AN AIRBORNE GAMMA RAY SURVEY OF THREE AYRSHIRE DISTRICTS

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PREFACE

The decision in 1990 by three Ayrshire district councils to commission a comprehensive aerial survey of gamma ray activity within their areas marked the fourth anniversary of the Chernobyl reactor accident. It also reflects an increasing awareness both in local government and beyond of the importance of broadening knowledge and understanding of the environment, and in taking steps to ensure the present and future quality of the environmental heritage which is temporarily entrusted to the whole community.

Radioactivity is of course around us all the time. Traces of naturally radioactive potassium, uranium,thorium and their decay products occur ubiquitously in rocks, soils, building materials, foods, and people themselves. The upper atmosphere is continually bombarded with high energy subnuclear particles from outer space, leading to the production of a number of short lived cosmogenic nuclides, such as radiocarbon and tritium, and to a significant direct flux of secondary and tertiary cosmic rays at ground level. Primordial nuclides and cosmic ray products generate a substantial part of the natural background to which we are all exposed, and which has been the backdrop to the evolution and development of life on this planet.

More recently though anthropogenic activities have added significant quantities of radioactive nuclei whose ultimate fate frequently rests in the environment in one way or another. Atmospheric testing of atomic and thermonuclear weapons led to a marked increase in background radiation particularly in the 1950's and early 60's, the results of which could be measured globally. Harnessing nuclear energy, the use of radioisotopes in medicine, science, or for industrial purposes, the presence of nuclear powered satellites above us, nuclear submarines beneath our seas, and the ultimate fate of fissile and other active materials incorporated in atomic weapons, all carry long term environmental implications with local, national and international consequences.

The international nature of radioactive pollution was dramatically brought home by the accident at the Chernobyl power station in 1986, as was its importance at a local level when the fallout reached the UK shortly afterwards. Considerable public anxiety arose as the difficulties of obtaining reliable information and advice became apparent. Local and national authorities were inundated with requests for information which they largely did not have - particularly concerning the levels and effects of the fallout on a local scale. While these problems, which were by no means confined to the UK, stemmed partly from lack of planning for such eventualities, and partly to communication problems, they also arose largely from a dearth of reliable basic information on radiation levels and types throughout the country.

Provision of detailed monitoring data for a country with a landmass of more than 250000 km^2 at short notice is an impossible task using ground based monitoring or sampling methods. Moreover without detailed pre-existing baseline studies it is very difficult to establish clearly the extent of any change.

Recognition of the need for such baseline studies underpins this project, which therefore represents an investment on behalf of the three commissioning bodies in the future of their districts. The results will prove priceless if circumstances arise which change the radioactive environment. There are however more immediate benefits. As well as defining the overall quality of the radiation environment within the study zone, this work can be used to help plan and interpret detailed ground based investigations and other studies. Examples are radon monitoring and environmental health programmes including regular sampling conducted in collaboration with the Regional Chemist, with which the results are highly complementary. They also have considerable educational potential in indicating the origins and distribution of many significant components of environmental radioactivity, and the balance between natural and anthropogenic sources.

The decision to proceed with this work reflects both long term thinking and a commitment to open exposition of the environmental quality of the districts which is both commendable and rare. It is to be hoped that in addition to productive follow up work within the survey zones, this work can ultimately be extended to other districts in Scotland to form an extensive and unique regional environmental resource.

David C.W. Sanderson,
East Kilbride,
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The work itself would not have been successful without the outstanding contribution of Captain David Adams, PLM helicopters, whose aeronautical and logistic skills were once again the key to completion of the project on time and to cost. CAA air traffic control in Glasgow and Prestwick were extremely helpful in accommodating the somewhat unusual flight requirements of the survey. Arran Haulage are also to be thanked for assisting with fuel transport and for enduring an extremely dusty arrival at their depot.

Finally SURRC would also like to thank NEL for cooperation and help with helicopter operations in East Kilbride for the period of the survey.

SUMMARY

An aerial radiometric survey of Cunninghame, Kilmarnock & Loudon and Kyle & Carrick districts was conducted by SURRC from July 16th to 2nd August 1990. A 16 litre NaI spectrometer was used to map the distribution of radiation from ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl, and also to estimate the total gamma dose rate from all sources over an area of 2500 km^2. A helicopter, chartered from PLM (Inverness) ,was used to survey the districts at a height of 100m above ground, flight lines being spaced by approximately 1 km and oriented north-south within the study zone.

More than 6000 gamma ray spectra were recorded in the survey. Integrated count rates for each nuclide have been collated and calibrated to ground level area inventories based on a comparison between airborne and terrestrial gamma fluxes over sites of known radioactivity. Extensive field based studies were conducted in parallel with the aerial survey to support the calibration. Detailed colour contour maps show the distribution of radionuclides with roughly 1 km resolution throughout the area.

The survey is intended to provide a comprehensive baseline against which any future changes can be measured. In the event of any future nuclear accident it will be possible to state clearly what has been added to the existing background.

The variations in natural background sources have been defined and can be related to underlying geological features. Granite masses in the north of Arran and SW of Loch Doon show elevated levels of potassium, ^{214}Bi (denoting post-radon uranium series activity) and ^{208}Tl (from the decay of thorium). By contrast the ultrabasic rocks which occur on the mainland in all three districts show natural radioactivity levels between 5 and 10 times lower. Sandstone areas give intermediate results. ^{214}Bi is a radon daughter product which may be of value in indicating the variation in radon source term underlying domestic problems.

^{137}Cs has been mapped in detail. Peak fallout occurs principally in the SE of Kyle & Carrick (> 25 kBq m^{-2}),in parts of central Arran (>15 kBq m^{-2}), and more generally inland (> 10 kBq m^{-2}). Some coastal areas have been virtually unaffected by Chernobyl. Marine ^{137}Cs was detected notably on salt marshes near to the Irvine racecourse and on the Western coast of Great Cumbrae. Part of this inventory derives probably derives from Sellafield, and perhaps from Hunterston. Local sampling programmes here would be of interest. Close to the Hunterston "A" power station a small area with over 10 times natural gamma activity was encountered by helicopter. Scottish Nuclear were informed of these findings and conducted a prompt ground level investigation to identify the source of the activity, associated with an obsolete precipitator plant. This source of activity will be removed during decommissioning, and it is suggested that a repeat survey be conducted once this has been done.

