Scottish Universities Research & Reactor Centre

AN AERIAL GAMMA RAY SURVEY OF CHAPELCROSS
AND ITS SURROUNDINGS IN FEBRUARY 1992

D.C.W. SANDERSON, J.D. ALLYSON,
A.N. TYLER

SCOTTISH UNIVERSITIES RESEARCH AND
REACTOR CENTRE, EAST KILBRIDE

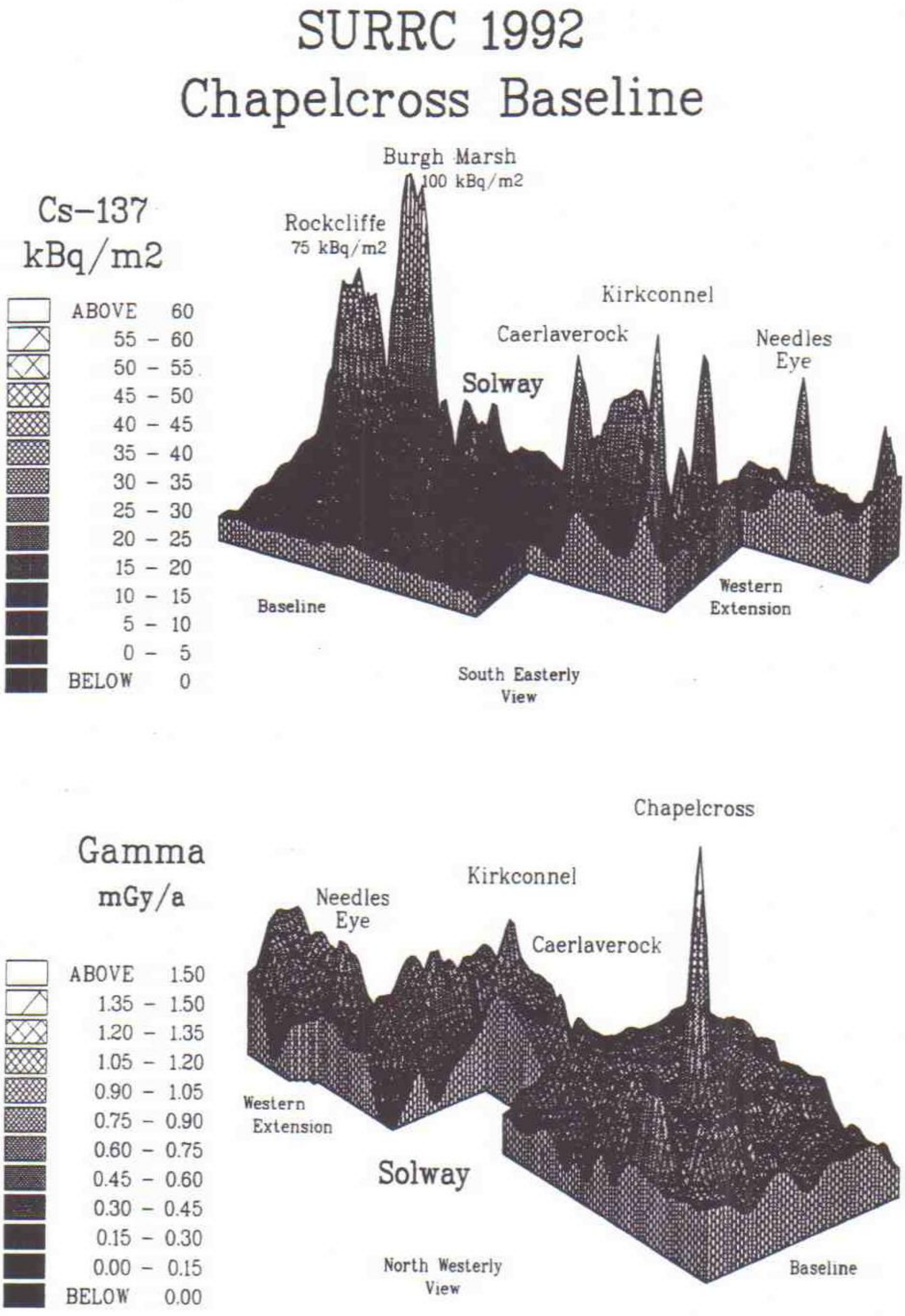
East Kilbride Glasgow G75 0QF Telephone: 01355 223332 Fax: 01355 229898

CONTENTS

Acknowledgements

We would like to acknowledge the considerable contribution to this work of Roger Cheshire, (BNF), whose logistic support and navigational input resulted, as usual, in a rapid and effective survey. We would also like to thank Capt. Steve Hogarth (Dollar Helicopters) and supporting staff for skilful and efficient flying, and Bob Millard (BNF, Chapelcross) for undertaking an on site gamma survey in May 1992 to allow cross comparison of local dosimetry.

The survey and emergency standby provision were commissioned from SURRC by British Nuclear Fuels plc.



Frontispiece : 3D plot of the Chapelcross 1992 aerial survey results

SUMMARY

A short aerial gamma ray survey was conducted in the vicinity of the Chapelcross site from 4th-7th February 1992 to define existing background radiation levels, against which any future changes can be assessed. A twin engine AS 355 "Squirrel" helicopter chartered from Dollar Helicopters was used for this work. It was loaded with a 16 litre NaI gamma spectrometry system at SURRC in East Kilbride on the afternoon of 3rd February and flown to an off-site operational base at Lockerbie that evening. Over the following four days over 3500 gamma ray spectra were recorded from a main survey area of 21 x 25 km surrounding the site, and from a extension examining coastal zones up to 25 km further west. Additional NS and EW "tie lines" out to 40 km from the site were added for the purpose of future extendability.

The main survey grid, bounded by OS coordinates NY100590, NY 100800, NY 350800 and NY 350590, was surveyed in a series EW flight lines spaced apart by 500m. Survey speed and height were 120 kilometres per hour and 75 m. respectively. Gamma ray spectra were recorded every 10 seconds, interleaved with positional information collected on-line from a GPS satellite navigation system and time averaged radioaltimetry signals. 3500 spectra were recorded. The combination of line spacing and flight conditions results in a practically complete area survey with 500m spatial resolution. The same flight parameters were adopted for the western coastal extension and the tie lines. Data were recorded in continuous flight tracks through these to minimise flight times.

In addition a rapid response flight route was prepared which could be used to define arcs at 10km, 5km and 2km radii from Chapelcross in the event of a future incident. The path has been chosen to be navigable under most weather conditions, and falls within the area which has been mapped for baseline purposes. A survey aircraft arriving from East Kilbride could perform such a survey without pausing to refuel.

Survey results have been stored archivally and used to map the naturally occurring nuclides ^{40}K, ^{214}Bi, ^{208}Tl together with ^{137}Cs and total gamma ray flux. In interpreting the maps correctly the spatial averaging of the aerial measurements and the contouring process should be taken into account. This leads to a slight tendency to broaden spatial features and to reduce maximum values particularly for boundaries less than the spatial resolution (500m) of the survey. Small scale features will be underestimated. Radiation from the Chapelcross plant was readily detected at the perimeter and can be clearly seen in the gamma dose rate and ^{137}Cs maps. In the former case direct radiation from ^{16}N in the reactor heat exchangers and the release of ^{41}Ar gas from the reactors is largely responsible. The ^{137}Cs associated with the small-bore pipeline on-site was detected to the SW of the reactors. Signals from ^{234m}Pa were detected to the NE of the site, and are due to the on-site depleted uranium store in this area. These local observations are broadly consistent with expectations based on-site dosimetry measurements. Further afield the contamination of the Solway Firth, its intertidal sediments and adjacent tide washed pastures by ^{137}Cs is readily detectable, and the distribution visible on the radiometric maps. This is attributed for the most part to past marine discharges from Sellafield. The most extensively affected areas were near Kirconnel in the Nith, at Caerlaverock, Rockcliffe and Burgh marshes. Smaller areas of local enhancement occur close to the tidal limits of most rivers, notably the Southwick burn, Kirkbean Glen, Burnfoot, the river Annan, the Kirtle Water and river Sark. Terrestrial levels

of ^{137}Cs vary from those associated with weapons testing fallout (2-4 kBq m^{-2}) which occur in the main survey area, and the edge of the area contaminated from the Chernobyl accident where levels above 10 kBq m^{-2} are observed in the western extremities of this survey. Previous SURRC surveys have shown that this component is up to 3-4 times higher further to the West.

The natural radionuclides (^{40}K, ^{214}Bi, ^{208}Tl) show variations which reflect the local subsoil geology and surface geomorphology. Prominent features include the eastern edge of the Criffel pluton, Triassic shales are responsible for enhanced levels to the east of the Nith Valley, adjacent negative anomalies are associated with Silurian outcrops to the NE of the Lochar water. Carboniferous limestones and permian sandstones are responsible for the majority of the main survey grid. Natural sources in this survey zone define a relatively low natural background level, against which local signals close to the reactor site and deposited activity on tide washed pastures produce distinct enhancements. Radiation levels at Chapelcross site fall off rapidly with distance from the perimeter, approaching natural levels within approximately 0.5-1 km at the time of the survey. Those from the marine, estuarine and tide washed environments are mostly attributed to past Sellafield discharges. Further ground based investigation of these features would be desirable.

1. INTRODUCTION

A short aerial gamma ray survey was conducted in the vicinity of Chapelcross from 4th-7th February 1992 as part of a continuing programme of baseline mapping and emergency response definition for nuclear sites. It was commissioned by BNFL, and extends aerial survey emergency cover to both of the reactor sites (Calder Hall, and Chapelcross) operated by the company. The main purpose was define the existing radiation background from aerial survey heights to enable future changes to be assessed following repeat surveys. Additional objectives were to examine the natural and anthropogenic radiation levels associated with the periphery of the Solway coast as far West as the Criffel area, and to define a rapid response flight path which could be used for emergency purposes.

Aerial radiation survey techniques are particularly well suited to large scale environmental surveys and are highly complementary to subsequent ground based investigations. Their main strengths derive from the mobility of the observational platform, in this case a helicopter, and the spatial response of the detector, which averages signals over a field of view which can extend to several hundred metres. By recording a sequence of gamma ray spectra in flight, interleaved with navigational data and radioaltimetry it is possible to map the total radiation fields above a survey area. This leads to a highly effective means of locating areas of enhanced radiation, especially in remote locations or difficult terrain [1-7]. The method can be applied to total area searches at regional or national level, and the remote sensing nature of such measurements minimises exposure of survey teams to contamination or radiation hazards. These considerations, together with the speed of measurement, typically more than two orders of magnitude faster than ground based approaches, lead to important potential contributions to emergency response planning and implementation.

The ability to work in a complementary manner with ground based teams is no less important, allowing limited conventional resources to be effectively directed to areas of greatest need. Ground based in-situ spectrometry is capable of high spatial resolution and sensitivity, and leads naturally to sampling for investigation of radionuclide profiles and chemical speciation. However these methods alone are not particularly effective for large scale surveys due to their inherent lack of speed and low sampling densities. The combination of aerial observations and ground based studies provides a powerful approach to comprehensive evaluation of the radiation environment.

The radiation environment of BNF sites has been under study for many years for operational, regulatory, emergency response and research purposes. The majority of this work has been based at ground or sea level. However a brief aerial survey was conducted in Cumbria in October 1957 [8,9] immediately following the Windscale Fire. Although at that time the equipment available was not capable of spectral discrimination, the dominant nuclide, I-131, was estimated by scaling total counts to ground measurements. More recently SURRC has conducted some 12 aerial survey projects using fully spectrometric equipment. These have included upland areas of West Cumbria affected by the Chernobyl accident and historic Windscale discharges[10], the immediate surroundings of the Sellafield plant [11], and an area 2500 km^2 of Ayrshire districts for baseline definition purposes [12], and searches for lost radioactive sources [13].

2. SURVEY PLANS

2.1 Baseline Mapping

The survey area comprised a main rectangular box 25 x 21km approximately centred on the Chapelcross site, together with a western extension taking in the northern Solway estuary as far as Rough Firth. The main zone, bounded by OS coordinates NY 100590, 100800, 350800 and 350590 was selected to provide detailed coverage of all areas within 10km of the site, plus the northern and southern fringes of the Solway. This includes the towns of Annan, Gretna, Eastriggs and Ecclefechan, and would be the focus of immediate interest for possible post-incident investigations. The western extension includes the southern edges of the Criffel pluton, an area of enhanced natural radioactivity incorporating discrete small scale uranium mineralisation, and also provided an opportunity to measure tide washed pastures. These two survey areas are shown in figure 2.1 below. Additional NS and EW tie lines were specified with data recorded out to 40 km in each direction, to provide a basis for potential extendibility of future surveys.

