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AN AERIAL RADIOLOGICAL SURVEY OF THE MONTICELLO NUCLEAR POWER PLANT AND SURROUNDING AREA

MONTICELLO, MINNESOTA

DATE OF SURVEY: OCTOBER 29 - NOVEMBER 2, 1996

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H. W. Člark, Jr., Manager Radiation Sciences Section

ABSTRACT

Radioactivity surrounding the Monticello Nuclear Power Plant was measured using aerial radiological surveying techniques. The purpose of this survey was to document exposure rates and identify radiation sources within the survey area. The surveyed area included a 25-square-mile (65-square-kilometer) area that encompasses the plant site of which a large portion is located in the Mississippi River Basin. Data were acquired using an airborne detection system that measures gamma radiation. Exposure rates were computed from these data and plotted on a U.S. Geological Survey topographic map of the survey area. Estimated exposure rates in areas surrounding the plant site varied (a) from 6–8 microroentgens per hour (μ R/h) in the Mississippi River Basin and (b) below 6 μ R/h over the Mississippi River and portions of its basin that were included in the survey area. Man-made radiation (22–1,600 μ R/h) was found at the plant site; nitrogen-16 was the primary source of activity found at the Monticello Nuclear Power Plant. No other detectable sources of man-made radioactivity were found. Estimated exposure rates measured in the area surrounding the site during this survey agreed well with those measured during the 1970 preoperational survey even though the survey methodology and parameters were significantly different.

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1.0 INTRODUCTION

An aerial radiological survey of the Monticello Nuclear Power Plant and surrounding area was conducted by the Remote Sensing Laboratory (RSL) for the U.S. Nuclear Regulatory Commission during October 29 through November 2, 1996. This survey is part of an ongoing effort to characterize radiation levels surrounding commercial nuclear power plants. Commercial plant sites are surveyed prior to initial criticality and periodically thereafter until the plant is decommissioned and the site is returned to nonnuclear uses.

The Monticello Nuclear Power Plant is a boiling-water reactor having a capacity of 1,670 megawatts thermal and 545 megawatts electrical. The plant is operated by the Northern States Power Company. The plant began operating in 1971; a preoperational aerial radiological survey was conducted in 1970.¹

The survey consisted of aerial measurements of gamma radiation emanating from the survey area. The purpose of this survey was to measure the exposure rates in the area previously described and to determine the contributing isotopes. Results are reported as (a) color-coded radiation isopleths superimposed on a topographic map of the area and (b) gamma energy spectra of the contributing isotopes that were detected.

The RSL performs various types of radiological surveys for the U.S. Department of Energy (DOE) and other customers. The RSL capabilities include an airborne radiological surveillance system called the Aerial Measuring System (AMS). Since its inception in 1958, the AMS program has carried out radiological surveys of nuclear power plants, processing plants for nuclear materials, and research laboratories. The AMS aircraft have been deployed to nuclear accident sites and in searches for lost radioactive sources. The AMS aircraft also fly mapping cameras and multispectral camera arrays for aerial photography and thermal mappers for infrared imagery. Survey operations are conducted at the request of various federal and state agencies.

2.0 SURVEY SITE DESCRIPTION

The Monticello Nuclear Power Plant is located on the bank of the Mississippi River, 6.5 mi (10.4 km) northwest of Monticello, Minnesota. Nearby towns (within a 20-mi [32-km] radius) include Hasty, Becker, Enfield, Big Lake, St. Cloud, and numerous small communities. Coordinates for the plant site are latitude 45°19'57" N and longitude 93°50'28" W. The elevation in the area averages about 800 ft above mean sea level (MSL) in the river basin and 1,000 ft above MSL outside the basin. Figure 1 shows the plant site and survey boundary. The 25-sq-mi (65-sq-km) area is comprised predominantly of farmlands including large crop fields and numerous dairy farms. Appendix A provides a summary of the survey parameters.

