users based on the results of the Evolution2™ monitoring programme up until August 2009, and this was published in early 2011 (Brown and Etherington, 2011; Oatway *et al*., 2011).

In August 2009 a new beach monitoring system, Groundhog Synergy, was brought into operation as a replacement for the Groundhog Evolution2™ system. The main difference is that Synergy includes another array of detectors in addition to the sodium iodide detectors. These “FIDLER” detectors (Field Instrument for the Detection of Low-Energy Radiation) employ a thin crystal, 127 mm in diameter and 1.6 mm thick, and are designed to enhance the detection of low-energy photon radiation, particularly the 60 keV gamma emission of ^{241}Am and the Bremsstrahlung radiation resulting from ^{90}Sr/^{90}Y decays. The arrangement of the FIDLER detectors is shown in Figure 2.

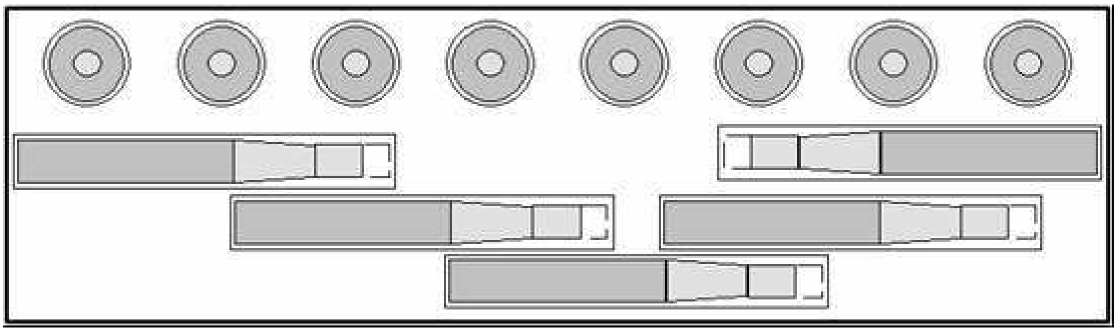

Figure 2. A schematic showing the arrangement of the Groundhog Synergy detector array in the carbon fibre housing case. *Reproduced by kind permission of Nuvia Ltd.*

The evaluation and assessment presented in this report is limited to a consideration of the performance of the Groundhog Synergy system for detection of alpha-rich objects. (Objects are classified as alpha-rich when the measured ^{241}Am activity exceeds the measured ^{137}Cs activity, and as beta-rich when the measured ^{137}Cs activity exceeds the measured ^{241}Am activity.) The reasons for applying this limitation in the scope of the study are two-fold:

(a) The FIDLER detectors have a relatively poor response at higher energies because they are constructed from thin (1.6 mm) crystals, and so they do not provide an improved capability for detection of the high energy gamma-ray emissions (662 keV) from ^{137}Cs. The low energy photon emissions associated with ^{137}Cs decay are low in intensity, and detection of these emissions or any low energy Compton-scattered photons would not provide an improved detection capability compared with that achieved through detection of the 662 keV gamma emission. Caesium-137 is detected by the NaI(Tl) detectors that are common to Synergy and Evolution2™, through measurement of its 662 keV gamma emission, which is not significantly attenuated in sand for the depths of interest. There are no significant differences in the configuration of the NaI(Tl) detectors in Synergy and Evolution2™ that would affect detection of objects containing ^{137}Cs, and so the response of the two systems for ^{137}Cs should be similar. The results of large-scale beach trials of the Synergy system (Beddow, 2010) provide evidence in support of this view.

(b) Strontium-90/yttrium-90 is detected through measurement of the Bremsstrahlung radiation spectrum. This spectrum does extend to lower energies, and the FIDLER detectors are therefore expected to have some sensitivity to $^{90}Sr/^{90}Y$. However, the large-scale beach trials showed that $^{90}Sr/^{90}Y$ sources are detected by the NaI(Tl) detectors, rather than the FIDLER detectors. Furthermore, the results of the beach trials indicate that the mathematical models used at both Nuvia and HPA predict significantly better detection capabilities for $^{90}Sr/^{90}Y$ than is actually achieved, as discussed in Section 8.1.2 of Oatway *et al.* (2011). This discrepancy needs to be understood before further modelling of the performance of the beach monitoring systems is performed, as recommended in Oatway *et al.* (2011). Lastly, it may be noted that neither beach monitoring system has yet detected a ^{90}Sr-containing object through detection of its $^{90}Sr/^{90}Y$ content.

Because of its use of FIDLER detectors, the Synergy system is more sensitive to alpha-rich objects containing ^{241}Am and as expected the number of alpha-rich objects being found has increased. In total, up till the end of March 2012, approximately 1500 objects have been detected by both the Evolution2^{TM} and Synergy systems. Of these, approximately 370 are alpha-rich objects detected between 2006 and August 2009 using the Evolution2^{TM} system, whilst approximately 650 are alpha-rich objects detected between August 2009 and March 2012 using the Synergy system. This increased find rate does not necessarily mean that there is an increase in the number of objects actually present on the beaches, since the increase could be completely attributable to improvements in detector sensitivity.

This study was carried out to evaluate the performance of the Synergy system and to assess the implications of the results of the Synergy monitoring programme obtained since August 2009 for the health risk assessment. It was carried out in two phases. In Phase 1, a detailed specification of the data required from Nuvia and SL was first developed. The data requested from Nuvia included a specification of the positions of the FIDLER detectors, calibration factors for these detectors, and background data measured using the Synergy system at a number of beaches. Qualitative comparisons of the activity distributions of objects found by the two systems were then made to determine whether the increased alpha-rich object find rate can be attributed in whole or in part to Synergy's increased sensitivity. In Phase 2, a quantitative analysis was performed using the methodology described previously (Brown and Etherington, 2011) to provide new estimates of alpha-rich object populations on the beaches. This analysis was based only on the results of the Synergy monitoring programme.

The original aim of Phase 2 was to determine whether there is a need to review HPA's assessment of overall risk to beach users. However, as work on Phase 2 progressed, it became clear that the best way to proceed would be to re-evaluate the overall risk to the health of beach users associated with alpha-rich objects on the beaches, rather than to determine whether a re-evaluation was needed. This allows a more complete account to be provided to interested parties of any impact that the use of the Synergy monitoring programme has on estimates of overall health risks. In this report, new estimates are provided of the overall risks of fatal cancer to a beach user from the ingestion of alpha-rich objects, this exposure pathway being the one which has the greatest potential for stochastic effects on health (Brown and Etherington, 2011). Comparisons are then made with the previous estimates of health risks presented in Brown and Etherington (2011).

It should be noted that due to the timing of the project into two distinct phases, slightly different versions of compiled data on objects detected and retrieved from the beaches have been used. This does not affect the conclusions of the project. The data used are clearly identified in the report.

2 EVALUATION OF SYNERGY MONITORING SYSTEM

The increase in the object find rate could be attributed either to an increase in the number of objects actually present on the beaches or to improvements in detection sensitivity due to the introduction of the Synergy system. If the increased alpha-rich object find rate of Synergy is entirely attributable to its increased sensitivity compared with Groundhog Evolution2™, then the activities of the additional objects detected by Synergy should be found within a well-defined activity range that depends on the detection limits of the two measurement systems.

2.1 Method

For any ^{241}Am-containing object on the surface of the beach, the Groundhog Evolution2™ system has a detection limit (DL) of 39 kBq under the measurement conditions employed for beach scans (Oatway *et al*., 2011). For the Synergy system, a “typical” detection limit for ^{241}Am-containing objects measured under similar conditions is 14 kBq, as shown in Table 1 (Davies, 2011).

Table 1. Summary of the typical and worst case limits of detection for measurements of ^{241}Am objects by Synergy (with a 95 % confidence level) as estimated by Nuvia

Depth, mm	^{241}Am activity, kBq	
	Typical	Worst
0	14	30
50	180	420
100	1600	4250
200	130000	310000

Note: Reproduced by kind permission of Nuvia Ltd.

A measurement method that has a DL of *x* kBq will detect an object containing that activity on 95% of occasions. Another way of expressing this is to say that the detection probability for that object is 95%. Given a specified DL, it is possible to determine the detection probabilities for objects with other activities when measured under the same conditions as were used to specify the DL. These calculations were performed for DLs of 14 kBq (the Synergy DL) and 39 kBq (the Evolution2™ DL) using the HPA program *BP_Evolution v2.0*, which is described in Appendix A3 of Oatway *et al*. (2011). The resulting object detection probabilities are shown in Figure 3.

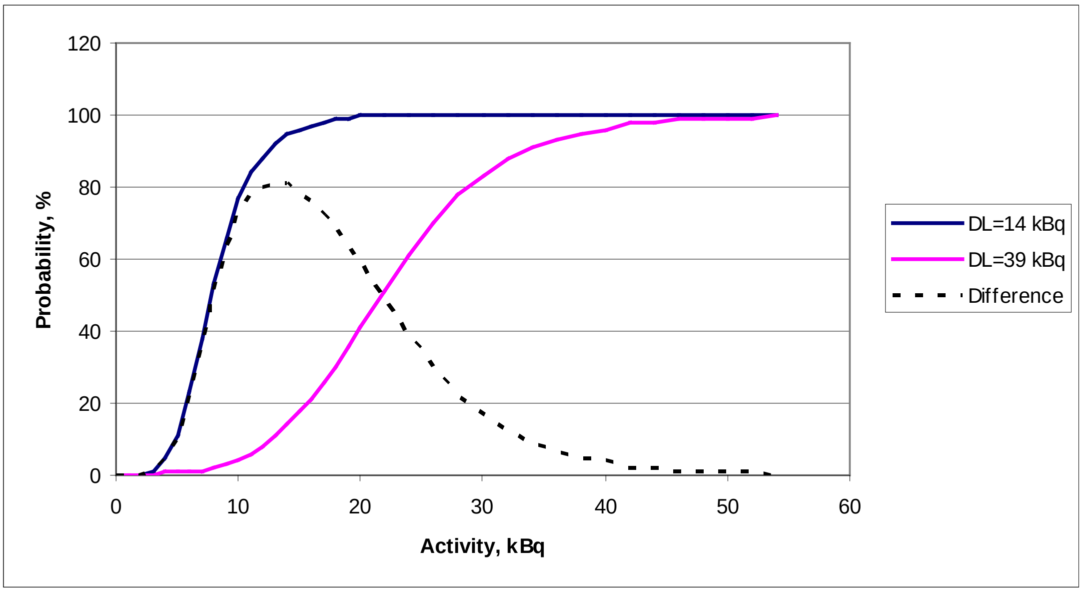

Figure 3. Object detection probabilities vs. activity of ^{241}Am for a measurement with detection limits (DL) of 14 kBq ^{241}Am and 39 kBq ^{241}Am.

This figure shows that most of the additional alpha-rich objects detected by Synergy on the surface of the beach should be found in the approximate activity range 8 – 22 kBq. For surface objects with activities greater than about 40 kBq, detection probabilities for the two systems are almost identical, and are close to 100%. Similarly, for surface objects with activities less than about 3 kBq, detection probabilities of the two systems are both close to 0%.

Therefore, if the hypothesis is made that the increased object find rate of Synergy is entirely attributable to its increased sensitivity, then a comparison of the activities of objects found on the surface under similar conditions should meet the following criteria:

Criterion 1: if elevated numbers of alpha-rich objects are found by Synergy, these objects should have ^{241}Am activities predominantly in the range 8 – 22 kBq;

Criterion 2: there should be almost no difference in the numbers of objects found with activities above about 40 kBq;

Criterion 3: neither system should find objects with activities less than about 3 kBq.

To make a fair comparison, the find data to be compared should be:

- from an area (or areas) of a beach that has been monitored by both systems;
- obtained during monitoring campaigns that are close enough in time so that object populations are not expected to change significantly;

- for objects at similar depths. The easiest way to achieve this is to consider results only for objects found on or near the surface.

It is implicit in making this comparison that removing objects from the beach after they are detected does not affect the number of objects on the beach measured subsequently over the time period of the comparison. Given that object detection probabilities for alpha-rich objects in the activity range of interest are low for depths greater than about 2 cm, it may be supposed that recycling of objects from depths greater than 2 cm to the surface would ensure that object removal does not have a significant effect on alpha-rich object populations measured on or near the surface.

