PHOENIX MEMORIAL LABORATORY

MEMORANDUM REPORT NO. 3

Atmospheric Dilution of Gaseous Effluents from the Phoenix Laboratory Stacks

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INTRODUCTION

Atmospheric concentrations of gaseous effluent radioactivity generated by the Ford Nuclear Reactor (FNR), and discharged to the atmosphere through a 17 meter stack on top of the Phoenix Memorial Laboratory (PML), were studied as part of the preparation of a proposal for operating the FNR at 2 megawatts. This report calculates the atmospheric dilution expected at locations in the vicinity of the reactor building during various meteorological conditions. It concludes that a dilution factor of 16 is a conservative factor to use in calculating the atmospheric concentrations of gaseous effluent.

SOURCE AND CONCENTRATION OF RADIOACTIVE DISCHARGE

Investigations during operation at 1 megawatt indicate that the principal source of gaseous activity released through the stacks is Argon-41, resulting from neutron activation of the argon in air. Air is used in operation of the pneumatic rabbit system and it may also be used for cooling experiments in the beam tubes. Calculations indicate that at 2 megawatts the generation rate of Argon-41 is 1.25 microcuries per second in the pneumatic rabbit system and 10.4 microcuries per second per beam tube. Because of the large contribution from the beam tubes, they will not be air cooled during 2 megawatt operation. If air cooling of reactor beam tubes is not permitted, the Argon-41 released comes from the air used in operating the pneumatic rabbit system. The calculated Argon-41 activity in the stack discharge from this source with the reactor operating at 2 megawatts is 1.25 microcuries per second.* The discharge rate expected on the basis of blower specifications is 5.08×10^6 cubic centimeters per second. Thus, the calculated activity concentration is 2.5×10^{-7} microcuries per cc (μc/cc).

For continuous 2 megawatt operation, with no dilution factor, the calculated concentration is six times the non-occupational maximum permissible concentration (MPC) of 4×10^{-8} μc/cc.[1] Thus, a dilution factor is required for continuous operation. The calculations which follow indicate that a dilution factor of 16 is conservative for the existing exhaust system.

GASEOUS EFFLUENT SYSTEM

The Ford Nuclear Reactor is located in a building separate from but attached to the Phoenix Memorial Laboratory. There are four stacks on the roof of the laboratory immediately adjacent to the reactor building (See photograph, page 3). Stack No. 1 discharges the effluent from the fume hoods on the first floor of the laboratory. Stack No. 2 services the hot cell area of the first floor of the laboratory and the gaseous effluent system in the reactor building. Stack No. 3 services the fume hoods

