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AN AERIAL RADIOLOGICAL SURVEY OF THE MILLSTONE NUCLEAR POWER STATION AND SURROUNDING AREA

WATERFORD, CONNECTICUT

DATE OF SURVEY: SEPTEMBER 1990

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ABSTRACT

An aerial radiological survey was conducted during the period of September 10 to 18, 1990, over a 40-square-mile (104-square-kilometer) area surrounding the Millstone Nuclear Power Station (MNPS). The MNPS is located on the Long Island Sound shoreline, three kilometers south of Waterford, Connecticut. The purpose of the survey was to measure and document the terrestrial gamma ray environment of the plant and surrounding areas.

A contour map showing radiation exposure rates at 1 meter above ground level was constructed from the aerial data and overlaid on an aerial photograph and a United States Geological Survey map of the area. The exposure rates within the survey region are quite uniform. The area is characterized by an exposure rate of 10-12 microroentgens per hour including an estimated cosmic ray contribution of 3.6 μR/h. This is typical of natural background. The only exception to the natural background readings is the Millstone station itself, which is characterized by an exposure rate consistent with the standard operation of the reactor units.

Radionuclide assays of soil samples and pressurized-ion-chamber gamma ray measurements were obtained at five locations within the survey boundaries. These measurements were taken in support of, and are in agreement with, the aerial data. The radiological environment near the plant is consistent with normal plant operation.

CONTENTS

1.0 INTRODUCTION

An aerial radiological survey was conducted from September 10-18, 1990, over the Millstone Nuclear Power Station and surrounding area at Waterford, Connecticut. The purpose of the aerial survey was to measure and document the gamma radiation environment of the area surrounding the plant site.

The survey was performed by personnel of EG&G Energy Measurements, Inc. (EG&G/EM), which operates the Remote Sensing Laboratory for the United States Department of Energy Nevada Operations Office (DOE/NV). One of the main functions of the Remote Sensing Laboratory is to maintain and manage an aerial surveillance program called the Aerial Measuring System (AMS). Since its inception in 1958, the AMS has continued a nationwide effort to document baseline radiological conditions at nuclear energy-related sites of interest to DOE. These sites include power plants, manufacturing and processing plants, and research laboratories utilizing nuclear materials.

The aerial survey of the Millstone Nuclear Power Station was conducted at the request of the United States Nuclear Regulatory Commission and was cosponsored by the Nuclear Regulatory Commission and the United States Department of Energy.

2.0 SITE DESCRIPTION

The Millstone Nuclear Power Station is operated by Northeast Utilities and located three kilometers south of Waterford, Connecticut, on a peninsula extending into the Long Island Sound. The station is built on the former site of the Millstone Point granite quarry.[1] The terrain of the surrounding area is rocky, with elevations to 350 feet (107 meters). Although the Millstone station itself is at sea level, the majority of the survey area is at elevations of 100 to 200 feet (30 to 60 meters). Two large rivers, the Niantic and Thames, are within the survey boundaries.

The survey area, shown in Figure 1, is an irregularly shaped region bordered by the Thames River to the east and the Long Island Sound/Niantic Bay shoreline to the south. The area surveyed is approximately 40 square miles (104 square kilometers).

Presently there are three reactors located at the Millstone site, having a combined maximum electrical output of 2,678 megawatts (Table 1). During the period of the survey, only the two pressurized water reactors, Millstone 2 and 3, were in operation.[2] Millstone 2 was operating at 100% capacity and Millstone 3 was operating at 49% capacity.

3.0 NATURAL BACKGROUND

Natural background radiation originates from three primary sources: radioactive elements present in the soil, airborne radon, and cosmic rays of extraterrestrial origin.

Natural terrestrial radiation levels depend upon the type of soil and bedrock immediately below and surrounding the point of measurement. In urban areas, these levels also depend on the nature of roadway and construction materials. Terrestrial gamma radiation originates primarily from the radioactive decay of elements naturally found in the soil and bedrock, namely, radioactive potassium and isotopes produced in the uranium and thorium decay chains. In general, local concentrations of these isotopes produce radiation levels at the surface typically ranging from 1 to 15 μR/h (9 to 130 mrem/yr).[3] Areas with high uranium and/or thorium concentrations may exhibit slightly higher levels.

One member of both the uranium and thorium radioactive decay chains is radon, a noble gas which can both diffuse through soil and travel through the air. Therefore, the level of airborne radiation due to radon and its daughter products depends on a variety of factors for a given location including, for example, meteorological conditions, mineral content of the soil, and soil permeability. Typically, airborne radiation from radon and its progeny contributes from 1 to 10 percent of the natural background radiation levels.