A preliminary inspection of object detection data resulted in a decision to make the comparisons for selected areas of Braystones beach, Sellafield beach and St Bees beach. (Rates of object detection on other beaches are too low for a valid comparison to be made). For each area of beach, and for each monitoring system, the following information was provided by Sellafield Ltd:

a the date(s) monitored;
b the area monitored, in hectares;
c a quantitative definition of the boundaries of the area monitored;
d the number of alpha-rich objects found in the defined area;
e the ^{241}Am activity of each object;
f a best estimate of the depth of the object when retrieved.

HPA requested that repeated scans over the same area should not be summed, since this would result in an overestimate of the object population.

2.2 Results and discussion

In this Section, comparisons are made of the activity distributions of the numbers of alpha-rich objects found by the two monitoring systems at three beaches: Braystones (sandy areas) (Figures 4-7), Sellafield “high sand” (Figures 8-11) and St Bees (Figures 12-15). (“High sand” indicates areas of the beach that are at a higher elevation). The comparisons are made over defined areas of beach during defined time intervals and within specified depth ranges. In these Figures, the term ‘frequency’ is used to indicate the number of objects in each 1 kBq-wide activity interval.

Figures 4, 8 and 12 show maps of the “overlap” (“intersect”) areas for each of the three beaches. These are the areas of the beach monitored by both systems during the period from one year prior to 24th August 2009 (the date on which Synergy was first used) to one year after 24th August 2009.

Subsequent figures show comparisons of activity distributions for alpha-rich object finds for each beach, selected according to the following object selection criteria.

Figures 5, 9 and 13 show comparisons of alpha-rich object finds for each of the three beaches over the whole beach monitoring programme, and include all finds irrespective of object depth (ie, all object finds were selected). Because different areas were monitored by the two systems, the comparison is not quantitative.

Figures 6, 10 and 14 show comparisons for objects found only in the overlap areas, and at all object depths, during the period from one year prior to 24th August 2009 to one year after 24th August 2009. Because the same areas were monitored by the two systems, the figures provide a quantitative comparison for the number of objects found and the number of objects per hectare.

Figures 7, 11 and 15 present similar data to those shown in Figures 6, 10 and 14 but only for object depths less than or equal to 2 cm. This depth was chosen as the smallest value that would provide sufficient numbers of object finds to make a valid comparison. Again, the comparisons are quantitative because the same areas were monitored by the two systems

No data are presented for Evolution2 in Figures 14 and 15 because no objects were found by the Evolution2 system in the overlap area at St Bees during the period of interest. On the 'high-sand' area of Sellafield beach, four particles with activities greater than 200 kBq have been found. These high activity particles have not been included in Figures 9 – 11 in order to improve clarity in the activity region where object detection is predicted to be improved.

The data in Figures 6, 7, 10, 11, 14 and 15 may be inspected and an assessment made of the degree to which the three criteria described Section 2.1 are met.

Criterion 1

For all three beaches, elevated numbers of objects are found in the Synergy data in the approximate activity range expected. The lower activity limit for detection of objects by Synergy is approximately 3 kBq, as expected. However, Figures 7, 11 and 15 show that the upper activity limit for the distribution of elevated numbers of detected objects is somewhat higher than the expected value of about 40 kBq. The likely reason is that objects detected at depths in the range 0 – 2 cm have been included, rather than objects detected only on the surface. Since the DLs for objects at 1 and 2 cm are higher than those for particles at the surface, the distribution of elevated numbers of detected objects is shifted to higher activities. It is judged that this criterion is broadly met.

Criterion 2

An unexpected difference between the activity distributions of objects found by Synergy and Evolution2 is that, on Braystones beach, the Synergy system detects somewhat more higher activity objects (above about 70 kBq) than were found by Evolution2. For objects found within 2 cm of the surface, Synergy found four objects, whereas Evolution2 found two objects. The difference is also seen when no depth selection is performed, although the comparison is less reliable because of the strong dependence of detection probability on depth. However, this difference is not found in the data for Sellafield beach. At present, this relatively minor difference, seen clearly in only one of the three beaches investigated, remains unexplained. Since it is a minor difference, it is judged that the criterion is broadly met.

Criterion 3

No objects with activities less than about 3 kBq were found by either system, so this criterion is met.

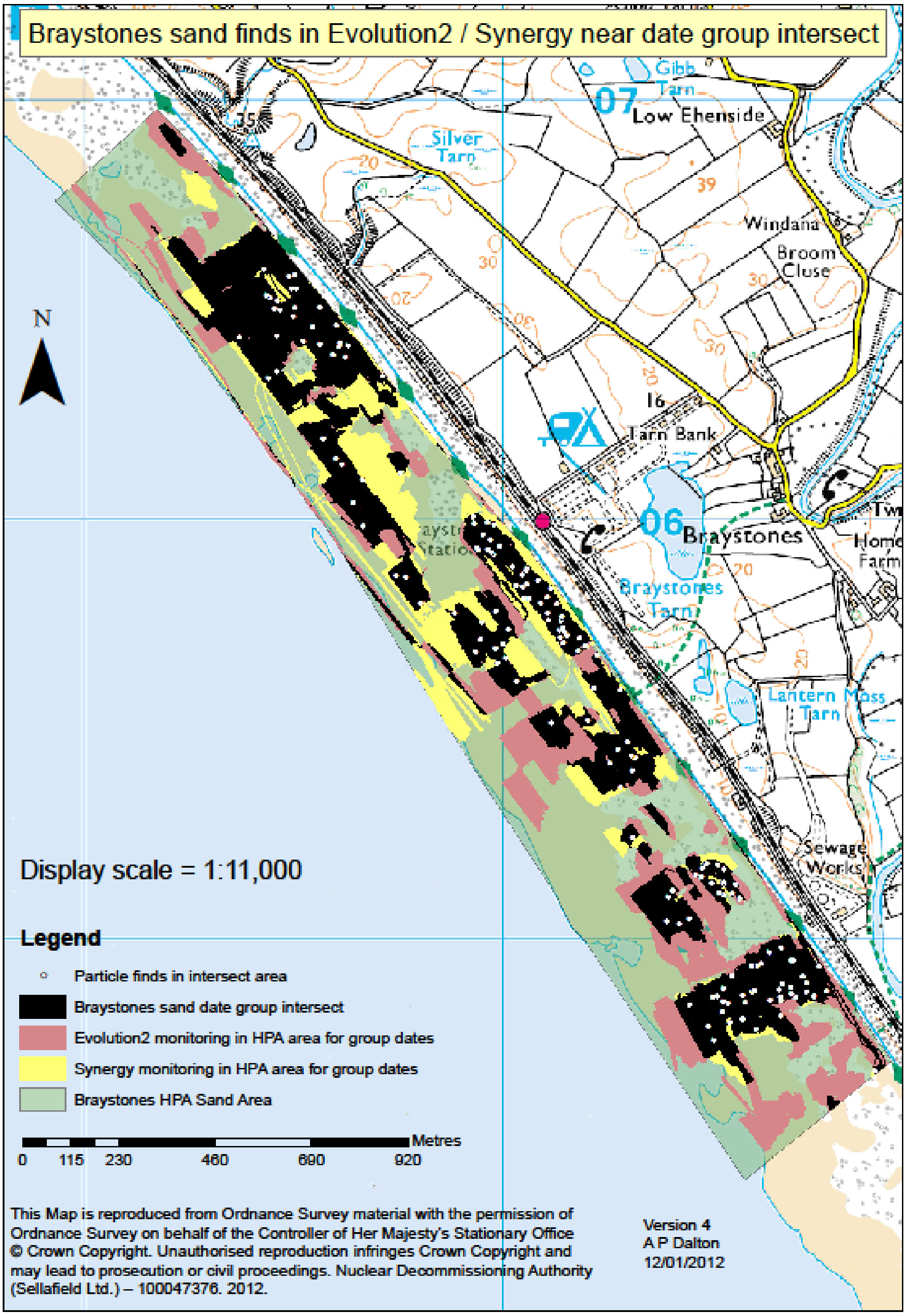

Figure 4. Areas on Braystones beach monitored by Evolution2 and Synergy (black areas)

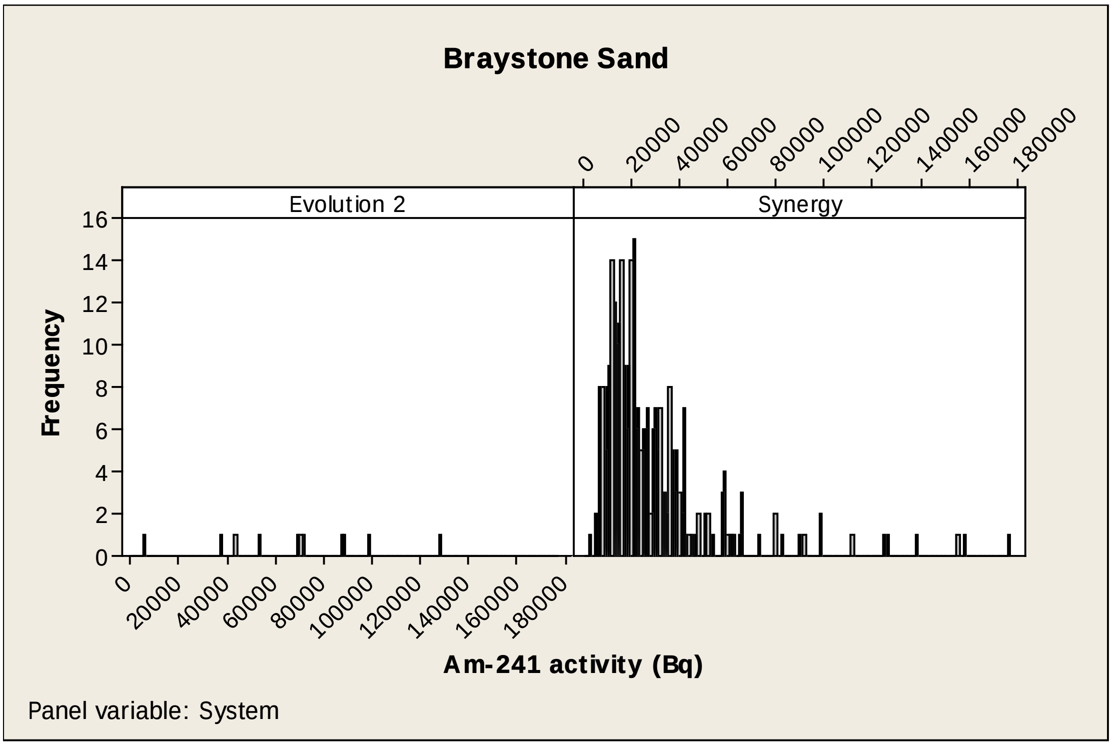

Figure 5. Numbers of alpha-rich objects found on Braystones beach by the two systems. All monitored areas, all monitoring campaigns, all object depths.

