AUSTRALIAN NUCLEAR SCIENCE
AND TECHNOLOGY ORGANISATION
LUCAS HEIGHTS SCIENCE AND TECHNOLOGY CENTRE

A REPORT TO
WORLD GEOSCIENCE CORPORATION LTD.

on

AN ASSESSMENT OF THE ENMOS AIRBORNE GAMMA-RAY SPECTROMETER AND TECHNOLOGY

by

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November 1996

1.0 INTRODUCTION

Dr Nick Dytlewski and Dr Chris Waring visited World Geoscience Corporation's (WGC) offices in Perth on 24th and 25th July 1996 to assess the ENMOS system for environmental applications related to mining radioactive minerals and the nuclear industry. The ENMOS system represents the latest, commercially operating system for airborne radiometric surveys. It incorporates design features which utilise advances made in computer, and microelectronic technologies over the past years for data acquisition and processing. WGC has carried out an airborne radiometric survey of the RUM JUNGLE site using this system.

Other persons present at the briefing given by WGC were:

Tony McGill (Northern Territory Department of Mines and Energy)
Julian Glynn (Aerodata Holdings)
Bohuslav Pavlik (Picodas Group)
Greg Street (WGC)
Paul Roocke (WGC)
Pavel Jurza (WGC)
P. Robert Groves (WGC)

In the 1970's, gamma-ray surveys were carried out without a consistent methodology, making standardisation of data and intercomparisons difficult. A standardised methodology was recommended in 1976 in the IAEA Technical Report Series No. 174, which was subsequently revised in 1979 (IAEA Technical Report Series No. 186) and again in 1991 (IAEA Technical Report Series 323). These now provide internationally accepted standards for airborne gamma-ray surveys.

Airborne surveys have predominantly been driven by the need for geological resource mapping in which the distribution of the natural radionuclides potassium, uranium and thorium are measured. As a result of the accidents at Chernobyl and Three Mile Island, there is a need to extend airborne surveys to measure man-made radionuclides such as ^{137}Cs and ^{60}Co that might be emitted in nuclear accidents. In addition, dose rate maps are increasingly needed for environmental monitoring and baseline studies.

The airborne data for man-made radionuclides can be processed in the standard way as recommended by the IAEA, however the depth and spatial distributions of man-made radionuclides can be different from those typically found for natural radionuclides, and so the conversion factors for deriving a surface activity must be estimated. For man-made radionuclides, there is as yet, no recommended methodology.

Older gamma-ray data acquisition systems typically featured multiple NaI detectors whose outputs were summed together into a single data stream, which was then processed into a spectrum usually comprising 256 channels of data. The main difficulty with this type of system was that the gains of the individual detectors varied with temperature and it was necessary to heat the system to a constant temperature in order to control the drift in gain. Another problem with the older systems was the high count rates from summing the detector outputs that lead to significant dead-time corrections. In addition, because the processing system was essentially hard-wired and required manual calibrations, there was only limited scope for in-flight for adjustments of the spectrometer system.

2.0 THE ENMOS SYSTEM

The ENMOS system is a gamma ray spectrometer system which incorporates real time navigation, data acquisition and collection of gamma ray data using a Picodas gamma (PGAM) spectrometer. The PGAM spectrometer has a separate data processing system for each NaI detector, each with data conversion into a spectrum of 1024 channels.

The signals from each of the NaI detectors are processed by an ADC flash converter with a conversion time of approximately 0.6 μs. The dead-time for individual detectors is approximately 3 μs, which for a count rate of 30 kHz in a single detector produces a dead-time of about 10%. The dead-time of an individual detector does not affect acquisition by other NaI detectors in the system. Thus, for most applications, the effect of dead-time in the PGAM spectrometer will be small. In addition, anti-coincident circuitry is used to remove coincident pulses due to Compton scattering from different detectors.