Despite the presence of readily measurable anthropogenic sources in many parts of the three districts the overall environmental quality appears to be high. Natural sources account for the majority of the measured gamma ray dose rates, and the higher

activity rock types apparently occur in sparsely populated zones. Follow up studies to examine further details of these patterns at ground level, and to investigate domestic and urban contexts would be valuable. The archival results generated in this project represent a useful resource for such studies, and also secure the possibility of detecting future changes in the event of an accident involving significant quantities of radioactivity.

INTRODUCTION

Aerial radiation survey methods are based on the ability of gamma radiation - the most penetrating of nuclear radiations - to propagate up to a few hundred metres in air from the originating source of radioactivity. It is possible to monitor the flux of gamma radiation above ground or sea level using highly sensitive gamma ray spectrometry equipment mounted in aircraft flown close to the ground. Whereas environmental radioactivity measurements using portable field based spectrometers may take from 15 minutes to 30 minutes per site, or environmental soil cores extracted from single sites may take several days each to analyse, high volume aerial survey equipment can make sensitive readings every few seconds while moving on preset paths above the land surface. The net result of course is an immensely rapid and powerful environmental survey tool - which alone amongst survey techniques is capable of rapid, economical coverage of large zones with a high ratio of measured to unmeasured areas.

The principles of the method are not new, having been applied to uranium exploration and geological mapping for over 40 years [refs 1-10]. Much of the early work, discussed in more detail elsewhere [ref 11] was hampered by the limitations of bulky and crude detection equipment and the absence of low cost computing for map formation. More powerful geological aerial survey systems and procedures were developed in the 1970's [refs 12-17] specifically to improve the reliability and economics of uranium resource mapping. Geological equipment of this sort has also been used for environmental purposes, most notably in 1978 when the Cosmos 954 satellite deposited the contents of a nuclear reactor over the Great Slave Lake in northern Canada [ref 18,19]. Several thousand radioactive sources were recovered from a barely populated area over 1500 km by 300 km. Geological survey equipment was also used in an acclaimed rapid national mapping exercise undertaken in Sweden immediately after the Chernobyl disaster [ref 20].

Much confusion might have been avoided at the time, and also in the succeeding period had such techniques been available in the UK. This together with an awareness of the inherent difficulties of using conventional methods to map fallout on a national or regional scale prompted SURRC to examine the potential of developing aerial survey methods for highly detailed local mapping of natural and anthropogenic nuclides. Successful feasibility studies have been followed by a continuing programme of technical development and survey work [refs 21-25], aimed at developing the environmental applications of the method.

The decision to survey the districts of Cunninghame, Kilmarnock & Loudon and Kyle & Carrick, followed a series of meetings held in Ayrshire in 1989 and 1990. Outline definition of the project objectives, survey specification and timetable was agreed in late April 1990 as follows. The project aims were (i) to map the gamma ray background of the three districts, (ii) to provide an archival data base for future reference, and (iii) to report any features requiring further attention. The survey was to be conducted with 1 km line spacing and 0.5 km resolution along each flight line using an aerospatiale squirrel helicopter flown at 120 kph. An outline schedule was agreed comprising detailed planning in May and June, fieldwork in July and August, data collation and analysis to proceed through the autumn months with a view to preparation of maps and report at the end of 1990. It has been possible to keep to this schedule and the following sections outline the essential details of each stage.

FLIGHT DETAILS & FIELD WORK

Presurvey planning comprised definition of the target flight lines and scheduled timings which were marked on a series of 1:50000 OS survey maps covering the three districts. Figure 1 indicates the overall area being surveyed with target flight lines marked on. After consultation with PLM helicopters it was decided to operate the helicopter from the NEL site to allow for efficient detector operation and data transfers at the start and end of each day. Fuel was stored on site for daily use, Prestwick airport serving for re-fuelling during the southernmost survey reaches. It was also necessary to transport some fuel to Arran for use in the field. It was estimated that 50 hours of helicopter time would be needed, and that roughly three weeks of flight availability should cover the fieldwork allowing for reasonable expectations for weather. The helicopter was chartered from 16th July until 2nd August 1990.

The SURRC gamma spectrometer used for this survey comprised a 16 litre NaI detector array, a custom built high precision power supply, a data logging computer containing a dual channel pulse height analysis system and facilities for logging navigational data and height above ground from radioaltimetry. A Decca chain receiver and decoder was hired for the duration of the survey for incorporation into the spectrometer. Extensive laboratory bench tests were conducted to ensure that the spectrometer was in good condition before and during the survey. The equipment was installed in the helicopter on 16th July and tested briefly. The survey started fully on 17th.

Before each days flights the detector performance was rigorously checked, with particular attention to the energy resolution at ^{137}Cs, which was maintained at values from 9-11% (662 keV fwhm). Spectral gain was continually monitored using ^{40}K (1462 keV) in flight small adjustments being made for minor thermal drifts as needed. Gain drifts were kept below 1% throughout the survey.

During flights gamma ray spectra were recorded every 10s, and integrated to form spectral channels containing the gross count rates for ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl and an integral count rate representing the total hard gamma dose. ^{134}Cs integrals were recorded, however this short lived component in the Chernobyl fallout had already decayed beyond the detection limits from the air and is not therefore of further interest to the study. Both full spectra and integrated count rates were stored on hard disc during flights, and transferred to duplicated archival magnetic tapes at the end of each days flights. The tapes were checked each day using a ground based computer to ensure data integrity.

As an additional navigational check to provide a traceable record to cross check the Decca navigator a VHS video camera, kindly provided by the Glasgow University audio-visual service was mounted in the front of the helicopter and used to log selected parts of the flight paths.

A programme of ground based measurements and soil sampling was conducted in parallel with the flight programme to secure the basis of the aerial survey calibration. In making comparisons between ground based and aerial observation it is important to take account of the field of view of an airborne detector. Raising a detector above ground opens the detection geometry so that the area on the ground being sampled increases very rapidly. Typical areas of investigation are such as to give 90% of the detected signal from a circle diameter 4-5 times the height above ground [refs 26,27,28]. Thus each observation at a survey height of 100m is averaged over a circle of diameter 500 m. Care must be exercised in matching aerial and ground based results to avoid being misled by the difference in spatial response between ground based readings representing areas of a few square metres and those from the air representing up to 200,000 m^2. This can lead the inexperienced into difficulties of interpretation, especially where non-uniformity of radioactivity is encountered. Previous SURRC surveys have been calibrated to a carefully selected set of sites in the Solway region which have reasonably well characterised ^{137}Cs levels and show a good correlation from ground to air. It was possible to demonstrate concordance between this calibration and 1400 independent results collected by MAFF in West Cumbria in 1988 [ref 22]. To build upon this for other nuclides and over an extended range of soil types a systematic procedure was adopted to define a series of calibration sites under the Ayrshire survey.