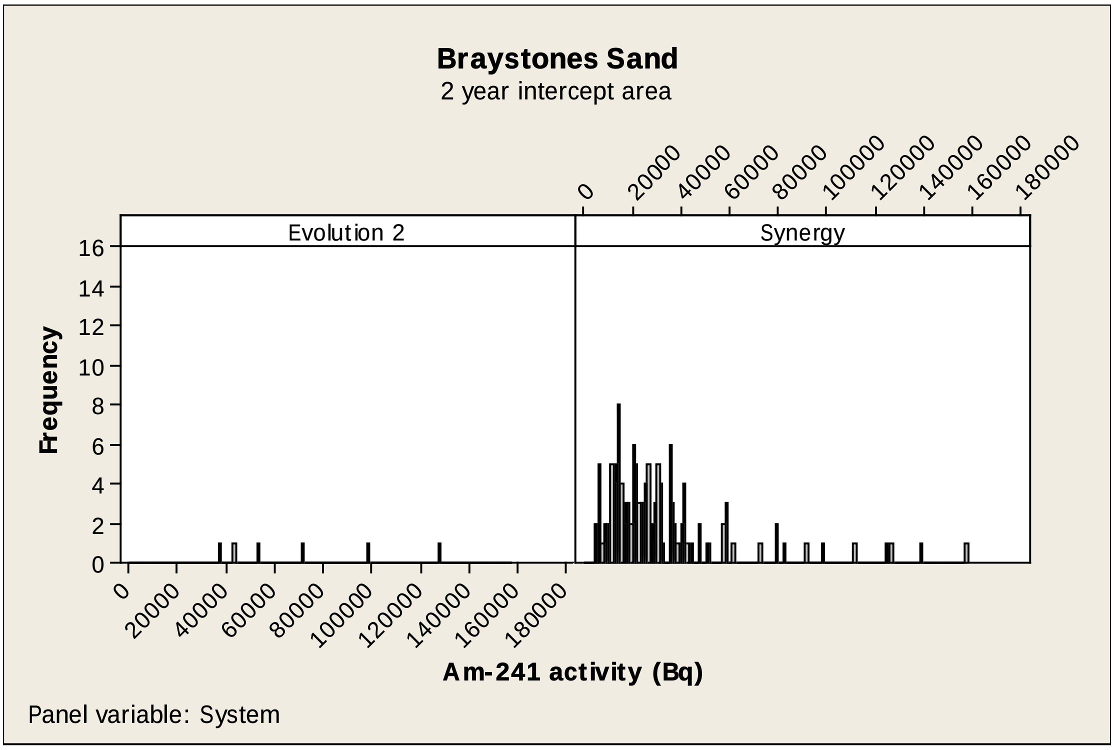

Figure 6. Numbers of alpha-rich objects found on Braystones beach by the two systems. "Overlap" areas only, monitoring campaigns within 1 year of August 2009, all object depths.

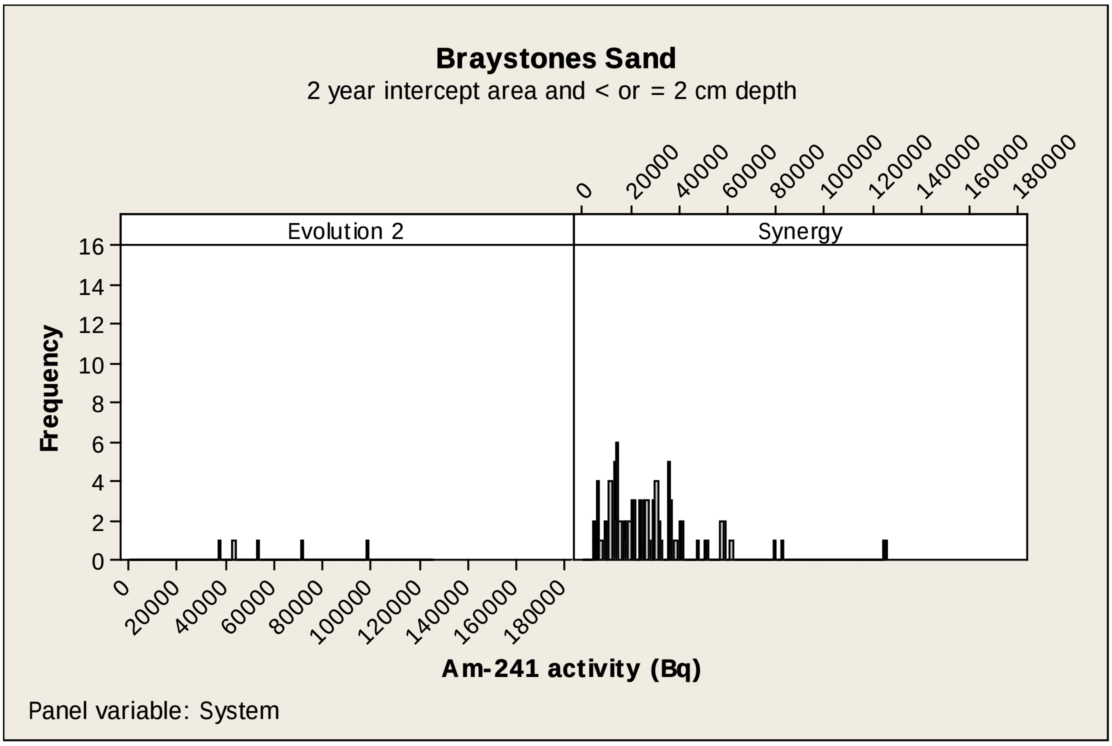

Figure 7. Numbers of alpha-rich objects found on Braystones beach by the two systems. "Overlap" areas only, monitoring campaigns within 1 year of August 2009, objects found at depths less than or equal to 2 cm.

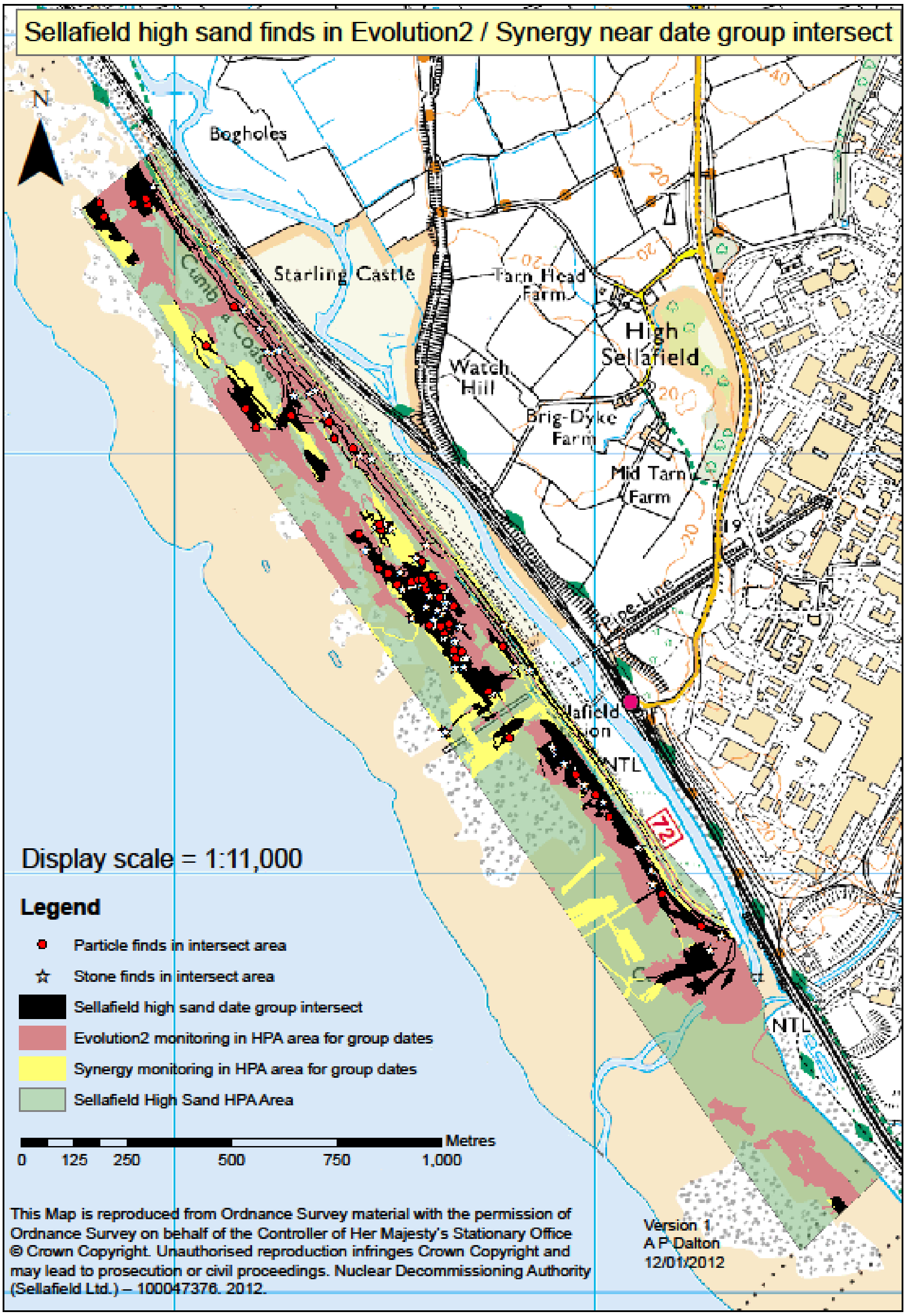

Figure 8. Areas on Sellafield "high sand" beach monitored by Evolution2 and Synergy (black areas)

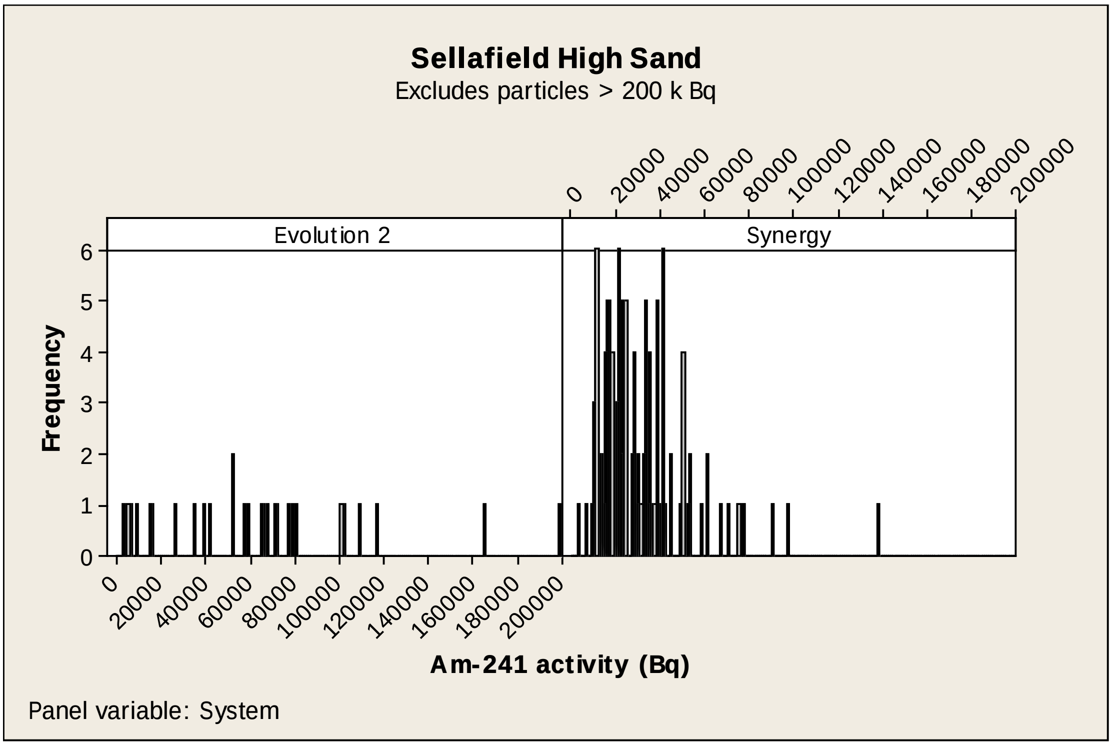

Figure 9. Numbers of alpha-rich objects found on Sellafield "high sand" beach by the two systems. All monitored areas, all monitoring campaigns, all object depths.