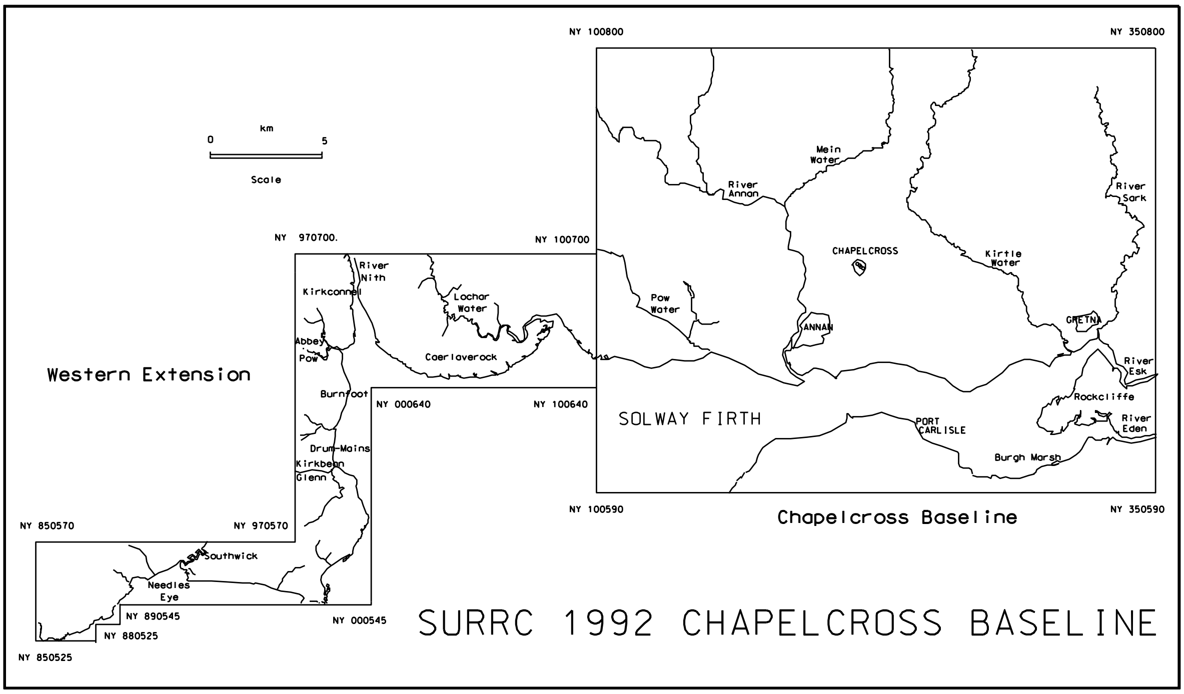
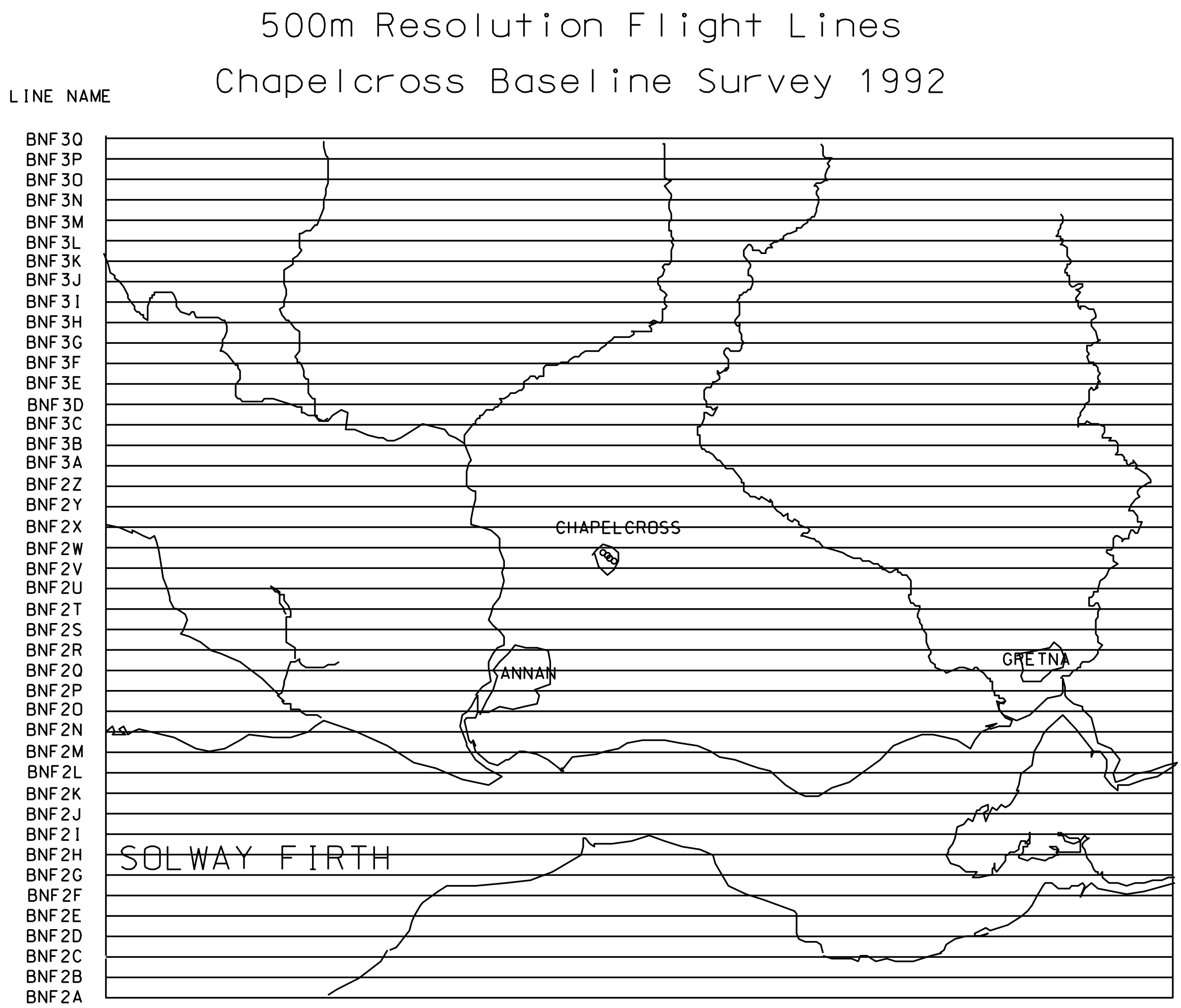


Figure 2.1 The main survey area and western extension. Chapelcross Baseline 1992.

Target spatial resolution for the main survey was 500m. To achieve this the main baseline area was subdivided into a series of parallel EW-WE flight line spaced 500m apart and labelled sequentially as shown in figure 2.2. Flight speed and integration period were selected to provide comparable spatial resolution along the flight lines. The western extension was free flown in a single set of progressing vertical and horizontal flight lines roughly spaced apart by 500 m.

Provision was made to conduct the survey from an off-site field base in Lockerbie, where the helicopter could land and re-fuel, and working space for data reductions was available. This location would also be suitable for future repeat work, if needed in conjunction with the Chapelcross helicopter pad.



2.2 Emergency Response Plan : General

In addition to the baseline mapping exercise an emergency response grid has been defined, which would form the basis of an initial investigation in the event of a call-out following an incident with the potential for release of radioactivity to the environment.

The emergency response grid was designed with the standard SURRC criteria[11] in mind as follows:

> 2.2.1 It should be possible to conduct the initial exploratory measurements immediately on arrival at Chapelcross without stopping to refuel.

Fuel limitations on arrival set a practical design limit of 45 minutes flying time. At the nominal survey speed of 120 kph this sets a limit of 90 line km.

2.2.2 The results should, so far as possible, define range and trajectories of terrestrial deposition within a 10km radius of the site.

The grid was designed to define approximate arcs around the site at distances of 10 km, 5km and 2km

2.2.3 The flight path should be navigable under as wide a range of weather conditions as possible.

The grid avoids obstacles and high ground so far as possible. This is helped by the generally favourable topography within the main baseline survey area, which excludes upland areas to the north and west.

2.2.4 It should be possible to navigate the path and to reconstruct the data by dead reckoning in the event of failure of navigational equipment.

The flight plan is composed of a series of straight lines between readily visible landmarks which approximate the desired trajectory. Usually the precise flight path is recorded in real time from on board navigational instruments and used to reconstruct the data for mapping purposes. However in the event of failure of such systems the grid could be flown by line of sight, and the track reconstructed simply by noting the times and index numbers of each waypoint and interpolating between them. Procedures to reconstruct tracks on this basis have been tested successfully by SURRC while operating in the Niger Delta, and are catered for in SURRC aerial survey software [13].

2.2.5 Radiological risks of flying into high dose rates, of contaminating aircraft, and or resuspending deposited activity should be minimised.

The order in which the grid is flown is such that the aircraft completes the most distant arcs before approaching the site. The equipment gives a real time display of radiation levels. In the event of extremely high activity being detected the aircraft can increase altitude to decrease detector sensitivity and simultaneously reduce radiation levels to crew. If necessary the aircraft can break off without fully approaching the site. Finally, if the closest zones caused minor contamination of the aircraft this would not affect preliminary readings.

2.2.6 It should be possible to analyse the results rapidly and to compare them with previous results so that changes can be quantified and further survey actions defined.

The equipment produces results which can either be analysed on board the aircraft after landing or readily transferred to commonly available PC's for simple analysis. Statistical analysis, working calibration and mapping can all be performed rapidly on site. Hard copy of tabular results can be produced from any printer in monochrome, suitable for facsimile transmission. Colour hard copy can be produced at later stages.

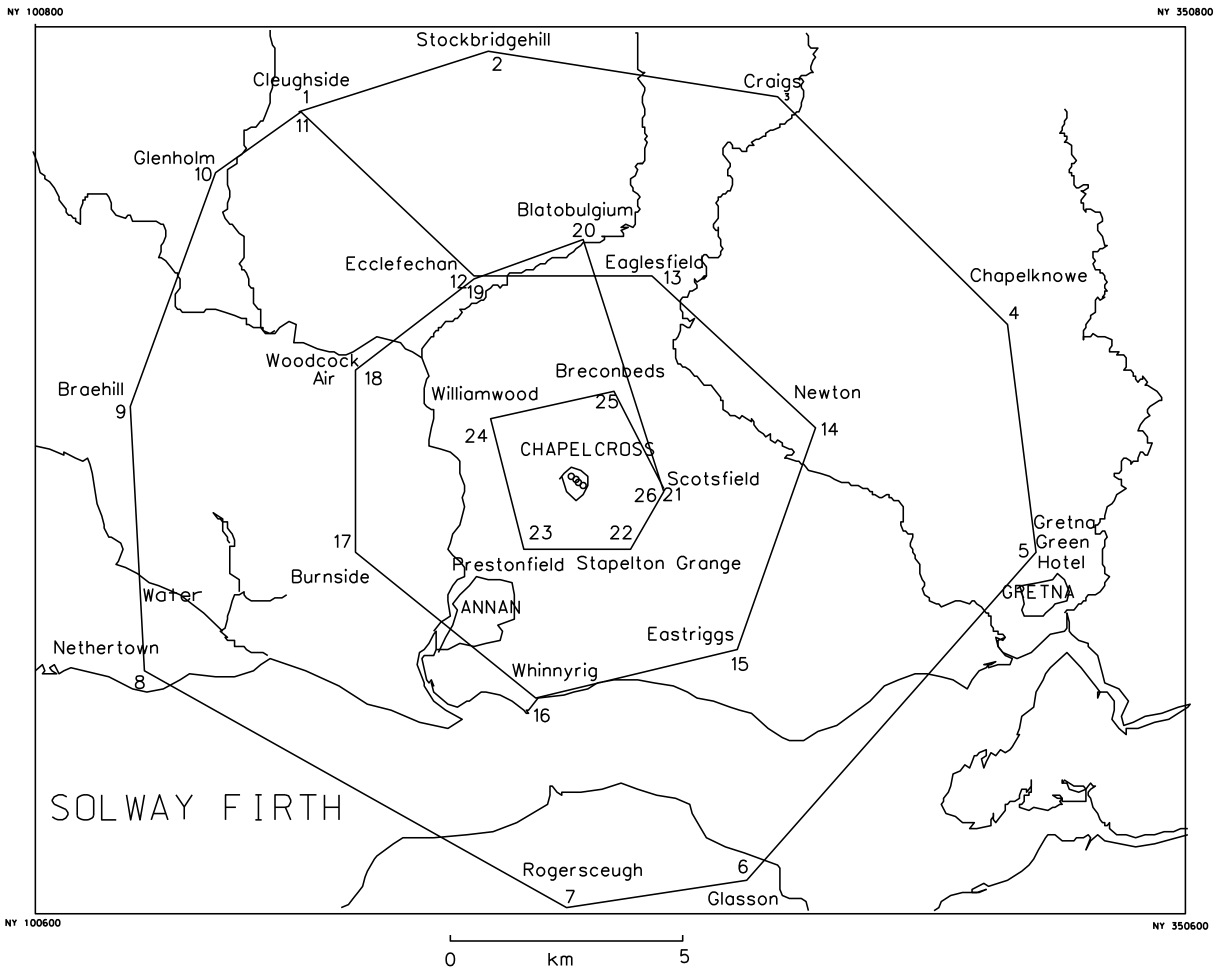


Figure 2.3 Emergency Response Flight Plan : Chapelcross.