Four sites were identified - at Myres Hill, near Eaglesham Moor, near the Raithburn Valley by Lochwinnoch, by the Leana burn in SW Kyle & Carrick, and on Arran near Drummadoon at Lakin Farm. On each of these sites a seris of three concentric arcs was defined at ground levels and a series of 17 spots readings with associated soil cores taken to define the average radioactivity at ground level in a manner which reflected the proportions of signal reaching the aircraft at survey height. The centres of the sites were marked and aerial survey readings taken while hovering at a series of different heights over each of the four sites at least once during the course of the survey. Comparison between the ground based and aerial readings for each of these sites provides a powerful means of checking the detector calibration without the potential problems of spatial mismatch.

The weather during the survey period was excellent and it was possible to complete all of the target flight lines within the allocated dates and within the flight time allowed for. The majority of the mainland was tackled first, with Arran being measured remarkably efficiently in just two days flying.

Towards the end of the survey , on 27th July a coastal line was flown in the neighbourhood of the Hunterston power station. Care was taken to avoid infringements of CAA navigation rules, and the flight path remained well clear of any structures and of the nuclear site itself. In the course of this flight however a narrow but intense radiation signal was encountered to the south of the Hunterston "A" station, and leading towards the summit of Goldenbury hill. On return to SURRC the energy spectrum from this source was examined and found to contain substantial ^{137}Cs and lesser ^{60}Co components - equivalent to more than 10 times the mean gamma ray activity of the surroundings. Apart from this feature the vicinity of the plant was notably within the range of natural levels. After consideration it was decided to consult the Safety Directorate of Scottish Nuclear to attempt to identify the source of activity and define any immediate actions which may be needed.

This was done by telephone on Monday 30th July, and elicited a prompt and positive response. It was suggested that the signal may have originated from precipitation plant originally used to decontaminate the Magnox fuel cooling pond during the stations earlier operations, and possibly projecting radiation signal over the site boundary fence. To evaluate this it was agreed that SURRC would conduct a repeat aerial survey the following day and that Scottish Nuclear would conduct measurements at ground level in the vicinity of the elevated readings. The outcome of both studies was to confirm the initial aerial observations, and the initial interpretation put forward by Scottish Nuclear. It appears that the activity is contained, on site. Furthermore the local topography apparently provides a degree of shielding, not available to the detector at higher altitudes, which partially mitigates the peak radiation dose rates off site. This combined with the inaccessibility of the location makes it unlikely that the source represents an immediate hazard to the general public. Nevertheless it is desirable that it should be shielded or removed to prevent this possibility entirely. Scottish Nuclear have supplied a statement (Appendix B) which clearly indicates an intention to do this during decommissioning of the Hunterston A plant, and this should resolve any remaining problem. We were most impressed by the prompt and serious manner in which the operators responded to our initial observations, and suggest that environmental officers from Cunninghame follow these findings up through the Hunterston local liaison committee.

Following this site specific investigation the integrity of the data set was checked once again and the helicopter discharged on the 1st July.

ANALYSIS & MAPPING

The analysis of the data set proceeded in separate stages leading towards the production of final maps. The first stage was to form compressed summary files collating individual readings and their corresponding positions and altitudes along each flight lines. The individual summary files were printed out and checked for any gross anomalies. Thereafter the survey area was split into three separate grids, to break down the task into subcomponents of manageable proportions. Grid 1 comprised the mainland south of an East-West line through Ayr, grid 2 comprised the mainland area to the north of this line, while grid 3 consisted of Arran, and Great and Little Cumbrae islands. The survey of all three areas comprised more than 6000 entries.

The summary files for each line were collated within the three grids to form area files, and at this stage the background count rate for the detector, recorded at high altitude or over clear seawater, was subtracted. Detector background rates are shown, together with other calibration constants in appendix A.

The next stage of the calibration procedure involved stripping the spectral interferences between adjacent channels using a matrix stripping technique. Pure energy spectra for each of the sources under investigation (^{137}Cs, ^{134}Cs, ^{40}K, ^{214}Bi(U series), ^{208}Tl(Th series)) were measured in the laboratory and used to define spectral stripping factors representing the fractions of each channel which are contributed to each other channel in the spectrum. The spectral stripping procedure involves multiplying the vector representing measured counts by the inverse of the stripping factor matrix (appendix A) to obtain pure count rates for each nuclide. The values of stripping factors for the detector array used were rechecked and found to be in agreement with previous determinations.

The altitude dependence of stripped count rates from each channel was determined by analyzing results from the four static calibration sites. For altitudes above about 20 m. and below 300m. an exponential altitude dependence gave extremely good fits to measured data. Empirically determined coefficients for such a function also corresponded closely with theoretical linear attenuation coefficients in air, especially for ^{137}Cs. The inevitable variations around the nominal survey height of 100m (typically +-20m) recorded by radioaltimetry during flight were corrected for using inverse exponential terms with the coefficients defined in appendix a.

Finally the stripped counts were converted to calibrated data - for each nuclide in kBq m^{-2} , for gamma dose rate in mGy/a - using linear equations derived by regression analysis of ground level concentrations against aerial observations for the four new calibration sites and for three preexisting sites. It is pleasing to note that the revised calibration is in line with earlier sensitivity estimates from previous studies, although each new observation adds to the confidence which can be placed on it. Again calibration constants are defined in Appendix A.

Archival records of the full calibrated data sets have been prepared and are lodged with each district environmental health office. The important caveats to remember are that each observation represents an average reading for an extremely large area, and that the results tabulated under ^{134}Cs are already below minimum detectable levels and therefore simply represent the residual unstripped interferences from other channels.

The calibrated data sets were used to produce colour contour maps, initially produced for each grid and for each nuclide, and then joined together in a graphics package before colour printing.

RESULTS & DISCUSSION

Figures 2 to 6 show the distributions of ^{137}Cs , ^{40}K, ^{214}Bi, ^{208}Tl and gamma dose rate throughout the areas, and will be considered individually.