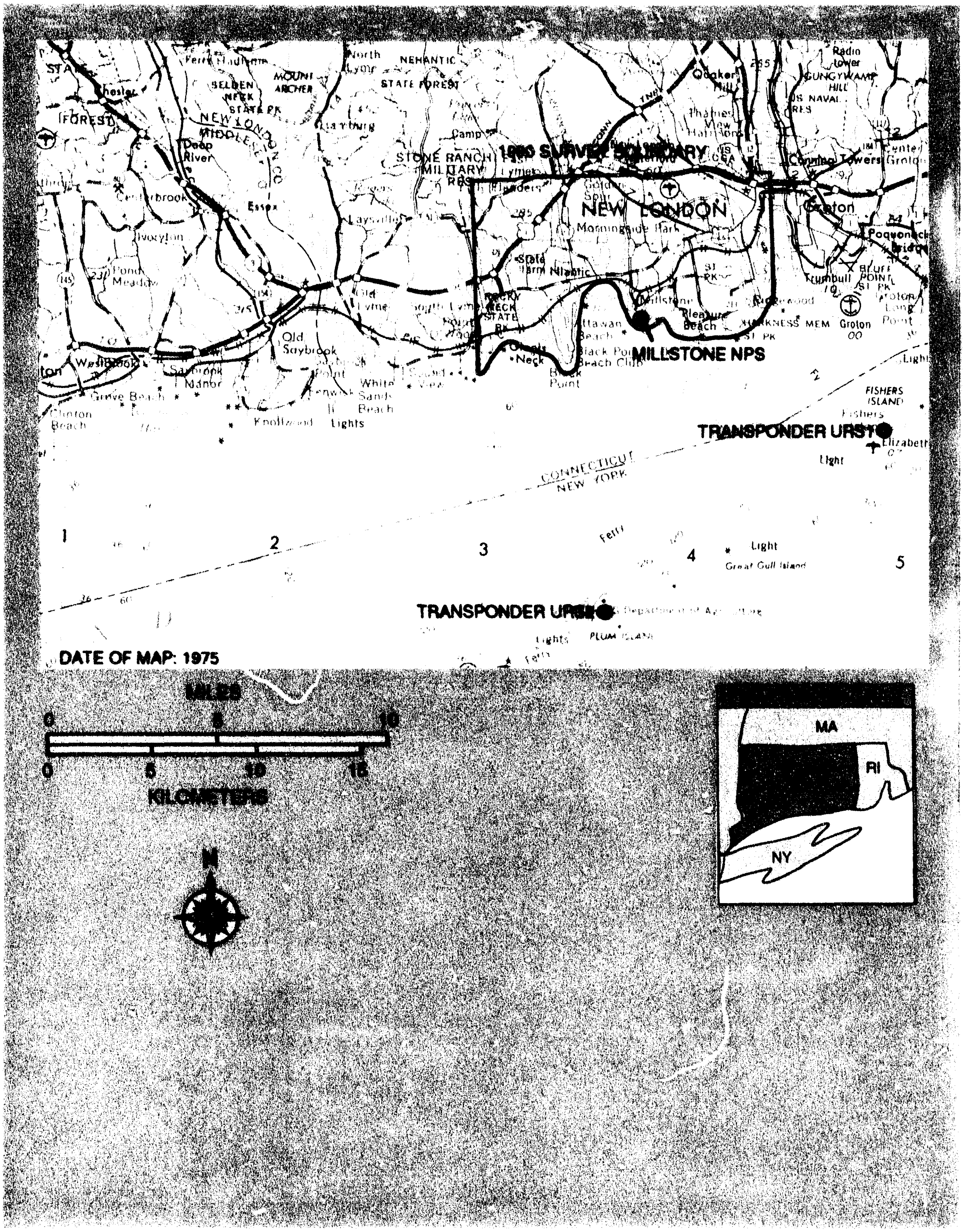


FIGURE 1. *GENERAL VIEW OF THE MILLSTONE NUCLEAR POWER STATION AND SURROUNDING AREA*

Table 1. Millstone Nuclear Power Station Reactor Specifications[1]			
	Millstone 1	Millstone 2	Millstone 3
Type	Boiling Water Reactor	Pressurized Water Reactor	Pressurized Water Reactor
Current Capacity	659.5 MW	862 MW	1156 MW
Began Operation	December 1970	December 1975	April 1986
Reactor Manufacturer	General Electric Company	Combustion Engineering, Inc.	Westinghouse Electric Corp.
Turbine Generator Manufacturer	General Electric Company	General Electric Company	General Electric Company
Engineer-Constructor	Ebasco Services, Inc.	Bechtel Corporation	Stone & Webster Engineering Corp.