The topography consists of mostly flat lands with some gently rolling terrain, a portion of which includes the Mississippi River Basin. Most of the area has been developed for townsites and farms. During this survey period, the trees had lost most of their foliage, and the underlying vegetation was mostly dormant. Several types of crops were being harvested; fields were also being plowed.

3.0 SURVEY METHODS

Standard aerial radiation survey techniques developed for large-area gamma radiation surveys and discussed briefly in this report were used.² The survey methodology has been successfully applied to more than 300 individual surveys at various locations stateside and abroad beginning in the late 1960s.

3.1 Aerial Radiation Measurements

This survey was conducted to collect gamma radiation data over an area comprising 25 sq mi (65 sq km) of the Monticello Nuclear Power Plant and surrounding area using a sodium iodide, thalliumactivated, NaI(Tl), gamma-ray detection system mounted on a Messerschmitt-Bolkow-Blohm (MBB) BO-105 helicopter (Figure 2). The system was flown at an airspeed of 80 mph (36 m/s) and at an altitude of 150 ft (46 m) above ground level (AGL). The survey consisted of 104 parallel flight lines spaced 250 ft (76 m) apart, entailing 520 flight-line mi (832 flightline km). Information pertaining to the position of the aircraft was provided by the Global Positioning System (GPS) with a real-time correction for selective availability input to the Radiation and Environmental Data Acquisition and Recorder, Version IV (REDAR IV).3 Real-time altitude measurements were also made through a radar altimeter that measured the return time for a pulsed signal and converted this delay to aircraft altitude. For altitudes up to 2,000 ft (610 m), the manufacturer's stated accuracy is ± 2 ft (0.6 m) or ± 2 percent, whichever is greater. Altitude







FIGURE 2. MBB BO-105 HELICOPTER WITH DETECTOR PODS

data were also recorded by the data-acquisition system so that variations in gamma signal strength caused by altitude fluctuations could be identified.

3.2 System Characteristics

The diameter of the detector's footprint or field of view is several times the survey altitude. The data are collected during each second of flight, using the survey parameters previously described. For example, the count rate for a single datum point is the averaged count rate measured within an area having a radius of about 600 ft (183 m) for an average gamma-ray energy of 1,250 keV.

Because of the large footprint, localized or point sources detected by the aerial system, especially those with high intensity and distributions much less than the footprint, appear to be spread over a much larger area than would be indicated by ground-based measurements. Such localized sources were detected at the Monticello Nuclear Power Plant.

For uncollimated detectors such as those used in this aerial survey, the source-to-detector distance and the attenuation by the air effectively limit the field of view to a circular region directly beneath the detector. The size of the field of view is a function of the gamma-ray energy, the depth of the gamma-ray emitter in the ground, and the detector's response. Radionuclide activities on or in the soil and exposure rates normalized to 1 meter AGL are customarily reported but only as large-area averages. Activity inferred from aerial data for a source uniformly distributed over an area much larger than the footprint of the detectors generally agrees well with ground-based measurements. However, the activity for a point source, a line source, or a source area less than the detector's field of view will be underestimated, sometimes by orders of magnitude. When this occurs, the aerial data simply serve to locate and identify such sources within the limits of detectability for the system.4

Apparent source broadening makes comparison with ground-based measurements difficult for localized or point sources. Radionuclides that occur as hot particles are averaged by the aerial detection system, appearing as uniform large-area distributions. Ground surveys, however, would locate the hot particles within a smaller area and show the surrounding areas to be background only. Table 1 contains estimates of the detection system's footprint size for several energies of interest.