^{137}Cs is a fission product with a half life of 30.25 years which has found its was into the environment from a number of pathways. Atmospheric testing of atomic weapons produce global fallout of which ^{137}Cs forms a durable component. The distribution of weapons testing Cs reflects the long term average rainfall pattern over many years. Although accurate and spatially detailed estimates are sadly not available from the pre-Chernobyl period those results which are available suggest that typical inventories of 2-5 kBqm^{-2} are the most that could be expected from this source in the survey zone. The other origins are from low level discharges to the marine environment from Hunterston, and from the much more significant discharges associated with nuclear fuel reprocessing at Sellafield particularly in the 1970's. Coastal areas and in particular an area of mudflats and salt marshes near Irvine, and part of the Western coast of Great Cumbrae appear to be affected to a greater degree than their surroundings from this source. Finally the Chernobyl accident deposited rather greater inventories of Cs and other nuclides in the course of only a few days - possibly even in single rain showers - leaving an extremely variable deposition pattern which can be seen in the maps. The high levels of ^{137}Cs to the SE of Loch Doon and in Central Arran are most probably derived from this source. It will also be noted that roughly half the survey are has received more than 10 kBq m^{-2} of Cs , but that the immediate coastal fringes appear to be less heavily affected. This may be a reflection of the rainfall pattern in the districts.

The natural sources of radioactivity all show combinations of behaviour which can be related to the underlying geology beneath the areas. A fuller discussion is presented in appendix C. It is however most notable that the granite areas show readily distinct signatures in all three natural nuclides, but also that sandstones, mudstones the ultrabasic rocks and the main fault systems running through the areas are all represented in the maps. It may also be noted that the overall activity of ^{40}K dominates most sites, although the gamma ray yield is low and that the ^{214}Bi is one of 8 associated disintegrations from the Uranium decay series which ^{208}Tl represents a 36% probability branch in the six nuclide thorium series decay chain. When all these factors are considered it becomes apparent that natural sources of radioactivity outweigh the anthropogenic components in most areas and produce the majority of the external radiation doses. This being so the overall quality of the radiation environment in these three districts is generally good, and should certainly not be a cause of immediate public anxiety.

Further environmental investigations of the distribution of radon in the areas would be of considerable interest particularly if coupled to a geological interpretation of the potential source term derived from these results. It would also be extremely interesting to examine the extent to which individual domestic radiation levels are correlated with those predicted from the remotely sensed external readings represented here.

As indicated above local factors at Hunterston may mitigate the potential effects of offsite radiation from the disused precipitator plant. The commitment to removing this feature during decommissioning the Magnox station is to be welcomed and it is suggested that consideration be given to a repeat survey once this has been done.

REFERENCES

[1] STEAD F.W. Airborne radioactivity surveying speeds for uranium prospecting, 1950, Eng. Min. J., 74-77.

[2] PEIRSON D.H. and FRANKLIN E. Aerial prospecting for radioactive minerals, 1951, Brit. J. Applied Physics, Vol 2.

[3] GODBY E.A. CONNOCK S.H.G. STEHLES J.F. COWPER G., & CARMICHAEL H. Aerial prospection for radioactive minerals, 1952, Atomic Energy of Canada Report 13.

[4] PRINGLE R.W. ROULSTON K.E. BROWNELL G.W. LUNBERG H.T.F. The scintillation counter in the search for oil, 1953, Mining Engineering, 1255-1261.

[5] PEIRSON D.H. and PICKUP J. A scintillation counter for radioactivity prospecting, 1954, J. Brit. Inst. Radio Eng., vol 14, 25-32.

[6] WILLIAMS D. and BISBY H., The aerial survey of terrestrial radioactivity, 1960, AERE report R-3469.

[7] WILLIAMS D. and CAMBRAY R.S. Environmental survey from the air, 1960, AERE report R-2954.

[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] 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.

[11] SANDERSON D.C.W., SCOTT E.M., BAXTER, M.S., 1990, Use of airborne radiometric measurements for monitoring environmental radioactive contamination, IAEA SM306/138, p411-421, International Atomic Energy Agency, Vienna.

[12] DARNLEY, A.G., Airborne gamma ray survey techniques, in Uranium Exploration Methods, 1973, IAEA, Vienna.

[13] GRASTY, R.L., Uranium measurement by airborne gamma-ray spectrometry, Geophysics, 40, 1975, 503-519.

[14] IAEA, Recommended Instrumentation for Uranium and Thorium Exploration, 1974, Technical report No 158.

[15] IAEA, Radiometric reporting methods and calibration in uranium exploration, 1976, Technical report No. 174.

[16] DICKSON B.H., BAILEY, R.C., GRASTY, R.L. Utilizing

multichannel airborne gamma-ray spectra, Can. J. Earth Sciences, 18(2), 1981, 1793-1801.

[17] GRASTY, R.L., GLYNN, J.E., GRANT, J.A.,The analysis of multichannel airborne gamma-ray spectra, Geophysics, 50(12), 1985, 2611-2620.

[18] 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.

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

[20] 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.

[21] SANDERSON D.C.W., SCOTT E.M., BAXTER M.S., PRESTON T., A feasibility study of airborne radiometric survey for UK fallout, SURRC report March 1988.

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

[23] SANDERSON D.C.W, SCOTT E.M., BAXTER,M.S., The use and potential of aerial radiometrics for monitoring environmental radioactivity, Institute of Civil Engineers, Nuclear contamination of water resources, 99-106, 1990.

[24] SANDERSON D.C.W., EAST B.W., SCOTT,E.M., Aerial radiometric survey of parts of North Wales in July 1989, SURRC Survey Report, East Kilbride.

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

[26] 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.

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

[28] LOVBORG,L., The calibration of portable and airborne gamma spectrometers - theory, problems and facilities, Riso report, R2456, 1984.

[25] GRASTY, R.L., The design, construction and application of airborne gamma-ray spectrometer calibration pads - Thailand, Geological Survey of Canada Paper 87-10, 1987.

APPENDIX A : CALIBRATION CONSTANTS USED IN AERO109

(i) Detector Background (161) /cps

	1	2	3	4	5
cps	43.34	20.94	19.09	9.56	8.42

(ii) Stripping Matrix

	1	2	3	4	5
1	1	0.33	0.54	1.52	2.67
2	0.07	1	0.98	0.99	3.51
3	0.0	0.02	1	0.161	0.22
4	0.0	0.0	0.0	1	1.77
5	0.0	0.0	0.0	0.06	1

(iii) Calibration Constants

	1	2	3	4	5	6
Slope	0.198	0.131	2.79	0.606	0.245	0.0007
Itcpt	-3.37	0.05	-9.6	-0.67	-0.2	0

(iv) Exponential Altitude Coefficients

	1	2	3	4	5	6
a /m^{-1}	0.00962	0.0075	0.006	0.0066	0.004	0.0062

AERIAL RADIOMETRIC SURVEY

During the implementation of the Ayrshire Baseline Coastal Survey by SURRC in late July 1990 an anomaly was discovered in the vicinity of Hunterston 'A' Power Station. At a height of 100 metres, a dose-rate of 5 milli-grays per annum was measured, about ten times higher than natural background. The source of radiation was identified mainly as Caesium 137.