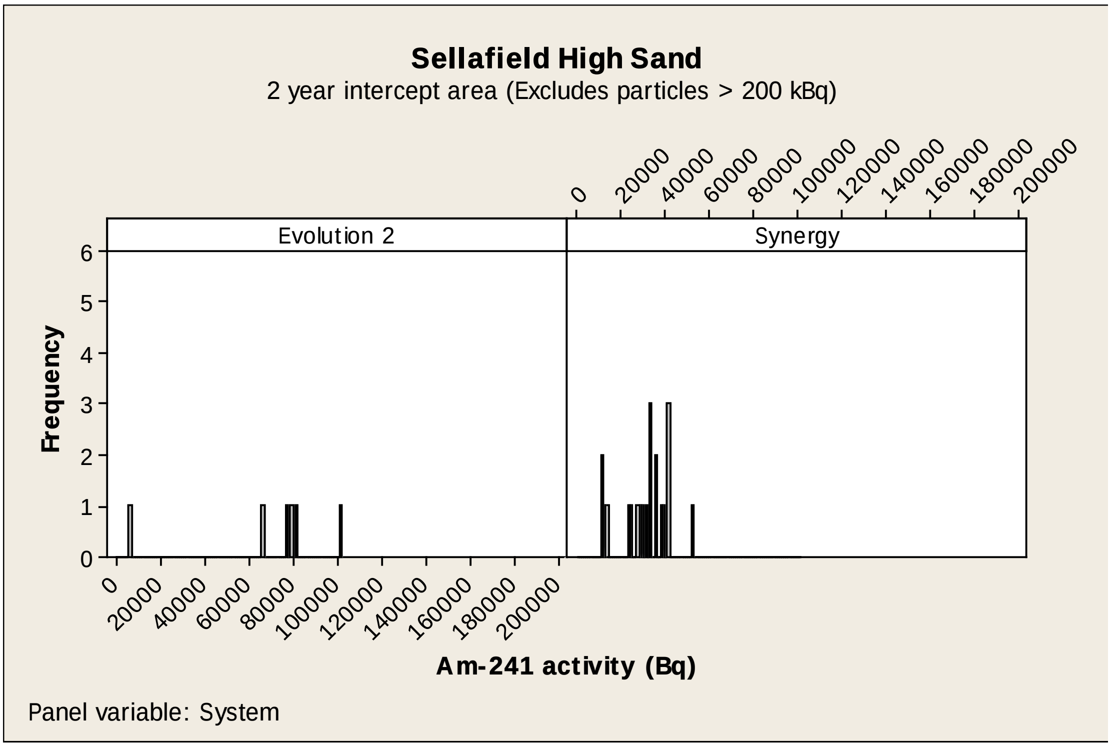

Figure 10. Numbers of alpha-rich objects found on Sellafield "high sand" beach by the two systems. "Overlap" areas only, monitoring campaigns within 1 year of August 2009, all object depths.

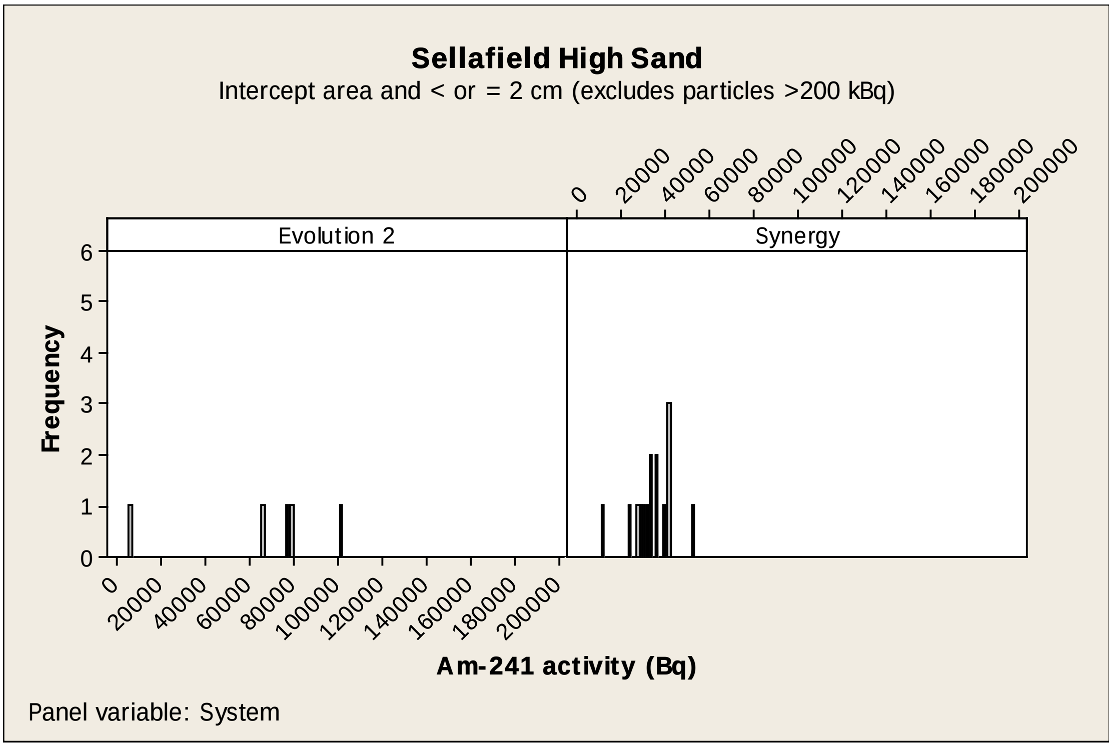

Figure 11. Numbers of alpha-rich objects found on Sellafield "high sand" beach by the two systems. "Overlap" areas only, monitoring campaigns within 1 year of August 2009, objects found at depths less than or equal to 2 cm.

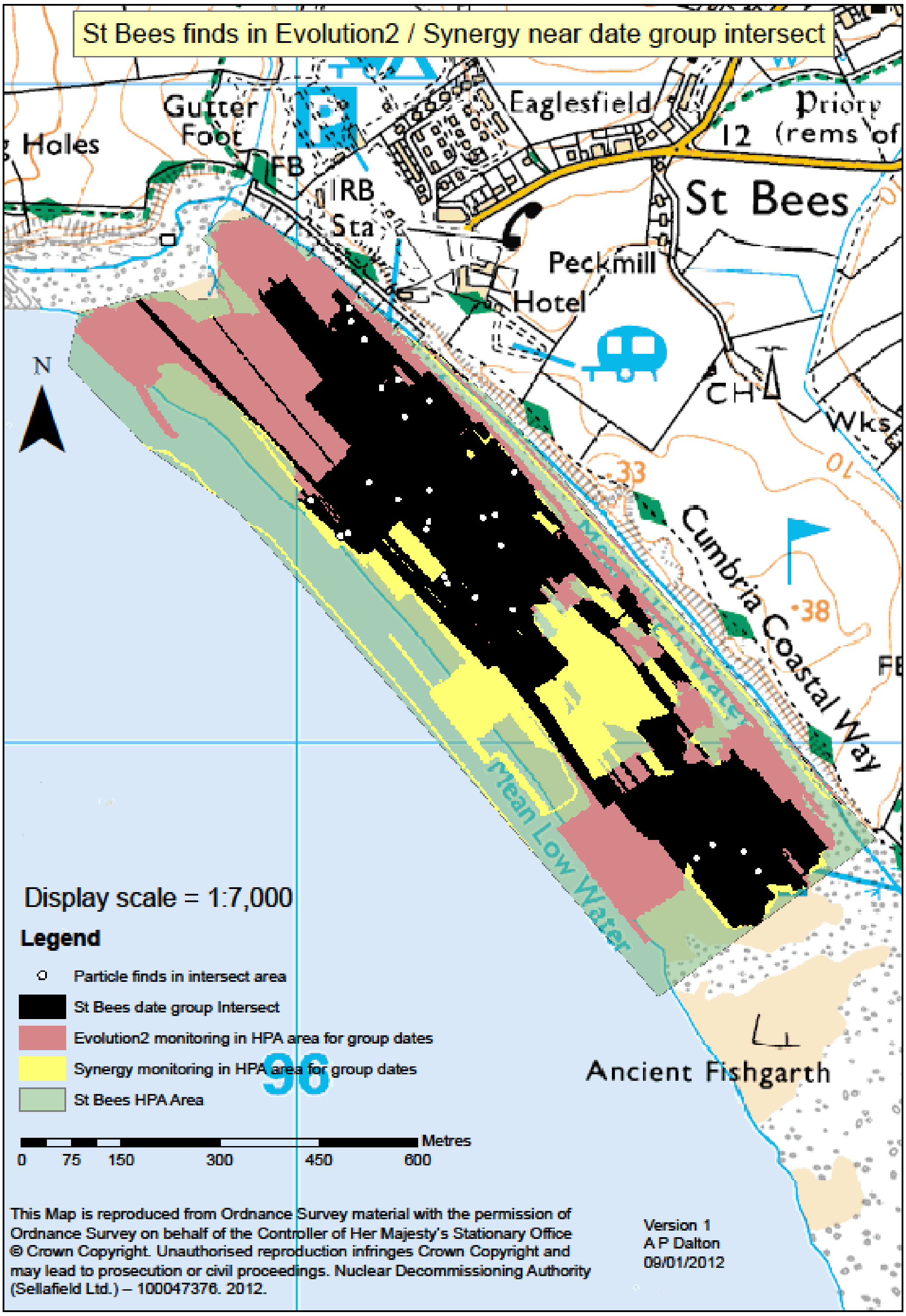

Figure 12. Areas on St Bees beach monitored by Evolution2 and Synergy (black areas)

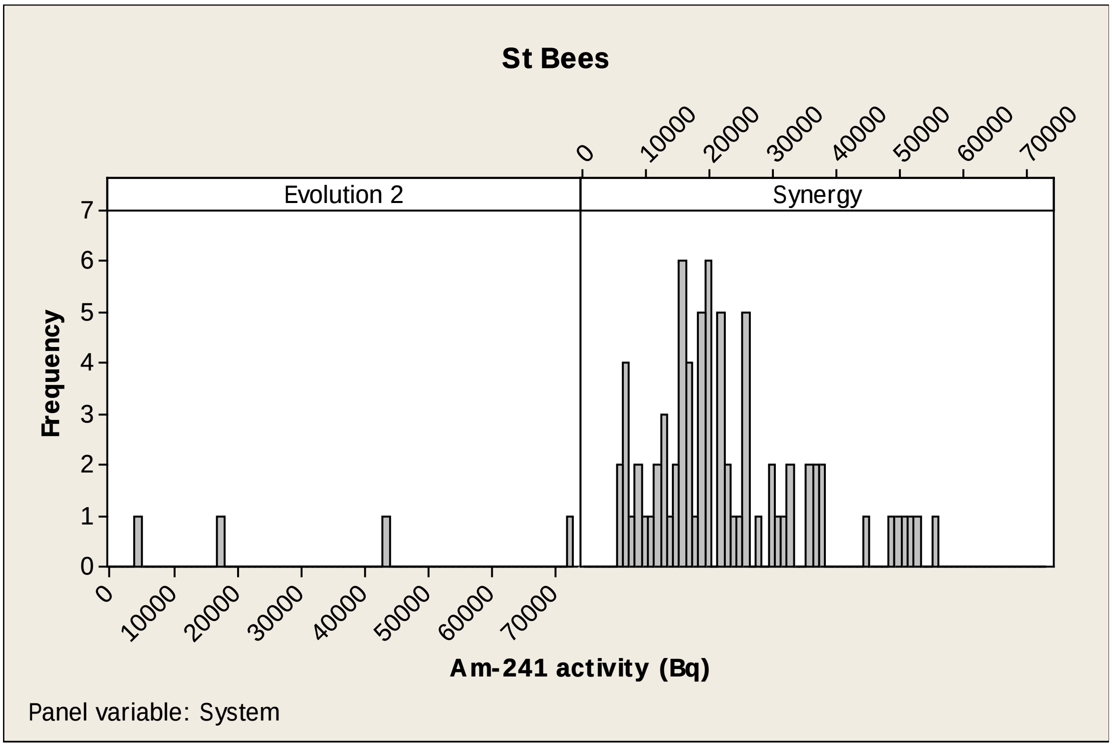

Figure 13. Numbers of alpha-rich objects found on St Bees beach by the two systems. All monitored areas, all monitoring campaigns, all object depths.