The positions of the emergency response waypoints shown in figure 2.3 and listed below (Table 2.1) in order of execution. Nominal flight altitude and speed are 75m and 120 kph (64.7 knots), although these may be varied on individual occasions to take account of weather or other circumstances. Radiometric data are to be recorded with 10 second integration time, interleaved with navigational fixes and time-averaged radioaltimetry.

The northern approach is along the A74/M74, main trunk road and the first waypoint at Cleughside is a recognisable feature from the road, thus easing the task of taking up survey en-route from East Kilbride. When arriving from the north data might also be recorded in the form of an extended test line from East Kilbride although there would be no constraints on flight speed, and altitude specification would be at the pilots discretion. At the end of each

Table 2.1. Waypoints of the Emergency grid.

Point	Location	Latitude	Longitude	OS Ref.
1	Cleughside	55°5.32'N	3°18.9'W	NY 159782
2	Stockbridgehill	55°6.13'N	3°15.1'W	NY 199796
3	Craigs	55°5.60'N	3°9.2'W	NY 262785
4	Chapelknowe	55°2.91'N	3°4.4'W	NY 312734
5	Gretna Green Hotel	55°0.17'N	3°3.62'W	NY 319683
6	Glasson	54°56.0'N	3°10.2'W	NY 253607
7	Rogersceugh	54°55.5'N	3°13.7'W	NY 215598
8	Nethertown	54°58.4'N	3°22.4'W	NY 121654
9	Braehill	55°1.67'N	3°22.3'W	NY 121715
10	Glenholm	55°4.5'N	3°20.6'W	NY 140767
11	Cleughside	55°5.32'N	3°18.9'W	NY 159782
12	Ecclefechan	55°3.37'N	3°15.6'W	NY 193745
13	Eaglesfield	55°3.47'N	3°11.9'W	NY 232746
14	Newton	55°1.52'N	3°7.81'W	NY 275709
15	Eastriggs	54°59.1'N	3°10.7'W	NY 249665
16	Whinnyrig	54°58.2'N	3°14.3'W	NY 209649
17	Burnside	54°59.9'N	3°18.0'W	NY 170681
18	Woodcock Air	55°2.16'N	3°17.7'W	NY 170723
19	Ecclefechan	55°3.37'N	3°15.6'W	NY 193745
20	Blatobulgium	55°3.82'N	3°13.2'W	NY 219753
21	Scotsfield	55°0.83'N	3°11.4'W	NY 237697
22	Stapelton Grange	55°0.00'N	3°12.0'W	NY 230683
23	Prestonfield	55°0.04'N	3°14.3'W	NY 206683
24	Williamwood	55°1.49'N	3°14.7'W	NY 202710
25	Breconbeds	55°2.05'N	3°12.4'W	NY 226720
26	Scotsfield	55°0.83'N	3°11.4'W	NY 237697

grid flight the pilot will be asked to free fly to the landing point, which will either be (i) the field-base at Lockerbie, (ii) the Chapelcross helipad or (iii) Carlisle airport. Subject to fuel availability it may be possible to reconfirm any features of special interest en-route to landing.

It is intended to rehearse the emergency grid at suitable intervals to acquire time series data and to ensure practicability under diverse conditions.

3. FIELDWORK

3.1 Detector Description

The spectrometer comprised an 16 litre NaI detector coupled to an SURRC aerial radiometrics rack containing instrumentation power supplies, EHT, pulse height analyser and data logging computer. The installation incorporates a flexible power supply capable of operation from mains, under self power for a period of roughly one hour (which may be supplemented with external batteries) and for unlimited periods when supported by the aircraft 28 V dc supply. The equipment was shock mounted to a laminated fibreboard baseplate rigidly mounted to the rear section of the helicopter floorpan. This installation was devised to ease rapid installation following the 1990 Sellafield survey with Dollar helicopters, and has been approved by CAA following brief flight trials in 1991[14]. Problems were identified in this trial with the durability of a 12/24V inverter which provides power within the rack. A manufacturers modification was subsequently implemented with satisfactory results on the bench. Navstar XR-4 GPS satellite navigation system was incorporated in the spectrometer, following successful functional trials in 1991. This survey provided the first practical opportunity to test the complete modified installation under survey conditions.

The detector consisted four identical 10x10x40 cm NaI scintillators, operated through a bifet summing amplifier and trimmed to give composite energy resolution of 10% at 662 keV (3rd February 1992). Resolution of better than 11% was maintained throughout the survey. The selection of a 16 litre detector for this survey was made to provide optimal sensitivity for baseline mapping. For emergency response purposes a smaller 8 litre detector would be considered in preference; both detector packs have been cross calibrated on several occasions.

3.2 Installation

The equipment was initially installed in a twin Squirrel helicopter which arrived at the designated landing site on the NEL campus in the early afternoon of Monday 3rd February. The main spectrometer installation was rapid; the most time-consuming step being to mount the GPS antenna and cable on the rear of the tail boom. For rapid installation under emergency response conditions it would be desirable to have GPS antennae as permanent fixtures. Unfortunately a problem with aircraft radioaltimeter was uncovered during installation, and a decision made to substitute a different aircraft. Accordingly the system was flown to Cumbernauld airport, transferred to a reserve twin engine squirrel aircraft (G-PLAX), and then flown to the survey field base at Lockerbie. Despite this delay the aircraft was equipped and on-station on 3rd February, ready for final testing prior to survey operations on the following day.

3.3 Flight Testing and fieldbase establishment

The survey was based at the Lockerbie Manor Hotel, an area of the car park being reserved for landing and refuelling the aircraft. A temporary field based was established at the hotel on 3rd February. A complete set of spares parts for the spectrometer and computing systems for data backup and preliminary analysis was transported to the hotel by car and an office area set up. Mains power was supplied to the aircraft to maintain detector bias and battery levels overnight using a circuit breaker and extension cable.

Functional tests of the spectrometer were made both during the short flight from East Kilbride to Cumbernauld, and on the early evening flight from Cumbernauld to Lockerbie. Spectrometer stability was confirmed by monitoring the position of the natural 40-K peak (at 1462 keV), and a preliminary set of background readings was taken in the aircraft at an altitude of 2000 ft en route to Lockerbie.

Flight tests were completed on 4th February with radioaltimeter calibration, and testing of a new automatic position capturing routine based on GPS (see below). An intermittent problem was observed arising from residual vibrations transmitted through the rack shock mounts. A spare unit was substituted to enable the survey to proceed, the system being fully operational by 1300. Subsequent investigations has confirmed that two internal components in the original computer were vibrating against each other. This has been mitigated for future use by re-locating peripheral interface cards within the system. Additional damping has subsequently been added within and beneath the rack.

3.4 Recording

The recording technique adopted in flight followed standard SURRC procedures. Gamma ray spectra were recorded into 511 channel pulse height spectra with an integration time of 10 seconds. Full spectra and a table of 8 selected regions of interest were written directly to hard disc, labelled with time and date of acquisition, time averaged radioaltimetry data and interleaved with positional information for each spectral pair. This provides all the information needed to form maps automatically once on the ground.

A significant development was introduced on this survey, using the GPS satellite navigation system for automatic positional capture. On previous surveys positional information was derived from Decca navigation equipment installed on the aircraft, and input manually to the spectrometer between each spectral pair. This has been successful, and enables avionics instrumentation to be used. However precision is limited to some 200 m, the Decca facilities are not available on all possible survey aircraft, and a considerable operator workload is committed simply to track logging. The procedure adopted in this survey was to capture RS-232 data from a Navstar XR4 GPS system every 2 seconds, providing time, latitude longitude, 95% triangulation error estimates and satellite status information, when needed within the acquisition cycle. These signals were decoded within the SURRC data logging programme and appended to spectroscopy files in an identical manner to previous surveys, thus ensuring compatibility with mapping software. A parallel navigational log summary was also recorded to permit assessment of the GPS performance. Options to revert to external input or to record data for retrospective track reconstruction have been retained for use in the event of GPS failures. The triangulation error estimates recorded from 4th to 7th February varied somewhat throughout the survey, as indicated in figure 3.1. The majority of fixes were within 50-100m, with some better than 30 m and a few instances where 100m or greater uncertainties arose, mainly from poor satellite geometry. This level of precision represents an improvement over Decca navigation, and is satisfactory for mapping at 500m spatial resolution. The possibility of improving accuracy using differential GPS for high resolution aerial survey applications will be investigated at a later date.

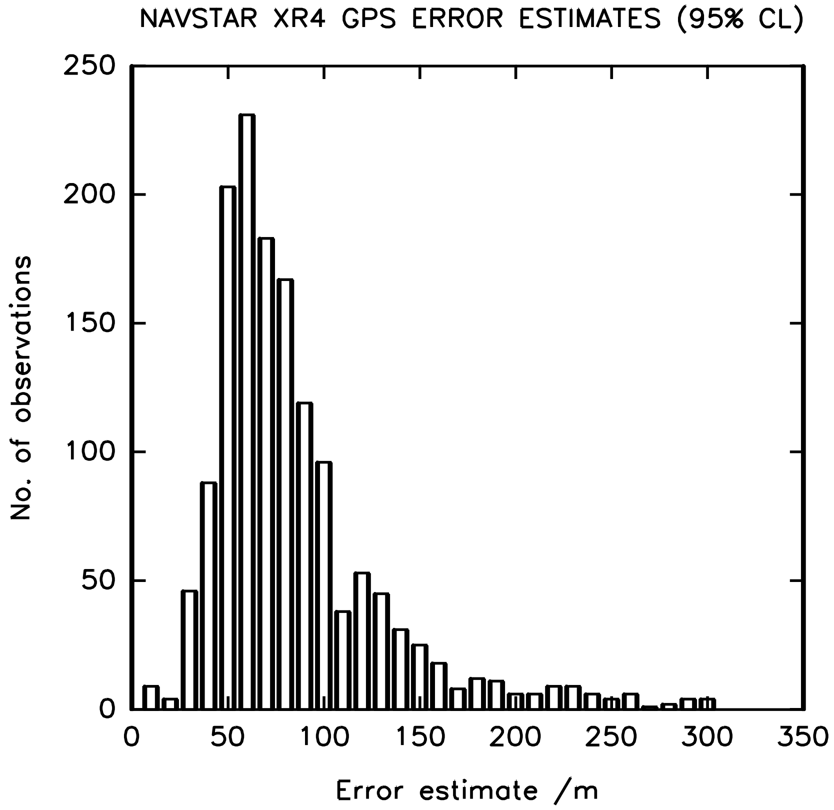


Figure 3.1 GPS error estimates recorded during the Chapelcross survey.

The choices of 10 second integration time, 65 knot speed and 75 m nominal ground clearance were made after consideration of the spatial response of the detector, performance data for the helicopter, and the counting statistics of the 16 l. detector. The field of view of the detector varies with survey height and gamma ray energy[15-17]. There is also a slight topographic influence. However the most important feature for practical purposes is the influence of aircraft height. A static detector receives 90% of its signal from a centre weighted zone with diameter at 662 keV of roughly 4-5 times the ground clearance. At 75-100 m altitude this means an effective spatial smoothing of 300-500 m. Allowing the aircraft to transit a distance up to this circle of investigation within each reading leads to a safe and economical flight without loss of spatial detail. It is extremely important to take the spatial characteristics of these data into account when interpreting features recorded, and when making comparisons with ground based results.

The detector display during flight indicated the position, acquisition status, average height above ground and integrated counts, gross and net rates within 8 spectral regions of interest. This display was updated every 10 seconds in flight. All of these data plus full pulse height spectra were recorded on hard disc.

