EPA-520/5-75-018

^{16}N SKYSHINE SURVEY AT A 2400 MW(t) NUCLEAR POWER PLANT

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs

^{16}N SKYSHINE SURVEY AT A 2400 MW(t) NUCLEAR POWER PLANT

C.R. PHILLIPS[1]

W.M. LOWDER[2]

C.B. NELSON[3]

S.T. WINDHAM[1]

J.E. PARTRIDGE[1]

DECEMBER, 1975

[1] U.S. ENVIRONMENTAL PROTECTION AGENCY
EASTERN ENVIRONMENTAL RADIATION FACILITY
P.O. BOX 3009
MONTGOMERY, ALABAMA 36109

[2] U.S. ENERGY RESEARCH AND DEVELOPMENT AGENCY
HEALTH AND SAFETY LABORATORY
376 HUDSON ST.
NEW YORK, NEW YORK 10014

[3] U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RADIATION PROGRAMS
ENVIRONMENTAL ANALYSIS DIVISION (AW-461)
401 M ST. S.W.
WASHINGTON D.C. 20460

FOREWORD

The Eastern Environmental Radiation Facility (EERF)participates in the identification of solutions to problem areas as defined by the Office of Radiation Programs. The Facility provides analytical capability for evaluation and assessment of radiation sources through environmental studies and surveillance and analysis. The EERF provides technical assistance to the State and local health departments in their radiological health programs and provides special analytical support for EPA Regional Offices and other federal government agencies as requested.

This study is one of several current projects which the EERF is conducting to assess environmental radiation contributions from fixed nuclear facilities.

Charles R. Porter
Director
Eastern Environmental Radiation Facility

ACKNOWLEDGEMENT

This study was made possible by the cooperation of the staff of the Cooper Nuclear Power Station, particularly Mr. Robert Wilbur. The progress of the study was aided by the close coordination of staff from EPA, ERDA and NRC, including Allan Richardson (EPA), Peter Raft (HASL), Mike Boyle (HASL), Blaine Murray (NRC), and Jacob Kastner (NRC).

CONTENTS

TABLES

FIGURES

ABSTRACT

A field study was executed to determine environmental levels, distribution, and composition of turbine-contributed ^{16}N gamma radiation from an operating boiling water reactor electric generating plant.

Exposure measurements made with Pressurized Ionization Chambers (PIC's) at several distances and in several directions from the turbine building indicated that ^{16}N "skyshine" rather than direct gamma exposures contributed the major portion of environmental exposures.

Power level and distance dependencies were determined and a predictive model indicated that a distance of 500 meters and a power level of 801 MW(e) would yield a dose rate of 10 mrad/yr.

Introduction

The ^{16}N dose from the turbine building of a boiling water reactor can be considered to be composed of direct and scattered components. The direct component is from full energy photons not affected by shielding or air scatter. The scattered component is due to small- and large-angle (skyshine) scattered photons. The small-angle scatter is primarily the result of interactions along the line-of-sight between source and receptor. The large-angle or skyshine component is a result of large-angle photon scatter by air molecules. At plants which have turbine buildings with substantial side shielding and open tops, skyshine can be the principal source of ^{16}N exposure.

Several studies have been conducted to assess the dose rate from ^{16}N in the vicinity of a nuclear power reactor (1,2,3). In each of these direct radiation comprised some significant portion of the ^{16}N exposure. Typical plans for future boiling water reactors incorporate extensive side shielding for all components above the operating floor of the turbine generator building and some top shielding as well, if deemed necessary. The direct component of ^{16}N dose from such plants should be minimal. In contrast to earlier designs, where the principal source of ^{16}N gammas was the high pressure turbine and its associated steam lines, newer designs locate the moisture separators (typically combined with reheaters) above the operating floor making them the greatest potential source. In order to assess the ^{16}N doses from such a plant, a joint survey was conducted at the site of the Cooper Nuclear Power Station in Brownville, Nebraska. An initial survey was conducted on February 11 – 15, 1975, using instrumentation from the EPA Eastern Environmental Radiation Facility (EERF) in Montgomery, Alabama. A follow-up survey was performed April 21 – 24, 1975, primarily with instruments from the ERDA Health and Safety Laboratory (HASL), New York City, New York.

Site Information

The Cooper Nuclear Power Station is an 801 MW(e) base-loaded nuclear power plant utilizing a 2400 MW(t) boiling water reactor. High density concrete walls (figure 1) shield the components above the operating floor (turbines, moisture separators, and associated steam lines) along a line-of-sight to the outside environment on the north, east, and west sides of the building. Components other than the moisture separators are only partially shielded to the south. The terrain to the north of the turbine building is relatively flat and unobstructed allowing measurements to be made from the walls of the turbine generator building to distances of 500 to 600 meters. The Missouri River flows along the east side of the plant with the plant property extending to the east of the river as shown in figure 2. Access to this part of the site is difficult. The terrain to the south of the plant is slightly rolling, but measurements could be made to distances of a few hundred meters from the turbine generator building. The reactor building and switchyard to the west of the turbine building precluded profile measurements in that direction.