On-board computer processing is used to provide real-time gain control and spectral alignments, which avoids the need for good temperature control of the detectors. Spectra from individual detectors are acquired and the positions of peaks from selected isotopes (such as ^{40}K, ^{214}Bi and ^{208}Tl likely to be present in all spectra) are determined. From these peak positions, non-linear corrections are made to digitally align the separate spectra, which are then stacked together. This method produces a resultant spectrum with a better resolution and lower dead-time than older systems. The use of a computerised system for gain control and data collection also has the advantage that the software source code can be readily modified to suit other requirements.

During measurements, data is acquired in intervals of one second. Tests performed on the PGAM system, as per IAEA guidelines, indicate that for count rates up to 30 kHz in a 4 detector (NaI) configuration, the system has 100% accumulation time for the 1 second period. There is no lost information due to the system being busy, in acquiring and processing the collected data. This data is then stored and stamped with altimeter reading, time, GPS position, etc.

Real-time processing allows data to be viewed by the operator and/or pilot of the aircraft as it is acquired. If anomalies are detected, they may be tracked and checked during free flight. This tracking capability could be used for following a radioactive plume emitted from a nuclear incident, or for other transient radiation events.

2.1 Data Processing

The procedure developed by World Geoscience Corporation (WGC) utilises the full spectrum of radiometric data collected. Monte-Carlo calculations of the photon transport from expected radionuclides on the ground, interactions in the air column and interactions in the PGAM spectrometer are used to derive a set of unit response spectral functions for particular radionuclides and particular altitudes. These unit responses are fitted to measured spectra to derive the count rate for each radionuclide. This procedure utilises all peaks in the gamma spectra from a particular radionuclide or chain or radionuclides and the associated Compton scatter distribution. The same procedure is applied both to man-made and naturally-occurring sources.

The methods of data reduction used by WGC (determination of spectral stripping factors, variation with altitude, attenuation coefficient of air, detector sensitivity, etc) follow the internationally approved methodology as recommended by the IAEA, and will not be discussed further here. WGC has adequate knowledge of these protocols, the assumptions contained within them, and their limitations.

For each spectrum, the signal is assumed to result from a uniform distribution of radionuclides on the ground. This is reasonable for natural radionuclides, in areas of low topographic relief, but might not be the case for man-made radionuclides that reside in specific locations such as reactors, isotope processing lines and in storage facilities. Furthermore, the activity distribution of man-made radionuclides released in accidents can be highly localised. Thus the activity distribution for man-made radionuclides may often be more equivalent to point or line sources rather than an infinite plane. In the transformation from airborne survey data to ground location maps, this localisation effect may have the effect of modifying the intensity of features, and distributing them over a wider area than in reality. However it is, in the absence of other methods, best to follow existing procedures used for natural radionuclides.

Conversion from corrected airborne count rates to ground activity (Bq/m^2) or dose rate (μGy/h) requires an assumption on the depth distribution of the radionuclides. WGC uses two depth distribution models, a thin surface layer model for deposits of man-made (artificial) radionuclides and a uniform with depth model for naturally-occurring radionuclides. Under the assumption of a thin surface layer, the surface contamination from man-made radionuclides produces a uniform hemispheric distribution of gamma flux above the ground. In contrast, the homogeneous-with-depth distribution used for natural elements produces a cosine distribution above the ground. There is also a difference in the how the ground activity is expressed, for man-made radionuclides where the level of contamination would be of concern, the ground activity per unit area (Bq/m^2) is derived, whereas for naturally occurring radionuclides the ground activities per unit mass or volume is derived.

The depth distribution of radionuclides will affect the derived dose rates, particularly for radionuclides which emit gamma rays of different energy. Absorption and scattering within the soil column will reduce the flux of lower energy gamma rays emanating from the soil surface. This would change the factor used to derive the ground level dose rate from the airborne survey.

From the grided raw data, WGC use smoothing and interpolation routines to produce contour maps of radionuclide surface activities (Bq/m^2) and dose rates (μGy/h). Using advanced image reconstruction algorithms, WGC produce sharper images from the measured smoothed images, which produces radionuclide distribution maps more closed aligned to reality.