The procedures for archival backup and data transfer are described more fully in section 4. The essential feature is that duplex backup copies of all data and initial reductions were made on the aircraft and transferred to a ground based computer before clearing the primary copies and resuming survey.

3.5 Field Measurements

The main baseline survey was conducted sequentially starting from the top left hand corner. Lines BNF3Q,3P,3O,3N,3M,3L,3K,3J,3I,3H,3G,3F and 3E were flown on 4th February, with 50 gamma spectra each per line. The lines BNF3D,3C,3B,3A,2Z,2Y,2X,2W,2V,2U, 2T,2S,2R,2Q,2P,2O,2N,2M,2L,2K,and 2J were flown on 5th February, with the latter lines, which corresponded to areas adjacent to the Solway Firth, surveyed at the end of the afternoon when the tide was low. The remaining lines from the main baseline grid, BNF2I,2H,2G,2F,2E,2D,2C,2B,2A were collected early on 6th February again targeting the low tide period of the day. Thereafter a short flight around the Chapelcross perimeter and along the route of the discharge pipeline from the site to the Solway preceded investigation of tie lines reaching for 40 km in N, S, E, and W directions from grid centre. A late afternoon survey was conducted of half of the western extension, principally the area west to the river Nith. The remaining portion west to Rough Firth was finished early on 7th February, and the aircraft returned to Cumbernauld. Some 2232 spectra were recorded from the main grid, with a further 1271 from the tie lines and western extensions, making a total of 3503 spectra.

Each daily flight was preceded by a check on the resolution of the 662 keV line from ^{137}Cs, using a 370 kBq reference source placed beneath the aircraft. Detector gain was continuously monitored using the natural ^{40}K peak, and maintained within 1% of 6 keV per channel at all times.

In parallel with the aerial survey a series of 31 soil/sediment cores was collected, as part of an SURRC PhD research project from an area of Caerlaverock Merse within the survey zone. The cores were collected from an expanding hexagonal sampling grid designed to permit comparisons between in-situ gamma spectrometry results and inventory estimates derived from high resolution gamma spectrometry in the laboratory, and also to determine the extent of spatial variability of natural and anthropogenic nuclides in the study site. This provided an opportunity to compare aerial and ground based results. Therefore a set of aerial observations was recorded in the hover above this sampling location on 6th February. The core results and sampling plan are presented in appendix B.

4. DATA ANALYSIS

Each full record stored by the spectrometer includes quality assurance information on acquisition time, positional fixes, radioaltimetry data, a table of integrated count rates in preselected regions of interest together with estimates of their associated poisson errors, plus the full spectra recorded over 511 channels. Gain stabilisation is achieved using the natural 40-K peak. A gain monitor is based on comparing the ratio of two windows arranged to bisect the 1462 keV full energy peak. If this ratio is significantly different from 1 then gain adjustments can be made. Keeping the gain monitor between 0.7 and 1.3 is equivalent to better than +-1% gain shift, and this in turn has been shown previously to have a negligible effect on spectral characteristics.

The acquisition rate during survey was high - resulting in over 3500 gamma spectra recorded over the four survey days. The emphasis of SURRC data handling procedures has been to allow such sets to be reduced rapidly and in a manner which automatically leaves a traceable quality assurance trail. A suite of programmes has been developed in the "AERO" package, capable of flexible reduction, analysis, mapping, statistical summarisation and spectral display. Production of mapped survey data follows five main stages described below together with a brief statement on quality assurance and a summary of the present status of the calibration. During the survey all steps up to display of preliminary maps were conducted on the afternoon of 6th February. Preparation of hard copies of maps and archival results was conducted afterwards at SURRC.

4.1 Summary file formation.

The first stage of data reduction was the formation of compressed summary files - each containing a series of single line entries for each spectral observation. These comprise the positions, altitudes and 6 integrated count rate estimates at preselected energy windows. Windows were chosen, as in previous SURRC surveys to estimate ^{137}Cs, ^{134}Cs, ^{40}K, ^{214}Bi, ^{208}Tl and the total dose rate using an integrated window above 450 keV. Each line of survey data was initially assigned a single summary file. Formation of summary files, and tabular printout was conducted during the survey in a manner which kept pace with the previous flight. Numerical assessments were therefore available on the day of flying.

4.2 Background Subtraction

The second stage of data analysis was to link the summary files forming the survey area together into area records of net count rate. Detector background count rates (recorded at high altitude or over clean water) were subtracted at this stage. A complete summary file describing the net data set was formed in the process, together with a header recording the background count rates used. This net file is also printable in tabular form, and is available for mapping or for subsequent calibration.

4.3 Spectral Stripping.

Spectral interferences occur with NaI spectroscopy due to the combined effects of unresolved full energy peak overlap (line interference) and scattering both in transport from source to detector and also within the detector. This leads to multiple contributions to net count rates within each integrated window, particularly when approaching background count rates. These are deconvoluted using a matrix stripping method which depends on values for the fractional interference from pure nuclide sources into each region of interest. A matrix of fractional interferences between each channel is assembled and inverted. Stripped counts for each channel are obtained by matrix multiplication of the inverse stripping matrix and a vector representing net count rates. Again a full file copy of the data set is produced in printable form, available for mapping or further analysis.

As with previous surveys the stripping matrix was estimated by laboratory measurements of pure nuclide sources. In this case however a set of standard 1 m^2 calibration pads, doped with potassium, U series and Th series activities was used for the first time in preference to small scale laboratory sources. The pads themselves were purchased in 1991 through the Geological Survey of Canada[18] and are an internationally traceable standard for field spectrometry. Stripping ratios between the natural nuclides and the two Cs windows were measured before the survey. These compared quite closely with the previous values measured using smaller scale sources, however it was noted that there was more scattering within the concrete calibration pad. As discussed in previous reports[11,13], there are reasons to believe that systematic errors due to inadequate allowance for scattering when measuring pure spectral sources may affect result in over-stripping of ^{137}Cs and a slight under-stripping of ^{134}Cs. It is possible to avoid passing systematic errors on to calibrated data, providing calibration equations allow for non-zero intercepts, as has been the practice in SURRC surveys. Nevertheless deficiencies in stripping will reflect in reduced precision close to detection limits. To investigate the effect of adopting revised stripping factors the net data set was stripped twice using the original stripping matrix and the new values. Results of comparisons between mean values of stripped count rates determined from both sets, and from regression analysis are presented in table 4.1.

Channel	1	2	3	4	5	6
Data	^{137}Cs /cps	^{134}Cs /cps	^{40}K /cps	^{214}Bi /cps	^{208}Tl /cps	>450 kev
Original[1]	35.06±79	15.0±20	44.36±21	6.78±9.7	12.14±14	449±359
New[2]	37.4±79	14.9±22	45.05±21	5.93±8.7	12.0±14	449±359
a[3]	1.002 ± 0.0008	0.951 ± 0.007	1.02 ± 0.0008	0.895 ± 0.001	0.989 ± 0.0003	1
b[4]	2.297 ± 0.007	0.231 ± 0.191	-0.176 ± 0.004	-0.133 ± 0.01	-0.011 ± 0.005	0

Table 4.1 Comparison between Chapelcross data stripped with the original matrix and values recorded from IAEA recommended pads.

Notes : 1. Mean stripped count rate using the original stripping matrix
2. Mean stripped count rate using the new stripping matrix
3. Slope of regression of new vs old stripped count rates
4. Intercept from regression of new vs old stripped rates.

It can be seen that both sets of data are remarkably similar. With the exception of ^{214}Bi the regression slopes are within 5% of unity; for ^{214}Bi the deviation of 10.5% is well within the estimated uncertainty (of ± 15%) in calibration factors. The two caesium nuclides are little affected, although it is noted that ^{137}Cs has a significant regression intercept, in keeping with expectations, given the increased scattering with the concrete potassium pad compared with previous bulk potassium sources used for calibration in the laboratory. The use of the new stripping matrix was therefore considered not to have a significant effect upon calibration procedures, or comparability of this data set with previous surveys. It should be noted that atmospheric scattering has not yet been taken into account in determining stripping factors. As reported before on many occasions this is a difficult effect to estimate accurately. However experiments based on absorbers used in conjunction with calibration pads, and parallel Monte-Carlo simulations, are underway at SURRC and may eventually lead to the determination of a final set of corrections for stripping in standard aerial survey detectors.

Another extension to stripping concerns interference from ^{16}N close to the reactors themselves. Activation of ^{16}O by the (n,p) reaction in reactor cooling circuits produces ^{16}N, with a 7.13 s half life and high energy gamma ray emissions at 6.13 MeV (68.9%), 7.115 MeV (4.7%) and 2.74 MeV (0.9%). The unshielded external cooling ducts of early Magnox reactors provide an intense local source of this radiation while the reactors are operating. Interference from this nuclide was noted during the 1990 survey near Sellafield, arising from the Calder Hall station. The same phenomenon was observed at Chapelcross, affecting some 22 spectral observations out of the complete set of 3500 spectra. Uncorrected data show an apparent U and Th signal with overstripping in Cs channels. The K^{40} signal is difficult to interpret since these same locations tend to be influenced by local effects from ^{41}Ar at 1293 keV. The following steps were taken to correct for ^{16}N interferences.

An initial set of maps of stripped data was prepared and used to identify the 22 spectra showing anomalies close to the site boundary. These spectra were assembled and re-integrated, setting an additional window from 2.85-3.06 MeV, to monitor scattered radiation due to ^{16}N. This window is above the energy of the highest terrestrial gamma source (^{208}Tl at 2.62 MeV). The re-integrated data were then analysed in a spreadsheet, and count ratios between the new high energy channel and all other channels were determined. Stripping ratios of 4,2.8, and 3.4 were determined for channels 3,4 and 5 relative to the high energy window. These fractions of the original net data were subtracted, and the resulting values inserted into the complete survey file. Re-stripping of the complete set using the pad matrix described above resulted in a data set with first-order corrections for ^{16}N interference in the 22 observations close to the site. Although this resulted in a marked improvement, the procedure is not perfect due to the complexity of local scattering of these high energy photons, and to the other nuclides present in spectra recorded at the site boundary (principally ^{41}Ar, ^{234}mPa).

4.4 Altitude Correction and Calibration.

The final conversions to calibrated data combined altitude corrections with sensitivity estimates. Stripped data were first converted to standardised values at 100m altitude. The form of the altitude dependence is exponential integral, however a simple exponential approximation is adequate for survey heights over 30m above ground. Coefficients were determined in 1990 during the SURRC survey of Ayrshire [12]. Calibration was achieved using a set of linear equations determined by comparison of ground based readings from known sites with aerial survey data. The calibrated data set has been printed out and is stored archivally at SURRC for future reference.

4.5 Mapping

Radiometric maps were produced from the calibrated data following standard procedures. The calibrated data files was read into the AERO program, and latitude and longitude coordinates transformed to OS grid references, which were also used as plotting coordinates. This produced an implicit set of x and y values for each observation. Thereafter the calibrated level for each nuclide was sequentially selected for allocation to the z variable. A new routine to allow concatenation of "XYZ" files was used at this stage to produce complete records for each nuclide individually, covering the whole survey. These files can be read back into the package directly as a quick entry point to mapping, and can also be exchanged with standard mainframe graphics packages. Before mapping, the z values were examined statistically (histograms, summary statistics) and assigned to up to 15 colour codes using linear or logarithmic coding. Linear coding was applied to all channels except ^{137}Cs, for which the range of observed values spanned 2 orders of magnitude. A decision was made to apply logarithmic colour coding to this variable, the scale initially being selected to provide a distinct contrast between (i) the extremely low levels associated with global weapons testing fallout in the immediate surroundings of the Chapelcross site (0-3 kBq m^{-2}), (ii) the terrestrial deposition attributed to Chernobyl in the western edge of the survey (~10 kBq m^{-2}), and (iii) the signals on tide washed pastures (~ 100 kBq m^{-2}). Consideration was subsequently given to adoption of the same coding as applied to the 1990 Sellafield survey, to facilitate comparability of the two data sets. This results in a modest loss of contrast, but has been implemented here for the purpose of comparability. It is noted that there is no single colour scale which can be expected to display each individual survey in an optimal manner. Therefore it may be necessary in the future to re-mapped data from earlier projects on differing colour scales for ease of comparison with other data sets, for ease of presentation or for detailed examination of specific features or boundaries.