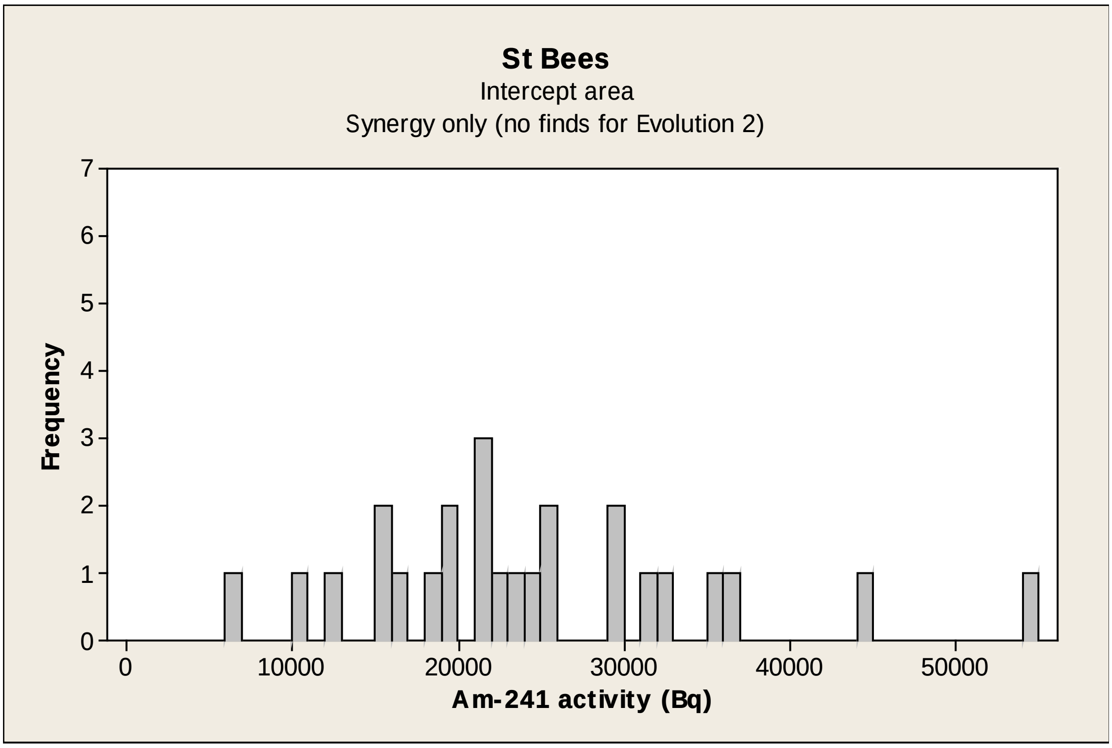

Figure 14. Numbers of alpha-rich objects found on St Bees beach by the Synergy system. "Overlap" areas only, monitoring campaigns within 1 year of August 2009, all object depths. No objects were found by the Evolution2 system in the overlap area during this period.

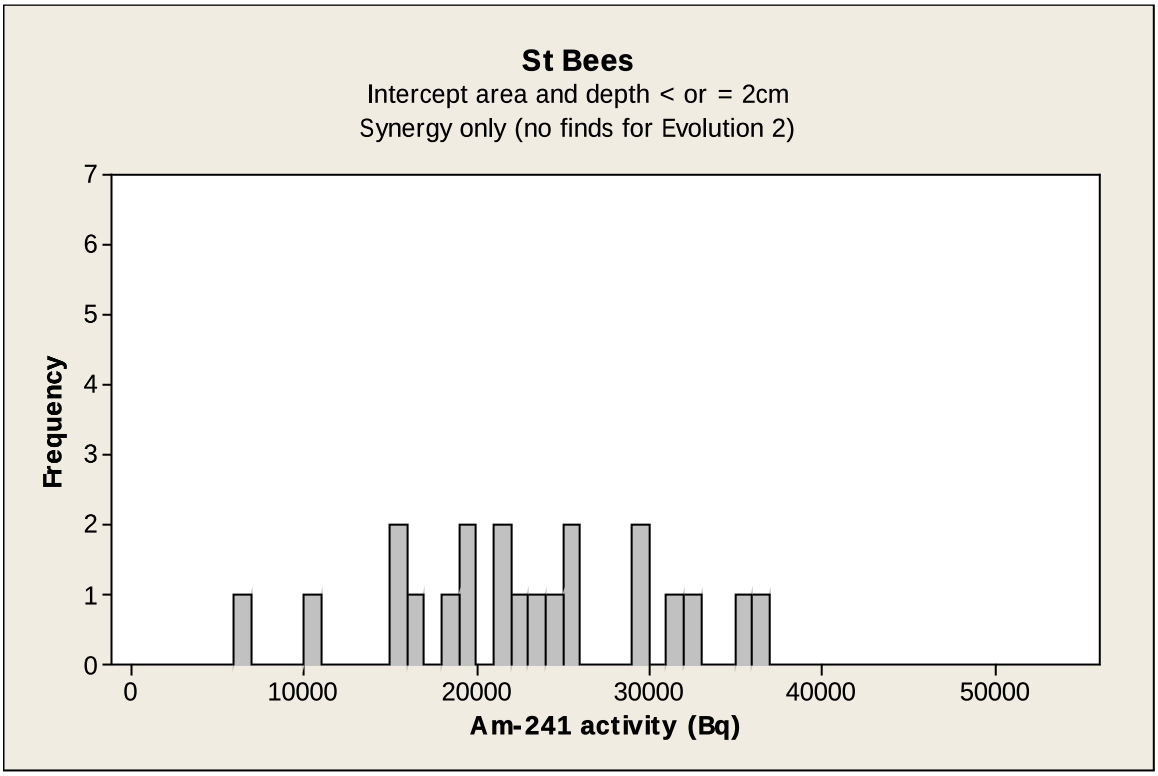

Figure 15. Numbers of alpha-rich objects found on St Bees beach by the Synergy system. "Overlap" areas only, monitoring campaigns within 1 year of August 2009, objects found at depths less than or equal to 2 cm. No objects were found by the Evolution2 system in the overlap area during this period.

Table 2 presents the number of alpha-rich object finds, the area monitored, and the find rate per hectare for each beach, for each monitoring system and for each of the object selection criteria described above. These data show that, as expected, the find rate per hectare summed over all object activities is greater for Synergy, by a factor of about 3 for Sellafield "high sand" beach and about 20 for Braystones beach.

Table 2. Numbers of alpha-rich object finds and find rate per hectare

Beach Area	Monitoring System	Object selection criteria	Number of object finds[a]	Area monitored, Ha[a]	Find rate, Ha^{-1}
Braystones Sand	Evolution2	All finds	11	128.79	0.085
		"Overlap" areas only 24/8/09 +/- 1 year	6	31.56	0.19
		"Overlap" areas only 24/8/09 +/- 1 year depth ≤ 2 cm	5	31.56	0.16
	Synergy	All finds	301	150.14	2.00
		"Overlap" areas only 24/8/09 +/- 1 year	135	31.56	4.3
		"Overlap" areas only 24/8/09 +/- 1 year depth ≤ 2 cm	88	31.56	2.8
Sellafield "high sand"	Evolution2	All finds	28	135.64	0.21
		"Overlap" areas only 24/8/09 +/- 1 year	6	12.19	0.49
		"Overlap" areas only 24/8/09 +/- 1 year depth ≤ 2 cm	5	12.19	0.41
	Synergy	All finds	117	59.37	2.0
		"Overlap" areas only 24/8/09 +/- 1 year	22	12.19	1.8
		"Overlap" areas only 24/8/09 +/- 1 year depth ≤ 2 cm	15	12.19	1.2
St Bees	Evolution2	All finds	4	107.3	0.037
		"Overlap" areas only 24/8/09 +/- 1 year	0	19.14	0
		"Overlap" areas only 24/8/09 +/- 1 year depth ≤ 2 cm	0	19.14	0
	Synergy	All finds	75	88.99	0.84
		"Overlap" areas only 24/8/09 +/- 1 year	25	19.14	1.3
		"Overlap" areas only 24/8/09 +/- 1 year depth ≤ 2 cm	21	19.14	1.1

[a] Data on object finds up to 9th September 2011 provided by Sellafield Ltd (Dalton, 2011)

3 ESTIMATION OF THE POPULATION OF ALPHA-RICH OBJECTS ON THE BEACHES

Theoretical evaluations of the detection efficiency of the Synergy system for alpha-rich objects have been carried out and object detection probabilities determined, as described below. These detection probabilities have been used to estimate the population of objects* on each beach from the results of the Synergy monitoring programme.

3.1 Efficiency of detection of objects

A Visual Basic 6.0 program that determines detection probabilities for the Groundhog Evolution2™ system is described in Oatway *et al*. (2011). The code performs Monte Carlo simulations of the passage of a detector array across the location of an object buried at a specified depth in a beach. This code has been adapted so that it can be applied for evaluating alpha-rich object detection probabilities for the Synergy system. The main code modifications required were changes to the geometry of the detector array description to allow simulation of an 8-detector FIDLER array.

The operation of the program is best described with reference to a specific example. Figure 16 shows the input/output screen at the end of a simulation run carried out to determine the detection probability for objects at a depth of 0.0 m containing 10 kBq of ^{241}Am, when the detector array is travelling at a speed of 1.0 ms^{-1}. The first step in a simulation run is to read in a background data set, in this case from the file *..\data\syn_stbees_201105.txt*, which contained 31822 records of measurements made at St Bees beach.

Next, the scan speed, object activity and object depth for the simulation run are chosen. All of the calculations presented in this report were made for a scan speed of 1 m s^{-1}. Any value for object activity may be specified; for this study, object activities of 1, 10, 100 and 1000 kBq were chosen. The choice of object depth is limited to those depths for which calibration factors are available.

After specification of the input data, various simulation options and parameter values can be set that determine how the simulation proceeds. A simulation step size of 0.05 m was chosen, and all of the calculations were carried out using the 0.3 m overlap option.

Net count rates measured by each detector as it passes over the object are simulated using calibration factors that specify the measured count rate per unit activity for various object depths and positions relative to the detector. The corresponding total count rates are determined by summing these net count rates with background count rate values taken from the background data set. Detection criteria are set to determine whether any

* The terms population of objects and object population are used interchangeably in this report to be the best estimate of the number of objects present on a beach and is taken to be representative of the number present at any time that the beach is used.

increase in the count rate can be attributed to the presence of an active object. Synergy uses the same criterion for detection of an alpha-rich object as was used by Groundhog Evolution2™. This criterion is described in detail in Section A3.4 of Oatway *et al*. (2011).

Tables 3-6 show computed detection probabilities for the Synergy system for alpha-rich objects with ^{241}Am activities of 1, 10, 100 and 1000 kBq. Values have been determined for selected beaches: Braystones beach, Drigg beach, Seascale beach, Sellafield beach ("high sand" and "low sand") and St Bees beach. These include the beaches for which estimates of object populations are required for the health risk assessment. For completeness, the tables include those additional beach areas for which detection probabilities were previously estimated for Evolution2™ but have not been estimated for Synergy.

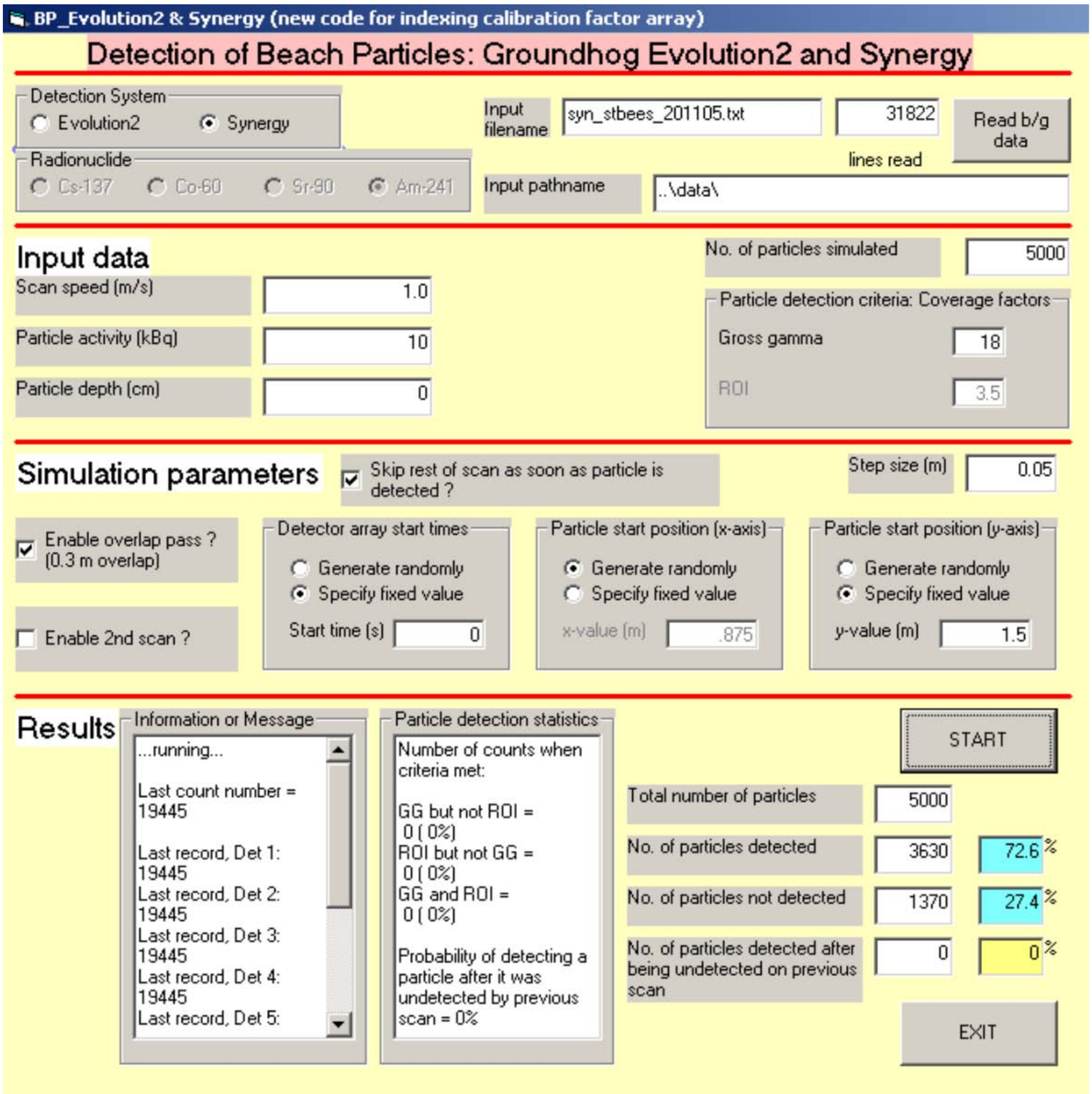

Figure 16. Input/output screen for Visual Basic program to determine detection probabilities