The accuracy of the absolute, quantitative values of surface activity or dose rate will depend on the locality and seasonal conditions as no *a priori* corrections are available for soil depth profiles, topographic relief, vegetation cover and soil moisture content. If an airborne survey is to be used to establish environmental radiation baseline conditions as part of an ongoing monitoring program, it would be necessary to establish the soil moisture levels at the time of the radiometric survey and ensure that similar soil moisture conditions existed at the times of repeat surveys. Soil moisture can vary the radiometric response, particularly in monsoonal Northern Australia.

3.0 AIRBORNE SURVEYS

3.1 Rum Jungle Survey

WGC carried out the survey of Rum Jungle in July 1996 following discussion with ANSTO staff. The images produced by WGC clearly show elevated count-rates around the Rum Jungle mine site, Rum Jungle South Mine and the East Branch of the Finniss River downstream from the confluence with Old Tailings Creek, Figure 1. Elevated uranium daughter concentrations in the East Branch of the Finniss river is probably due to accumulation of weathering products from before mining, or tailings washed into the river during operation of the mine.

WGC used the count rates from the various radionuclides to derive the dose rates in nGy/h at ground level, Figure 2. This map shows that the dose rates at the site are comparable to the natural activity at many locations in the region.

Evidence of the effectiveness of the image reconstruction algorithms is seen in the Rum Jungle maps. Figure 3 superimposes the dose rate contours onto an aerial photograph of the Rum Jungle site taken in April 1988 after the completion of the rehabilitation project. There is no significant “shadowing” away from known features, and the shape of the features on the survey shows a good match to features on the aerial photograph. In particular the two water filled open cuts (appear dark grey to black on the aerial photo) are well delineated as having very low dose rates on the derived dose rate contours.

Figure 3 also shows that the areas subject to remediation, the Old Tailings Dam, Intermediate Overburden Heap, Whites Overburden Heap, Dysons Opencut (now filled with tailings and covered) and Dysons Overburden Heap all show relatively low dose rates. [Figure 4 is a plan of the Rum Jungle site after rehabilitation showing the locations of the various features.]. Higher dose rates occur over the Acid Dam, and unrehabilitated areas such as that between White’s and Dysons opencuts. Some of these areas are covered with vegetation. The higher dose rates in these area is either due to the original geological anomaly or to dispersion of material during the mining and processing operations. The dose rates in these areas are comparable with the natural background radiation over a large area east of the Rum Jungle mine site, Figure 2.

3.1 Comparison of Rum Jungle Survey with Ground-based Measurements

Some comparison between the absolute values of the dose rates as deduced from the airborne survey with ground measurements at the Rum Jungle Creek South site were made possible with data provided by Tony McGill. At spot points, agreement appeared to be in the range of 20 - 30%.

Since the briefing, Dr John Harries measured radiation dose rates at a number of locations at the Rum Jungle mine site. The survey was carried out on 22 August 1996 using a Eberline ESP-1 radiation survey meter (serial number 03486) with a HP-270 general purpose G-M probe (serial number 719311) with energy compensation. The probe has a relatively flat response that rapidly drops off below 40 keV. At 40 keV the response is 80%. The survey meter was hand-held at waist height for the measurements. The instrument calibration was checked at ANSTO after the survey using a caesium-137 (661 keV) dose rate calibration system.

The dose rate was measured for 500 m along a track which crosses the Rum Jungle site north-west from White's Opencut, across the rehabilitated stockpile area and into the undisturbed vegetation. At each location, counts were accumulated for five or more successive 36 second periods (0.01 hour). The total counts for each 36 second period were averaged, and converted to dose rate using the conversion coefficient for the probe and the results expressed in μGy/h.

The results from the ground based survey were compared on Figure 5 with results taken from dose rate contours provided by WGC (Paul Roocke fax to John Harries on 24 September). There is a good general agreement in the shape of the profile between the ground based measurement and the airborne survey along the transect, but the ground measurements were about double the dose rates derived from the airborne survey. Part of the discrepancy is due to cosmic rays, which contribute about 0.04 μGy/h to the ground survey but are not included the airborne survey results.