Once colour-coded the individual data points were plotted in their appropriate colours on a high resolution monitor and the subject to a spatial contouring procedure whereby each screen pixel was replaced by the colour code corresponding to the average value of all data points within an 800m "neighbourhood", weighted inversely in proportion to distance from the implied position. Screen capture routines were used to store the resulting images, which were then printed using a Tektronix 4697 colour inkjet printer. Topographic detail was added using a CAD/CAM system.

4.6 Quality Assurance

Attention was given to quality assurance at all stages of the work. The recording technique and data nomenclature are designed to enable a continuous check of spectrometer operation possible in flight, and to allow rapid traceability of full records from each reading for quality control purposes thereafter. The archive for the survey is fully retrievable, doubly backed up, and use has been made of ASCII text only files for all data storage to enable quality assurance checks to be made. The data reduction stages are all self recording, and the archive is so structured that primary data can be examined readily where any unusual features have been located. Finally the algorithms used have been tested with known data.

4.7 Status of the calibration constants

The values of stripping factors and calibration constants used in this work are shown in appendix A. These represent current SURRC working values at the time of the survey. Such values are under continual review, and may therefore be subject to future change. Their status is as follows.

The stripping factors have been discussed above. Although experiments with absorbers and transport calculations in progress are expected to lead to further revisions to stripping matrices in the future, this is only likely to effect Cs estimates close to the detection limit of approximately 1 kBq m^{-2}. For spectra where full energy photons comprise the major contribution to window count rates, stripping has a neutral effect. An error analysis of the stripping process was conducted in 1988 following the SURRC survey of West Cumbria[10]. This showed that the combined statistical errors in full energy peak estimates for ^{137}Cs at levels above 15 kBq m^{-2} were better than +-10%. In the tide washed pasture context the statistical precision of ^{137}Cs is typically better than 2%.

The gamma dose rate estimates were derived by scaling integrated spectra above a 450 keV threshold to ground based dose rate measurements on calibration sites. This high energy threshold method derives from a ground based technique designed to avoid problems associated with the low energy over-response of scintillation detectors. It is believed to be accurate within +-10-15% for evaluating dose rates from natural media. The potential of systematic underestimation from anthropogenic sources with complex vertical distributions has been recognised, but not yet quantified.

The calibration data for nuclide inventories, and any associated systematic errors, depend on comparison between ground sites where inventories have been estimated by gamma spectroscopy of collected cores with correlated aerial survey data. The values used here derive from an SURRC 1990 analysis of data from sites where ground to air comparisons could be made, spanning a range of ^{137}Cs activities from 0-300 kBq m^{-2}. It is implicit in the calibration process that the vertical distribution of activity in the survey area is comparable with that from calibration sites. Furthermore it is vital that lateral spatial association, and spatial variability of deposition be considered when comparing aerial survey and ground measurements. Aerial survey results are spatially smoothed over 10^4-10^5 m^2 whereas soil cores typically represent sampling areas of $10^{-2}m^2$, or less. Ideally calibration experiments would be conducted over uniform areas of deposition. While this may be practicable for natural radioactivity, it rarely, if ever occurs with anthropogenic deposition in the environment.

The original calibration performed 1988 used data obtained from 12 sites in SW Scotland selected from over 50 analysed to maximise Cs contrast. An extremely good correlation between aerial and ground based data was obtained. The resulting working calibration was concordant in West Cumbria (1988) with spatially matched results from 1400 soil samples collected by MAFF on a 200m cartesian grid, however the high degree of spatial variability exhibited by the latter, and the relatively small numbers of associated aerial survey observations limited more detailed conclusions. SURRC surveys in 1989 were calibrated by re-flying calibration sites and lines through West Cumbria using new detectors and projecting sensitivity estimates onto them, and collecting a limited number of extra cores from each survey to confirm traceability. Procedures for overlaying two or more aerial survey data sets and cross comparing their results were developed for this purpose.

Finally in 1990 a new set of local calibration sites was defined in Ayrshire with ground samples collected in a manner which attempts to overcome the problem of spatial matching. In this work each site has a pattern of 17 soil sampling locations laid out on three concentric arcs around a marked centre with an area density which approximates the field of view of a static aerial survey detector. Aerial survey readings are taken on these sites while hovering at various heights above the centre marker, thus providing better counting statistics than obtained during dynamic calibration measurements, and data to determine altitude corrections.

The unweighted mean of the 17 soil cores gives a better ground estimate of mean activity than single cores or other sampling configurations. These new sites produced a total of over 150 soil samples for high resolution gamma spectroscopy. A preliminary analysis of roughly half of these data together with old sites was used to determine 1990 working values which were used to calibrate these data. The working values are not significantly different from those used in earlier surveys - suggesting that sensitivity estimates may be approaching final values. For ^{137}Cs they are also within error of theoretical sensitivity estimates based on laboratory efficiency determination and geometrical integration of uniform activity distributions.

The expanding hexagonal sampling plan tested at Caerlaverock (see Appendix B) extended this concept of spatial weighting of soil cores so that response functions at different altitudes could be evaluated. The results from both in-situ gamma spectrometry and soils cores at this site indicate that it had maximal Cs^{137} activity it the centre point, with a significant fall-off at radial distances beyond 32 m. from the centre point. Natural nuclides were much more uniformly distributed. The weighted estimate for ^{137}Cs, based on high resolution gamma spectrometry, for the activity seen at 100m altitude is 50.8 kBq m^{-2}. This value compares with observed values of 49.8 kBq m^{-2} (BNWES168A , 66 m height), 41.6 kBq m^{-2} (BNWES168b, 74 m) and 39.6 kBq m^{-2} (BNWES169a, 100m) recorded above the calibration mark on 6th February, and evaluated using the "working" sensitivity values. The aerial survey results thus appear to underestimate inventory by some 20-30% on this site. Given the lateral variability (by more than 50% over the detector field of view), and the possibility that vertical activity profiles are variable throughout the tide-washed zones, it was decided to note this potential under-response but to retain earlier working values for the purpose of mapping, thus ensuring consistency with previous surveys, and avoiding over-estimation of inventories for near surface terrestrial sources.

The vertical distribution determined at Caerlaverock showed a pronounced sub-surface maximum at 10-15 cm depth, which is one obvious contributory factor for the systematic under-response in estimating inventory on the tide washed pasture. Where the lateral dimensions of tide washed pastures are smaller or comparable with the field of view of the detector, then there is further potential for compounded under-estimation of Cs inventories by aerial survey. Therefore it is recommended that the inventory estimates be interpreted cautiously as representing probable lower limits to the inventories of tide washed contexts. These factors should not be overlooked in making comparisons with ground based observations.

5. RESULTS

The baseline maps for ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl and gamma dose rate are presented in figure 5.1 to 5.5 respectively. In interpreting these maps the spatial averaging of the aerial measurements and the contouring process should be taken into account, together with the comments on underresponse from buried sources above. This leads to a slight tendency to broaden spatial features and to reduce maximum values particularly for boundaries less than the spatial resolution (500m) of the survey. Small scale features will also be underestimated.

The ^{137}Cs map (figure 5.1) shows a number of features associated with the various components of this nuclide in the environment. Close to the site itself, and within the outer perimeter fence it was possible to detect signals associated with the small-bore discharge pipeline to the SW of the reactors. This discharge stream is considerably diluted as it leaves the site, joining a larger flow of inactive water, which then follows the path of a disused railway embankment to the coast. The residual signal levels after dilution were not detected at aerial survey heights, although they are regularly monitored at ground level. This is a satisfactory confirmation that the dilution and partial burial of the discharge pipeline results in significant reduction to external dose rates arising from the authorised discharge.

Terrestrial levels of ^{137}Cs in the surroundings of Chapelcross are typically of the low order characteristic of global weapons testing fallout in the West of Scotland (2-4 kBq m^{-2}), suggesting that this area was little affected by the Chernobyl accident, and that there is no evidence for a local terrestrial source of Cs contamination. Further to the west, between the Pow and Lochar waters, terrestrial inventories of ^{137}Cs rise to levels above 10 kBq m^{-2}. This is attributed to the fallout from the Chernobyl accident. Previous SURRC surveys, and Scottish Office data are consistent with this interpretation, based on ^{134}Cs. It is known from this earlier work that the Chernobyl deposition is higher still, by some 3-4 times, further to the West, although the detailed deposition pattern has yet to be mapped from the air.

The tide washed pastures adjacent to the Solway Firth and it's rivers, and the intertidal sediments on exposed mudflats, can also be seen to carry substantial burdens of ^{137}Cs. The highest levels recorded in this survey, equivalent to inventories of 100 kBq m^{-2} or more, are associated with tide washed areas such as salt marshes. The most extensively contaminated areas identified here were near Kirconnel in the Nith, at Caerlaverock, Rockcliffe and Burgh marshes. Smaller areas of local enhancement occur close to the tidal limits of most rivers, notably the Southwick burn, Kirkbean Glen, Burnfoot, the river Annan, the Kirtle Water and river Sark. This activity is predominantly attributed to past marine discharges from Sellafield. The intertidal activity distribution is consistent with the results of a hovercraft based survey undertaken in 1984 by the British Geological Survey[19], however this earlier study was confined to the sedimentary environment, and therefore did not detect any of the terrestrial deposition sites. The presence of ^{137}Cs in tide washed pastures is generally consistent with earlier SURRC aerial survey results[1,10,11], and with the findings of smaller scale ground-based studies[20,21], and BNF data[22]. These maps provide an extremely clear guide as to the superficial distribution, which can be used to direct further investigations in addition to the baseline function. The radiological and environmental implications of this activity will be briefly discussed later.