Table 1.	Approximate Detector Footprint Radius for Relative Count-Rate
	Contributions from Terrestrial Sources at a Survey Altitude of
	150 ft (46 m) AGL

Emitted Gamma-Ray Energy (keV)	Radius where 99% of Detected Counts Originate ft (m)	Radius where 90% of Detected Counts Originate ft (m)	Radius where 50% of Detected Counts Originate ft (m)
60	650 (198)	353 (108)	155 (47)
200	850 (259)	435 (133)	178 (54)
600	1,067 (325)	560 (171)	214 (65)
1,500	1,715 (523)	772 (235)	260 (79)
2,000	2,145 (654)	850 (259)	275 (84)
3,000	2,862 (872)	1,007 (307)	308 (94)

Detector sensitivity is not constant throughout the footprint. The maximum sensitivity occurs directly beneath the detector; the sensitivity decreases with increasing horizontal distance between the source and airborne detector. In addition, the incident gamma rays from even a monoenergetic source include scattered gamma rays once the incident radiation reaches the airborne detectors. Footprint sizes are, therefore, dependent on the soil distribution, air scatter, source geometry, etc.

4.0 ANALYSIS

The collected data were processed during field operations to map the radiation profile of the Monticello Nuclear Power Plant area. The data-processing objectives were to (a) establish the spatial distribution of the gamma radioactivity and (b) identify the radionuclides contributing to the gamma-ray exposure rate. To achieve the desired results, the data were processed as color-coded exposure-rate isopleths and superimposed on a U.S. Geological Survey topographic map of the surveyed area. Gamma-ray spectra were examined for all anomalies that were significantly elevated (a factor of two or more) above typical terrestrial values. Analysis procedures are discussed briefly in this report and detailed in separate publications.^{4,5}

4.1 Data-Processing Algorithms

When analyzing survey data, isoradiation contour maps are generated from algorithms for total terrestrial (gross count) and total man-made activity. These two algorithms are used as the primary quality checks on the data relative to spatial distribution, location, and intensity of gamma-emitting radionuclides.

4.1.1 Total Terrestrial Activity

The total terrestrial count rate is the count rate from all gamma rays having energies in the range of 38 keV $\leq E \leq$ 3,026 keV, the range where most naturally occurring and man-made gamma emitters exist. The total terrestrial count rate, corrected for variations in the aircraft altitude, is written as follows:

$$CR_{GC} = \left(\sum_{E=38}^{3026} CR(E) - NTB\right) e^{-A\Delta H}$$
(1)

where

- CR_{GC} = total terrestrial count rate (counts per second, cps)
- CR(E) = detected count rate at energy E (cps)
 - NTB = nonterrestrial background (*i.e.*, count rate produced by airborne radon, gamma emitters from the detector platform, and gamma rays of cosmic origin) (cps)
 - A = site-specific atmospheric attenuation coefficient (ft⁻¹)
 - ΔH = variation from the planned survey altitude (ft)

A has been found to be constant over the duration of a survey and is determined from data taken at multiple altitudes over a fixed test line located near or within the survey area. NTB represents the nonterrestrial background count rate and is calculated from test-line count rates measured before and after each survey flight (using the previously determined value of A). The value of A is used to correct all measurements to yield the correct terrestrial gamma-emission rate. (Such a correction could be gamma-ray energy-dependent. At present, the assumption is made that the relative contributions to the measured spectrum do not vary between the test line and the survey area, so an average correction is appropriate).

A three-point sliding interval average was applied to the total terrestrial count-rate data to reduce statistical fluctuations in the data:

$$CR_{i,avg} = \frac{1}{3} (CR_{i-1} + CR_i + CR_{i+1})$$
 (2)

 $CR_{i,avg}$ is the averaged value at the *i*th location, and CR_{i-1} , CR_i , and CR_{i+1} are consecutive, corrected gross count rates along a single flight line. Present analysis codes do not average nearest-neighbor data on adjacent flight lines; three-point averaging has been found to be adequate. The exposure rate is calculated from this averaged gross count rate.