Field Measurements

The February measurements were intended to provide an overall indication of the ^{16}N radiation at different locations on the plant site as well as to provide an estimate of the background exposure rate. Measurements were made primarily with

Figure 1. Turbine building-operating floor

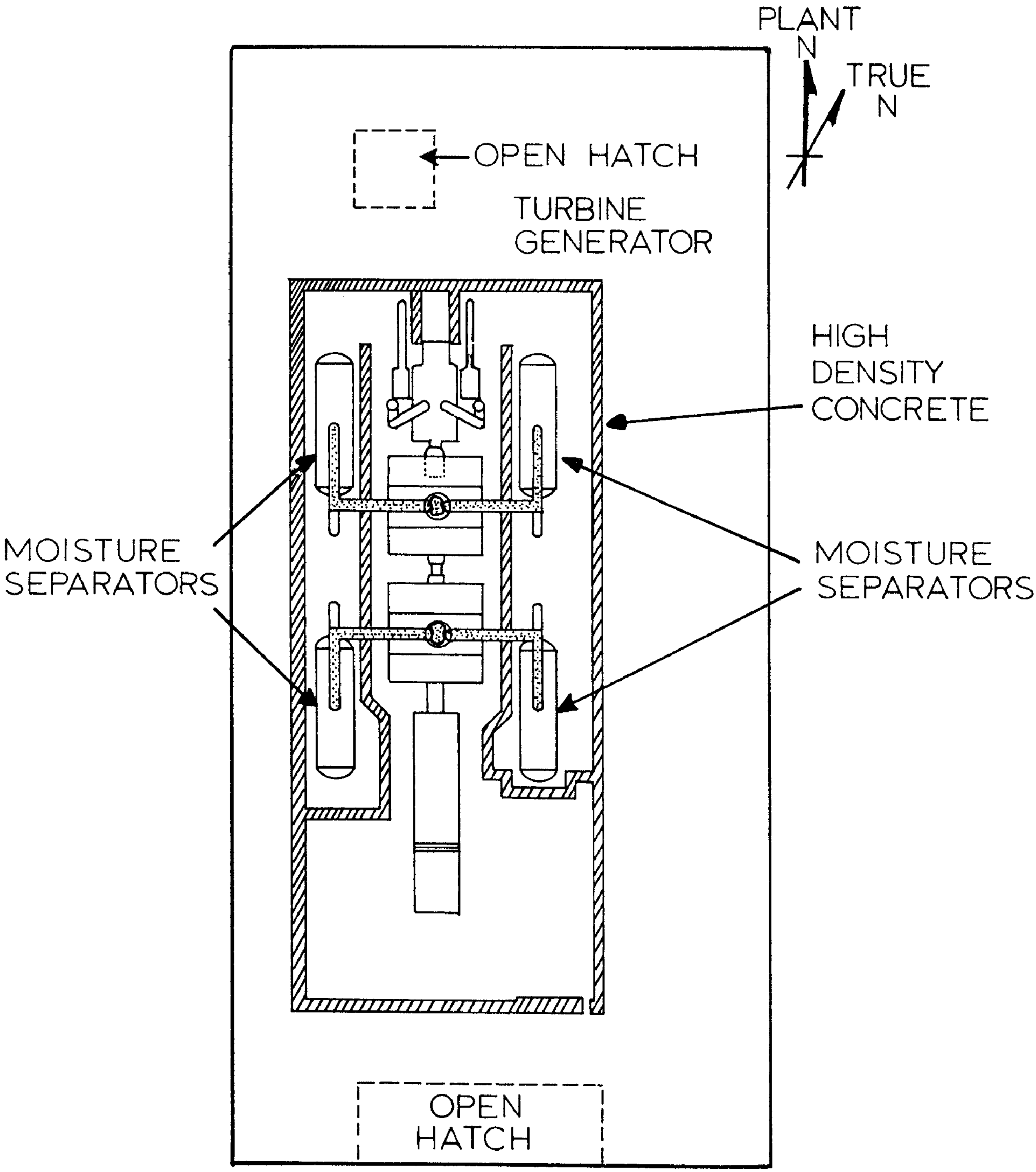
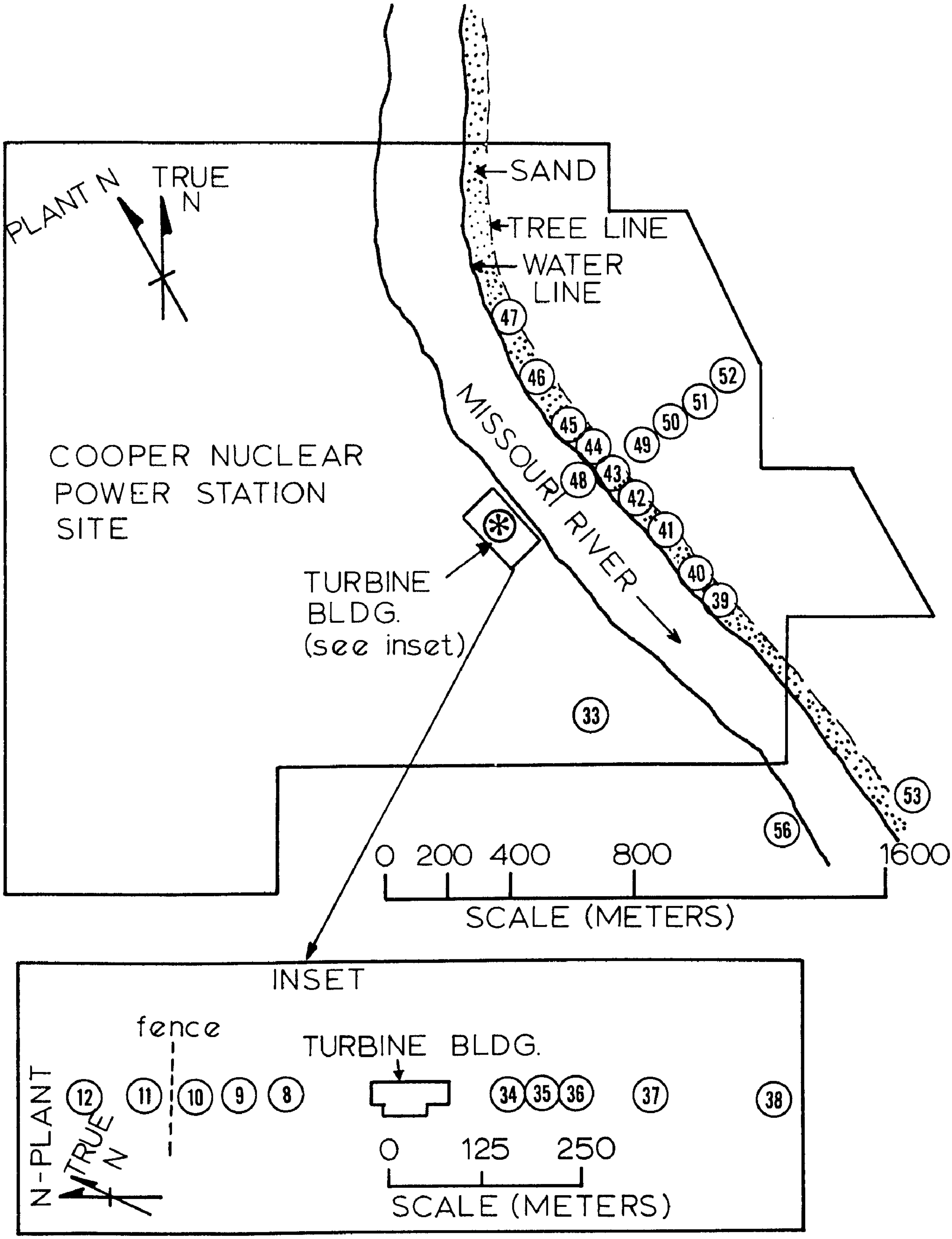