Table 3. Object detection probability for Groundhog Synergy & Evolution2™, object activity = 1 kBq

Depth (m)	Scan speed (ms^{-1})	Am-241 detection probability (%)	
		Synergy	Evolution2
Barnscar beach, sandy areas (5100 – 5500)[a]			
0.0001	1.0	- [c]	0.3
0.05	1.0	-	0.3
0.1	1.0	-	0.3
0.15	1.0	-	0.3
Braystones beach, sandy areas (27000 – 28000)[a] (3600)[b]			
0.0001	1.0	0.4	0.3
0.05	1.0	0.2	0.2
0.1	1.0	0.2	0.2
0.15	1.0	0.2	0.2

a. No. of Evolution2 object simulations, corresponding to a single pass through the background data file.
b. No. of Synergy object simulations, corresponding to a single pass through the background data file.
c. No value estimated for Synergy.
Notes:
1. 0.3 m overlap pass included.
2. 0.05 m simulation step size.
3. Simulated count rate measured over 1 s.
4. Simulated object x-coordinates chosen randomly in the 0 – 2 m range (x-axis is the detector axis).
5. Object starting y-coordinates (y-axis is the direction of travel) chosen to maximise detection probability (simulating the outcome of 10 times oversampling).

Table 4. Object detection probability for Groundhog Synergy & Evolution2™, object activity = 10 kBq

Depth (m)	Scan speed (ms^{-1})	Am-241 detection probability (%)	
		Synergy	Evolution2
Barnscar beach, sandy areas (5100 – 9000)[a]			
0.0001	1.0	- [c]	7
0.05	1.0	-	0.3
0.1	1.0	-	0.3
0.15	1.0	-	0.3
Barnscar beach, shingle areas (3500 – 6400)[a]			
0.0001	1.0	-	2
0.05	1.0	-	0.3
0.1	1.0	-	0.3
0.15	1.0	-	0.2
Braystones beach, sandy areas (27000 - 45000)[a] (3600 – 5400)[b]			
0.0001	1.0	74	5
0.05	1.0	0.3	0.3
0.1	1.0	0.2	0.2
0.15	1.0	0.2	0.2
Braystones beach, shingle areas (2200 – 3300)[a]			
0.0001	1.0	-	2
0.05	1.0	-	0.3
0.1	1.0	-	0.3
0.15	1.0	-	0.3

Depth (m)	Scan speed (ms^{-1})	Am-241 detection probability (%)	
		Synergy	Evolution2
Drigg beach, sandy areas (8300 – 15000)[a] (4500 - 7200)[b]			
0.0001	1.0	80	9
0.05	1.0	0.3	0.2
0.1	1.0	0.2	0.1
0.15	1.0	0.2	0.1
Seascale beach, sandy areas (14000 – 25000)[a] (4900 - 6900)[b]			
0.0001	1.0	68	6
0.05	1.0	0.3	0.2
0.1	1.0	0.2	0.1
0.15	1.0	0.2	0.1
Seascale beach, shingle areas (2800 – 5000)[a]			
0.0001	1.0	-	2
0.05	1.0	-	0.1
0.1	1.0	-	0.1
0.15	1.0	-	0.1
Sellafield beach, "low sand" areas (5500 – 10000)[a] (1400 - 2100)[b]			
0.0001	1.0	75	5
0.05	1.0	0.6	0.3
0.1	1.0	0.3	0.2
0.15	1.0	0.3	0.2
Sellafield beach, "high sand" areas (6200 – 9700)[a] (3200 - 4400)[b]			
0.0001	1.0	66	4
0.05	1.0	0.3	0.4
0.1	1.0	0.2	0.3
0.15	1.0	0.2	0.3
St. Bees beach, sandy areas (23000 – 42000)[a] (5500 – 8100)[b]			
0.0001	1.0	71	5
0.05	1.0	0.3	0.2
0.1	1.0	0.2	0.2
0.15	1.0	0.2	0.2

a. No. of Evolution2 object simulations, corresponding to a single pass through the background data file.
b. No. of Synergy object simulations, corresponding to a single pass through the background data file.
c. No value estimated for Synergy.
Notes:
1. 0.3 m overlap pass included.
2. 0.05 m simulation step size.
3. Simulated count rate measured over 1 s.
4. Simulated object x-coordinates chosen randomly in the 0 – 2 m range (x-axis is the detector axis).
5. Object starting y-coordinates (y-axis is the direction of travel) chosen to maximise detection probability (simulating the outcome of 10 times oversampling).

Table 5. Object detection probability for Groundhog Synergy & Evolution2™, object activity = 100 kBq

Depth (m)	Scan speed (ms^{-1})	Am-241 detection probability (%)	
		Synergy	Evolution2
Barnscar beach, sandy areas (5100 – 14000)[a]			
0.0001	1.0	-[c]	100
0.05	1.0	-	10
0.1	1.0	-	0.3
0.15	1.0	-	0.2
Barnscar beach, shingle areas (3500 – 9600)[a]			
0.0001	1.0	-	100
0.05	1.0	-	3
0.1	1.0	-	0.3
0.15	1.0	-	0.2
Braystones beach, sandy areas (27000 – 72000)[a] *(3600 - 6900)*[b]			
0.0001	1.0	100	100
0.05	1.0	51	6
0.1	1.0	0.4	0.3
0.15	1.0	0.2	0.2
Braystones beach, shingle areas (2300 – 6100)[a]			
0.0001	1.0	-	100
0.05	1.0	-	2
0.1	1.0	-	0.3
0.15	1.0	-	0.3
Drigg beach, sandy areas (8300 – 22000)[a] *(4500 - 8700)*[b]			
0.0001	1.0	100	100
0.05	1.0	58	12
0.1	1.0	0.3	0.2
0.15	1.0	0.2	0.1
Seascale beach, sandy areas (14000 – 37000)[a] *(4900 - 9300)*[b]			
0.0001	1.0	100	100
0.05	1.0	43	9
0.1	1.0	0.3	0.1
0.15	1.0	0.2	0.1
Seascale beach, shingle areas (2700 – 7500)[a]			
0.0001	1.0	-	100
0.05	1.0	-	2
0.1	1.0	-	0.1
0.15	1.0	-	0.1
Sellafield beach, "low sand" areas (5500 – 15000)[a] *(1400 – 2700)*[b]			
0.0001	1.0	100	100
0.05	1.0	50	7
0.1	1.0	0.6	0.2
0.15	1.0	0.4	0.2
Sellafield beach, "high sand" areas (6200 – 17000)[a] *(3200 – 6000)*[b]			
0.0001	1.0	100	99

Depth (m)	Scan speed (ms^{-1})	Am-241 detection probability (%)	
		Synergy	Evolution2
0.05	1.0	41	5
0.1	1.0	0.3	0.4
0.15	1.0	0.2	0.3
St. Bees beach, sandy areas (23000 – 62000)[a] (5500 – 11000)[b]			
0.0001	1.0	100	100
0.05	1.0	47	6
0.1	1.0	0.3	0.2
0.15	1.0	0.2	0.2

a. No. of Evolution2 object simulations, corresponding to a single pass through the background data file.
b. No. of Synergy object simulations, corresponding to a single pass through the background data file.
c. No value estimated for Synergy.
Notes:
1. 0.3 m overlap pass included.
2. 0.05 m simulation step size.
3. Simulated count rate measured over 1 s.
4. Simulated object x-coordinates chosen randomly in the 0 – 2 m range (x-axis is the detector axis).
5. Object starting y-coordinates (y-axis is the direction of travel) chosen to maximise detection probability (simulating the outcome of 10 times oversampling).

Table 6. Object detection probability for Groundhog Synergy & Evolution2™, object activity = 1000 kBq

Depth (m)	Scan speed (ms^{-1})	Am-241 detection probability (%)	
		Synergy	Evolution2
Barnscar beach, sandy areas (5200 – 14000)[a]			
0.0001	1.0	-[c]	100
0.05	1.0	-	100
0.1	1.0	-	11
0.15	1.0	-	0.3
Barnscar beach, shingle areas (3500 – 9600)[a]			
0.0001	1.0	-	100
0.05	1.0	-	100
0.1	1.0	-	3
0.15	1.0	-	0.3
Braystones beach, sandy areas (27000 – 72000)[a] (3600 - 8500)[b]			
0.0001	1.0	100	100
0.05	1.0	100	100
0.1	1.0	50	7
0.15	1.0	0.4	0.3
Braystones beach, shingle areas (2300 – 6100)[a]			
0.0001	1.0	-	100
0.05	1.0	-	100
0.1	1.0	-	2
0.15	1.0	-	0.3
Drigg beach, sandy areas (8300 – 22000)[a] (4500 – 11000)[b]			
0.0001	1.0	100	100

Depth (m)	Scan speed (ms^{-1})	Am-241 detection probability (%)	
		Synergy	Evolution2
0.05	1.0	100	100
0.1	1.0	58	13
0.15	1.0	0.4	0.2
Seascale beach, sandy areas (14000 – 37000)[a] (4800 – 11000)[b]			
0.0001	1.0	100	100
0.05	1.0	100	100
0.1	1.0	43	10
0.15	1.0	0.3	0.2
Seascale beach, shingle areas (2800 – 7500)[a]			
0.0001	1.0	-	100
0.05	1.0	-	100
0.1	1.0	-	3
0.15	1.0	-	0.1
Sellafield beach, "low sand" areas (5500 - 15000)[a] (1800 – 3300)[b]			
0.0001	1.0	100	100
0.05	1.0	100	100
0.1	1.0	49	8
0.15	1.0	0.7	0.2
Sellafield beach, "high sand" areas (6200 – 17000)[a] (3200 – 7100)[b]			
0.0001	1.0	100	100
0.05	1.0	100	99
0.1	1.0	40	5
0.15	1.0	0.3	0.4
St. Bees beach, sandy areas (23000 – 62000)[a] (5500 –13000)[b]			
0.0001	1.0	100	100
0.05	1.0	100	100
0.1	1.0	47	7
0.15	1.0	0.3	0.2

[a] No. of Evolution2 object simulations, corresponding to a single pass through the background data file.
[b] No. of Synergy object simulations, corresponding to a single pass through the background data file.
[c] No value estimated for Synergy.
Notes:
1. 0.3 m overlap pass included.
2. 0.05 m simulation step size.
3. Simulated count rate measured over 1 s.
4. Simulated object x-coordinates chosen randomly in the 0 – 2 m range (x-axis is the detector axis).
5. Object starting y-coordinates (y-axis is the direction of travel) chosen to maximise detection probability (simulating the outcome of 10 times oversampling).