Cosmic rays interact with elements of the earth's atmosphere and soil producing an additional source of gamma radiation. Radiation levels due to cosmic rays vary with altitude from 3.3 μR/h at sea level to 12 μR/h at an elevation of 10,000 feet (3,050 meters).[4] The cosmic ray contribution in the Millstone survey area is estimated to be about 3.6 μR/h.

4.0 SURVEY EQUIPMENT AND METHODS

The Aerial Measuring System (AMS) used to perform the Millstone survey is comprised of a radiation detector system and a data acquisition computer mounted aboard a high-performance Messerschmitt-Bolkow-Blohm (MBB) BO-105 helicopter and a mobile data analysis computer system. The mobile computer system allows the spectral radiation data collected with the helicopter system to be reduced and presented as isopleth contour maps of exposure rates and isotopic intensities.

4.1 Aerial Measuring System

The MBB BO-105 helicopter shown in Figure 2 was used as the aerial platform. The helicopter carried a crew of two and a lightweight version of the Radiation and Environmental Data Acquisition and Recorder Model IV (REDAR IV) system. Two detector pods, each containing four 2- × 4- × 16-inch down-looking and one 2- × 4- × 4-inch up-looking, log-type thallium-activated sodium iodide, NaI(Tℓ), scintillation detectors were mounted on the side landing skids of the helicopter. The down-looking detectors have a measurement range up to 600 μR/h terrestrial activity. The up-looking detectors are utilized to monitor airborne radon variations.

FIGURE 2. *MBB BO-105 HELICOPTER WITH DETECTOR PODS*

The energy signals produced through the interaction of gamma rays with the NaI(Tℓ) crystals were analyzed by successive-approximation analog-to-digital convertors in the REDAR IV system, which is a multimicroprocessor, ruggedized data acquisition and real-time analysis system. REDAR IV has been designed to operate in the severe environments associated with platforms such as helicopters, fixed-wing aircraft, and various ground-based vehicles. The system displays all required radiation and system information in real time to the operator via video displays and multiple LED readouts. The gamma ray, helicopter position, and weather data are acquired at one-second intervals and recorded on magnetic cartridge tapes for postflight analysis on a ground-based minicomputer system.

The helicopter position was established by two systems: an ultrahigh frequency ranging system (URS) and a radar altimeter. The URS system continually triangulates the position of the helicopter between a URS master station mounted in the helicopter and two remote URS transponders by measuring the round-trip propagation time between the units. One transponder was located on a communications building located at the Fishers Island Annex of the United States Naval Underwater Systems Center, Fishers Island, New York. The second URS transponder was located on a water tower at the United States Department of Agriculture's Animal Disease Center on Plum Island, New York. These two sites (Figure 1), along with the helicopter master unit, formed an approximate equilateral triangle from which positioning and steering of the aircraft during the survey were accomplished. The accuracy of this system is nominally ± 10 feet (3 meters). Similarly, the radar altimeter determines the helicopter's altitude by measuring the round-trip propagation times. For altitudes up to 2,000 feet (610 meters), the accuracy of this system is ± 2 feet (0.6 meter) or ± 2%, whichever is greater.

The position information from the URS system and radar altimeter were simultaneously recorded, along with the spectral information, on magnetic tape and directed to an aircraft steering indicator used to direct the aircraft along the predetermined flight lines.

The Millstone area was surveyed by flying a predetermined series of uniformly spaced parallel lines at a constant altitude above ground level (AGL) while maintaining a constant ground speed. Line spacing, altitude, and speed were chosen to optimize system sensitivity and resolution while still maintaining a safe flight configuration. For the Millstone survey, the line spacing used was 500 feet (152 meters) at an altitude of 300 feet (91 meters). The helicopter ground speed was 70 knots (36 meters/second).

4.2 Radiation and Environmental Data Analyzer and Computer System

A minicomputer-based system, the Radiation and Environmental Data Analyzer and Computer (REDAC) system, was housed in a modified Airstream mobile home (Figure 3) and used during the survey to evaluate the aerial data immediately following each survey flight. The REDAC system consists of a Data General 32-bit minicomputer system with floating point co-processor; four (4) megabytes of memory; two multidisk hard drives with more than 1 gigabyte of storage; two 9-track, 1600-BPI magnetic tape drives; two 4-track, 1/4-inch cartridge drives; a 36-inch-wide carriage pen plotter; a laser printer; a system CRT; and three graphics terminals and hardcopy units. This system has an extensive library of software routines available for complete data processing in the field.