The ground based measurement is a very localised measurement, collecting data from a few metres around the measurement location. This could present problems at a site like Rum Jungle where there are clearly large variations in dose rate over relatively small distances. Another effect which could lead to higher ground-based dose rate measurements would be if the radionuclides were mainly in a surface layer rather than the distributed with depth. The airborne study principally records gamma rays above 500 keV and derives doses based on the known decay chains, whereas the ground based survey is more sensitive to lower energy gamma rays emitted by the radionuclides. Correlating the two measurements requires assumptions on how the radionuclides are distributed with depth.

It is clearly important to undertake a more extensive comparison between the dose rates derived from the airborne measurements and ground based dose rate measurements, preferably in an area with a more uniform distribution of radionuclides than the abandoned Rum Jungle mine site.

3.2 Other Airborne Surveys

WGC have surveyed the site of the Ontario Hydro Bruce and Douglas Point Nuclear Power Plants in Canada. This site has eight operating CANDU reactors, grouped into two banks of four reactors (BRUCE 1-4, and BRUCE 5-8) with generating capacities in the range 800-900 MWe. The nearby Douglas Point power plant is shut down.

The high energy gamma ray map (normally used to record cosmic rays) of this site shows gamma rays clearly coming from the two operating Bruce nuclear power plant banks. These high energy gamma rays are emitted in the decay of the activation product ^{16}N ($T_{1/2}$ = 7.3 s) which is created from fast neutron reactions with the cooling water in the reactor core, $^{16}O(n,p)^{16}N$. The decay of ^{16}N produces two gamma-rays of energy 6.13 MeV and 7.11 MeV. The activity distribution map clearly indicates that there are more than two reactors operating within each reactor complex, but because the reactor separations are smaller than the spatial resolution of the aerial survey, it is not possible to identify how many reactors were operating at the time.

As well as the Bruce reactors, the dose rate map showed gamma rays originating from the closed Douglas Point station and other buildings indicating other nuclear activities. The spatial definition was sufficient to associate the elevated count rates from the airborne survey with particular buildings on the aerial photograph. Radiation levels returned to background levels 100-200 m beyond these buildings. This was also the case for the ^{137}Cs and ^{60}Co distribution maps. The ^{40}K and dose rate maps showed a large variability in the fields of the surrounding agricultural land, probably indicating the effects of differing soil moisture content from differing land usage and the addition of fertiliser. Local farmers had claimed that their fields were affected by the nearby nuclear power stations. The surface activity and total dose rate maps from the airborne survey suggests that the slightly elevated radiation levels in their fields was not related to the proximity to the nuclear facilities.

ANSTO also reviewed some WGC surveys from European facilities. Results were consistent with what would be expected from the known operations of those facilities. One effect noticed was a distinctive “skyshine” effect at one location, where a high activity source was located below ground level, but the storage location has only minimal overhead shielding in the roof. This produced a halo of Compton scattered radiation around the location.

With the enhanced resolution of the airborne ENMOS gamma-ray survey system, WGC have been able to detect ^{41}Ar emissions in the presence of ^{60}Co. This is achieved by removing the two ^{60}Co peaks from the recorded spectra (at 1.17 MeV and 1.33 MeV), leaving the 1.29 MeV signal from the decay of ^{41}Ar. This flexibility in the ENMOS system has considerable advantages in enabling certain man-made radionuclides to be targeted for investigation.

4. CONCLUSIONS

The ENMOS technology represents a significant improvement in instrumentation and data processing. This has been achieved by applying methods made possible by advances in microcomputer technologies. The enhanced capability over previous systems, enables a wider and more diverse range of measurement information to be collected, which in turn, permits new applications of airborne surveys to be explored.

If ground level dose rate measurements are required, there is need for ground based confirmation of the factors used to convert the activity levels as measured by the airborne equipment to dose rates on the ground. It would be worthwhile to check these conversion factors in a range of field situations in Australia.

