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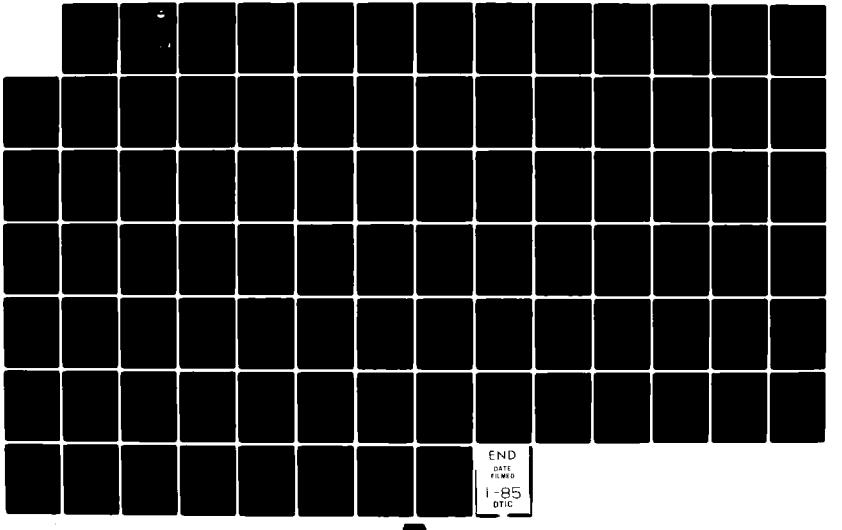

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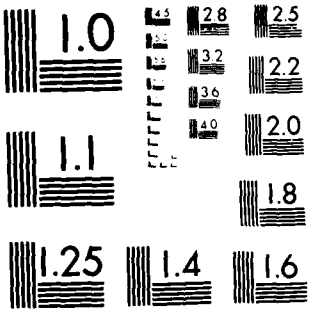

USAF OEHL REPORT
85-004EH111KVA

VENTILATION IN THE HOSPITAL OPERATING ROOM

USAF Occupational and Environmental Health Laboratory
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas 78235

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JOHN J. COUGHLIN, Colonel, USAF, BSC
Commander

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The USAF Occupational and Environmental Health Laboratory (USAF OEHL) investigated several aspects of the problem of ventilation in hospital operating rooms. The study reviewed existing nationally recommended ventilation rates and also discusses five factors that would affect the selection of a minimally acceptable ventilation rate in the operating room: such as, control of temperature/humidity, control of odors, control of flammable anesthetic agents, control of infections, and control of exposure to waste anesthetic agents.

The report studies the effect of fresh air ventilation on exposure to waste anesthetic agents in depth. Forty-eight graphs illustrate the expected instantaneous and time weighted average nitrous oxide and halogenated agent air concentrations as a function of time under a variety of conditions. The mathematical model and FORTRAN computer program used to develop the data for the graphs are included as appendices to the report. Continued on Back.

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The fresh air ventilation rates used in the model ranged from two to 15 air changes per hour. The operating room volumes used in the model were 2100 and 4655 cubic feet. Three different conditions of anesthesia delivery were studied: intubation without a shut-off valve between the delivery tube and the mask, intubation with a shut-off valve between the delivery tube and the mask, and a mask with 0%, 15%, and 30% mask leakage due to a poor fit. Finally, the effect of multiple surgical procedures on the anesthetic agent concentration in the operating room is addressed.

The graphs and mathematical model provided in the report permit the reader to compare expected anesthesia agent concentrations to any of the guidelines published in the literature. If necessary, the reader can use variables applicable to his/her particular operating room in the mathematical model and construct similar graphs. The study concludes that:

a. area air sampling should be performed during intubation cases rather than mask cases to determine if there is excessive anesthesia cart leakage.

b. the value of a shut-off value between the anesthesia delivery tube and the mask decreases the longer the surgery lasts, but increases if multiple surgical cases are performed during the day.

c. the leakage from the anesthesia cart determines the equilibrium anesthetic agent concentration in the operating room.

d. a scavenging device is needed to control leakage from the mask.

e. five fresh air changes per hour may not be suitable to control the anesthetic agent concentration in the operating room when a mask and poor technique are used to deliver the anesthesia.

f. it is not possible to select a single, minimally acceptable ventilation rate applicable to all operating rooms.