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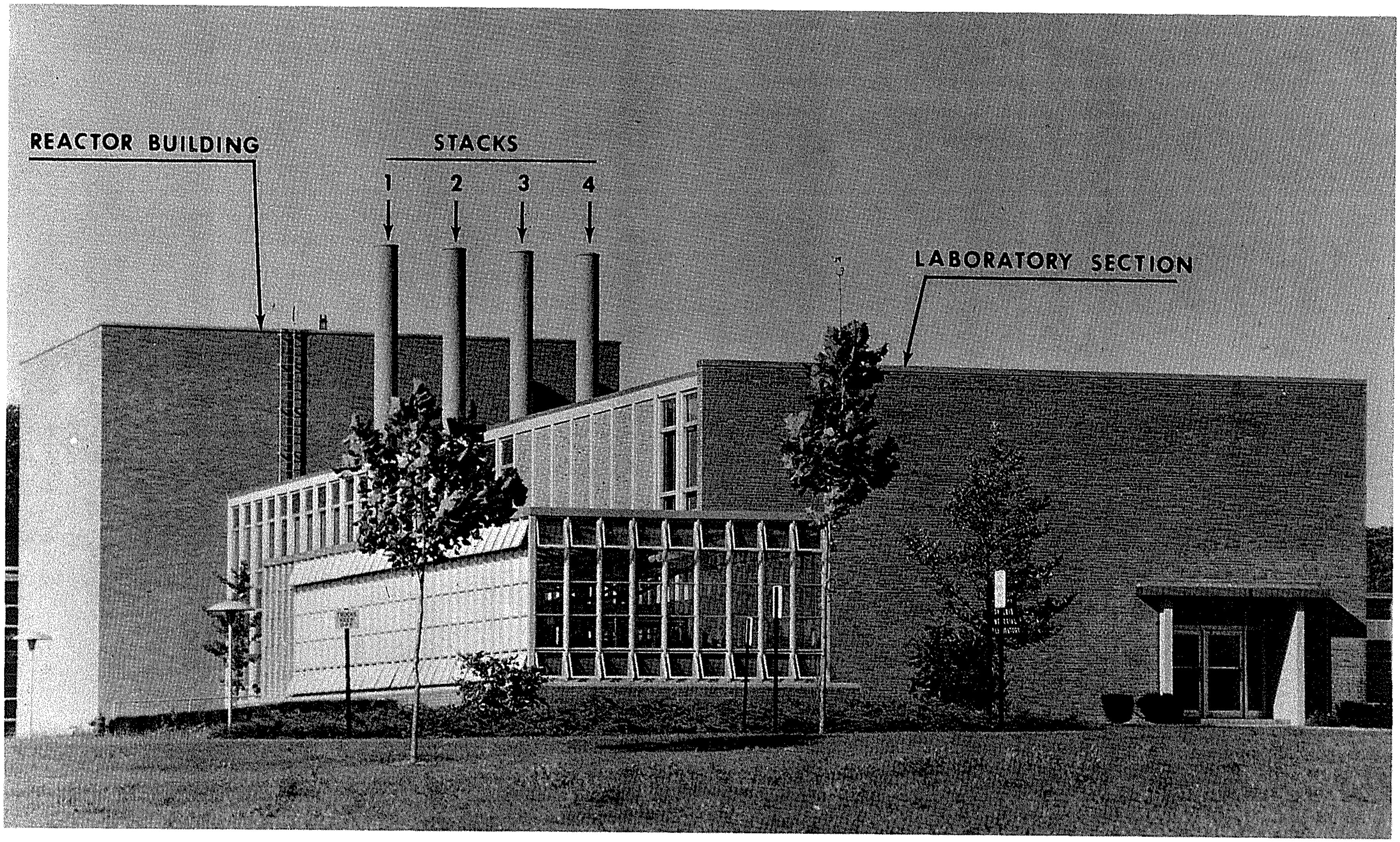
* See Appendix



Phoenix Memorial Laboratory and Ford Nuclear Reactor on the third floor of the laboratory. Stack No. 4 is not used and is capped. Stack No. 2 is the only stack serving the reactor. There is no routine discharge of radioactive gases from any other stack. Further discussion in this report will assume discharge of radioactive gas only through Stack No. 2.

The top of the stack is 17 meters above finished grade at the entrance to the laboratory, 9 meters above the roof of the laboratory and 3 meters above the reactor building roof. The stack has a diameter of 0.81 meters and is operated with a discharge rate of 5.08×10^6 cubic centimeters per second. The stack effluent is at ambient temperature. Before reaching the stack, the effluent passes through a fiberglas prefilter and an absolute filter (Flanders GA-10-A) which removes 99.97 per cent of all particles with a diameter greater than 0.3 micron.

REACTOR SITE

The reactor is located approximately in the center of the 900 acre North Campus of The University of Michigan. The University controls all the land within 457 meters of the reactor site except for a small portion of highway right-of-way to the south.

The major non-university installation in the area is the Veterans Administration Hospital, 457 meters south of the reactor site.

There are presently ten buildings on the North Campus in addition to the Phoenix Memorial Laboratory and the adjoining reactor building. These are: the Mortimer E. Cooley Building, 123 meters to the southeast of the reactor; the Automotive Engineering Laboratory, 92 meters to the northeast; a library storage building and bindery, 183 meters to the southeast; a printing shop building, 274 meters to the southeast; the Aeronautical Research Laboratories, 366 meters to the northeast; the Fluids Engineering Laboratory, 213 meters to the north; and the Cyclotron Building, 457 meters to the northeast. In addition, the Institute of Science and Technology Building is under construction 159 meters to the south of the reactor. This building complex will have a six story structure 183 meters from the reactor. All others are either two or three stories.

The Northwood Student Apartments, operated by the University, are 457 meters to the north of the reactor site. The center of this housing area is about 760 meters away from and approximately 17 meters above the reactor site.