FIGURE 3. ***MOBILE COMPUTER PROCESSING LABORATORY***

4.3 Aerial Data Analysis

The aerial radiation data consist of contributions from naturally-occurring radioisotopes and a radiation background generated by the aircraft, the detector system, and cosmic rays. For this survey, the major emphasis was placed on mapping the gamma ray radiation environment of the area surrounding the Millstone

Nuclear Power Station. Isopleth maps were produced by processing the data using two different methods: gross count (GC) and man-made gross count (MMGC) extractions.[5]

4.4 Gross Count Data

The gross counting method is based on the integral counting rate in that portion of the gamma spectrum between 38 and 3,026 keV:

$$GC = \sum_{E = 38 keV}^{3026 keV} S_{GC}(E) \quad (counts/sec) \qquad (1)$$

where GC is the gross counting rate, E is the photon energy in keV, and $S_{GC}(E)$ is the energy spectrum containing the number of gamma rays collected at the given energy E per unit time. The gross counting rate, measured in counts per second at the survey altitude of 300 feet (91 meters), was converted to an exposure rate in microroentgens/hour (μR/h) at a height of 1 meter above the ground by the application of a conversion factor determined from the documented test line in Calvert County, Maryland.[6] The conversion equation used is:

$$ER\ (1\ meter) = \left(\frac{GC(A)-B_A}{1250}\right) e^{aA} \quad (\mu R/h) \qquad (2)$$

where ER (1 meter) is the exposure rate (μR/h) extrapolated to 1 meter AGL and $GC(A)$ is the gross count rate in counts/second at altitude A (feet). The background, B_A, attributed to cosmic rays, airborne radon, and aircraft-induced electronic noise, is defined as:

$$B_A = \sum_{E = 38 keV}^{3026 keV} S_{water}(E) \quad (counts/sec) \qquad (3)$$

where $S_{water}(E)$ is the energy spectrum determined by acquiring data at survey altitude over the Long Island Sound. The attenuation coefficient a in the exponential term represents the altitude-related attenuation of the terrestrial background and was determined empirically at the survey site by taking data at different altitudes ranging from 300 to 1,000 feet (91 to 305 meters) over the survey area test line. The value measured was:

$$a = 0.002\ ft^{-1} \qquad (4)$$

At the constant survey altitude of 300 feet (91 meters), Equation 2 now becomes:

$$ER\ (1\ meter) = \frac{GC-B}{679} \quad (\mu R/h) \qquad (5)$$

This conversion assumes a uniformly distributed source covering an area which is large compared with the detector's field of view, approximately 600 feet (180 meters) at the survey altitude of 300 feet (91 meters). The exposure rate values could be one to two orders of magnitude higher for a localized point source since the AMS averages all sources over a comparatively large area. The sum includes all naturally-occurring gammas from potassium-40 (^{40}K), uranium-238 (^{238}U), thorium-232 (^{232}Th), and their decay products, as well as contributions from airborne radon, cosmic rays, and man-made radionuclides.

4.5 Man-Made Gross Count Data

Anomalous, or nonnaturally-occurring, gamma ray sources can often be found from increases in the gross counting rates. However, subtle anomalies are often difficult to find using the gross counting rate in areas where the magnitude is variable due to geologic or ground cover changes. For example, Figure 4 shows the natural background of the Millstone survey area, which was found to vary from 4 to 12 μR/h by moving several meters from the shoreline to a rocky area. Differential energy data reduction methods can be used to increase the sensitivity of the AMS to gamma ray emitters.

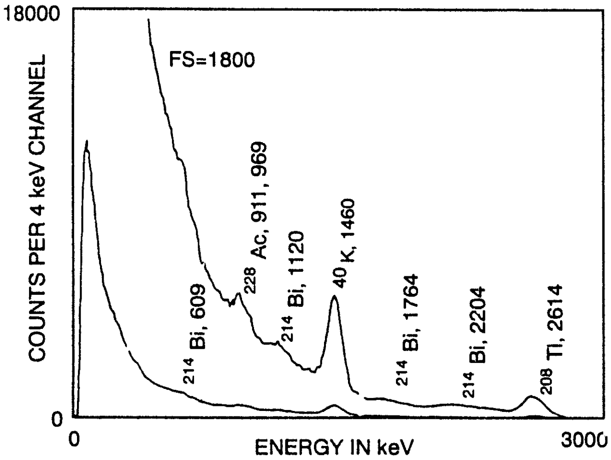


FIGURE 4. ***TYPICAL BACKGROUND GAMMA ENERGY SPECTRUM***

A man-made gross count rate algorithm has been designed to identify changes in spectral shapes. This algorithm takes advantage of the fact that while background radiation levels often vary by factors of two or more within a survey area, the background spectral shape remains essentially constant. More specifically, the ratio of natural components in any two integral sections (windows) of the energy spectrum will remain nearly constant in any given area:

$$\frac{\sum_{E=a}^{b} S(E)}{\sum_{E=c}^{d} S(E)} \approx Constant \equiv K \qquad (6)$$

where $S(E)$ is an energy spectrum, E is the photon energy in keV, and a-d are energy values where $a < b \leq c < d$.

In practice, a value of the constant K defined in Equation 6 can be obtained from the natural terrestrial background of the survey area:

$$K = \frac{\sum_{E=a}^{b} S_{background}(E)}{\sum_{E=c}^{d} S_{background}(E)} \qquad (7)$$

This allows a comparison of low-energy to high-energy windows to be made by:

$$CR_{NET} = \sum_{E=a}^{b} S_{GC}(E) - K \sum_{E=c}^{d} S_{GC}(E) \quad (counts/sec) \qquad (8)$$

where CR_{NET} is the net count rate from anomalous gamma rays. In general, CR_{NET} will vary about zero and become significantly positive in the presence of anomalous gamma rays whose energy lies between a and b. The variance of CR_{NET} can be computed from the results of Equation 8 or from energy window count rates.

For the Millstone survey, the value of the constant K in Equation 7 was determined from a region within the survey area chosen as a "typical" background area. Then, Equation 8 was applied to the data using the values:

$$a = 38\ keV \qquad b = c = 1394\ keV \qquad d = 3026\ keV \qquad (9)$$

These values take advantage of the fact that the majority of the gamma rays emitted by long-lived, man-made isotopes are less than 1,394 keV in energy.

The man-made gross count algorithm is designed to respond to a wide range of nuclides and, therefore, is quite general in nature. This renders the sensitivity of the algorithm to specific nuclides to be less than optimal. If detection of a specific nuclide is desired, more sensitive algorithms can be devised.

5.0 RESULTS

5.1 Terrestrial Gamma Exposure Rates

Terrestrial gamma exposure rates within the survey area are shown in the form of a contour map in Figure 5. The levels shown do not include an estimated cosmic ray contribution of 3.6 μR/h. The highly variable airborne radon component is not included.

Over nearly the entire survey area, the exposure rates shown represent normal fluctuations in background due to varying amounts of uranium and thorium decay chain isotopes and ^{40}K in the soil. These levels range from 4 μR/h over shoreline and wetland areas to 12 μR/h over the rocky areas. The land area in the survey region appeared to have a background activity between 10 and 12 μR/h (including cosmic contributions). The inferred exposure rate at the reactor buildings was 60-120 μR/h with two of the three reactors operating. A gamma ray energy spectrum collected outside the plant boundary is shown in Figure 4.

Two previous aerial surveys have been conducted by EG&G/EM at this site. The first survey employed a Beechcraft Twin Bonanza airplane flying at a 300- to 500-foot AGL altitude, 1-mile line spacing, and 140-knot speed and was performed before the power station became operational.[7] It found only background radiation levels which are consistent with the values seen in the current survey away from the plant boundaries.

The second survey employed a Hughes H-500 helicopter flying at a 150- to 300-foot AGL altitude. The results of this survey are unpublished. However, the exposure rate measurements away from the plant boundaries agree with the levels shown in this report.

5.2 Man-Made Gamma Emitters

The man-made gross count (MMGC) algorithm (Equation 8) was used to search the aerial data for man-made emitters and to produce a contour plot. Because plant activity is adequately described by the exposure rate contour, the MMGC contour is not presented in this report. The exposure rate contour figure shows no evidence for man-made emitters outside the boundaries of the Millstone station. Shown in Figure 6 is a background-subtracted gamma ray spectrum taken over the plant during operation. This spectrum is characteristic of cobalt-60 (^{60}Co), an activation product commonly produced when structural reactor materials are exposed to neutron radiation.[8]

5.3 Ground-Based Measurement Results

Ground-based exposure rate measurements and soil samples taken at five locations within the Millstone survey boundaries served as a method of quality control by independently verifying the integrity of the aerial measurements. At each location, numbered 1 through 5 in Figure 5, a Reuter-Stokes pressurized ion chamber placed at a height of 1 meter AGL was used for each *in situ* exposure rate measurement. Soil samples taken to a depth of 15 cm were also obtained. These samples were sealed and shipped to the EG&G/EM Santa Barbara Operations office, where they were dried and their gamma activities measured using a calibrated high-purity germanium detector system. *In situ* exposures were computed from the primary isotopic concentrations in the soil. Details of this system and the procedures used to collect and analyze soil sample data are outlined in Reference 9.