Figure 2. February survey locations



pressurized ionization chambers (PIC's) which had been previously calibrated at the EERF using an NBS-certified ^{226}Ra source. Spectral measurements were made at some locations using a 10-cm x 10-cm NaI(Tl) detector in conjunction with a multichannel pulse-height analyzer. Exposure rate profiles were made along the turbine axis to the north and south of the plant. A partial profile perpendicular to the turbine axis to the east was made but was limited to those locations accessible on either side of the river. North-south profiles were also obtained along each side of the river centered on this east axis. Several measurements were also made on the roof of the cooling water intake structure, located to the east of the turbine generator building. The roof of this building is above the floor of the turbine generator building and therefore provided a location close to the source shielded only by the side walls. Additional measurements were made near the river bank at Brownville State Park (About 4 km north of the plant) to provide an estimate of local background. Data from this survey are shown in table 1. The survey locations are indicated on figures 2, 3 and 4. A short time prior to the survey the plant had shut down for an inspection, and at the time of the survey was in the process of returning to its normal operating level. The power level was increasing gradually from 76% to 90% of full power over the period of the study, except for a brief period during measurement 63 when it was temporarily reduced. Measurements at location 7 were taken at several power levels to observe exposure rate dependence with power level.

During the follow-up survey (April 21 to 24), a complete profile of ^{16}N exposure rates was obtained in the northerly direction along the turbine axis, as well as a partial profile along the south axis. Difficulties in gaining access to the east shore of the river prevented measurements perpendicular to the turbine axis. The data for this survey are shown in table 1 (Measurements B1-B10) and table 2. The reactor operated at 2355 MW(t) during this portion of the study, except for a brief drop to 60% of full thermal power during the night of April 23–24. Measurements were made primarily with PIC's. NaI(Tl) and Ge(Li) measurements were made at selected locations to assess terrestrial background and to detect any direct component of the ^{16}N exposure. In order to provide an intercomparison between the February and April data a few measurements using an EERF PIC were also made. There were no indications of any exposure from other sources associated with the reactor, including the plume, during either measurement period.

Analysis of Data

Evaluation of Spectral Data

Spectroscopic data indicated the presence of some high energy photons in the profiles taken to the south and to the east. In the case of the south data, these are to be expected due to the partial shield wall. In the east direction it would appear that the shield wall is thin enough to permit direct radiation to make a small contribution to the ^{16}N exposure rate. Even though they contain some direct radiation, the exposure rates to the south and east are of the same order of magnitude as exposure rates at corresponding locations to the north. Because of its lack of any direct component the north profile was used to evaluate skyshine.