On being advised of this finding Scottish Nuclear worked closely with SURRC to identify the source of the radiation.

Further aerial measurements by the SURRC complemented by dose-rate and activity measurements by SNL staff identified the source of radiation as residual radioactivity in a tall precipitator tower within the liquid effluent treatment plant at Hunterston 'A' Power Station which had been used in a continuous process for removing soluble activity from pond water to reduce radioactivity discharges to the sea.

During Station operation the levels would have been masked by radiation coming from reactor plant gas in its passage through the boilers. Now that the Station is shut down, the precipitator towers will be removed as part of the station decommissioning programme. The residual activity contributes negligible radiation dose to staff at ground level.

APPENDIX B : STATEMENT FROM THE SAFETY DIRECTORATE OF SCOTTISH NUCLEAR

7 December 1990
NSKM5013Q470(2)

APPENDIX C AYRSHIRE SURVEY

INTERPRETATION OF NATURAL ENVIRONMENTAL RADIATION

Introduction

When interpreting the radiological maps, especially in comparison with geological maps, certain environmental factors have to be taken into consideration. These include

a. Variation in the depth of overburden and soil type.
b. Variations in vegetation cover, ie. forest and farmland.
c. Glacial erosion and deposition.
d. Geometrical effects, due to valleys and ridges.
e. Bodies of water, ie. Loch Tanna on Arran.

In addition to the environmental factors, the data have been collected from 1km spaced flight lines, and smoothed by the mapping process, producing results of at least a 1km resolution. With such a resolution, the results obtained correspond and demonstrate well the main geological formations and structure of the survey area.

Arran

The radiological maps, demonstrate a area of very high levels of natural radiation (^{40}K=195.00 KBq, ^{214}Bi=11.38KBq and ^{208}Tl=4.55kBq) which dominates the northern part of the island. This corresponds to the Tertiary granite.

The Tertiary granite is surrounded by Dalradian metasediments of complex history. The metagreywackies to the north west are associated with particularly high ^{40}K (180 KBq) and ^{208}Tl (4.2 KBq), whilst the Dalradian slates to the north east are low in natural radionuclides. To the south are upper Devonian and lower Carboniferous sediment associated with low levels of radioactivity.

The geology of the rest of the island is dominated by the central ring complex of broken masses of Mesozoic sediments, Tertiary lavas, diorite and gabbro intrusions. To the south, the geology consists of Permian and Triassic red beds. This whole area have consistently low levels of radioactivity. The Tertiary red beds to the south west are associated with slightly higher levels of ^{208}Tl and ^{40}K. However, there are particularly high levels of ^{208}Tl and ^{40}K which correspond to Felsite outcrops around the southern part of the island.

Cunninghame and Kilmarnock and Loudon

There is a marked contrast in the distribution of radioactivity on either side of a line running from Johnstone, running south west through Lochwinnoch, to Ardrossan. This line corresponds directly with the Paisley Ruck Fault.

To the north west of the fault are predominantly low levels of radioactivity associated with the Permo-Carboniferous basic lava. The coastal areas have moderate levels of ^{208}Tl and ^{40}K which relates to the Devonian sandstone. High anomalies of ^{40}K and ^{208}Tl in the Hunterston area relate to Felsite (acid igneous) exposures in this area.

To the south east of this line are moderate values of ^{40}K and ^{214}Bi and high levels of ^{208}Tl. These areas relate well to the sandstone, siltstone and mudstones with coals, of the Namurian and Westphalian sections of the Carboniferous. Areas of lower natural radioactivity correspond to the basaltic lavas of the lower Carboniferous. These features extend south as far as Straiton.

An area of lower activity in the Tarbolton and Mauchline region correspond well to the Perm-Carboniferous dune bedded sandstone and basaltic lavas.

Kyle and Carrick

To the West of Straiton, the natural levels again drop demonstrating the transition from the Westphalian siltstones, mudstones and seat earths into the Dinantian limestones, calciferous sandstones and lower Devonian sandstones, and intermediate lavas just south of Ayr.

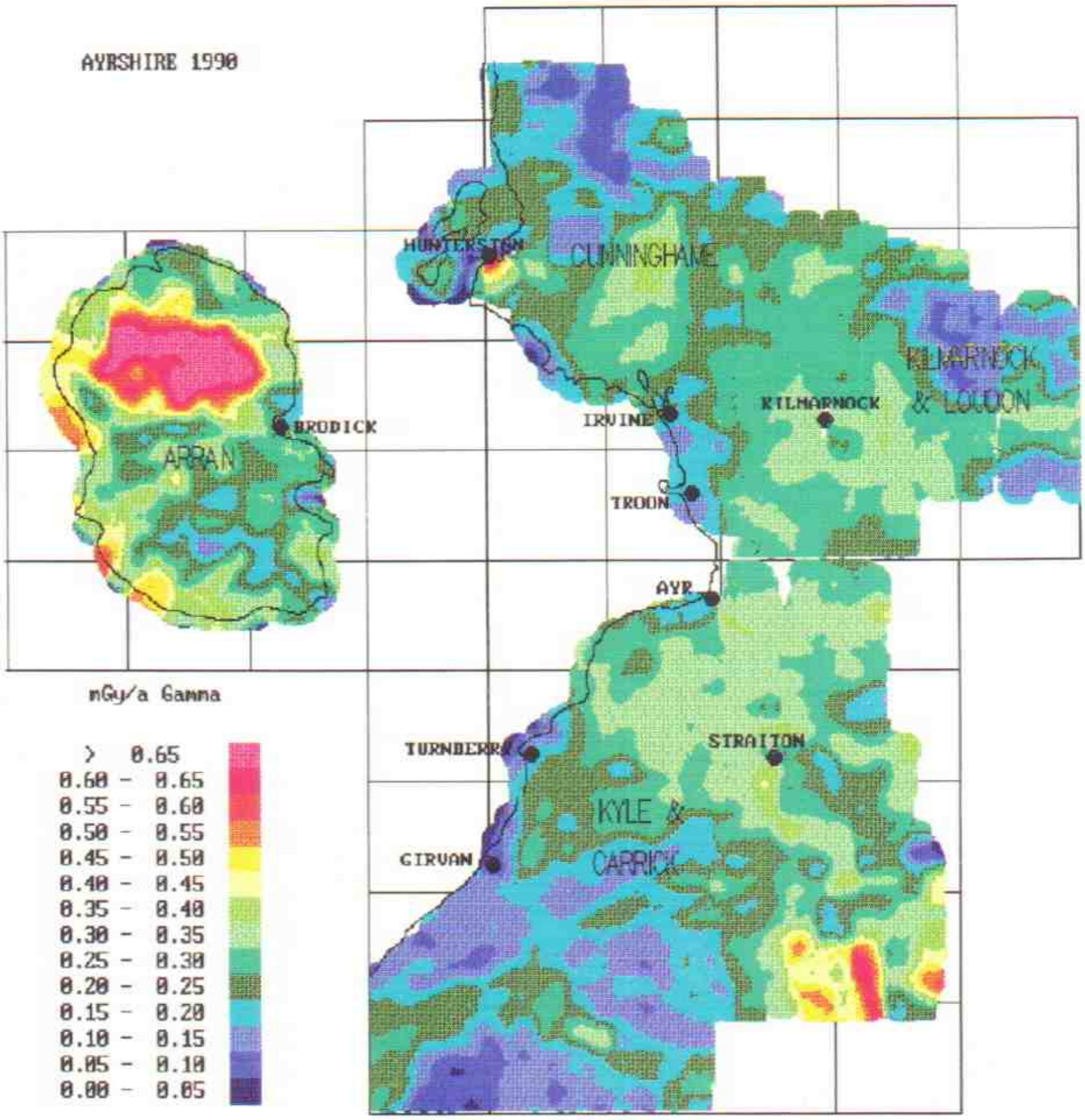
Features just south of the line between Girvan and Straiton are dominated by the Southern Upland Fault. South of Girvan the fault forms a 10km wide zone of parallel and sub parallel strike slip faults which runs south west into Ballantrae. This zone contains intermediate lavas and sandstone in the north east which merges into basic and ultra basic lavas in the south west. This whole zone is shown by a long zone with an especially signature of low natural radioactivity.