The calculated soil sample exposure rates are compared with ground-based ion chamber results and aerial measurements in Table 2. All exposure rate measurements include an estimated cosmic ray contribution of 3.6 μR/h. The ion chamber results also include a small (less than 0.2 μR/h) airborne radon component. At all sites, the inferred aerial data is in excellent agreement with both the ion chamber and soil sample data.

6.0 CONCLUSIONS

A 40-square-mile (104-square-kilometer) area, centered on the Millstone Nuclear Power Station

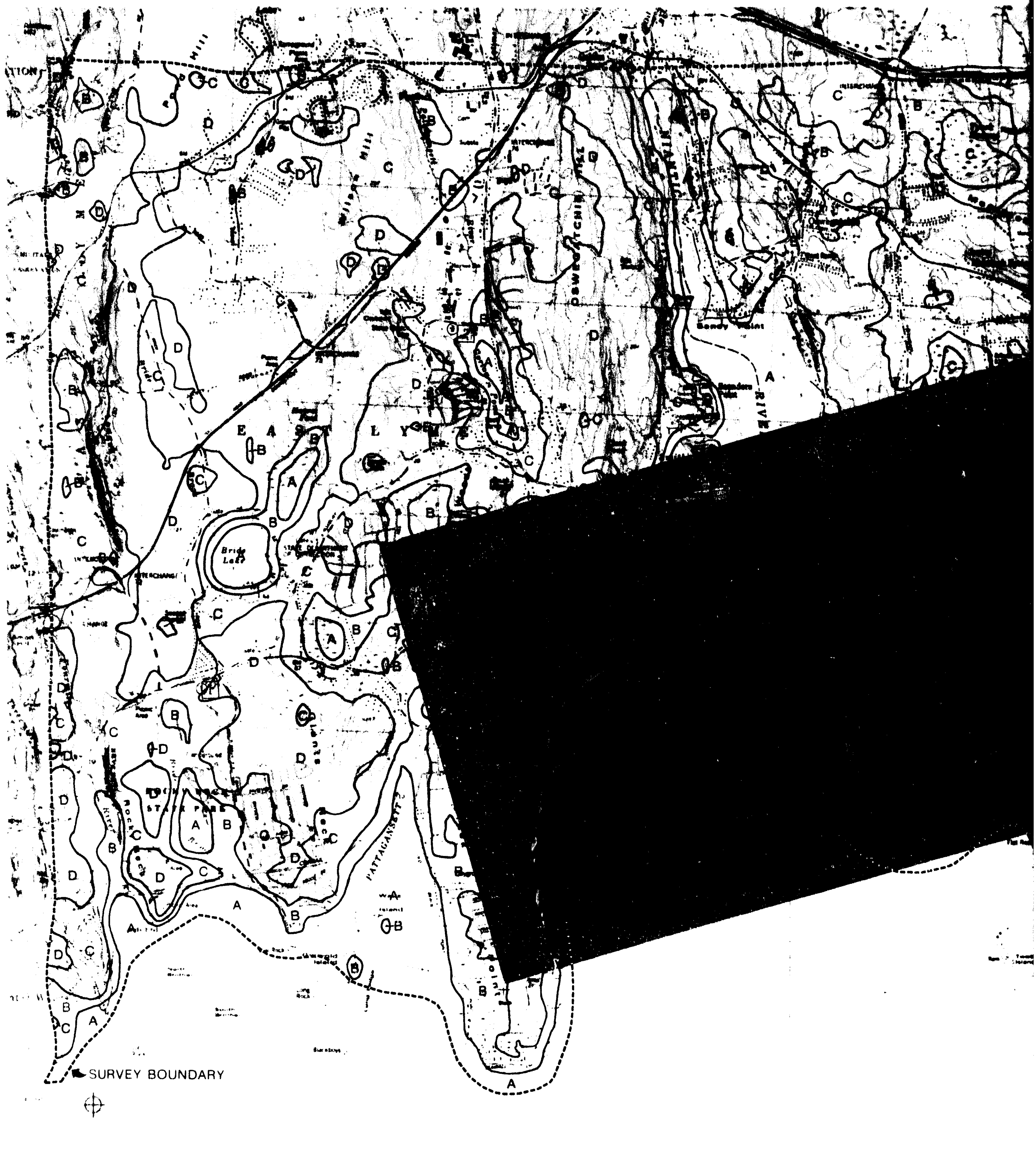
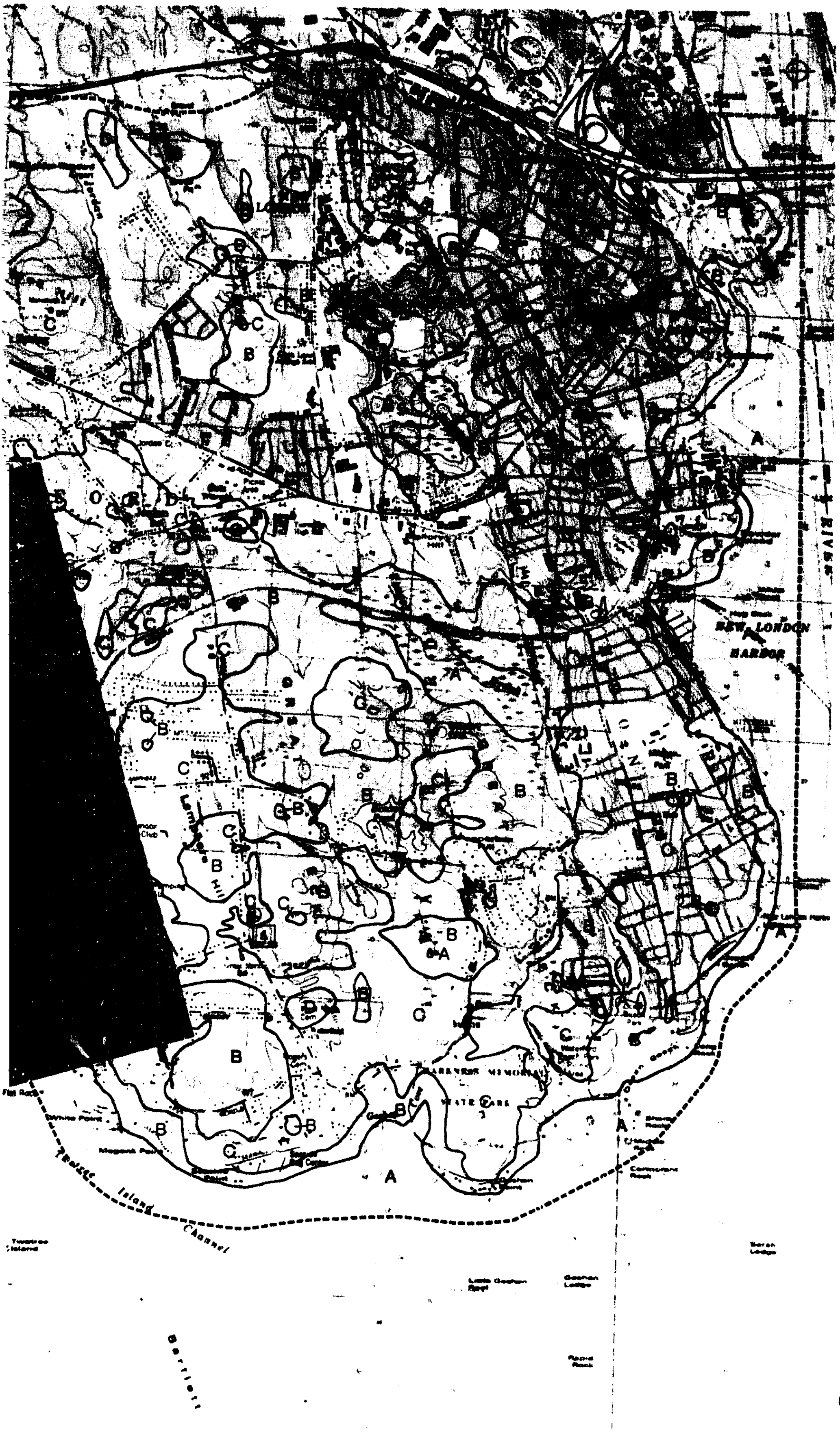


FIGURE 5. *GAMMA RADIATION EXPOSURE RA*



LETTER LABEL	EXPOSURE RATE* AT 1 METER (μR/h)
A	< 4
B	4 - 6
C	6 - 8
D	8 - 11
E	11 - 15
F	15 - 20
G	20 - 40
H	40 - 60
I	60 - 120

*Terrestrial external exposure rates are inferred from aerial data collected at 300 ft (91 m) AGL. For total external exposure rate, an estimated cosmic contribution of 3.6 μR/h must be added.