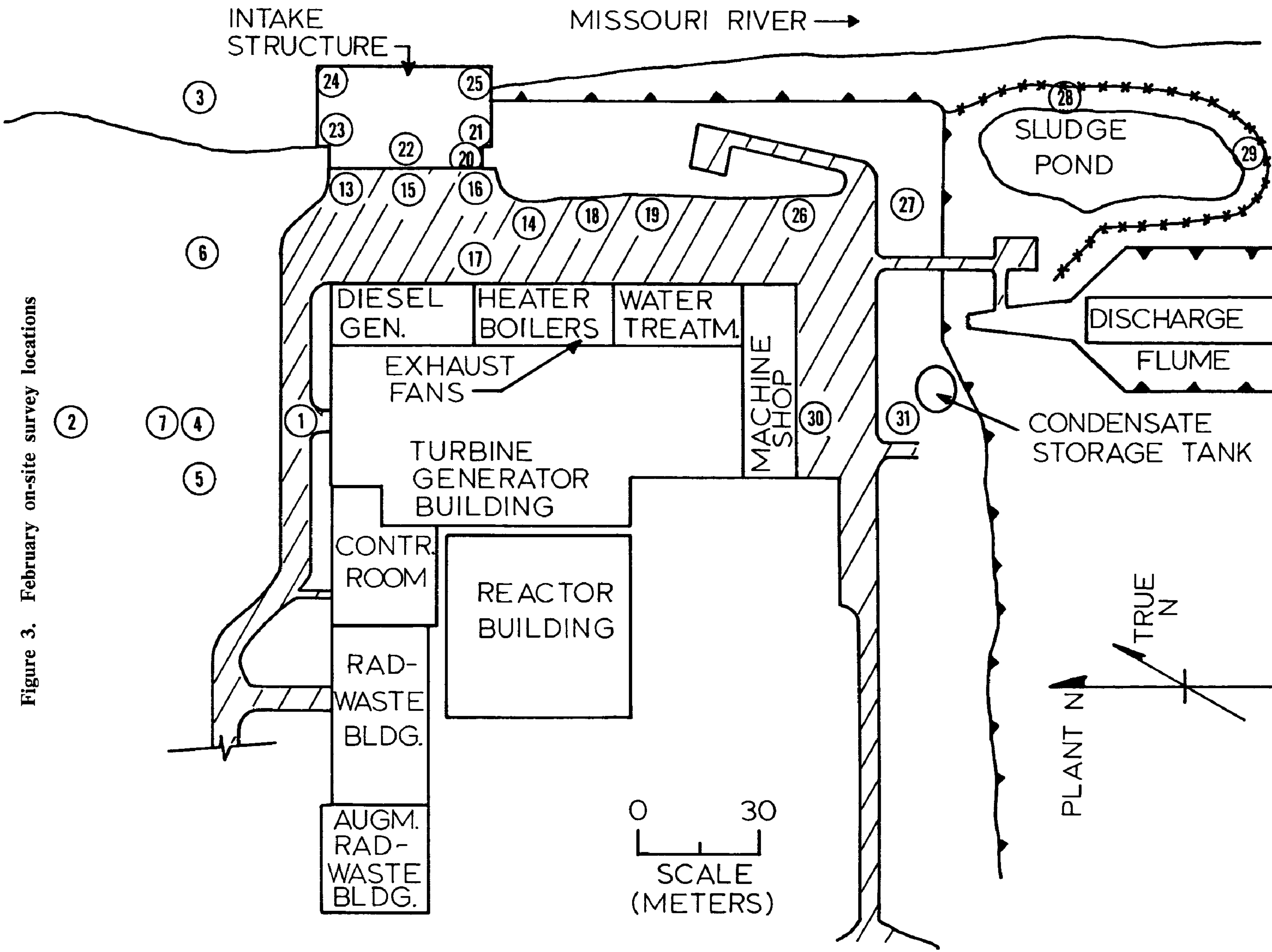
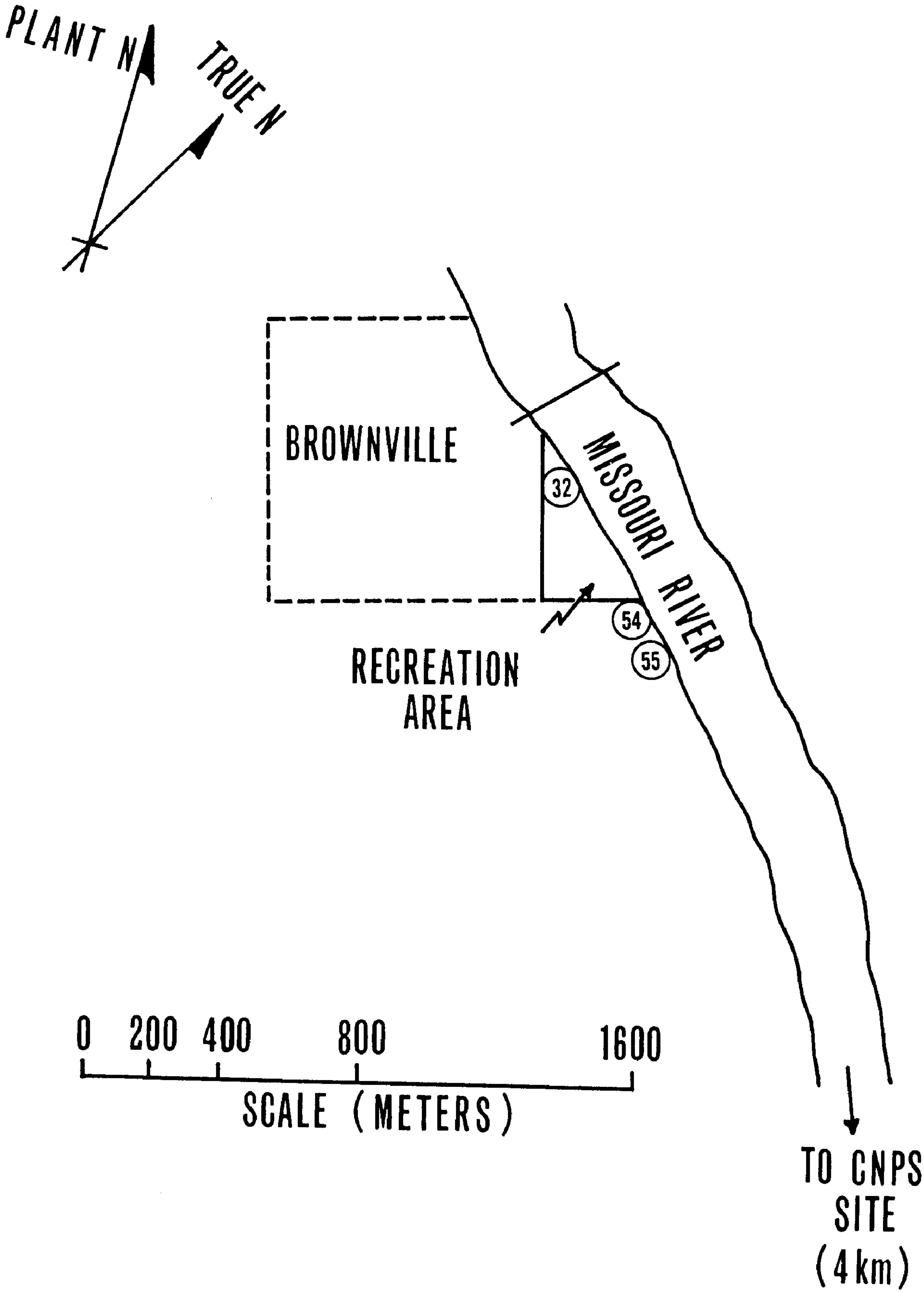