The following distances and locations from the North Campus area are of particular interest to this analysis because each is the nearest inhabited building of a particular type.

TABLE I

Distance from Stack to Various North Campus Areas

Distance (meters)	Location
92	Automotive Engineering Laboratory Air Intake
183	Institute of Science and Technology Building
457	Northwood Student Apartments Nearest Reactor Site

The 92 meter distance is the nearest air intake of another building. The 183 meter distance is the distance to the top of the Institute of Science and Technology Building, the tallest building in the area. The 457 meter location represents those Northwood Student Apartments which are nearest the reactor site and the point of highest elevation.

METEOROLOGICAL CONSIDERATIONS

The calculation of the atmospheric concentrations of effluent gaseous radioactivity at various locations around the PML stack are based on methods described in an unpublished report by E. W. Bierly, E. W. Hewson and G. C. Gill of the Meteorological Laboratories, Department of Engineering Mechanics, The University of Michigan.[2] In this report, the following phenomena are considered:

1) Plume Fumigation - Solar heating causes mixing to occur as the nocturnal surface inversion is destroyed, thus bringing part of the plume to the ground. This condition lasts for a short time and occurs only at sunrise.

2) Plume Looping - This condition occurs during daylight hours when a strong lapse rate prevails and thermal eddy currents cause part of the plume to be carried to the ground.

3) Aerodynamic Downwash - Large eddies formed in the lee of a building during high winds will cause part of the plume to be carried to the ground.

4) Plume Trapping - When an inversion base occurs above a stack, the vertical diffusion of a plume is markedly suppressed and the plume is confined between the inversion base and the ground.

METEOROLOGICAL CALCULATIONS

In the calculations reported herein, it was assumed that the effective height of the stack was equal to the actual physical height. This assumption, appropriate to the low stack discharge velocity of the PML stack, made the calculations independent of the volume and velocity of the effluent.

Consideration was not given to the frequency of occurrence of the various meteorological conditions since this type of frequency data for the FNR site is not presently available. It was assumed that each meteorological condition exists 100 per cent of the time. Therefore, the calculations will yield conservative estimates of the atmospheric concentrations and dilutions.

In general the lower the wind speed, the higher the resulting concentrations. A wind speed of 2 meters per second is considered a probable lower limit for steady state conditions. Below this speed, the wind direction fluctuates greatly and steady state conditions cease to exist. The average wind speed in the Ann Arbor area is 5 meters per second. Calculated concentrations are plotted for each condition as a function of radial distance from the stack.

1) Plume Fumigation

A form of Hewson's equation[3] for the calculation of ground level concentration, χ, applicable to both long and short distances from the source, is

$$\chi = \frac{Q}{uH_e\left[\left(\frac{\pi x}{36}\right) + d + H_e \tan 15^\circ\right]} \mu c/m^3$$