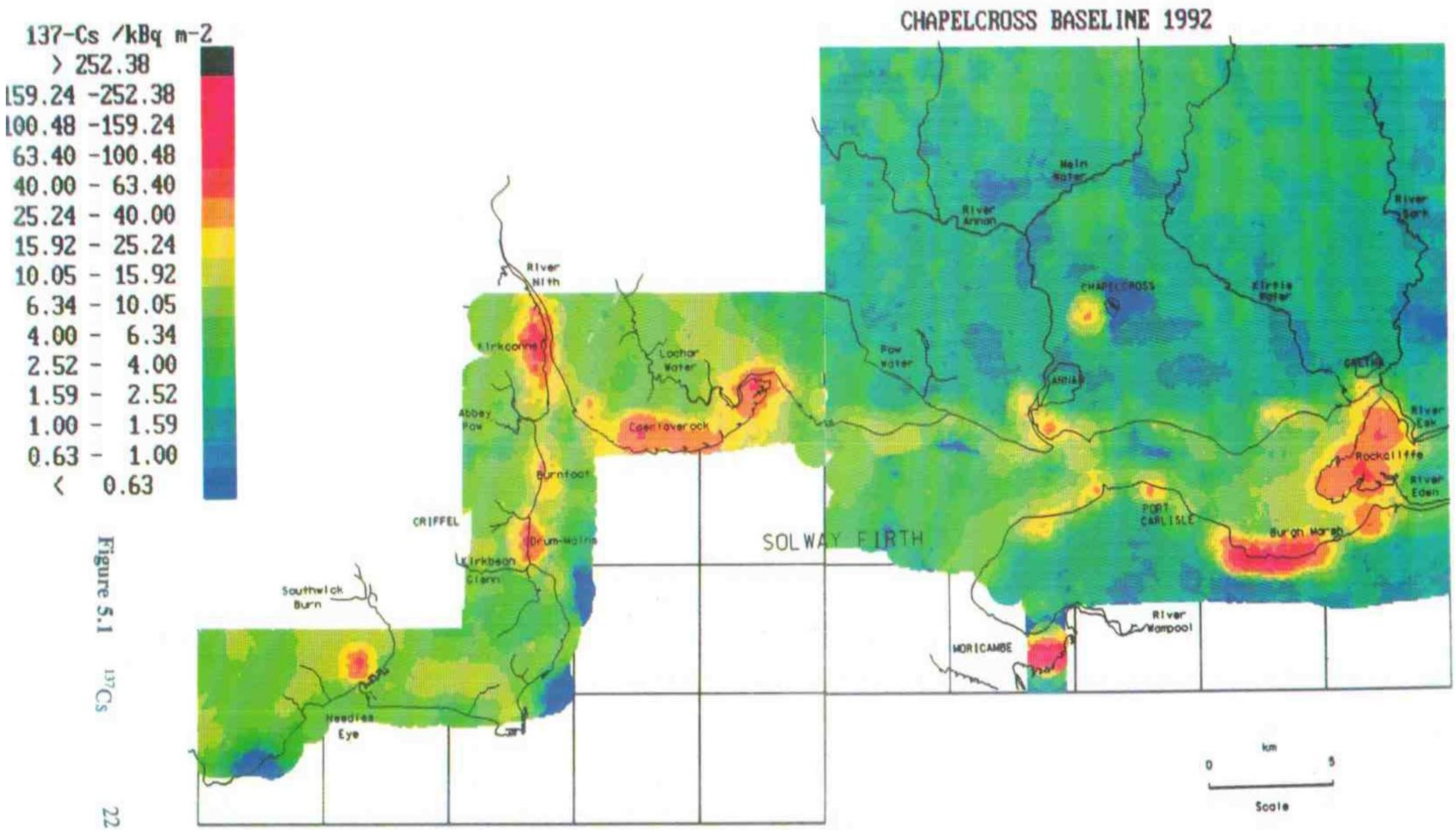


Figure 5.1 ^{137}Cs

The natural radionuclides (^{40}K, ^{214}Bi, ^{208}Tl) show variations which reflect the local subsoil geology and surface geomorphology, and can be seen in figure 5.2-5.4. The inferred levels of ^{40}K in the top 30 cm of terrestrial columns range from below 15 to above 200 kBq m^{-2}, the highest levels being associated with the Criffel pluton at the Western edge of the survey zone. Similarly the ^{214}Bi and ^{208}Tl inventories range from 1-10 and 0.5-5 kBq m^{-2} respectively, but are implicitly associated with U and Th series activity of at least an order of magnitude greater. It should be noted that the branching ratio for ^{208}Tl of 0.36 implies higher slightly higher parent activities of the Th series than the U series. This puts the additional artificial sources into context, as at greatest a comparable additional to natural radioactivity. Local anomalies close to the reactor site are attributed to ^{41}Ar interference with the ^{40}K channel, and unresolved ^{16}N interference with ^{214}Bi and ^{208}Tl, despite stripping out first order influences as described above. Therefore these apparent features on the maps should not be taken as indicative of highly enriched natural sources. Thorium, uranium and potassium are generally quite well correlated geochemically, although variations in their relative proportions occur and are characteristics of different rock formation processes.

Prominent features in all three maps include the edge of the Criffel pluton, located in the SW quadrant of the western extension, and responsible for significant enhancements to all three natural sources. Triassic shales are responsible for enhanced levels immediately to the E of the Nith Valley. The adjacent negative anomalies are associated with Silurian outcrops to the NE of the Lochar water. Carboniferous limestones and permian sandstones underlie the for the majority of the main survey grid, describing a moderately low and slightly variable natural radiation environment which is also modulated by variable peat cover and water.

The overall gamma dose rate map, shown in figure 5.5, is influenced by the combined contributions of the natural nuclides, ^{137}Cs and the miscellaneous local radiation sources associated with the Chapelcross site. Cosmic radiation, although a significant minor source of radiation exposure (typically 0.35 mGy/a at UK surface ground levels) is not included in this assessment, but would register in the response of portable gas filled ionisation detectors or geiger counters. All of the aforementioned contributions can be seen in the gamma dose rate map, which has been scaled to show the variations in natural levels.

Radiation from the Chapelcross plant was readily detected at the perimeter and can be clearly seen in the gamma dose rate and ^{137}Cs maps. In the former case direct radiation from ^{16}N in the reactor heat exchangers and the release of ^{41}Ar gas from the reactors are largely responsible, and represent a well known and controlled source of radiation exposure in the immediate vicinity of the site. The presence of a significant source of ^{234m}Pa was observed in a single spectrum recorded over the perimeter closest to a known depleted uranium store; however a ground level earthwork between this store and the perimeter fence makes it unlikely that this source is relevant to off-site dosimetry. It should be noted that the contour levels shown in figure 5.1 here were selected to reveal small variations in natural dose rates, against which future environmental changes can be seen with high sensitivity. This results in a scale with a top level below that of conventional health physics concern. For example a dose rate of 0.1 μSv per hour corresponds to 0.87 mGy/a, presented here as a high colour code. It is not surprising that enhancements to the relatively low local gamma dose rate are detected beyond the perimeter location, given the reactor design and sensitivity of the aerial survey spectrometer. Dose rates at ground level may be further reduced locally as