Figure 3. February on-site survey locations

Figure 4. February northern survey locations



Background Considerations

Background from terrestrial and fallout gamma emitters was estimated by analyzing spectroscopic data obtained during the April portion of the survey.[1] Net ^{16}N levels were calculated by subtracting from the HASL ion chamber total readings (1) a 3.9 μR/hr cosmic ray background and (2) the estimated gamma background based on spectrometric measurements at the same or a nearby location. There is an apparent discrepancy between the PIC and spectrometer gamma exposure rates for the measurement at 581 meters south of the plant (table 2). For this location the ^{16}N level was estimated from the 511 keV annihilation radiation peak in the Ge(Li) spectrum as calibrated with data from other locations. EPA ion chamber data in the vicinity of the plant were corrected using an 8.3 μR/hr background (3.9 μR/hr cosmic + 4.4 μR/hr gamma). It was assumed for these measurements that the background did not change appreciably from location to location or from February to April. In this regard it should be noted that the total exposure rates at the Brownville State Park; (9.4 μR/hr – EPA, Feb.; 9.2 μR/hr – HASL, April; and 9.3 μR/hr – EPA, April), are consistent from February to April but are about 1 μR/hr higher than the levels inferred for typical on-site locations.

Intercomparison of EPA/HASL Data

In addition to the 9.3 μR/hr (EPA) vs. 9.2 μR/hr (HASL) values at Brownville State Park, the values 87.7 μR/hr (EPA) and 85.6 μR/hr (HASL) for essentially the same location (#7) compare closely. Instrumental problems prevented additional comparisons.

Power Level Dependence

Lowder (1) has proposed a power level dependence for ^{16}N exposures from power reactors of the form $d = d_0 p \exp(-\lambda \tau_0 / p)$, where d_0 is the exposure rate that would result at full power with no reactor-turbine building delay, p is the fraction of full power, λ is the decay constant for ^{16}N, and τ_0 is the effective decay time between the reactor and those turbine building components which comprise the ^{16}N source. This model assumes (1) that the concentration of ^{16}N steam (μCi/g) leaving the reactor is independent of power level, (2) the steam flow rate (g/s) is proportional to power level, and (3) that the effective time for ^{16}N decay in the source components does not depend on power level.

The data for location 7 were used to determine least squares estimates of d_0 and τ_0. The results of this least squares fit are shown in table 3. The limited range of power variation introduces a high correlation between the parameters (.995) and large standard deviations in their estimates. While the model and its assumptions cannot be considered verified on the basis of such limited data, the model does provide an adequate empirical description of the data. The effective steam delay time of 7.0 seconds at full power is comparable to the value (8 seconds) Lowder, et al. obtained at Oyster Creek (1).

[1]The analysis of the HASL data will be contained in the forthcoming publication, Lowder, et al., "Determination of ^{16}N Radiation Field at a BWR Power Station."

Distance Dependence

A theoretical model of the skyshine would require transport calculations beyond the scope of this study. Instead the following empirical model was used:

$$d = \frac{a_o p \exp(-\lambda\tau_o/p) P_o}{4\pi r^2} \exp(-r/\ell)(1 + b\, r/\ell)$$

where:
- d – the ^{16}N exposure rate (μR/hr)
- a_o – a conversion factor [μR-m^2/hr per MW(e)]
- p – the fraction of full power
- P_o – the full plant power [MW(e)]
- λ – the decay constant for ^{16}N (s^{-1})
- τ_o – the effective delay time at full power (seconds)
- r – the distance between the receptor and the center of the moisture separators (meters)
- ℓ – an effective attenuation length (meters)
- b – an effective linear buildup factor

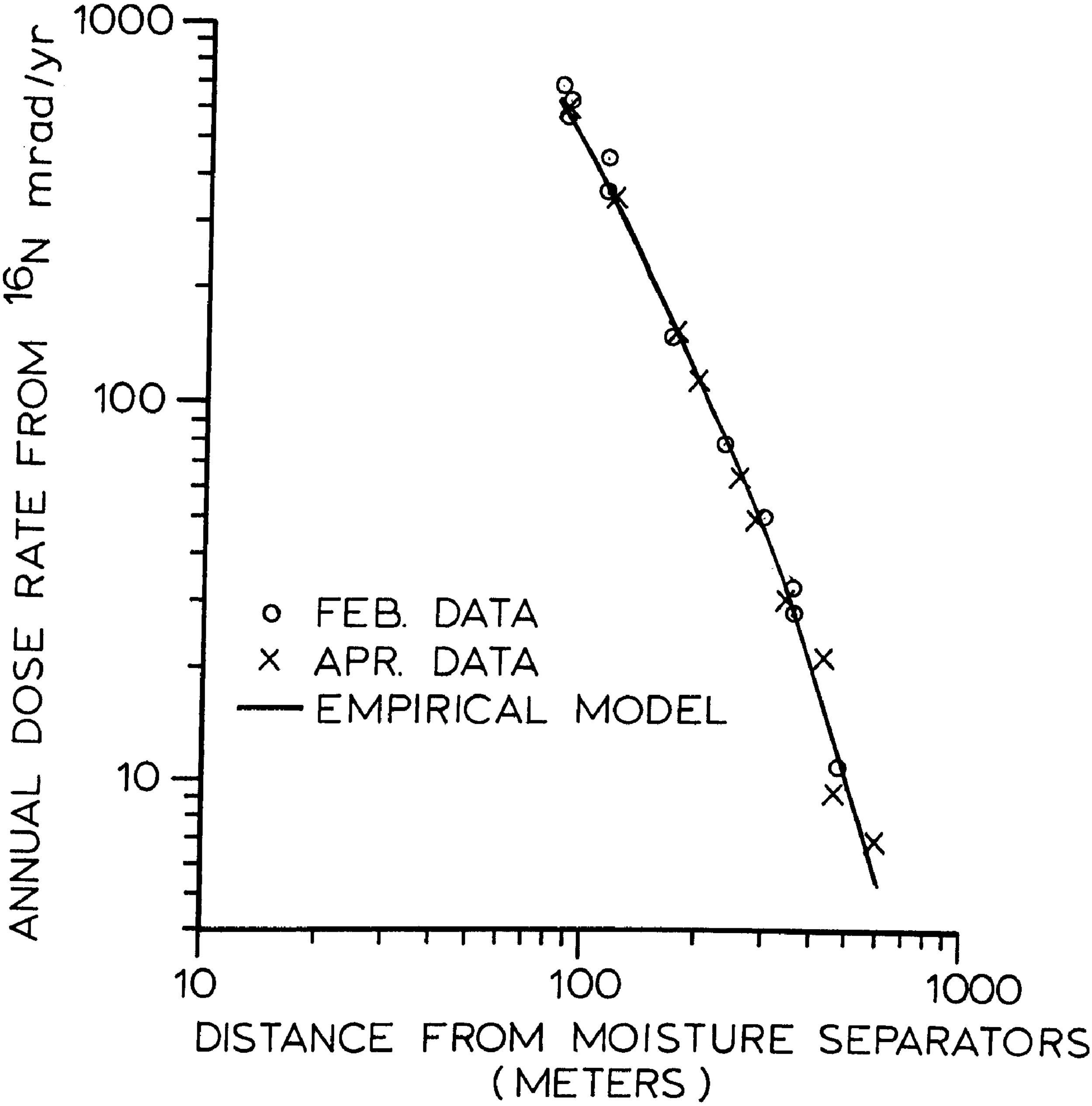
This model combines the power dependence model from the previous section with a point source model corrected for attenuation and linear buildup.