3.2 Estimating the population of alpha-rich objects on the beaches at any one time

Monitoring conducted using the Synergy system between August 2009 and March 2012 has found a total of 658 alpha-rich objects within a monitored area across the five beaches (Braystones, Drigg, Seascale, Sellafield and St Bees) of approximately 677 hectares. Details of these finds are recorded in Sellafield Ltd's Beach Monitoring Summary Spreadsheet (Dalton, 2012) and these data were used to estimate the object population on each of the beaches. Descriptions of the five beaches are given in Oatway *et al.* (2011).

Table 7 provides a summary of the alpha-rich objects found by the Synergy system which have been used in this assessment.

Table 7. Summary of alpha-rich objects found using Synergy system

Class[a]	Total number of objects found[b]	Maximum activity, kBq[c,d]	Beach where the object with maximum activity was found
Alpha rich particles	655	252	Sellafield
Alpha rich stones	3	618	Sellafield

a) Alpha-rich objects classified on positive measurements of ^{241}Am activity that exceed measured ^{137}Cs activity.

b) Objects are those found between 24th August 2009, the first use of the Synergy system, and 15th March 2012, the date of the last entry in the database supplied by Sellafield Ltd. to HPA (Dalton, 2012).

c) A kilo-becquerel (kBq) is 1000 Bq.

d) Detected activity for alpha-rich objects is the ^{241}Am activity.

In the assessment described in Brown and Etherington (2011), two independent methodologies were used to estimate the populations of objects on the beaches based on the finds made by the Groundhog Evolution2™ system. These are described in detail in Oatway *et al*. (2011). The methods were intended to reduce uncertainties as much as possible, and the results were generally found to be in good agreement, showing no significant differences when considering all the uncertainties in the data from which they were obtained. The method used for the HPA assessment (Method 1) was chosen because it takes account of the available information on object depths on the beaches. To enable comparison with the previous assessment of health risk, this assessment again used Method 1 to estimate the population of objects. The estimated populations of alpha-rich objects on each beach are presented in Table 8.

Table 8. Estimated population of alpha-rich objects[a]

Representative object activity (^{241}Am)[b]	Particles[c]		Stones[c]	
	particles g^{-1} of sand[d]	particles ha^{-1} beach	stones g^{-1} of sand[d]	stones ha^{-1} beach
Braystones				
10 kBq	$1.8\ 10^{-9}$	6	-	-
100 kBq	$3.2\ 10^{-11}$	0.1	-	-
1000 kBq	-	-	-	-
Total	$1.9\ 10^{-9}$	6	-	-
Drigg				
10 kBq	$1.2\ 10^{-9}$	4	-	-
100 kBq	$2.0\ 10^{-11}$	0.06	-	-
1000 kBq	-	-	-	-
Total	$1.2\ 10^{-9}$	4	-	-
Seascale				
10 kBq	$5.8\ 10^{-10}$	2	-	-
100 kBq	$1.8\ 10^{-11}$	0.05	-	-
1000 kBq	-	-	-	-
Total	$6.0\ 10^{-10}$	2	-	-
Sellafield				
10 kBq	$4.7\ 10^{-9}$	14	-	-
100 kBq	$2.0\ 10^{-10}$	0.6	$2.0\ 10^{-12}$	0.006
1000 kBq	-	-	$2.4\ 10^{-12}$	0.007
Total	$5.4\ 10^{-9}$	16	$4.4\ 10^{-12}$	0.01
St Bees				
10 kBq	$1.6\ 10^{-9}$	5	-	-
100 kBq	$1.8\ 10^{-11}$	0.05	-	-
1000 kBq	-	-	-	-
Total	$1.6\ 10^{-9}$	5	-	-

[a] Object populations were estimated using method 1 as described in Oatway *et al.* (2011).

[b] Activities are representative of the activity bands 3-30 kBq (represented by 10 kBq), 30-300 kBq (represented by 100 kBq) and >300 kBq (represented by 1000 kBq).

[c] A "-" indicates that the population of objects was not estimated for this activity or beach.

[d] Objects are assumed to be within a depth range of 0 - 0.15 m.

In Table 9 the population of objects per hectare of each beach is compared with the average find rate for the Synergy system (Dalton, 2012). As expected the estimated object population for particles is higher than the find rate because the object population includes those particles that are present but not detected.

For stones, Table 9 shows that the estimated population is slightly lower than the current find rate. This is not considered to be significant as the population has been estimated from only a few finds (see Table 7) and is therefore subject to large uncertainties.

Table 9. Comparison between estimated alpha-rich object populations and average find rate by the Synergy system

Beach	Number of objects per hectare of beach			
	Estimated particle population[a,b]	Particle find rate using the Synergy system[b,c]	Estimated stone population[a,b]	Stone find rate using the Synergy system[b,c]
Braystones	6	1.2	-	-
Drigg	4	0.1	-	-
Seascale	2	0.2	-	-
Sellafield	16	1.9	0.01	0.02
St Bees	5	0.8	-	-

[a] Object population obtained from Table 8.

[b] A "-" indicates that no objects have been estimated for this activity or beach.

[c] Value supplied by Sellafield Ltd (Dalton, 2012).

Table 10 gives the ratio between the particle populations estimated from object finds made by the Synergy and Groundhog Evolution2^{TM} systems.

Table 10. Ratio of the estimated alpha-rich particle populations (Synergy: Groundhog Evolution2^{TM})[a,b]

Representative activity[c]	St Bees	Braystones	Sellafield	Seascale	Drigg
10 kBq	3.8	5.6	32	28	0.4
100 kBq	1.3	0.8	2.2	1.1	0.4
1000kBq	-	-	-[d]	-	-
Total	3.7	5.1	23	16	0.4

[a] All particle populations were estimated using Method 1 as described in Oatway *et al.* (2011).

[b] A ratio >1 indicates that the estimated object population based on finds by the Synergy system is greater than the estimated object population based on the finds by the Groundhog Evolution2^{TM} system.

[c] Activities are representative of the activity bands 3-30 kBq (represented by 10 kBq), 30-300 kBq (represented by 100 kBq) and >300 kBq (represented by 1000 kBq).

[d] Although a particle with an activity within this band was found on Sellafield beach using the Groundhog Evolution2^{TM} system, no such particles were found using the Synergy system.

The new object populations in the 3-30 kBq activity band estimated from the Synergy system monitoring data are higher than those estimated from the Groundhog Evolution2^{TM} monitoring data with the exception of that for Drigg beach, as shown in Table 10. The differences in the estimates reflect the large uncertainty in the estimates based on the Groundhog Evolution2^{TM} data which result from the low detection efficiencies for objects in this activity range. For ^{241}Am, Evolution2^{TM} detection efficiencies are typically around 5% for 10 kBq objects at the surface, dropping rapidly to about 0.2% for objects at a depth of 5 cm. Any algorithm used to predict numbers of objects on the beach when the detection efficiencies are so low will produce results with a high uncertainty and numbers could be either under- or over-estimated. Estimates of the object populations determined from the Synergy monitoring data are less uncertain because the Synergy detection efficiencies for objects with ^{241}Am activities in the range 3 – 30 kBq are significantly greater than those for Evolution2. For instance, Synergy detection efficiencies are typically around 75% for 10 kBq ^{241}Am objects at the surface. For the higher activity bands, object populations estimated from monitoring data from the two systems are similar. This can be attributed to the fact that uncertainties in estimated object populations based on the results from both systems are less uncertain, because their detection efficiencies are both close to 100%.

The lower estimated object population for Drigg beach is not unexpected. Brown and Etherington (2011) identified that the uncertainties in the estimates of the number of objects present can be quite large and this was particularly the case for Drigg beach, because only a small number of alpha-rich objects were found by the Groundhog Evolution2™ system. Furthermore, only about 30% of Drigg beach had been monitored at that time. It was therefore recognised that the uncertainty in the predicted object population for Drigg beach was probably large. Consequently, HPA recommended that more monitoring of Drigg beach should be made to improve the accuracy of the assessment of the population of objects on the beach. The Synergy system has found more alpha- rich objects (13 in the period of August 2009 to March 2012) enabling a more robust estimate of the object population to be made.

Table 10 shows that following more monitoring using the Synergy system, the estimated number of objects on Drigg beach is lower and therefore the health risk reported by Brown and Etherington (2011) is likely to have been an overestimate.

Table 11 shows the same information as Table 10, for stones. Only a limited number of alpha-rich stone finds have been made using the Synergy system, and all of these were found on Sellafield beach. It is therefore only possible to make a very limited comparison between the estimated populations of stones for the two systems.

Table 11. Ratio of the estimated alpha-rich stone populations (Synergy: Groundhog Evolution2™) obtained using method 1[a,b]

Representative activity[c]	St Bees	Braystones	Sellafield	Seascale	Drigg
10 kBq	-	-	-[d]	-	-
100 kBq	-	-	6.8	-	-
1000 kBq	-	-	-[e]	-	-
Total	-	-	0.02	-	-

[a] A full description of the methodology is given in Oatway *et al.* (2011).

[b] A ratio >1 indicates that the estimated object population based on finds by the Synergy system is greater than the estimated object population based on the finds by the Groundhog Evolution2™ system.

[c] Activities are representative of the activity bands 3-30 kBq (represented by 10 kBq), 30-300 kBq (represented by 100 kBq) and >300 kBq (represented by 1000 kBq).

[d] Although a stone with an activity within this band was found on Sellafield beach using the Groundhog Evolution2™ system, no such stones were found using the Synergy system.

[e] Although a stone with an activity within this band was found on Sellafield beach using the Synergy system, no such stones were found using the Groundhog Evolution2™ system.

4 PROBABILITY OF ENCOUNTERING AN ALPHA-RICH OBJECT BASED ON THE SYNERGY MONITORING DATA

A revised estimate of the annual probability of encountering an object has been made using the new estimates of the population of objects for each beach determined using the Synergy system monitoring data. As no changes have been made to the estimates of beach usage since the assessment described by Brown and Etherington (2011), the revised probability of encountering an object is directly proportional to any change in the estimated particle population on the beach. Table 12 gives the estimated highest probability of encountering an object on each beach, obtained by scaling the probabilities estimated in Brown and Etherington (2011) by the change in the estimated object population (Table 10). Table 12 also shows the highest estimated probability of encountering an object based on Groundhog Evolution2^{TM} finds, for comparison. These data are taken directly from Oatway *et al.* (2011).

Across the five beaches considered, the 97.5th values of the distribution of the annual probability of a typical beach user encountering any alpha-rich object, based on the Synergy results, range from about 5 10^{-5} (chance of 1 in 200 thousand) to about 5 10^{-4} (chance of 1 in 20 thousand), depending on the beach. This can be compared with a range of about 1 10^{-6} to about 1 10^{-4} based on the Groundhog Evolution2^{TM} results. The estimated probabilities of encounter have increased for all beaches, except for Drigg, reflecting the increase in the estimated object population, particularly in the 3-30 kBq activity band. Table 12 shows that the probabilities of encountering an alpha-rich object on each of the five beaches, estimated from the results of the two systems, are broadly similar. There is no indication that the assessment undertaken by HPA (Brown and Etherington, 2011) using monitoring data from the Evolution2^{TM} system significantly underestimated the probability of a beach user encountering an object while using the beaches in the vicinity of the Sellafield site.

Table 12. Highest annual probability of encountering a radioactive object for a general beach user summed over all exposure pathways[a,b,c]

Beach	Particles		Stones	
	Synergy[d]	Groundhog Evolution2[TM e]	Synergy[d]	Groundhog Evolution2[TM e]
Braystones	$1.3\ 10^{-4}$	$2.5\ 10^{-5}$	-	-
Drigg	$8.1\ 10^{-5}$	$1.9\ 10^{-4}$	-	-
Seascale	$4.0\ 10^{-5}$	$2.5\ 10^{-6}$	-	-
Sellafield[(a)]	$3.7\ 10^{-4}$	$1.6\ 10^{-5}$	$2.9\ 10^{-7}$	$1.3\ 10^{-5}$
St Bees	$1.1\ 10^{-4}$	$3.0\ 10^{-5}$	-	-

[a] These probabilities of encounter are for the adult angler. For information to scale these values to other beach uses and age groups see Oatway *et al*. (2011).