Report No. 85-004EH111KVA

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Ventilation in the Hosptial Operating Room

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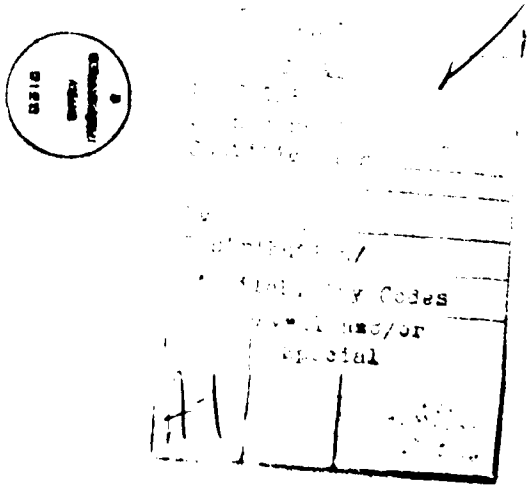

LIST OF ILLUSTRATIONS

I. INTRODUCTION

An Air Force Medical Service Center (AFMSC) and USAF Occupational and Environmental Health Laboratory (USAF OEHL) working group was formed on 9 Dec 83 to discuss ventilation in hospital operating rooms. Col Edna Hopkins (Wilford Hall USAF Medical Center/SGHSN) is special assistant to USAF SG for operating rooms. Col Hopkins reported that she is frequently asked about minimum acceptable ventilation rates in operating rooms. Design criteria found in AFR 88-15, "Air Force Design Manual - Criteria and Standards for Air Force Construction" and AFM 88-50, "Criteria for Design and Construction of Air Force Health Facilities," provide guidance for new construction, but there is no ventilation guidance for existing facilities. The working group was to investigate the minimum ventilation that would be acceptable for existing facilities. The USAF OEHL approached the problem from the industrial hygiene point-of-view. However, some nonindustrial hygiene areas are discussed to illustrate their impact on the problem.

II. REVIEW OF RECOMMENDED OPERATING ROOM VENTILATION RATES

A. Several national organizations were contacted to determine their recommended ventilation rates for medical facilities.

1. The National Fire Protection Association's (NFPA) National Fire Code 56A[9] discusses mechanical ventilation as a means of diluting flammable gases and maintaining the proper humidity. The Code also says that "the ventilation serves not only to maintain humidity, but also reduces the hazard of infection which is accomplished by dilution and removal of airborne microbial contamination. It also contributes to odor control and comfort of personnel." The Code does not make a specific ventilation recommendation, but mentions that "studies indicate that an air change rate equivalent to 25 room volumes of air per hour dilute bacteria dispersed into the room by human activity. When properly filtered, 80 percent may be recirculated with no more microbial contamination than 100 percent outdoor air filtered in the same manner." The NFPA was not able to provide a source for that statement.

2. The Joint Commission on the Accreditation of Hospitals (JCAH) does not have a recommendation for ventilation in the operating room. Previous accreditation manuals specified ventilation rates, but the rationale was to control flammable agents. The JCAH indicated that hospitals are free to establish their own ventilation policy.[14]

3. The American Hospital Association (AHA)[11] and the Centers for Disease Control (CDC)[13] recommend the Hill-Burton standards for operating room ventilation. These standards are the same as those found in Department of Health, Education, and Welfare (HEW) Publication 74-4000, "Minimun Requirements of Construction and Equipment for Hospitals and Medical Facilities,"[5] and an updated version of the same title, HEW Publication 79-14500.[6] The HEW Publication 74-4000 criteria is for a total of 25 air changes per hour (ac/hr) of which 5 ac/hr are fresh air. The HEW Publication 79-14500 criteria is for either 5 fresh/25 total ac/hr or 15 fresh/15 total ac/hr (i.e., 100% fresh air). The all-outdoor air rate may be used when required by local codes.

Both of the HEW publications indicate that these values are minimum acceptable rates and shall not be construed as precluding the use of higher ventilation rates. The CDC said that the Health Resources Administration of the Department of Health and Human Resources will publish an updated version in which 4 fresh/20 total air changes/hr will be recommended.

4. The National Institute for Occupational Safety and Health (NIOSH) Criteria Document 77-140 for Waste Anesthetic Gases and Vapors says that "recovery rooms, labor and delivery rooms, anesthetic gas storage areas, and other related areas in which scavenging techniques are not used shall be provided with air exchange rates in compliance with those specified by" the HEW Publication 74-4000.[3] The wording of this guidance is puzzling as it implies that if scavenging is used, the ventilation rate is not important.

5. The Georgia Institute of Technology investigated the need for operating room ventilation in the Bureau of Health Services Research Report 73-34, "Air Treatment for Odor Control in the Hospital."[2] The study involved a number of chemicals that could be found in the operating room. Based on the evaporation rates of the compounds, the study determined a minimum air exchange rate needed to exhaust the chemical odor. The study concluded that any ventilation rate greater than two fresh air changes per hour is a waste of energy. The study did not consider anesthetic gas/vapors or airborne microbial contamination in the operating room.

6. The American College of Surgeons[10] and the Association of Operating Room Nurses[12] do not have recommendations for ventilation in operating rooms.

7. The U.S. Army Environmental Hygiene Agency indicated that they had received U.S. Army Corps of Engineers Engineering Technical Letter 110-3-344 dated 4 Oct 83.[15] The letter updates the interior mechanical design criteria for new Army and Air Force medical facilities. Until AFR 88-50 dated Jan 82 is revised, the criteria provided in the Oct 83 letter will be used. The criteria for operating rooms set forth in the Oct 83 letter is 15 total ac/hr of which 5 ac/hr are fresh air unless a higher rate is required to meet cooling requirements. The basis for this recommendation could not be determined.