To the south east, the region is dominated by the Loch Doon granite and the Cairnsmore and the Carsphairn granite. The Loch Doon granite is mainly a biotite granite (high activity) and tonalite (intermediate) with an intervening transitional zone. This part produces a particularly high ^{40}K, ^{208}Tl and ^{214}Bi signature to the east. To the north west, the granite has norite (gabbroic) parts to it,producing a lower radioactive signature which is demonstrated well by ^{214}Bi and ^{40}K.

The Cairnsmore and Cairsphairn granite to the east of Loch Doon is a muscovite - biotite granite with a high radioactive signature. This is encircled by a lower activity granite - tonalite hybrid of lower activity which is demonstrated well by the radiation maps.

These granites have been intruded into Ordovician Caradoc and Ashgill shales, which is demonstrated by mudstones, shales and greywackes. These areas are predominantly low in natural radioactivity. The slight variation in the signature which does occur can be attributed to slight variations in rock type and variations in overburden thickness, such as peat.

LIST OF FIGURES



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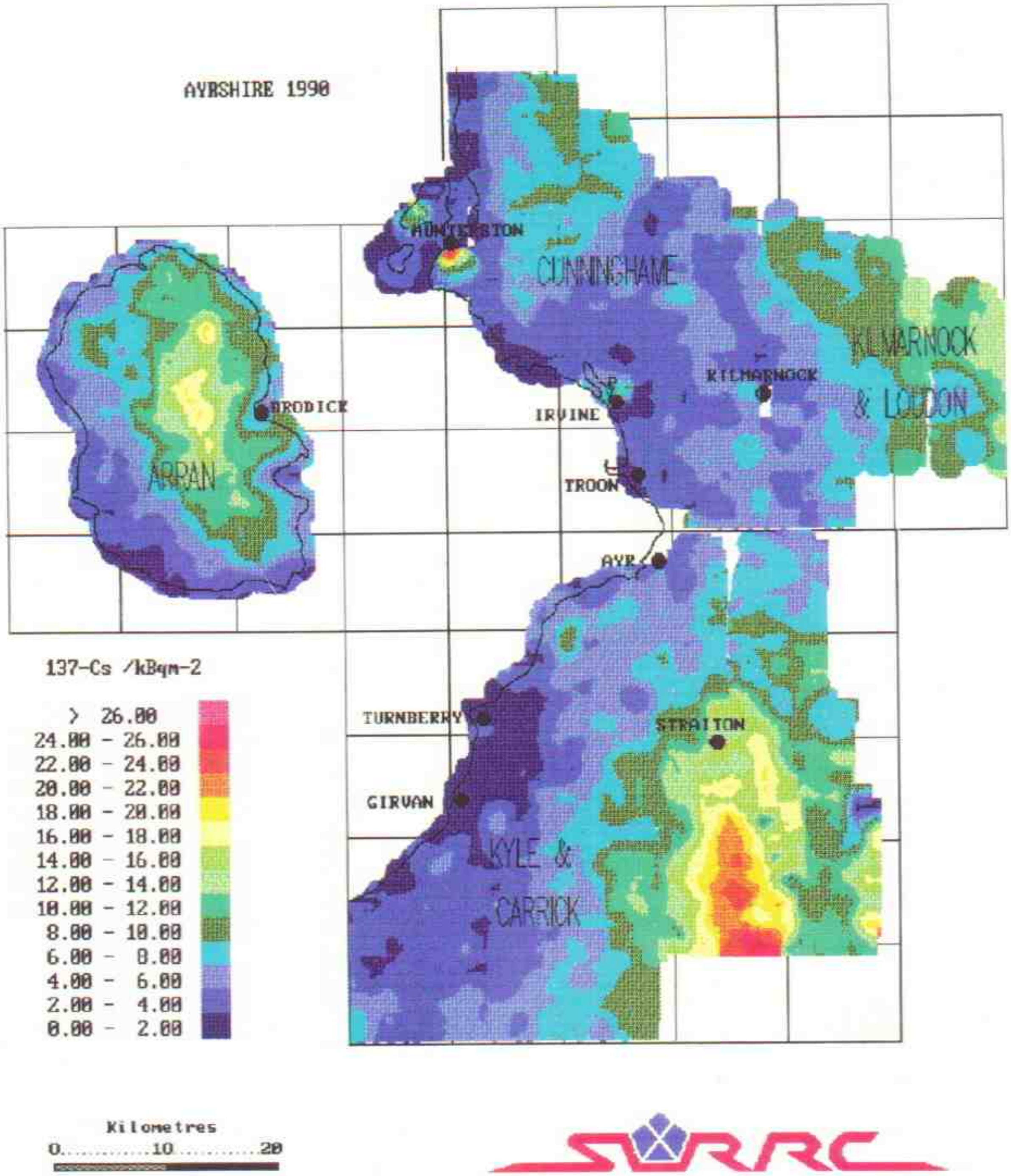
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KILMARNOCK & LOUDON
KILMARNOCK
BRODICK
IRVINE
TROON
ARRAN
AYR
TURNBERRY
STRAITON
GIRVAN
KYLE & CARRICK
137-Cs /kBqm-2
> 26.00
24.00 - 26.00
22.00 - 24.00
20.00 - 22.00
18.00 - 20.00
16.00 - 18.00
14.00 - 16.00
12.00 - 14.00
10.00 - 12.00
8.00 - 10.00
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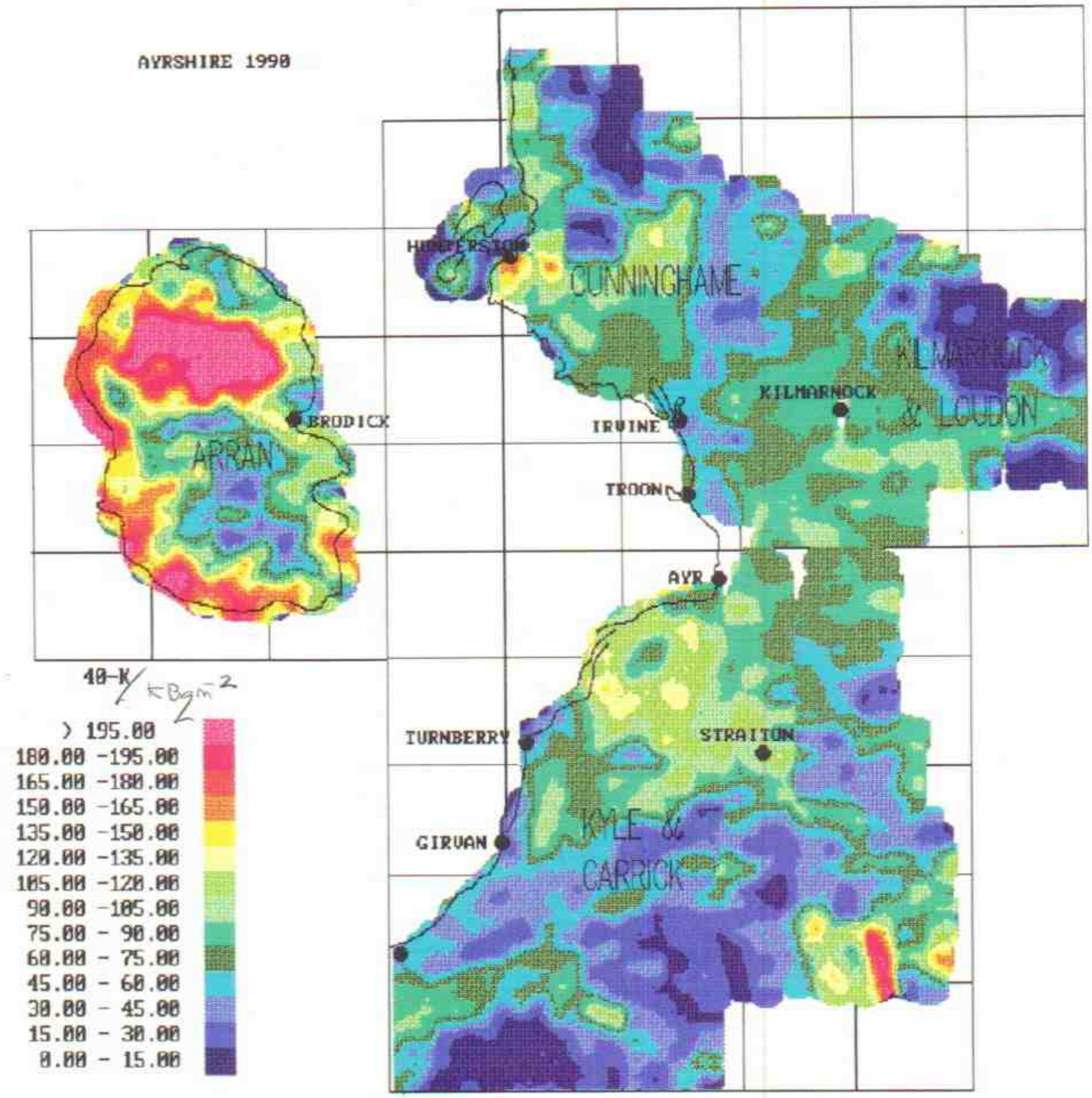