[b] Probability of encounter estimated using the object population estimated using method 1 (see Oatway *et al*. (2011) for description of method)

[c] '-' indicates that no estimate could be made of the probability of encountering a radioactive stone as no such stones have been found using the Synergy or Groundhog Evolution2[TM] monitoring systems.

[d] Scaled from the Groundhog Evolution2[TM] probabilities using the ratios given in Table 10.

[e] Groundhog Evolution2[TM] probabilities are the 97.5% values reported in Oatway *et al.* (2011)

5 OVERALL RISKS OF FATAL CANCER FOR A BEACH USER FROM EXPOSURE TO PARTICLES BASED ON THE SYNERGY MONITORING DATA

The overall risk of fatal cancer for a beach user takes into account both the probability that a particle may be encountered by the person and the risk of fatal cancer in the unlikely event that the person does encounter such a particle. Both factors depend on the activity of the particle, and so overall health risks were determined separately for each of the activity bands defined in Table 8, and then summed to give the total overall risk. This is the same method as that adopted in Brown and Etherington (2011). Table 13 shows the results of this calculation based on the Synergy monitoring data, and also presents similar data based on the earlier Evolution2[TM] monitoring data, taken from Brown and Etherington (2011), for comparison. For each activity band, the Table presents the highest particle activity found, the effective dose that would result if a beach user ingested the particle, the corresponding lifetime risk of cancer, the highest annual probability of ingesting a particle within that activity band, and the overall risk of fatal cancer, obtained by multiplying the lifetime risk by the annual probability of ingestion. The annual probability of ingesting a particle was computed as a distribution of values, and the 97.5th percentile of the distribution has been used for the calculation of overall risk. The annual probability of ingestion varies between beaches, and the highest value from across the five beaches was chosen for each activity band. Table 14 shows the same information for a 1 year old child, representative of young children.

Table 13. Highest estimated overall risks of fatal cancer associated with possible ingestion of alpha-rich particles as a result of using a beach for a period of 1 year for the two beach monitoring systems: adult beach user

Activity band, kBq	Highest activity particle in activity band, kBq	Effective dose[a], mSv	Lifetime risk of cancer if particle ingested, % [b]	Highest annual probability of ingesting a particle[c]	Overall risk of fatal cancer
Synergy					
1000 (>300)	-[d]	-	-	-	-
100 (30 – 300)	252 [e]	7.7	0.07	$8\ 10^{-10}$	$6\ 10^{-13}$
10 (3 – 30)	30 [e]	0.8	0.007	$2\ 10^{-8}$	$1\ 10^{-12}$
Total					$2\ 10^{-12}$
Evolution2™					
1000 (>300)	634 [f]	20	0.2	$4\ 10^{-12}$	$8\ 10^{-15}$
100 (30 – 300)	200 [f]	6	0.06	$2\ 10^{-10}$	$1\ 10^{-13}$
10 (3 – 30)	30 [f]	0.8	0.007	$1\ 10^{-8}$	$7\ 10^{-13}$
Total					$8\ 10^{-13}$

[a] Calculated doses take account of other radionuclides measured in the particles that will contribute significantly to the dose. For alpha-rich particles, the dose is from ^{241}Am, ^{238}Pu and ^{239}Pu.

[b] Lifetime risk is calculated for the highest activity particle in each activity band.

[c] Value is the 97.5th percentile of the distribution across all beach users.

[d] No objects in this activity band were detected by the Synergy system.

[e] Highest ^{241}Am activity detected by Synergy system.

[f] Highest ^{241}Am activity detected by Evolution2™ system.

The results of the calculation of overall risk using the Synergy monitoring data make use of the highest activity particle in each activity band found by the Synergy system. An alternative approach would have been to use the highest activity particle in each band found by either the Evolution2™system or the Synergy system. The result of the calculation of total overall risk (ie, summed over the three activity bands) is in fact rather insensitive to this choice of approach, because in all cases the contribution of the 3-30 kBq band to overall risk is dominant, and the maximum particle activity in this band was 30 kBq in all cases. It may be noted that, even if the Synergy system had found small numbers of particles in the '> 300 kBq' band, as was the case for the Evolution2™ system, this would have had an insignificant effect on the estimated overall risk.

Tables 13 and 14 show that the estimated lifetime risk of radiation-induced fatal cancer for an adult beach user has increased slightly from $8\ 10^{-13}$ to $2\ 10^{-12}$, while for young children using the beaches, it has decreased slightly from $1\ 10^{-11}$ to $8\ 10^{-12}$. Given the uncertainties associated with assessments of this type, it is judged that these changes are not significant.

Table 14. Highest overall risks of fatal cancer associated with possible ingestion of alpha-rich and beta-rich particles as a result of using a beach for a period of 1 year: child beach user (1 year old)

Activity band (central value), kBq	Highest activity particle in activity band, kBq	Effective dose[a], mSv	Lifetime risk if particle ingested, %[b]	Highest annual probability of ingesting a particle[c]	Overall risk of fatal cancer
Synergy					
1000 (>300)	-[d]	-	-	-	-
100 (30 – 300)	177 [e]	15	0.24	$4\ 10^{-10}$	$9\ 10^{-13}$
10 (3 – 30)	30 [e]	2.2	0.035	$2\ 10^{-8}$	$7\ 10^{-12}$
Total					$8\ 10^{-12}$
Evolution2™					
1000 (>300)	634 [f]	55	1	-[g]	-
100 (30 – 300)	200 [f]	17	0.3	$6\ 10^{-10}$	$2\ 10^{-12}$
10 (3 – 30)	30 [f]	2	0.04	$3\ 10^{-8}$	$1\ 10^{-11}$
Total					$1\ 10^{-11}$

[a] Calculated doses take account of other radionuclides measured in the particles that will contribute significantly to the dose. For alpha-rich particles, the dose is from ^{241}Am, ^{238}Pu and ^{239}Pu.

[b] Lifetime risk is calculated for the highest activity particle in each activity band.

[c] Value is the 97.5th percentile of the distribution across all beach users.

[d] No objects in this activity band were detected by the Synergy system.

[e] Highest ^{241}Am activity detected by Synergy system.

[f] Highest ^{241}Am activity detected by Evolution2™ system.

[g] Particles of this activity were only found on Sellafield beach and there is no evidence that young children spend time on this beach.

As noted earlier and shown in Table 10, the object populations estimated from the Synergy system monitoring data, particularly in the 3-30 kBq activity band, are higher than those estimated from the Groundhog Evolution2™ monitoring data, except for Drigg beach. Tables 13 and 14 show that it is the particles in this activity band that dominate the overall risk, but these Tables also show that the increase in the estimated object populations for these particles is not reflected in a corresponding increase in overall risk.

The reason is that the beach giving rise to the highest estimated object population for particles has changed, for both adults and young children. For adults, based on the Evolution2™ monitoring data, Drigg beach was associated with the highest annual probability of ingesting a particle ($1\ 10^{-8}$); the probability is lower for Drigg beach when based on the Synergy monitoring data ($5\ 10^{-9}$). For Sellafield beach, moving from the Evolution2™ to the Synergy monitoring systems has resulted in an increase in this probability from $6\ 10^{-10}$ to $2\ 10^{-8}$, and as a result Sellafield has become the beach giving rise to the highest annual probability for ingesting a particle, with the highest probability across all the beaches increasing from $1\ 10^{-8}$ to $2\ 10^{-8}$.

A similar effect is found for young children. Based on the Evolution2™ monitoring data, Drigg beach was associated with the highest annual probability for ingesting a particle

($3\ 10^{-8}$), while the probability based on the Synergy monitoring data is lower ($1\ 10^{-8}$). For Braystones beach, moving from the Evolution2^{TM} to the Synergy monitoring systems has resulted in an increase in this probability from $4\ 10^{-9}$ to $2\ 10^{-8}$, and as a result Braystones has become the beach giving rise to the highest annual probability for ingesting a particle, with the highest probability across all the beaches decreasing from $3\ 10^{-8}$ to $2\ 10^{-8}$.

As noted above, it is the particles in the 3-30 kBq activity band that dominate the overall risk, but it has also been noted that this is the activity range where the estimated object population is likely to be most uncertain. It is worth noting, therefore, that the estimated object population in the 3-30 kBq activity band would need to be a factor of about 10^5 larger for the estimate of overall risk for children to reach the Health and Safety Executive's upper limit for an acceptable level of risk for members of the public (ie, 1 in a million).

6 CONCLUSIONS

The work carried out shows that the elevated numbers of alpha-rich objects found by Synergy lie in a well-defined activity range that is approximately that expected from a straightforward consideration of the detection limits of the Synergy and Evolution2^{TM} systems. Three criteria were set to determine whether the increased object find rate of Synergy is entirely attributable to its increased sensitivity. Criterion 1 stated that for alpha-rich objects on the surface, any elevated numbers found by Synergy should have ^{241}Am activities predominantly in the range 8 – 22 kBq, and it is judged that this criterion is broadly met. Criterion 2 stated that there should be almost no difference in the numbers of objects with activities above about 40 kBq found by Evolution2^{TM} and Synergy on the surface, and this criterion is also judged to be broadly met. Criterion 3 stated that neither system should find objects with activities less than about 3 kBq, and this criterion is met. These findings represent good evidence that the increased object find rate can be attributed to the increased sensitivity of the Synergy monitoring system.

The fact that the number of alpha-rich objects in the 8 – 22 kBq activity range is a substantial fraction of the total number of alpha-rich objects found by Synergy indicates that the populations of objects at these lower activity levels are significantly greater than those for higher activity objects. This is shown clearly by Figures 5 – 7, 9 – 11, and 13 – 15, as is the fact that the presence of elevated numbers of objects at these lower activities is not clearly seen in the results of the Evolution2^{TM} monitoring programme. The reason for this is that the detection probabilities provided by Evolution2^{TM} in this activity range decrease rapidly with decreasing object activity, as indicated in Figure 3. These findings provide additional confirmation of the value of the Synergy monitoring system.

Object populations determined only from the Evolution2^{TM} monitoring data in the activity range where detection probabilities are low will be subject to significant levels of uncertainty. It should be expected that the higher detection probabilities associated with the Synergy monitoring data in the same activity range will result in significant reductions in uncertainty. Specifically, the Synergy monitoring system may be assumed to provide more reliable measurements of the numbers of objects on the beaches in the activity range that dominates the overall health risks (3-30 kBq). As discussed in Section 4, Brown and Etherington (2011) identified that there was a large uncertainty associated with the estimates of numbers of objects on Drigg beach due to the small number of objects that had been found there. The availability of more monitoring data for Drigg beach using the Synergy monitoring system has improved the estimate of the number of objects on Drigg beach and consequently the estimates of the overall health risks from ingestion for this beach.

New estimates of alpha-rich object populations on the beaches have been estimated based on the data from the Synergy monitoring programme and these have been used to re-evaluate the resulting overall health risks to beach users from the ingestion of alpha-rich particles. The re-analysis has resulted in an small increase in the estimated lifetime risk of radiation-induced fatal cancer for an adult beach user from $8\ 10^{-13}$ to $2\ 10^{-12}$, and a small decrease for young children using the beaches from $1\ 10^{-11}$ to $8\ 10^{-12}$. Given the uncertainties associated with assessments of this type, it is judged that these changes are not significant. The fact that the estimated overall risks associated with the ingestion of alpha-rich objects are very similar provides confidence in the findings of the earlier Brown and Etherington (2011) study.

The conclusions of HPA's study in 2011 remain unchanged. That is, based on the currently available information, it may be concluded that the overall health risks to beach users are very low and significantly lower than other risks that people accept when using the beaches. The highest calculated lifetime risks of radiation-induced fatal cancer are of the order of one hundred thousand times smaller than the level of risk that the Health and Safety Executive considers to be the upper limit for an acceptable level of risk (1 in a million) for members of the public and workers. The conclusion that it is very unlikely that deterministic effects such as skin ulceration could occur from encountering an object also remains unchanged.

This study fulfils the recommendations made in Brown and Etherington (2011) that an investigation should be carried out of the increases in the number of alpha-rich objects being found by the recently-introduced Groundhog Synergy beach monitoring system, and the implications for the assessment of overall risk considered. HPA continues to advise that continued regular monitoring of Sellafield beach and monitoring at one or two other beaches with high public occupancy will provide regulators and the public with continued reassurance that risks associated with radioactive objects in the environment remain very low.

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