where χ = ground level concentration in microcuries per cubic meter,

Q = source strength in microcuries per sec,

u = average wind speed in meters per sec,

H_e = effective stack height in meters,

x = horizontal distance downwind from the source in meters, and

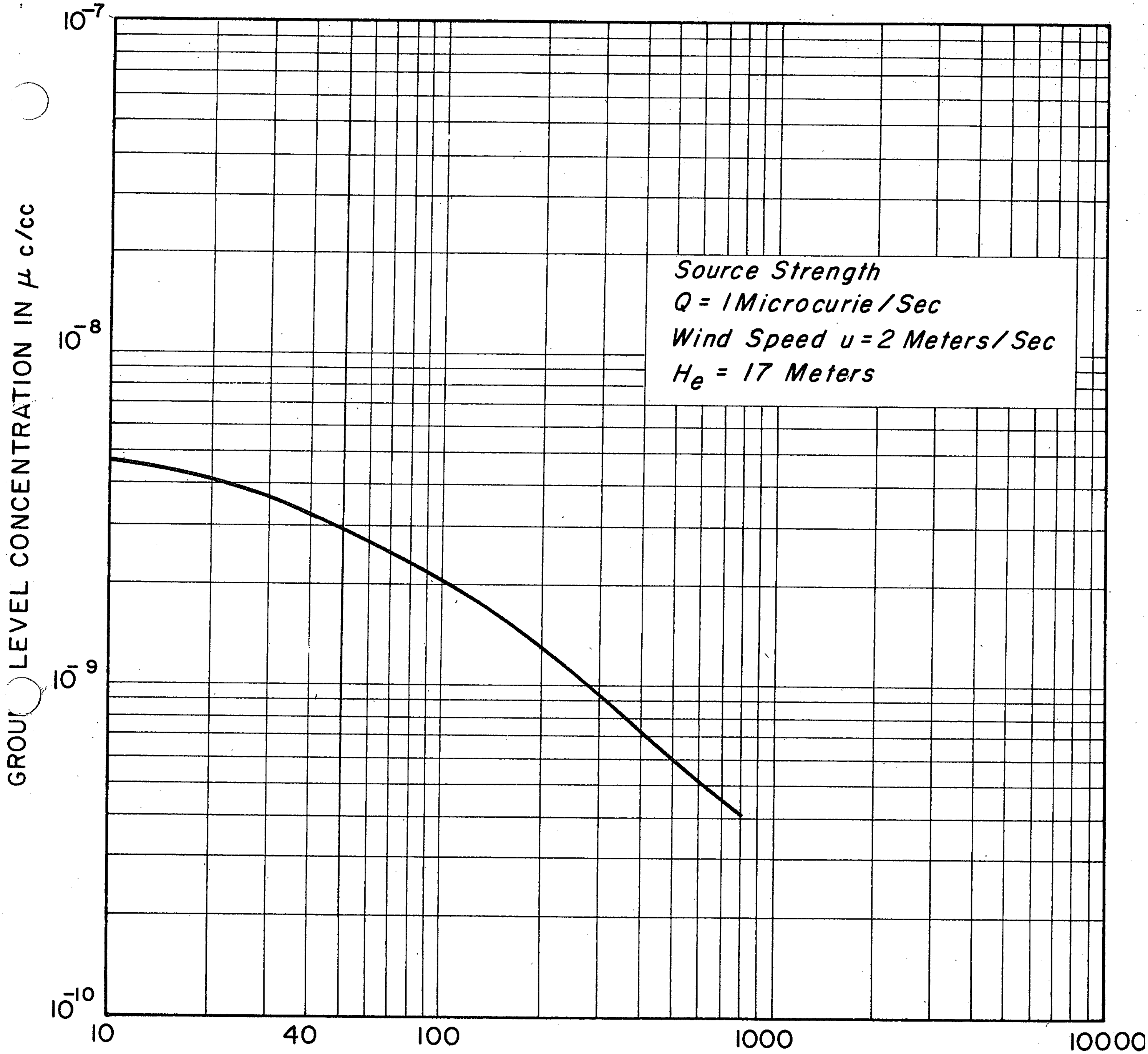
d = stack diameter

The concentrations calculated by this equation as a function of distance for a generalized source strength of one microcurie per second are shown in Figure 1. Effective stack height, H_e, for this and all subsequent figures was taken as 17 meters and the stack diameter, d, is 0.81 meters.

2) and 3) Plume Looping and Aerodynamic Downwash

The equation for looping derived by Holland[4] has been extended by Hewson, Gill and Bierly[5] to cover both looping and downwash. Looping conditions occur for wind speeds less than 10 meters per second and downwash occurs at wind speeds greater than 10 meters per second. The ground level concentration for both looping and downwash may therefore be calculated from the equation

$$\chi = \frac{2Q}{\pi C_y C_z u x^{2-n}}$$



RADIAL DISTANCE FROM BASE OF STACK IN METERS

FIGURE I

CONCENTRATION VS DISTANCE FROM STACK FOR PLUME FUMIGATION where C_y = horizontal crosswind diffusion coefficient,

C_z = vertical diffusion coefficient,

n = dimensionless coefficient whose value lies between 0 and 1, depending upon atmospheric stability,

x = distance from top of stack to point of interest at ground level in meters.

All other quantities are as defined previously.

The concentrations as a function of distance determined by this equation, with $n = 0.20$, $C_y = 0.44$ and $C_z = 0.36$ as specified in reference (2) are shown in Figure 2. A wind speed of one meter per second was selected for looping conditions to simplify the presentation in Figure 2. This wind speed provides a more conservative estimate for the atmospheric concentrations.