The total terrestrial count rate was then converted to an exposure rate, *ER*, as follows:

$$ER(\mu R/h) = \frac{CR_{GC}}{937}$$
(3)

The exposure-rate conversion factor, 937 cps/(μ R/h), was obtained from comparative ground-based and

aerial measurements of a well-characterized reference line. Two reference lines are maintained for survey calibration: one in Calvert County, Maryland,⁶ and a second in the Lake Mohave National Recreation Area near Las Vegas, Nevada.⁷ Data from the Calvert County test line were used for the Monticello Nuclear Power Plant survey because the Calvert County terrain is similar to the area covered by this survey. Table 2 lists the exposure rates and corresponding count rates (indicated by color codes shown in the contour map, Figure 3) measured at the survey altitude.

It should be noted that in areas of atypical mixes of gamma-emitting radionuclides, the converted values will underestimate the actual exposure rate. An estimated cosmic-ray contribution of $3.7 \,\mu$ R/h was added to these reported exposure-rate values.

4.1.2 Identifying Sources of Man-Made Radiation from Aerial Survey Data

Because man-made gamma emitters are expected from nuclear fission and neutron activation processes at reactor sites, the data were also processed for the presence of man-made gross count rate (MMGC) (*i.e.*, those gamma rays having energies in the range of 38 keV $\leq E \leq 1,394$ keV). This analysis provides a general overview of contamination within the survey area and also indicates the areas that should be further investigated. This analysis process revealed that the man-made radiation was localized within the site boundary as indicated by the color-coded isopleths of the total exposure-rate map presented in Section 5. Therefore, the man-made isopleth map was not presented in this report. The MMGC analysis is described in detail elsewhere.^{4,5}

4.1.3 Isotope-Specific Information from Aerial Survey Data

Aerial survey data are examined for spectral peaks due to various radionuclides that could reasonably be expected at the Monticello site: in particular, nitrogen-16 (¹⁶N). Spectral-stripping techniques were used to analyze aerial radiation data. (Peak fitting is not used because peak shapes from the Nal[T*l*] detectors are broad and frequently overlap.) Spectra from areas of interest (usually those with significant MMGC levels as those found within the site boundaries) are analyzed by subtracting, channel-by-channel, a spectrum of a known background area. These spectra are sums of all 1-second spectral data acquired around the site of interest:

Difference
$$Spectrum_i = SPEC_{i,site of interest}$$

- $K_{diff} \cdot SPEC_{i,background}$ (4)

The K_{diff} constant is selected to force the difference spectrum to zero at energies greater than 1,400 keV where background photopeaks exist. Spectral peaks are readily visible in the difference spectrum. The presence of an identifiable spectral peak is considered to be a prerequisite for proceeding with individual isotopic isopleth plots.

Color Code	Count (cp:	Rate s)	Exposure (μR/	e Rate ^a 'h)	l
Cyan	<	2,155	<	6	
Light Blue	2,155 -	4,029	6 –	8	
Dark Green	4,029 -	5,903	8 -	10	
Light Green	5,903 -	9,651	10 -	14	
Yellow	9,651 -	17,147	14 –	22	
Orange	17,147 -	45,257	22 -	52	
Magenta	45,257 -	157,697	52 -	172	
Pink	157,697 -	446,293	172 –	480	
Red	446,293 - 1	1,495,733	480 – 1	,600	

Table 2. Conversion from Count Rate to Exposure Rate

^a The exposure rate at 1 meter AGL is inferred from count-rate data collected at an altitude of 150 ft (46m). The listed values include a cosmic-ray exposure rate of 3.7 μ R/h.





Color Code	Exposure Rate (μR/h) ^a
	< 6
	6- 8
	8 - 10
Carlo and a set of	10 - 14
	14 - 22
	22 - 52
	52 - 172
	172 - 480
	480 - 1,600

^aThe exposure rate is inferred from countrate data collected at an altitude of 150 feet (46 meters). The listed values include a cosmic-ray exposure rate of 3.7 μR/h.