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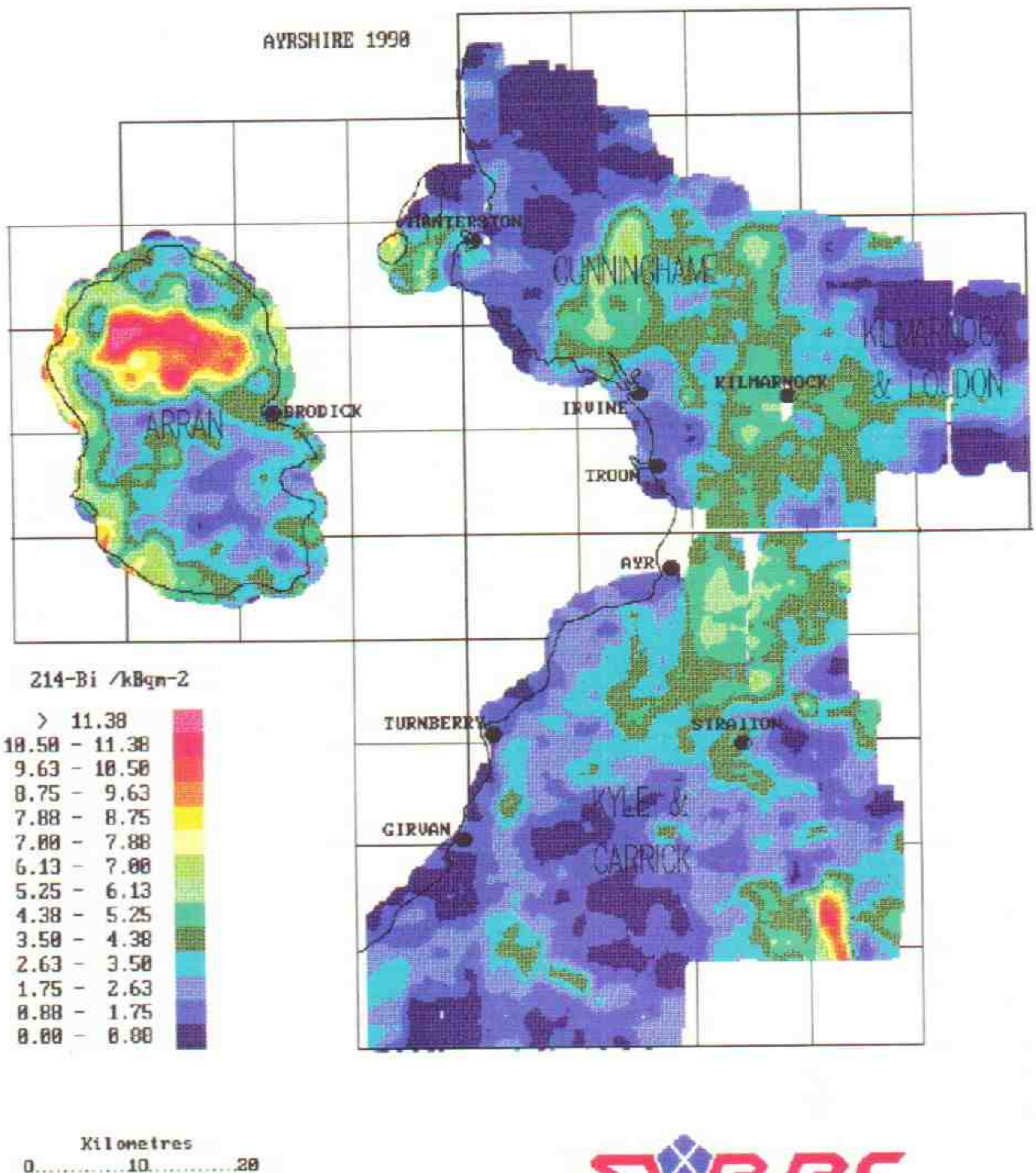
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KILMARNOCK
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AYR
ARRAN
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KYLE & CARRICK
TURNBERRY
STRAITON
GIRVAN
214-Bi /kBqm-2
> 11.38
10.50 - 11.38
9.63 - 10.50
8.75 - 9.63
7.88 - 8.75
7.00 - 7.88
6.13 - 7.00
5.25 - 6.13
4.38 - 5.25
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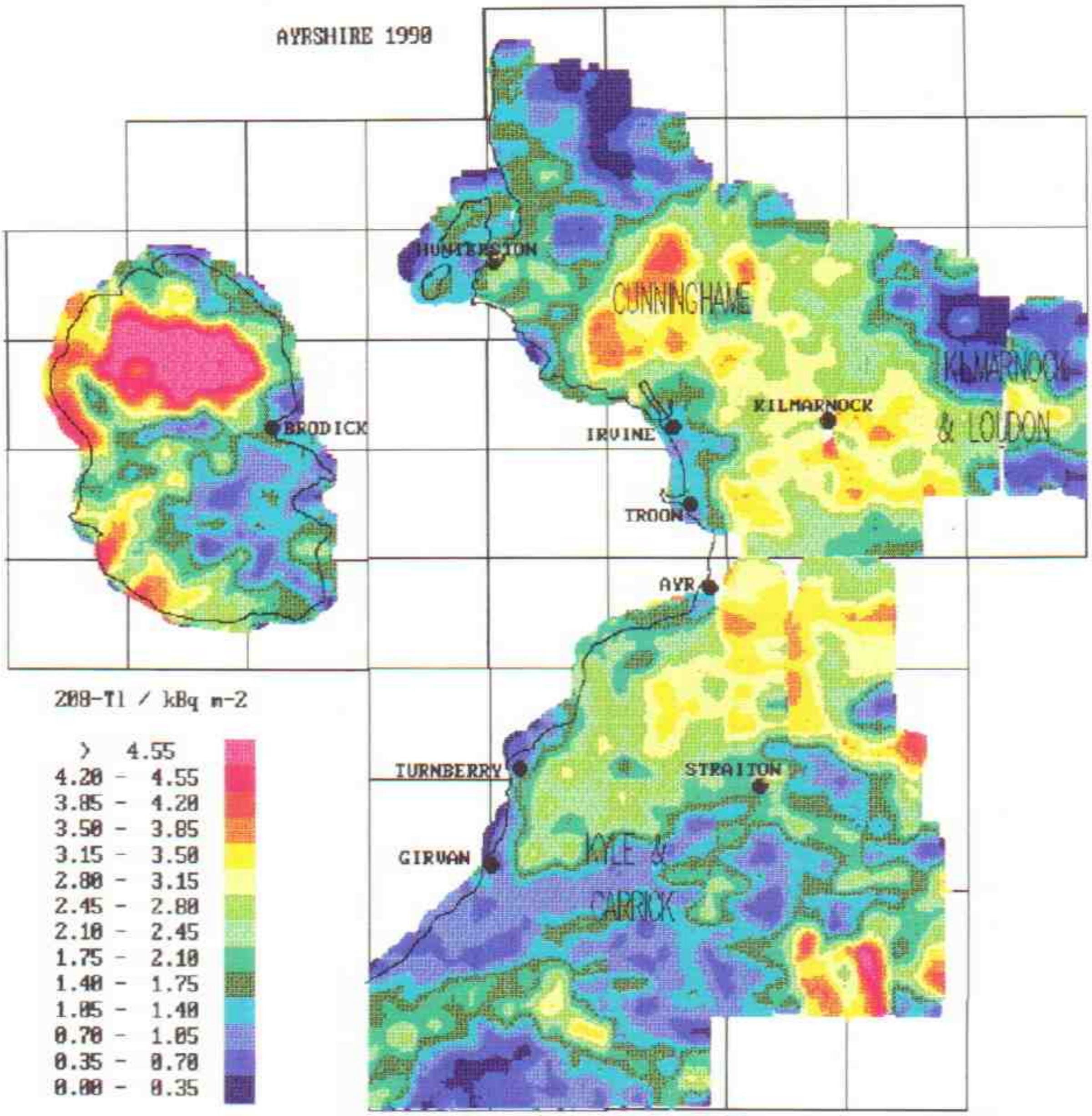

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