4) Plume Trapping

The equation for plume trapping conditions as developed by Hewson[6] is

$$\chi = \frac{Q \exp(-y^2/C_y{}^2 x^{2-n})}{\pi C_y C_z u x^{2-n}} \left\{ \sum_N \exp\left[\frac{-(z - H_e + 2Nh_{ib})^2}{C_z{}^2 x^{2-n}}\right] + \sum_N \exp\left[\frac{-(z + H_e - 2Nh_{ib})^2}{C_z{}^2 x^{2-n}}\right] \right\}$$

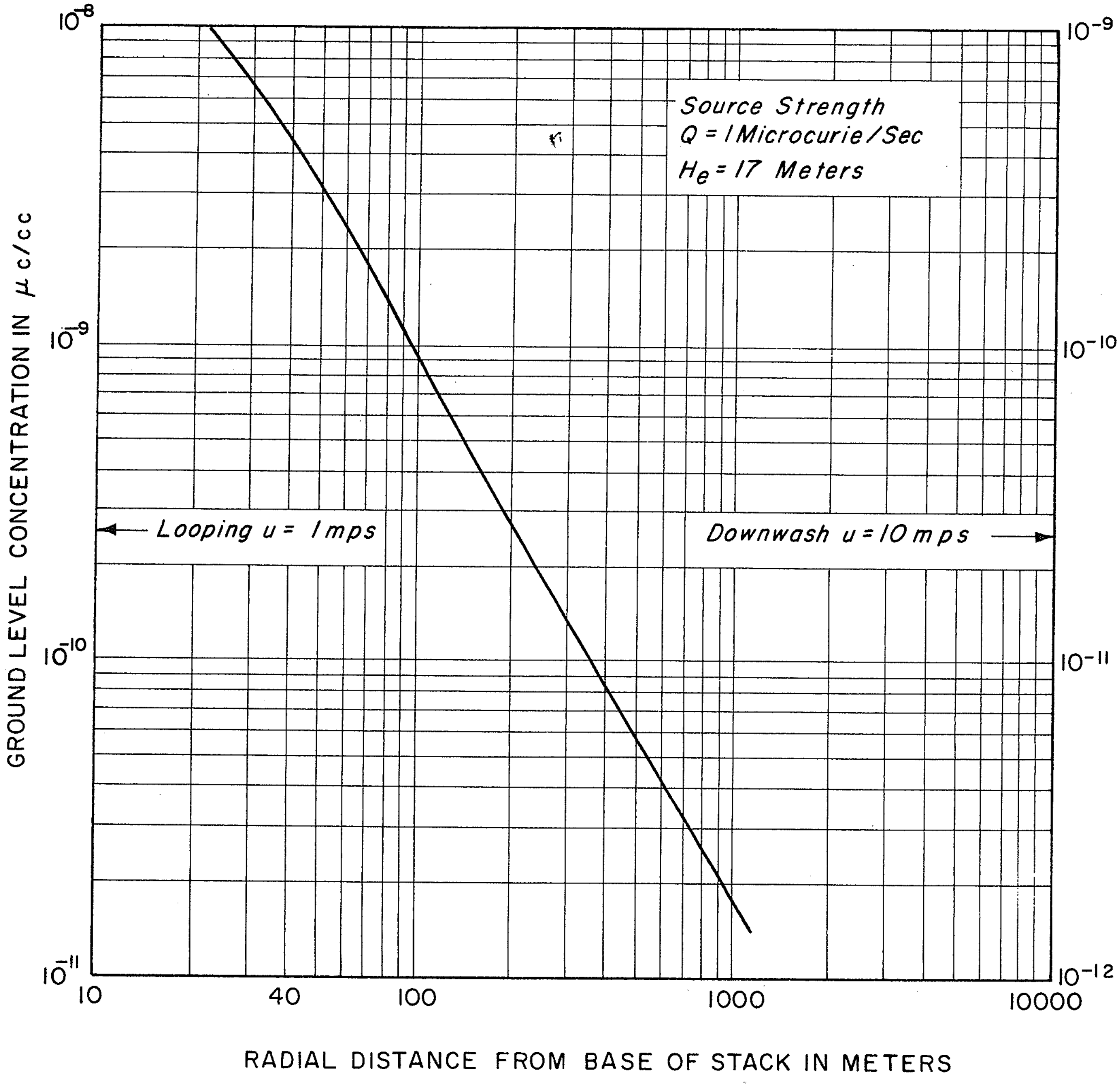


FIGURE 2

CONCENTRATION VS. DISTANCE FROM STACK FOR PLUME LOOPING AND DOWNWASH where y = horizontal distance crosswind from source in meters,