FIGURE 3. EXPOSURE-RATE MAP OF THE MONTICELLO NUCLEAR POWER PLANT AND SURROUNDING AREA

4.2 Natural Background Radiation

Natural background radiation originates from (a) radioactive elements present in the earth, (b) airborne radon, and (c) cosmic rays entering the earth's atmosphere from space. Natural terrestrial radiation levels depend on the type of soil and bedrock immediately below and surrounding the point of measurement. Within cities, the levels are also dependent on the nature of the pavement and building materials. The gamma radiation originates primarily from the uranium and thorium decay chains and from radioactive potassium. Local concentrations of these nuclides produce radiation levels at the surface of the earth typically ranging from $1-15 \mu R/h$ (9-130 mrem/yr). Some areas having high concentrations of uranium and/or thorium in the surface minerals exhibit even higher radiation levels, especially in the western states.⁸ The photopeak energies listed in Table 3 were found in the natural background spectrum.

Isotopes of the noble gas radon are members of both the uranium and thorium radioactive decay chains. Radon can diffuse through the soil and may travel through the air to other locations; therefore, the level of airborne radiation due to these radon isotopes and their daughter products at a specific location depends on a variety of factors including meteorological conditions, mineral content of the soil, and soil permeability. Typically, airborne radon contributes from 1 to 10 percent of the natural background radiation.

Cosmic rays interact with elements of the earth's atmosphere and soil. These interactions produce an additional natural source of gamma radiation. Radiation levels due to cosmic rays vary with altitude and geomagnetic latitude. Typically, values range from $3.3 \,\mu$ R/h at sea level in Florida to $12 \,\mu$ R/h at an altitude of 1.9 mi (3 km) in Colorado.⁹

5.0 AERIAL RADIOLOGICAL SURVEY RESULTS

The results in this report are presented as (a) a colorcoded exposure-rate isopleth map and (b) the gamma-ray energy spectra to identify detected sources.

5.1 Terrestrial Exposure Rates

Figure 3 is a plot of the inferred terrestrial exposure rates at 1 meter AGL at the Monticello Nuclear Power Plant and surrounding area. These values include a cosmic contribution of 3.7 μ R/h; the aircraft and airborne radon components of the nonterrestrial contribution have been removed. Minimum exposure rates (less than 6 μ R/h, cyan isopleths) that are due, as previously stated, to sources of cosmic origin were

Energy (keV)	Identification	
240	²⁰⁸ TI (239 keV), ²¹² Pb (238 keV)	
380	²²⁸ Ac (339 keV), ²¹⁴ Bi (387 keV, 389 keV), ²¹⁴ Pb (295 keV)	
511 (weak)	²⁰⁸ TI (511 keV)	
610	²¹⁴ Bi (609 keV)	
830 (weak)	²²⁸ Ac (795 keV), ²⁰⁸ TI (861 keV)	
930	²²⁸ Ac (911 keV, 964 keV, 968 keV), ²¹⁴ Bi (934 keV)	
1,130	²¹⁴ Bi (1,120 keV)	
1,230	²¹⁴ Bi (1,238 keV)	
1,460	⁴⁰ K (1,460 keV)	
1,750	²¹⁴ Bi (1,765 keV)	
2,200	²¹⁴ Bi (2,204 keV)	
2,610	²⁰⁸ TI (2,614 keV)	

 Table 3.
 Gamma-Ray Photopeak Identification— Background Within the Survey Area

detected over the Mississippi River and a significant portion of its basin. Exposure rates over land areas where naturally occurring gamma emitters exist vary within a small range depending on the terrain. This was especially the case in the Monticello survey area as typical exposure rates over land areas varied between 6-8 µR/h (light blue isopleths) at a 1-meter level. These exposure rates generally correlate with differences in the terrain, which are visible on the topographic map. Exposure-rate ranges significantly above the typical level $(6-8 \mu R/h)$ were seen over the reactor (480-1,600 µR/h maximum, red isopleth). Elevated exposure rates from man-made gammaemitting radionuclides are expected at facilities such as these. A small pond near the fossil fuel plant located in the northwest corner of the survey area. (Figure 1) was slightly elevated above typical background levels; exposure levels in this area were 10-14 µR/h. There were no other high-exposure-rate areas in the surveyed area.