The least squares fit of the distance data is summarized in table 4. Annual ^{16}N dose rates based on the empirical model and the observed data are plotted in figure 5. Exposure rates have been converted to dose rates using a conversion factor of 1 μR/hr = 7.688 mrad/yr. The February data have been adjusted to full power using the assumed power dependence model. Note that while the fitted model predicts a dose rate of 10 mrad/yr at 500 meters there is considerable scatter of the observed data about the model at this distance. The standard deviation of the calculated value at 457 meters is 2.5 mrad/yr. Since this value assumes no error contribution from the background determination or the model itself, it is a lower limit for the uncertainty of the dose rate at this distance. The absolute values of the correlation coefficients between parameters are all high ($> .9$) so that while the model provides a reasonable description of the data, there are substantial uncertainties in individual parameters. The calculated linear buildup factor (3.0) is extreme for an unshielded source, but is not unreasonable for this situation where the doses are essentially from radiation scattered through large angles.

Summary

Spectrometric measurements made north of the turbine generator building at Cooper Nuclear Power Station indicated that plant doses were predominately from ^{16}N skyshine. The power level dependence observed was consistent with a model assuming a constant concentration of ^{16}N reactor steam and a reactor-turbine building delay inversely proportional to power level. A $1/r^2$ distance model with attenuation and buildup was fitted to the data. At a distance of 500 meters a dose rate of 10 mrad/yr at 801 MW(e) is predicted. The lower bound for the standard deviation of this estimate is 2.5 mrad/yr. Both the power level and distance models were chosen to provide an empirical fit to the data but do not have any rigorous basis for their choice.

Figure 5. Annual ^{16}N dose rates at full power vs. distance (North Axis)



Since the dose rate will depend on the particulars of the turbine building components and shield configuration, it would be inappropriate to rely solely on the use of the empirical models of this study to predict doses from other plants. However, the data invite comparison to a more detailed analysis, which would have to include source term as well as transport modeling.

REFERENCES

(1) LOWDER, W. M., P. O. RAFT, and C. V. GOGOLAK. "Environmental Gamma Radiation through Nitrogen-16 Decay in the Turbines of a Large Boiling Water Reactor," HASL-271, (January 1973).

(2) BRINCK, W., K. GROSS, G. GELS and J. PARTRIDGE. "Environmental Radiation Study at Vermont Yankee," presented at the Nineteenth Annual Meeting of the Health Physics Society held in Houston, Texas, (July 1974).

(3) HAIRR, L. M., P. C. LECLARE, T. W. PHILBIN, and J. R. TUDAY. "The Evaluation of Direct Radiation in the Vicinity of Nuclear Power Stations," 18th Annual Health Physics Meeting, (June 1973).

(4) DIXON, W. J., editor, BMD Biomedical Computer Programs, University of California Press (1973).

Table 1

EPA
Pressurized Ionization Chamber measurements
Cooper Nuclear Station - February 1975

Measurement Number	Location	Time & Date	Gross Exp. Rate (μR/hr)	Approx. Power Level (MWe)
1	3 m north of Turbine Bldg. on center line	1113 2/12/75	45.5	606
2	61 m north of Turbine Bldg. on center line	1210 2/12/75	37.8	613
3	80 m from north end of Turbine Bldg. at 67.5°	1200 2/12/75	35.9	612
4	30.5 m north of Turbine Bldg. on center line	1204 2/12/75	64.4	612
5	33.5 m from north end of Turbine Bldg. at 336°	1212 2/12/75	51.6	612
6	48 m from north end of Turbine Bldg. at 50°	1309 2/12/75	48.9	612
7	37 m north of Turbine Bldg. on center line	1315 2/12/75	58.4	612
8	117 m north of Turbine Bldg. on center line	1330 2/12/75	20.5	612
9	183 m north of Turbine Bldg. on center line	1335 2/12/75	14.7	612
10	244 m north of Turbine Building on center line	1400 2/12/75	12.4	614
11	305 m north of Turbine Bldg. on center line	1513 2/12/75	10.6*	617
12	427 m north of Turbine Bldg. on center line	1630 2/12/75	9.2	617
13	Northwest corner of Intake Bldg. on line with north end of Turbine Bldg.	1632 2/12/75	63.9	617
14	18.3 m east of Turbine Bldg. just south of Intake	1635 2/12/75	123.7	617
15	center of Intake Bldg. East of Turbine - ground level	1640 2/12/75	82.7	617
16	Southwest corner of Intake Bldg. - ground level	1645 2/12/75	106.2	617
17	12.8 m east of Turbine Bldg. on line with south end of Intake	1650 2/12/75	118.4	617
18	21.3 m east of Turbine Bldg. and 22.9 m south of Intake Bldg.	1650 2/12/75	81.9	617
19	21.3 m east of Turbine Bldg. and 38.1 m South of Intake Bldg.	1700 2/12/75	53.4	617
20	Top of first level of Intake Bldg. - southwest corner	1700 2/12/75	134.4	617
21	Top of upper level of Intake Bldg. - southwest corner	1705 2/12/75	150.4	617
22	Top of upper level of Intake Bldg. of West side	1710 2/12/75	118.4	617
23	Top of upper level of Intake Bldg. - northwest corner of Bldg.	1714 2/12/75	94.0	617
24	Top of upper level of Intake Bldg. - northeast corner of Bldg.	1720 2/12/75	68.6	617