z = vertical distance in meters,

N = 0, ±1, ±2, ±3, ..., and

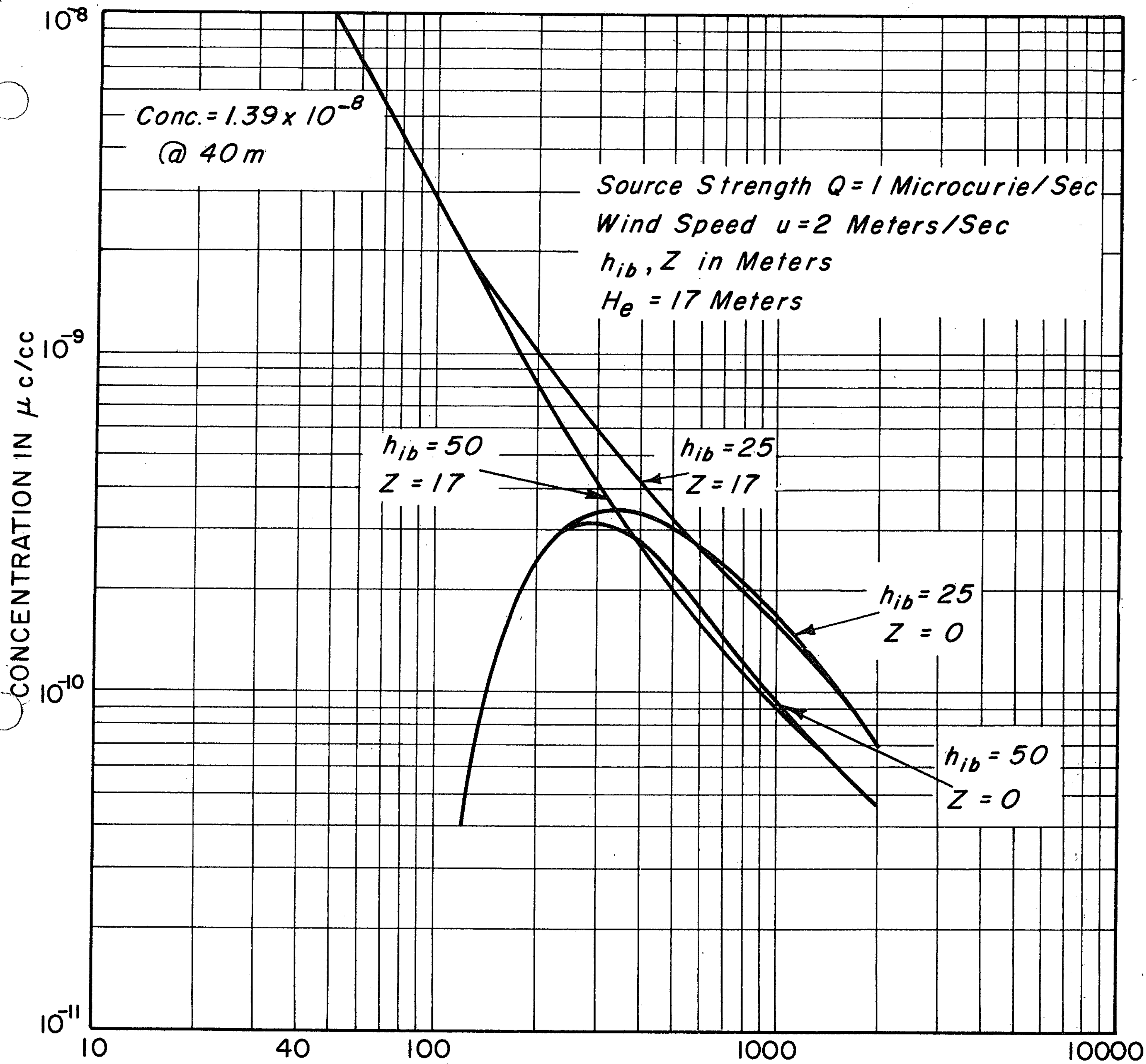
h_{ib} = height of the inversion base in meters.