The ENMOS system has the capability to have worthwhile applications in environmental monitoring around nuclear facilities and mines managing radioactive materials. A comparison of surveys made before and after any activities, would provide a direct measure of any changes in dose rate or distribution of radionuclides over the site. Any unexpected anomalies detected by the airborne survey could be investigated and resolved by ground measurement and sampling. The airborne surveys can also place measured radiation levels at facility sites in the context of general background radiation levels in nearby unaffected areas.

5. ACKNOWLEDGMENT

We gratefully acknowledge the contribution of Stuart Hankin in preparation of the images.

Figure 1. ENMOS radiometric data of Rum Jungle region showing distribution of uranium mass activity (Bq/kg)

Figure 2. ENMOS radiometric data of Rum Jungle region showing derived dose rate in nGy/hour.

Figure 3. Contours of dose rate derived by WGC superimposed on an aerial photograph of the Rum Jungle mine site taken in April 1988 after completion of the rehabilitation project.

Figure 4. Site Plan of the Rum Jungle mine site after completion of rehabilitation (from Final Project Report of the Rum Jungle Rehabilitation Project, NT Department of Mines and Energy, 1986)

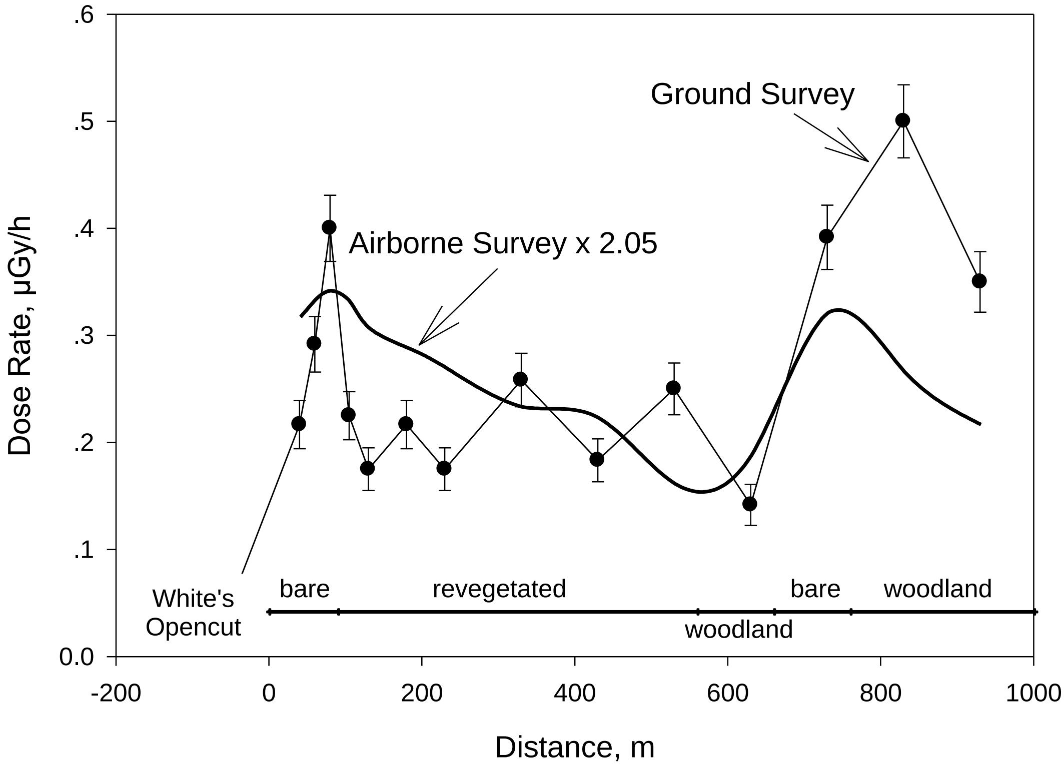

Figure 5. Comparison of Airborne and Ground-based Dose Rates along a Track across the Rum Jungle Mine Site (airborne results normalised to ground results)