Table 1
(Cont.)
EPA
Pressurized Ionization Chamber measurements
Cooper Nuclear Station – February 1975

Measurement Number	Location	Time & Date	Gross Exp. Rate (μR/hr)	Approx. Power Level (MWe)
25	Top of upper level of Intake Bldg. – southeast corner of Bldg.	1724 2/12/75	97.8	617
26	21.3 m east of Turbine Bldg. on line with south end	1708 2/12/75	40.9	617
27	21.3 m east of Turbine Bldg. even with north edge of Waste Tank	1715 2/12/75	30.3	617
28	East edge of sludge pond even with stack	1720 2/12/75	23.1	617
29	South edge of Sludge Pond on line with West side of Intake Bldg.	1725 2/12/75	17.7	617
30	South end of Turbine Bldg. at edge of building on center line	1740 2/12/75	24.4	617
31	South end of Turbine on center line even with Waste Tank	1745 2/12/75	22.6	617
32	Back at Park near Brownville, northeast, taken with NaI	1815 2/12/75	9.4	617
33	527 m south of Turbine Bldg. at gate on levee	0930 2/13/75	9.4	664
34	79.3 m south of Turbine Bldg. near center line	0940 2/13/75	22.6	664
35	104 m south of Turbine Bldg. near center line	0945 2/13/75	23.5	664
36	128 m south of Turbine Bldg. near center line	0950 2/13/75	20.7	665
37	250 m south of Turbine Bldg. at high voltage tower	0955 2/13/75	13.0	665
38	405 m south of Turbine Bldg. near center line	1005 2/13/75	10.7	665
39	East bank of river under high voltage lines	1005 2/13/75	8.9	665
40	East bank of river between locations 39 and 41	1120 2/13/75	10.5	666
41	East bank of river directly across river from stack	1130 2/13/75	11.7	667
42	East bank of river directly across river from south end of Turbine Bldg.	1135 2/13/75	12.1	667
43	East bank of river directly across from center of Turbine	1140 2/13/75	12.1	668
44	East bank of river – directly across from north end of Turbine Bldg.	1145 2/13/75	12.1	669
45	East bank of river – directly across from 61 m fence	1153 2/13/75	11.7	670
46	East bank of river – directly across from 274 m fence	1200 2/13/75	9.9	670
47	East bank of river – 131 m North of location #46	1208 2/13/75	9.7	670
48	30.5 m West of Location #43 54.8 m from east Tree line (on ice)	1225 2/13/75	9.6	670
49	67.1 m east of #43 in trees on east Bank (approx. 7.6	1235 2/13/75	10.3	670

Table 1
(Cont.)

EPA
Pressurized Ionization Chamber measurements
Cooper Nuclear Station – February 1975

Measurement Number	Location	Time & Date	Gross Exp. Rate (μR/hr)	Approx. Power Level (MWe)
	cm snow)			
50	128 m east of #43 in trees on east side (approx. 7.6 cm snow)	1242 2/13/75	9.6	670
51	189 m east of #43 in trees on East side (approx. 7.6 cm snow)	1246 2/13/75	9.4	670
52	On top of levee 1097 m east of Turbine Bldg. (approx. 5 cm snow)	1330 2/13/75	9.3	672
53	Background in woods south of Plant on east side of river	1350 2/13/75	9.4	673
54	On West Sand Bar 305 m south of Brownville State Recreation Area – background	1425 2/13/75	9.3	674
55	On West Sand Bar approx. 396 m South of Brownville State Recreation Area	1431 2/13/75	9.4	675
56	South of Plant on west bank of river – sand bar – background	1500 2/13/75	9.0	678
57	305 m North of Turbine on center line – retake of #11	1430 2/13/75	11.5	675
58	36.6 m North of Turbine Bldg. on center line – retake of #7	1605 2/13/75	65.8	685
59	79.6 m from north end of Turbine Building at 67.5° – retake of #3	1610 2/13/75	49.5	685
60	3 m north of Turbine Bldg. on center line – retake of #1	1612 2/13/75	53.5	685
61	33.5 m from north end of Turbine Bldg. at 336° – retake of #5	1623 2/13/75	73.2	685
62	61 m north of Turbine Bldg. at center line – retake of #2	1700 2/13/75	52.5	686
63	36.6 m north of Turbine Bldg. on center line – retake of #7	0800 2/14/75	79.2	731
	By-Pass Valves opened during measurements	0805 2/14/75	49.5	–
		0815 2/14/75	49.5	–
		0820 2/14/75	59.4	–
		0825 2/14/75	77.2	731

Table 1
(Cont.)