As stated previously, the value of the exposure rates estimated over localized sources such as those detected here may be underestimated by orders of magnitude. The actual high-exposure-rate area is smaller than it appears. It is likely that ground-based instruments will begin to sense activity above natural background at the orange or magenta contour intervals of localized anomalies. The airborne component of the exposure rate not included in these values (airborne radon and daughters) varies significantly in intensity and distribution during the course of the day. At a given time, the airborne component may be as large as 25 percent of the total exposure rate.

5.2 Isotopic Data

Both man-made and naturally occurring gamma emitters were detected in the Monticello survey area although the man-made gamma emitters were confined to the plant site boundaries.

5.2.1 Background Isotopes

Figure 4 is a gamma energy spectrum typical of the naturally occurring gamma emitters. The distinct photopeaks are those of the uranium and thorium decay chains and potassium.



FIGURE 4. TYPICAL BACKGROUND SPECTRUM OF THE SURVEY AREA

5.2.2 Man-Made Isotopes

As illustrated in the exposure-rate map (Figure 3), the extent of radiation levels significantly above typical background levels (cyan and light blue isopleths, $0-8 \ \mu R/h$) were confined to an on-site area (orange, magenta, pink and red contours, $22-1,600 \ \mu R/h$). Nitrogen-16 was the predominant man-made gamma emitter detected in the elevated exposure-rate area (collected from orange, magenta, pink, and red contour regions in Figure 3) as illustrated in the gamma energy spectrum depicted in Figure 5.

The exposure-rate levels were slightly elevated above typical levels over a small lake in the northwest corner of the survey area near the fossil fuel power plant. The light green isopleth located over the lake was due to elevated levels of ²³²Th and progeny (Figure 6). At that anomaly, exposure rates ranged from 10–14 μ R/h (light green isopleth). In this case, man-made and specific isotopic isopleth maps revealed no more information than the total exposure-rate map and hence were not included in this report. Other dark green isopleths revealed the presence of only naturally occurring gamma emitters.

6.0 CONCLUSIONS

The radiation levels (exposure rate) within the survey area except within the boundaries of the Monticello Nuclear Power Plant were within the range of those typically found in the United States $(1-15 \,\mu\text{R/h})$. Localized sources of exposure rate exceeded typical levels over the reactor. This localized source was ¹⁶N and is usually present during boiling-water reactor



FIGURE 5. GAMMA ENERGY SPECTRUM OVER THE REACTOR FACILITIES DEPICTING THE PRESENCE OF ¹⁶N





operations. Exposure-rate levels slightly above typical levels due to ²³²Th and progeny were detected in the northwest corner of the survey area over a small lake near the fossil fuel power plant. Although the spatial detail was quite different (the 1996 survey footprint

was about 600 ft [181 m] versus the 1970 footprint of about 1,500 ft [457 m]), overall the 1996 values compared well with those measured in 1970, considering the improvement in methodology, instrumentation, and sensitivity.

APPENDIX A SURVEY PARAMETERS

Survey Site:	Monticello Nuclear Power Plant
Survey Location:	Monticello, Minnesota
Survey Date:	October 29 to November 2, 1996
Survey Coverage:	25 sq mi (65 sq km)
Survey Altitude:	150 ft (46 m)
Aircraft Speed:	80 mph (36 m/s)
Line Spacing:	250 ft (76 m)
Line Length:	5 mi (8 km)
Line Direction:	East-West
Number of Lines:	104
Detector Array:	Eight 2- \times 4- \times 16-in Nal(Tl) detectors Two 2- \times 4- \times 4-in Nal(Tl) detectors
Acquisition System:	REDAR IV
Aircraft:	MBB BO-105 helicopter (Tail Number N40EG)
Project Scientist:	E. L. Feimster

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