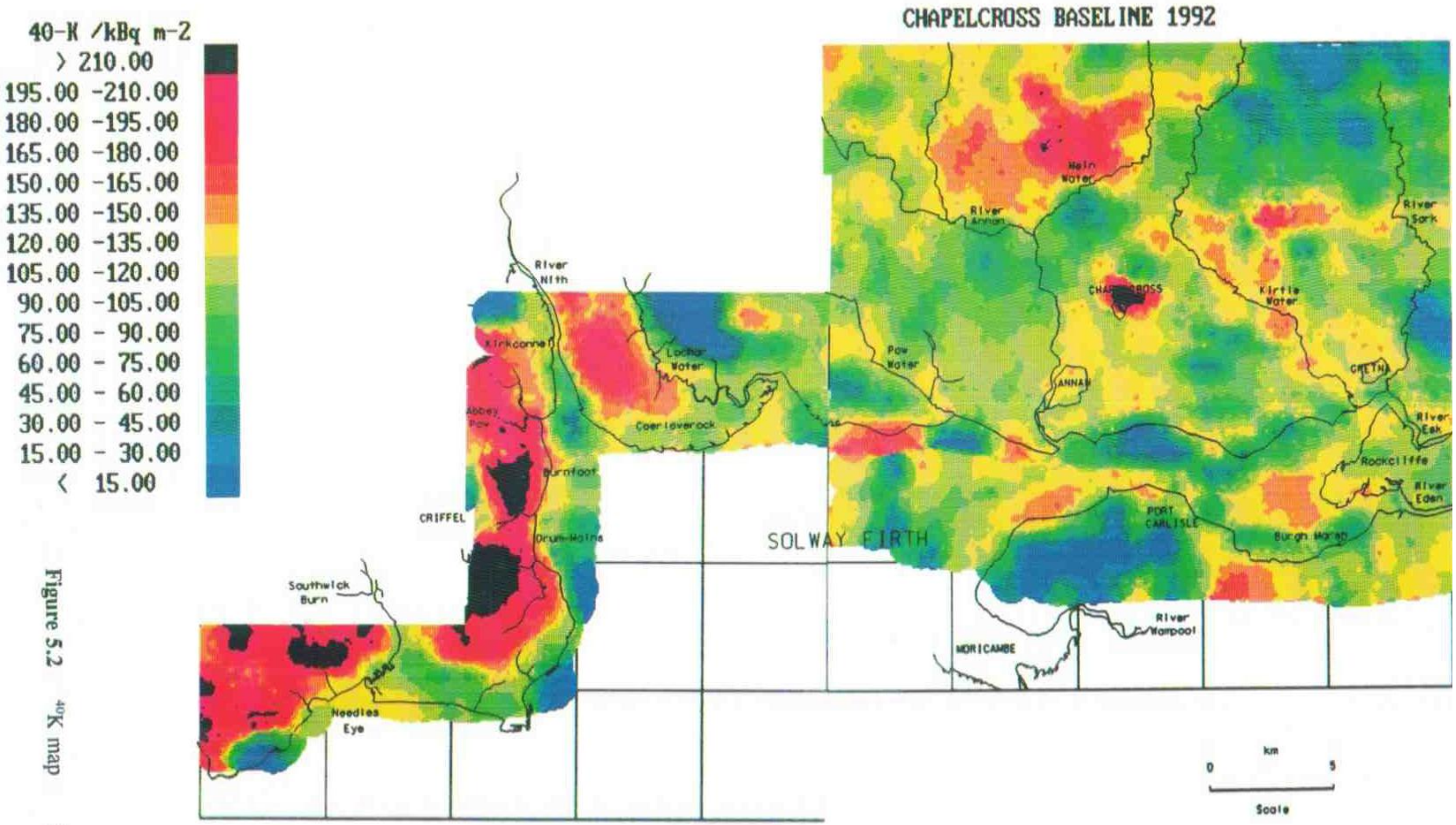


Figure 5.2 ^{40}K map 24

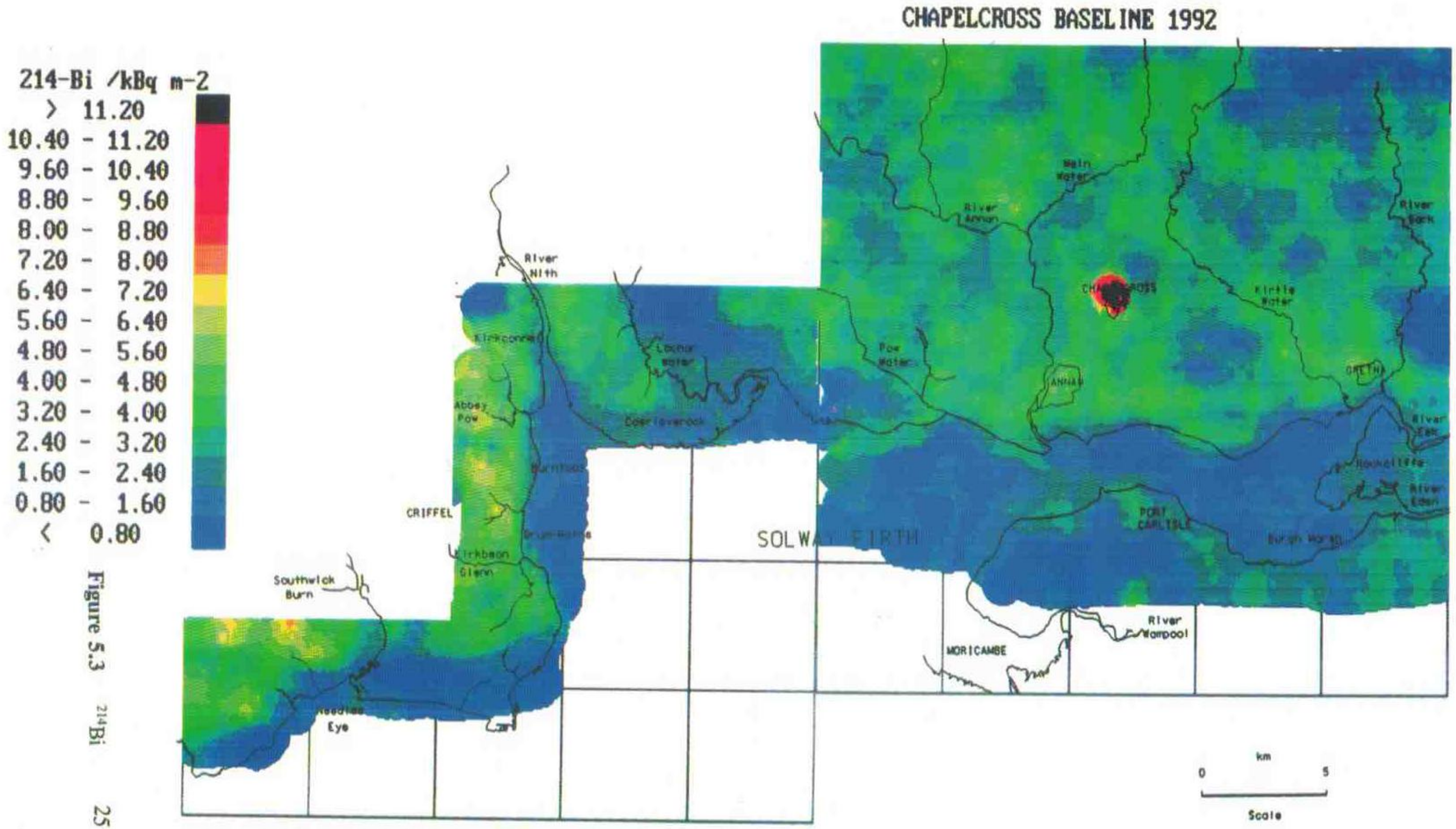


Figure 5.3 ^{214}Bi 25

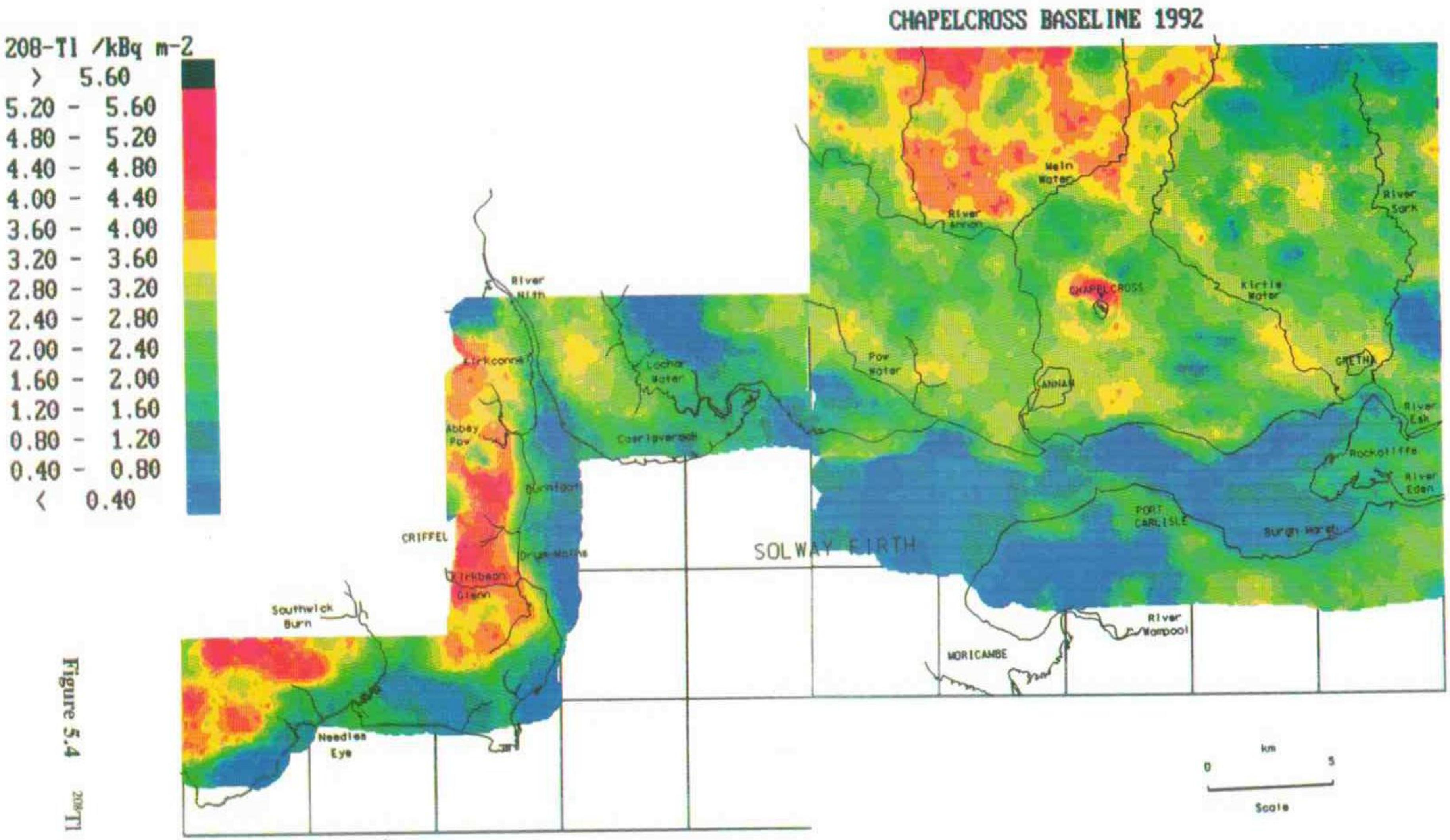


Figure 5.4 ^{208}Tl

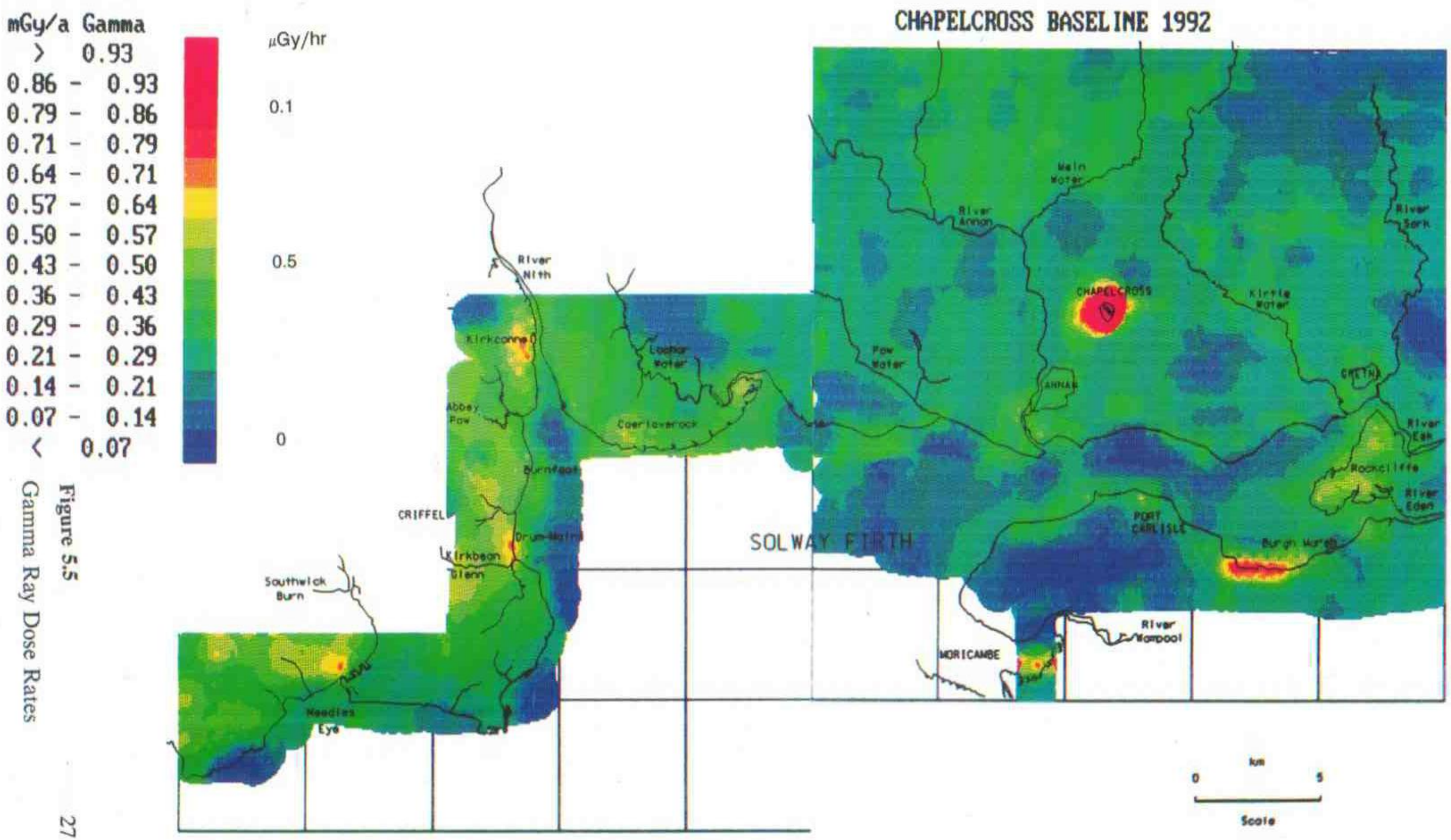


Figure 5.5
Gamma Ray Dose Rates

a result of surface topographic undulations and influenced by local shielding. A set of ground level dosimetry readings was taken on-site following the survey, to assess the consistency between dose rate estimates at the site boundary using conventional health Physics instrumentation and the aerial survey results from the perimeter outwards. These readings were undertaken at a time when three out of four reactors were operating, and were used to produce a local contour map for comparison. As expected the on-site levels rise close to the reactors themselves. As far as can be seen from this short comparison both ground-based and aerial survey dosimetry estimates are compatible with each other. It was noted that the lowest dose rate recorded on-site was some 42% higher than the top contour level from figure 5.5; therefore it is not surprising that the aerial survey detected the site out beyond the 500m -1 km distance from site centre.

Further afield it is notable that the local salt marsh Cs sources are identifiable as significant enhancements to overall gamma ray dose rates in their local vicinity, although the natural contributions are of comparable importance to even the most affected sites. The subsurface distribution of Cs recorded at Caerlaverock, implies that source burial may be a mitigating factor which limits the radiological importance of these levels of activity.

The dose rates due to Cs contamination are equivalent to up to 500 μGy/a in these cases. However doses delivered to members of the public are expected to be considerably mitigated by low occupancy factors for these sites. A habit survey, and dose assessment has been conducted recently on rivers in SW Scotland[21] to investigate the dosimetric implications of tide washed pastures identified during an earlier ground based[20] study of environmental radioactivity. The annual critical group dose after taking occupancy factors into account was evaluated as 60 μSv, which is comparable with the 1990 Chapelcross critical group assessment for stakenet fishermen of 54 μSv[22], both well beneath the ICRP principal dose limit of 1 mSv for members of the public. It is noted that the present survey results show a more comprehensive indication of the spatial distribution of activity than previously available, and that in the river Nith particularly the contamination of Kirconnel Merse was not so clearly identified in earlier studies. It would therefore be prudent to review critical group assessments of this study area to take the new results into account, particularly since there is some evidence that the aerial survey results may be underestimating buried or small scale sources.

The environmental significance of the maps lies in the demonstration of the current levels of contamination of tide washed pastures arising from past marine discharges. The proportion of discharged activity which has so far returned to land is extremely low, compared with estimates for the sea-bed sediment burden. Therefore it is important to assess future changes in the terrestrial levels arising from these discharges. The deposition sites identified have clearly received enhanced sediment loads from tidal inundation in the past, with accompanying contaminants. There is considerable further scope for local studies of vertical profiles, which may indicate the likely direction of future deposition trends, assuming that present processes continue to operate. There is further scope also for investigating the associations between radioactive and other forms, particularly chemical and biological, of marine pollutants in these deposition contexts. Finally, having defined present levels on these sites it will be of interest to revisit them in the future to monitor the changes associated with a dynamic estuarine system.

6. CONCLUSIONS

The survey has defined the gamma radiation environment of the Chapelcross site in unprecedented detail, thus enabling any future changes to be compared with 1992 levels. Radiation levels due to current activities on site fall rapidly with distance from the perimeter fence and were consistent with expectation given the nature of reactor operations on the site. The Chapelcross site is located in a general low terrestrial radiation environment, and therefore is detectable against it's local background. The baseline maps also clearly define a number of tide washed pasture areas adjacent to the Solway Firth and its associated rivers which have accumulated deposition arising from marine discharges from Sellafield. This information may be useful for directing further ground based investigations of the distribution and mobility of deposited radioactivity. Further to the west there were clear indications of enhanced terrestrial radiation associated with the Chernobyl accident. The off-site contributions to environmental dose rates are modest, although the gamma ray dose rates due to ^{137}Cs in the tide washed environment represent a significant fraction of the total gamma dose rate in a number of locations. The doses delivered to members of the public arising from this activity are likely to be mitigated by low occupancy factors for the locations affected, although it remains important that the uses of, and future changes to these environments be monitored closely. An emergency response grid has been defined within the baseline area, which could be surveyed rapidly in the event of an incident on site. The data recovered could be directly compared with those recorded in this study.

7. REFERENCES

1. SANDERSON, D.C.W., SCOTT, E.M., BAXTER, M.S., Use of Airborne Radiometric Measurements for Monitoring Environmental Radioactive Contamination, IAEA SM-306/138, 411-421, Vienna, 1990.

2. SANDERSON D.C.W, SCOTT E.M., BAXTER, M.S., The use and potential of aerial radiometrics for monitoring environmental radioactivity, in "Nuclear Contamination of Water Resources", Institute of Civil Engineers, pages 99-106, 1990.

3. CHAMBERLAIN, A.C., GARNER,R.J., and WILLIAMS, D., 1961, Environmental monitoring after accidental deposition of radioactivity, Reactor Science and Technology, 14, 155-167.

4. PEIRSON D.H. and CROOKS R.N., Survey of environmental radioactivity: A preliminary assessment of the use of helicopters in an emergency. 1961. AERE report M-927.

5. GRASTY R.L., 1980, The search for Cosmos 954, in Search Theory and Applications, ed HEVLEV & STONE, 1980, Plenum Publishing Corporation.

6. BRISTOW Q., The application of airborne gamma-ray spectrometry in the search for radioactive debris from the Russian satellite Cosmos 954, Current Research, Part B, Geol. Survey of Canada paper 1978-1B, 151-162.

7. LINDEN A. and MELLANDER H., Airborne measurements in Sweden of the radioactive fallout after the nuclear accident in Chernobyl, USSR., 1986 Swedish Geological Company, TFRAP 8606.

8. WILLIAMS D. CAMBRAY R.S. and MASKELL S.C. An airborne radiometric survey of the Windscale area October 19-22nd 1957, AERE report R-2890.