EPA
Pressurized Ionization Chamber measurements
Cooper Nuclear Station – April 1975

Measurement Number	Location	Time & Date	Gross Exp. Rate (μ R/hr)	Approx. Power Level (MWe)
B- 1	Upper Roof of Intake Bldg. southwest corner (repeat of #21 on 2/12)	1057 4/22/75	> 200	798
B- 2	Upper Roof of Intake Bldg. (repeat of #22 on 2/13)	1104 4/22/75	> 200	798
B- 3	Upper Roof of Intake Bldg. – northwest corner (repeat of #23 on 2/12)	1111 4/22/75	153.0	798
B- 4	Upper Roof of Intake Bldg. – northeast corner (repeat of #24 on 2/12)	1119 4/22/75	107.0	798
B- 5	Upper Roof of Intake Bldg. – southeast corner (repeat of #25 on 2/12)	1130 4/22/75	157.0	798
B- 6	457 m north of Turbine Bldg. on center line	1250 4/22/75	10.9	798
B- 7	283 m south of Turbine Bldg. under north edge of high voltage tower	1440 4/22/75	14.6	798
B- 8	Northwest corner of Intake Bldg. (on line with north end of Turbine Bldg.)(repeat of #13 on 2/12)	1517 4/22/75	105.0	798
B- 9	36.6 m north of Turbine Bldg. on center line (repeat of #7 on 2/12)	1605 4/22/75	87.7	798
B-10	Brownville State Recreation Area (repeat of #32 on 2/12)	1654 4/22/75	9.3	798

Table 2

Health and Safety Laboratory survey data – Cooper Plant

April 1975

Distance to Turbine Bldg. (meters)	Detector	Gamma Exposure Rate (µR/hr) ^{40}K	U	Th	^{137}Cs	Total	^{16}N
North Axis							
37	PIC					81.7	77
67	PIC					49.4	45
122	PIC*					24.3	20
	PIC**					28.3	24
146	PIC					19.7	15.6
	Ge(Li)	2.0	1.0	1.1	<0.1	(4.1)	
206	PIC					12.7	8.4
	Ge(Li)	2.3	0.9	1.1	<0.1	(4.3)	
238	PIC					10.9	6.5
297	PIC					8.5	4.1
	Ge(Li)	2.3	0.9	1.1	<0.1	(4.4)	
384	PIC					6.9	2.8
	NaI	2.1	0.6	0.9		(4.1)	
457	PIC					5.7	1.2
	Ge(Li)	2.7	1.0	0.8	<0.1	(4.5)	
549	PIC					5.4	0.9
	NaI	2.5	0.7	0.9			
	Ge(Li)	2.4	0.9	1.1	<0.1	(4.5)	
3500	PIC					5.3	<0.1
	NaI	1.8	1.8	1.5	-	(5.2)	
	Ge(Li)	1.9	1.2	1.6	<0.1	(4.9)	
South Axis							
302	PIC					9.0	4.5
	Ge(Li)	2.4	0.9	1.2	<0.1	(4.5)	
347	PIC					7.5	
378	PIC					7.4	
475	PIC					6.3	1.5
	Ge(Li)	2.2	1.3	1.3	<0.1	(4.8)	
581	PIC					5.6	1.7
	Ge(Li)	1.7	1.1	1.1	<0.1	(3.9)	

* 1 meter above ground.
** 15.2 meters above ground.

Table 3

Least squares estimation of power variation parameters

Model:

$$d = d_o p \exp(-\lambda t_o/p)$$

Parameters:

$(1/\lambda = 10.53$ seconds

$d_o = 154 \pm 28\ \mu R/hr^*$

$t_o = 7.0 \pm 1.8$ seconds*

d cal (μR/hr)	d obs (μR/hr)	p
57.6	58.4	.764
68.8	65.8	.855
76.2	79.2	.913
87.0	85.6	.996

Mean square error of fit = 4.4 $(\mu R/hr)^2$

The data are for location 7 and assume a total background of 8.3 μR/hr. Least-Squares fit calculated using BMD07R (4)

* 1 standard error

Table 4

Least squares estimates of distance variation parameters

Model:

$$d = \frac{a_o p \exp(-\lambda t_o/p)\ P_o \exp(-r/\ell)(1 + br/\ell)}{4\pi r^2} + 8.3$$

$1/\lambda = 10.53$ s

$P_o = 801$ MWe

$t_o = 7$ s

Parameters:

$$a_o = 1.2 \pm .37^* \times 10^4 \quad \frac{\mu R \cdot m^2}{MWe \cdot hr}$$

$\ell = 220 \pm 54^*$ meters

$b = 3.0 \pm 1.5^*$

$d_{cal} + 8.3$† (μR/hr)	$d_{obs} + 8.3$† (μR/hr)	r (meters)	p	D_{cal} (mrad/yr)
38.9	37.8	110	.765	235
64.3	64.4	80	.764	431
57.2	58.4	86	.764	376
21.9	20.5	166	.764	104
14.9	14.7	232	.764	50.5
12.1	12.4	293	.767	30.0
10.6	10.6	354	.770	17.7
9.2	9.2	476	.770	2
11.0	11.5	354	.843	20.9
68.3	65.8	86	.855	461
45.9	52.5	110	.856	289
75.6	79.2	86	.913	517
86.3	87.7	86	.996	600
90.0	85.3	83	.996	635
54.6	53.3	113	.996	356
29.4	28.3	168	.996	162
24.2	23.9	192	.996	123
16.9	16.7	252	.996	66.4
14.8	14.8	284	.996	49.7
12.2	12.4	343	.996	30.4
10.3	11.1	430	.996	15.7
10.0	9.5	457	.996	13.0
9.0	9.2	595	.996	5.2

* One standard error.
† Background.
1 μR/hr = 7.688 mrad/yr.
Mean square error of fit = 4.6 $(\mu R/hr)^2$.

The data fitted are for the north axis of both the February and April surveys. A background of 8.3 μR/hr was added to the net HASL data and assumed for the EPA data for purposes of the fit. r includes the distance between the center of the moisture separators and the north wall of the turbine building (49 m). Least squares fit calculated using BMD07R (4).

AU GAFS, AL(761625)800