All other quantities are as previously defined.

N refers to the number of reflections of the plume between the ground and inversion base. For one reflection (N = 0, ±1), and points of interest at ground level (z = y = 0), the above equation reduces to

$$\chi = \frac{2Q}{\pi C_y C_z u\, x^{2-n}} \left\{ \exp\left[\frac{-H_e^2}{C_z^2 x^{2-n}}\right] + \exp\left[\frac{-(2h_{ib} - H_e)^2}{C_z^2 x^{2-n}}\right] + \exp\left[\frac{-(-2h_{ib} - H_e)^2}{C_z^2\, x^{2-n}}\right] \right\}$$

Using the above equation with $n = 0.25$, $C_y = 0.15$, and $C_z = 0.12$, the concentration as a function of distance from the stack at ground level and at an altitude of 17 meters were calculated for inversion bases at 25 and 50 meters. A plot of these data is shown in Figure 3.



RADIAL DISTANCE FROM STACK IN METERS

FIGURE 3

CONCENTRATION VS. DISTANCE FROM STACK FOR PLUME TRAPPING

APPLICATION OF FIGURES 1, 2 AND 3

Figures 1 and 2 give the activity concentration in the gaseous discharge from the laboratory stack in μc/cc as a function of radial distance from the base of the stack for plume fumigation, plume looping and downwash conditions. Figure 3 gives the concentration in the gaseous discharge in μc/cc as a function of radial distance from the stack for plume trapping. Curves are shown on Figure 3 for a 25 meter and a 50 meter inversion base with concentrations at ground level ($Z = 0$) and at an altitude equal to the stack height ($Z = 17m$). All figures are based on a unit source strength of 1 μc/sec from the stack. The calculated source strength, (Q), is 1.25 μc/sec of Argon-41 when the reactor is operating at 2 MW with the pneumatic tube system in use. Environmental concentrations external to the reactor operating at 2 MW are calculated by reading the concentration at the appropriate distance from the figures and multiplying by 1.25

CONCLUSIONS

The Automotive Engineering Laboratory, a two story building and the nearest occupied building from the reactor site, has an air intake 92 meters from the base of the stack. An application of Figures 1, 2 and 3 shows that the highest concentration at this location for the four types of meteorological conditions considered occurs during plume fumigation. With a source of 1.25 μc/sec, plume fumigation produces a concentration of 2.6×10^{-9} μc/cc at the Automotive Laboratory air intake. This represents a dilution factor of 96. Any ground location farther away will exhibit lower concentrations so that the minimum dilution factor at any populated building at ground level is 96.

The Institute of Science and Technology Building, a six story building currently under construction, will be 183 meters from the laboratory stack. Its roof will be at the same level as the laboratory stack (Z = 17m). The highest calculated concentration at roof level at this location occurs under the condition of plume trapping. Under this condition a concentration of 1.4×10^{-9} μc/cc of A-41 is produced. Thus at this distance a dilution factor of 170 is the minimum predicted. An inversion base of 25 meters was assumed.

The nearest units of the Northwood Student Apartments are 457 meters away from the reactor on flat ground at the top of a hill whose elevation is approximately the same as the 17 meter laboratory stack. Here plume fumigation is the meteorological condition which produces maximum concentration. To account for the elevation of the apartment units, the calculation assumed an effective stack height of 1 meter. The calculated concentration of A-41 is 1.5×10^{-8} μc/cc. This corresponds to a dilution factor of 16.

Table II is a listing of the highest calculated concentration at each of the locations listed in Table I together with the meteorological condition which produces it. Of all the locations and meteorological conditions considered, the Northwood Apartment location, 457 meters north of the reactor, under the condition of plume fumigation, produces the maximum concentration. The calculated dilution factor for this case is 16. This conservative estimate of the dilution factor ignores the fact that plume fumigation conditions only occur at sunrise, plus the fact that only gas released between the hours of 2400 and 0800 will be carried to the ground when the inversion breaks up at sunrise. It has been estimated that fumigation conditions occur about 7 days per year.