9. CHAMBERLAIN A.C. GARNER R.J. and WILLIAMS D. Environmental monitoring after accidental deposition of radioactivity, 1961, Reactor Science and Technology, 14, 155-167.

10. SANDERSON D.C.W. & SCOTT E.M., Aerial radiometric survey in West Cumbria in 1988, MAFF FOOD SCIENCE REPORT N611, 1989.

11. SANDERSON D.C.W. ALLYSON, J.D. CAIRNS K.J., MACDONALD P.A., A brief aerial survey in the vicinity of Sellafield in September 1990, SURRC report, 1991.

12. SANDERSON, D.C.W., ALLYSON, J.D., MARTIN, E., TYLER, A.N., SCOTT, E.M., An Aerial Gamma-ray Survey of Three Ayrshire Districts. Commissioned by the District Councils of Cunninghame, Kilmarnock and Loudon, and Kyle and Carrick, 1990.

13. SANDERSON D.C.W. and ALLYSON J.D., An aerial gamma ray search for a missing ^{137}Cs source in the Niger Delta, May 1991, SURRC report, 1991.

14. SANDERSON D.C.W., CAIRNS, K.J., TYLER A.N., 1991, Radiometrics flight trials on the forth estuary, SURRC Aerial survey report.

15. LOVBORG, L., KIRKEGAARD, P., Numerical evaluation of the natural gamma radiation field at aerial survey heights, Riso report R 317, 1975.

16. DUVAL J.S. COOK B. and ADAMS J.A.S., Circle of investigation of an airborne gamma-ray spectrometer, J. Geophys. Res, 76, 8466-8470.

17. GRASTY R.L., KOSANKE, K.L., AND FOOTE, R.S., Fields of View of airborne gamma-ray detectors, Geophysics, 44(8), 1979,144-1457.

18. GRASTY R.L., HOLMAN P.B., AND BLANCHARD Y.B., 1990, Transportable Calibration Pads for Ground and Airborne Gamma-ray Spectrometers.

19. JONES D.G., MILLER J.M., ROBERTS P.D., 1984, The Distribution of ^{137}Cs in Surface Intertidal Sediments from the Solway Firth, Marine Pollution Bulletin, 15(5), 187-194.

20. BAXTER M.S., COOK., G.T., MCDONALD, P., 1989, An Assessment of Artificial Radionuclide Transfer from Sellafield to South West Scotland, DOE Report : DOE/RW/89/127.

21. MCKAY W.A., BONNETT, P.J.P., BARR H.M., HOWARTH J.M., 1991, Artificial Radioactivity in tide washed pastures in south west Scotland, DOE Report : DOE/HMIP/RR/91/056.

22. BNF, 1991, Annual Report on Radioactive Discharges and Monitoring of the Environment 1990, British Nuclear Fuels plc, Health and Safety Directorate, Risley.

APPENDIX A.

SUMMARY OF DETECTOR CALIBRATION : CHAPELCROSS BASELINE FEBRUARY 1992

1) Detector

16 l NaI detector - box of 4 10x10x40cm NaI crystals
Resolution 9-10.5% at 662 keV
DPS MkII power supply
Locland Computer
SURRC 19" RACK INSTALLATION
Recording with MCA26 software
Radalt 10 mV/ft output

2) Windows

Window	**Nuclide**	**Channels**	**Background (cps)**
1	^{137}Cs	95-130	43.4
2	^{134}Cs	125-150	20.9
3	^{40}K	220-270	19.1
4	^{214}Bi	270-318	9.6
5	^{208}Tl	390-480	8.4
6	>450 keV	75-500	174

3) Stripping Factors

Window	1	2	3	4	5
1	1	0.06	0	0	0
2	1.77	1	0.03	0	0
3	0.22	0.161	1	0.02	0
4	3.51	1.99	0.98	1	0.07
5	2.67	1.52	0.54	0.33	1

4) Calibration Constants
a: exponential altitude coefficient
b: slope of calibration line
c: calibration intercept

Window	Nuclide	a	b	c
1	^{137}Cs	0.00962	0.198	0
2	^{134}Cs	0.0075	0.131	0
3	^{40}K	0.006	2.79	0
4	^{214}Bi	0.0066	0.606	-0.67
5	^{208}Tl	0.004	0.245	-0.2
6	>450 keV	0.0062	0.0007	0.0

5) Mapping Coordinates

Latitude and Longitude of Grid Origins (NY 000 000)

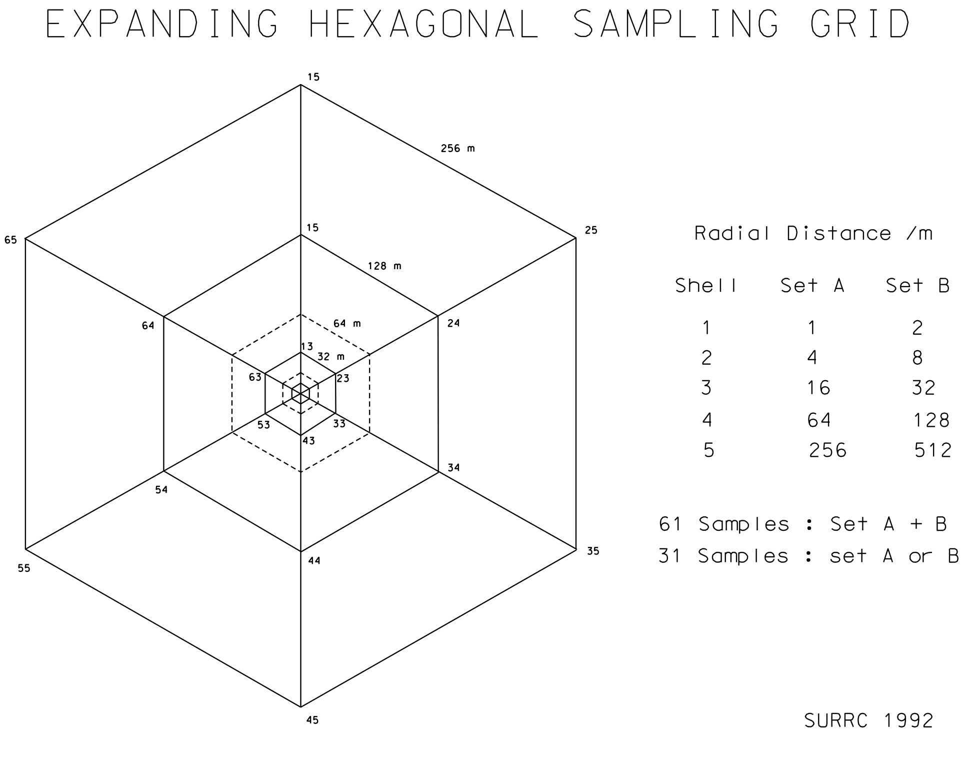
54.383^{o}N, 3.538^{o}W
Grid Angle 1^{o}

APPENDIX B. GROUND SAMPLES AND CALIBRATION SITE AT CAERLAVEROCK

When attempting comparisons between ground based and aerial survey results it is important to take the sampling errors and detector fields of view into account. This is commonly overlooked; however bearing in mind that the field of view of an aerial observation at 100m altitude includes signals from approximately $2x10^6$ kg of soil whereas a typical core sample contains 1 kg, it is clear that steps are needed to overcome scaling and sampling problems.

The principle of introducing a spatially weighted sampling pattern for ground to air comparisons was introduced in 1990 during a baseline survey of Ayrshire. In this case a 320 m circular areas were established with 17 sampling locations arranged in three radial shells, providing a centre weighted sampling plan appropriate to matching the approximate field of view for 662 keV at 100 m altitude. Four such sites were established in areas of areas of contrasting geology and soil type. This was successful but could only match fields of view at a single altitude and energy. To overcome this limitation an expanding hexagonal scheme has been devised, illustrated in figure A.1, and established experimentally as part of an NERC funded PhD studentship at Caerlaverock Merse during the Chapelcross survey.

Figure B.1 Expanding hexagonal sampling grid at Caerlaverock



The grid centre was located on an area merse showing elevated Cs levels for several hundred metres. 150 mm x 45 cm deep cores were extracted from the centre point, and from the 6 apices of 5 hexagonal shells spaced at radial distances of 2,8,32,128 and 256 metres. Thus 31 soil cores were collected.

Back in the laboratory each core was sectioned vertically, weighed, dried, homogeneised by fine grinding in a Thema mill measured on a shielded high resolution gamma spectrometer in standard geometry for 24 hours. Results were corrected for self absorption, and converted to activity per unit area estimates using standard IAEA traceable techniques. The inventories from 0-30 cm were computed for all positions. Table 1, below summarises the results for natural and anthropogenic nuclides

Table B.1 Integrated inventories from the Expanding Hexagon at Caerlaverock.

Activity	Hexagonal Spacing (m)				
kBq m^{-2}	2	8	32	128	256
^{137}Cs					
Range	76.5-90.2	71.1-95.6	75.6-96.2	22.4-119.6	24.4-103.7
Mean	84.0	83.4	83.4	78.8	39.4
Std. Dev.	5.2	7.5	7.1	33.6	19.9
Variance %	6.2	9.1	8.6	42.7	50.6
^{134}Cs					
Range	0.72-0.86	0.73-1.06	0.79-1.17	0.78-1.15	0.462-1.21
Mean	0.809	0.848	0.979	0.947	0.865
Std Dev.	0.054	0.123	0.158	0.126	0.229
Variance%	6.7	14.5	16.1	13.3	26.5
^{241}Am					
Range	12.8-16.2	12.28-18.77	10.62-15.2	0-19.3	0-16.2
Mean	14.6	14.9	13.2	9.4	7.04
Std Dev.	1.20	1.95	1.42	5.96	5.85
Variance %	8.2	13.1	10.7	63.3	83.2
^{40}K					
Range	100.6-162	116-187	101-147	110-187	95.5-178
Mean	133.0	144.0	121.8	142.3	137.4
Std Dev	19.0	21.0	14.2	28.9	29.5
Variance %	14.3	14.6	11.8	20.3	21.5
^{214}Bi					
Range	2.74-5.46	29.2-4.69	2.70-4.20	3.25-5.07	3.13-5.47
Mean	4.19	4.13	3.38	3.88	3.78
Std Dev.	0.83	0.59	0.55	0.67	0.81
Variance %	19.7	14.3	16.4	17.2	21.4
^{208}Tl					
Range	1.34-1.97	1.69-2.05	1.45-2.09	1.69-2.22	1.36-1.84
Mean	1.67	1.89	1.72	1.83	1.58
Std Dev.	0.24	0.14	0.20	0.18	0.18
Variance %	14.4	7.39	11.5	9.8	11.4

Statistical counting errors were typically better than ±2-3% for all nuclides. The observed scatter in results within each shell of the hexagon is attributed to the combined effects of subsampling errors; in this case controlled to an estimated +-5-10% level by using the large diameter coring tool and grinding samples before measurement, and spatial variability. There is clear evidence for marked spatial variability, particularly for the anthropogenic nuclides, which show a marked increase in variance between the inner and outer shells. Calculations of the expected activity seen by a detector at different observational heights were performed, by weighting the spatial contribution of each shell in a manner appropriate to the contribution of this level to the field of view of the gamma spectrometer. This is illustrated below for 662 keV.

Table B.2 Illustrating the Spatially Weighted Mean Activities for ^{137}Cs at Caerlaverock Sampling site.

	Radius metres	Percent Weighting	Cumulative Percentage	Activity Bq/m2	St. Dev. 1 σ
Detector Height 1 m					
	0	10	10	86020	1727
	2	70	80	84039	5189
	8	17	97	83376	7515
	32	3	100	83360	7140
		Weighted Mean		**84104**	**5502**
Detector Height 50 m					
	2	2	2	84039	5189
	8	7	9	83376	7515
	32	48	55	83360	7140
	128	35	90	78754	33594
	256	10	100	39375	19907
		Weighted Mean		**79031**	**21531**
Detector Height 100 m					
	2	1	1	84039	5189
	8	2	3	83376	7515
	32	35	32	83260	7140
	128	80	45	78754	33594
	256	100	20	39375	19907
		Weighted Mean		**50852**	**25272**

The fall-off in anthropogenic activity levels away from the hexagonal centre results in a reduced expectation for activity detected with increasing aircraft height. The natural nuclides are more uniformly distributed, and therefore are not affected in the same way. The aerial measurements at the Caerlaverock site were taken at a range of altitudes. ^{137}Cs certainly showed a decreasing estimate at increased heights, after correction for air attenuation. By contrast estimates for natural nuclides were not affected in the same way. The core results will be discussed more fully in A.N. Tyler's forthcoming PhD thesis.