Soil sample sites are shown in boxed numerals.

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RATE CONTOUR MAP

near Waterford, Connecticut, was radiologically surveyed at an altitude of 300 feet (91 meters) using the Aerial Measuring System. The only significant level observed above natural background was directly over the buildings which house the Millstone reactors. At the time of the survey, Millstone's two pressurized water reactors, Millstone 2 and 3, were operating at 100% and 49% capacity, respectively. Millstone 1, a boiling water reactor, was not in operation. The normal inferred exposure rates at 1 meter AGL varied from 10 to 12 μR/h (including 3.6 μR/h cosmic contributions) within the survey area.

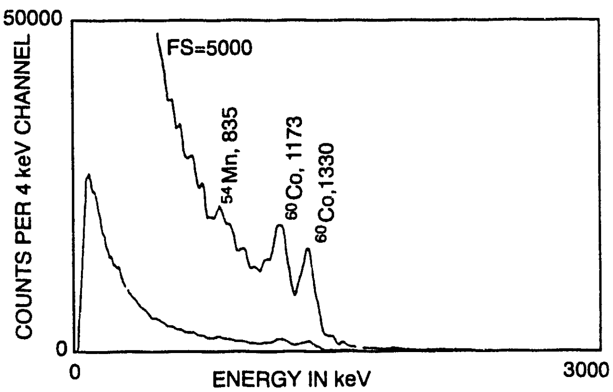

FIGURE 6. ***NET GAMMA ENERGY SPECTRUM OVER REACTOR***

Table 2. Results of Ground-Based Radiological Measurements Taken from the Area Surrounding the Millstone Nuclear Power Station in Waterford, Connecticut

Site ID No.	Soil Moisture (%)	Radionuclide Assay–Average Values				Gamma Exposure Rate (μR/h at 1 meter)		
		^{238}U (ppm)	^{232}Th (ppm)	^{137}Cs (pCi/g)	^{40}K (pCi/g)	Soil Analysis[a]	Ion Chamber[b]	Aerial Results[c]
Benchmark Sites								
1	12 ± 7	3 ± 1	17 ± 2	0.32 ± 0.15	18 ± 2	13 ± 2	11.8 ± 0.6	11.6±1.5
2	30 ± 7	2.9 ± 0.7	11 ± 3	0.60 ± 0.30	16.9 ± 0.7	10 ± 2	9.7 ± 0.5	9.6±1.5
3	9 ± 1	2.6 ± 0.6	8 ± 2	0.52 ± 0.40	16 ± 1	10 ± 1	10.5 ± 0.5	9.8±1.5
4	7 ± 2	2.4 ± 0.5	8.7 ± 0.3	0.07 ± 0.04	16.0 ± 0.2	10.2 ± 0.7	9.7 ± 0.5	9.6±1.5
Historical Site (Site Number 5)[d]								
1990	9 ± 2	2.6 ± 0.5	11 ± 2	1.5 ± 0.8	16 ± 1	11 ± 1	10.5 ± 0.5	9.6±1.5
1976	13 ± 2	2.8 ± 0.2	10 ± 1	6 ± 2	12 ± 2	11 ± 1	11.0 ± 0.6	

[a] Calculation includes a cosmic ray contribution of 3.6 μR/h and a moisture correction of the form 1/(1+m).

[b] Reuter-Strokes Model #RSS-111, Serial Number G003

[c] Aerial exposure rates include a cosmic ray contribution of 3.6 μR/h.

[d] The historical site is an area from which soil samples and ion chamber measurements were taken during a 1976 ground truth measurement in the Millstone survey area. It provides a direct comparison to the present ground-truth results.

Appendix A

Survey Parameters

Survey Site:	Millstone Nuclear Power Station
Survey Location:	Latitude: 41°18′31″ Longitude: 72°10′05″
Survey Area:	40 mi^2 (104 km^2)
Survey Date:	10-18 September 1990
Survey Altitude:	300 ft (91 m)
Line Spacing:	500 ft (152 m)
Line Direction:	North/South
Number of Lines:	94
Detector Array:	Eight 2- × 4- × 16-in NaI(Tℓ) detectors Two 2- × 4- × 4-in NaI(Tℓ) detectors
Acquisition System:	REDAR IV
Aircraft:	MBB BO-105 Helicopter
Project Scientist:	R.J. Vojtech

Data Processing:

Man-Made Energy Window: 38-1,394 keV
Gross Count Energy Window: 38-3,026 keV
Conversion Factor: 679 cps per μR/h
Cosmic Ray Contribution: 3.6 μR/h

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