It is concluded that a dilution factor of 16 may be applied to the concentration of gases discharged from the laboratory stack. The use of such a dilution factor predicts that occupied areas around the reactor site will not be subjected to an Argon-41 concentration exceeding the non-occupational maximum permissible concentration even with the reactor operating continuously at 2 MW and the pneumatic tube system in continuous use.

TABLE II

Maximum Atmospheric Concentrations

2 MW Operation - 17 Meter Stack

Q = 1.25 μc/sec (2.5×10^{-7} μc/~~sec~~ cc) Argon-41

Meteorological Condition	Distance (Meters)	Location	Maximum Instantaneous Concentrations (μc/cc)	Dilution Factor
Plume Fumigation	92	Automotive Engineering Laboratory Air Intake	2.6×10^{-9}	96
Plume Trapping*	183	Institute of Science and Technology Building	1.4×10^{-9}	170
Plume Fumigation**	457	Northwood Student Apartments	1.5×10^{-8}	16

* Concentration given for an altitude of 17 meters with a 25 meter inversion base. All other concentrations in the table are at ground level.

** For this calculation the effective stack height was taken as 1 meter to account for the rise in elevation to the north of the reactor site. At 457 meters, the elevation is approximately the same as the 17 meter stack height.

APPENDIX

Calculation of Argon-41 Discharge Concentration at 2 MW

The four pneumatic tube terminal stations at the reactor core have active lengths of 10 inches and inside diameters of 1.25 inches. The collective air volume of 804 cubic centimeters (cc) contains 7.6 cc of Argon-40 which would be exposed to a neutron flux of 4×10^{12} neutrons per square centimeter per second ($n/cm^2/sec$).

The number of Argon-41 atoms generated per second, R, is given by

$$R = V \sigma N \varphi$$

where V is the volume, σ is the microscopic cross section, N is the number of atoms per cc, and φ is the neutron flux.

$$R = \frac{7.6(0.53 \times 10^{-24})\ (6.02 \times 10^{23})}{2.24 \times 10^{4}}\ (4 \times 10^{12})\ \frac{\text{atoms}}{\text{sec.}}$$

$R = 4.32 \times 10^{8}$ Argon-41 atoms generated per second.

REFERENCES

1. Rules and Regulations, Title 10, Atomic Energy. Chapter 1, Part 20, Federal Register, November 17, 1960.

2. Bierly, Eugene W., Hewson, E. Wendell, and Gill, Gerald C., "Computations of Maximum Concentrations Under Various Meteorological Conditions at the Ford Nuclear Reactor The University of Michigan", Ann Arbor, Michigan, September 1960. (unpublished)

3. Hewson, E. W., "Stack Heights Required to Minimize Ground Concentrations", Trans. of ASME, 77, 1163-1172, 1955.

4. Holland, F. Z., "A Meteorological Survey of the Oak Ridge Area", Atomic Energy Commission, ORO-99, 1952.

5. Hewson, E. W., Gill, G. C., and Bierly, E. W., "Maximum Ground Concentrations in Relation to Stack Heights Under Various Meteorological Conditions at the Enrico Fermi Atomic Power Plant near Monroe, Michigan", Ann Arbor, Michigan, 1959.

6. Hewson, E. W., and Silverman, L., ed., "Meteorological Measuring Techniques and Methods for Air Pollution Analysis and Control", Ind. Hygiene and Toxicology, III, New York, Interscience, In Press.

The decay rate per second is given by

$$\lambda R = \left(\frac{0.693}{6.48 \times 10^3} \right) \quad (4.32 \times 10^8) \quad \frac{\text{disintegrations per second}}{\text{second}}$$

$$\lambda R = 4.62 \times 10^4 \text{ dps/sec} = 1.25 \text{ microcuries/second.}$$

The pneumatic tubes therefore produce an Argon-41 source strength at the rate of 1.25 μc/sec.

Since the laboratory stack air discharge rate is 5.08×10^6 cc/sec, the stack discharge concentration due to Argon-41 at a power level of 2 MW would be

$$\chi = \frac{1.25}{5.08 \times 10^6} \ \mu c/cc$$

$$\chi = 2.5 \times 10^{-7} \ \mu c/cc.$$