8. The Surgery Departments of two large hospitals in the San Antonio area were contacted. Both departments were unaware of any national standards for operating room ventilation rates.

B. The review of the literature indicates that the rationale for the ventilation rates recommended by many national hospital organizations are poorly documented.

III. ANALYSIS OF FACTORS AFFECTING VENTILATION RATES IN THE OPERATING ROOM

A. To discuss the various factors affecting ventilation rates in the operating room, the distinction between total and fresh air must be made. Fresh air is that which enters the system from outdoors. It is assumed to be

free of gaseous pollutants. Total air is the sum of the fresh air and the recirculated air from the room. The recirculation of room air helps to conserve energy, however, gaseous pollutants reenter the room and filters are needed to remove microbial organisms.

B. The minimum ventilation that is acceptable for existing operating rooms is governed by five factors: temperature and humidity control, control of odors, control of anesthetic gas/vapors due to fire hazards, control of infection, and control of anesthetic gas/vapors due to possible health effects.

1. The control of temperature and humidity is important for the comfort of operating room personnel. Since recirculated air can be treated to adjust the temperature and humidity of the air entering the room, fresh air is not needed. If there were no other conditions to consider, the total air flow could be 100% recirculated air. Both the airstream temperature and flow rate affect the amount of heat that is added or removed from the operating room. Consequently, there is an infinite number of acceptable flow rates that can be used to perform a given heating or cooling task. For example, for a given heat load, an airstream temperature of 55° F flowing at 50 cubic feet per minute (cfm) into the operating room may provide the same cooling effect as an airstream temperature of 65° F at 100 cfm. Therefore, there can be no nationally recommended minimum ventilation rate to control temperature and humidity. The minimally acceptable ventilation rate to control temperature and humidity can vary from hospital to hospital and is dependent on the airstream temperature and the heat load in the room.

2. The comfort of operating room personnel is not only a function of temperature and humidity, but is also related to odors in the area. These odors include body odors and various gaseous or vapor pollutants that cannot be removed by high efficiency filters. In this case, fresh air rather than recirculated air is needed to control the problem. The Georgia Institute of Technology found that two fresh air changes per hour are sufficient to dilute the odors so that they are not objectionable to operating room personnel.[2]

3. Nonflammable anesthetic agents are used in USAF medical facilities. Consequently, the minimum ventilation rate needed to control the fire hazard of anesthetic gases/vapors is not applicable.

4. The need to control infection via ventilation/filtration is suggested by the NFPA Code. Although the NFPA could not provide background information to substantiate this assertion, there are many medical journal articles that discuss ventilation and wound infection. However, the surgical procedure referenced in the articles is joint-replacement, and the literature is filled with contradicting views on the importance of ultraclean air during these operations. The need for clean air during other types of operations has not been so vigorously debated in the literature. With the exception of the NFPA Code, no reports were found that said there is a minimum ventilation rate needed to dilute or filter out a harmful concentration of organisms. However, there are articles like the NFPA Code that suggest such is the case. For example, Gruendemann and Meeker[7] say:

> "...there is little question that clean air systems reduce bacterial contamination of the surgical wound at the time of operation. It is known that wound infections are directly related to the type and number of organisms that are deposited in the wound and the host's ability to combat infection. Airborne contamination plays a more important role when a prosthesis is implanted into a surgical wound than when no foreign body is implanted."

In addition, E. Laufman[8] says:

> "Prior to the advent of joint-replacement and open-heart surgery, it was estimated that airborne contamination could be implicated in two percent of wound infections, a figure which probably still holds in reference to abdominal and many other types of surgery. Since joint-replacement and open-heart surgery have come upon the scene, the gap between the incidence of airborne contamination and contact contamination as causes of wound infection in patients who undergo these types of operations reportedly has become narrowed."

These two quotes indicate concern about infection regardless of the type of surgery. Therefore, one cannot ignore the possibility that the ventilation rate is an important consideration in reducing wound infections. Unfortunately, the literature does not provide a numerical correlation between a decreasing air change rate and an increasing infection rate. The professional attitude appears to be "don't tamper with success"; infections are adequately controlled by complying with nationally recommended ventilation rates. No one has addressed the question of how low the ventilation can be adjusted before an increase in infection is noticed. This factor requires further investigation that is beyond the scope of this report.

5. The possible harmful effects of chronic exposure to anesthetic agents can be found in many publications. However, no report was found that discussed the effect of dilution ventilation on the anesthetic gas/vapor concentration in the room. Although it is well known that scavenging techniques can greatly reduce the anesthetic gas/vapor concentration in the operating room, the role of fresh air dilution ventilation does not appear to be well publicized. The control of anesthetic gas/vapors via fresh air dilution ventilation is an industrial hygiene area of interest. To determine if there is a minimally acceptable ventilation rate, a mathematical model of the problem was developed. The model is addressed in the next section of this report.

IV. THEORETICAL ANESTHESIA GAS BUILD-UP AND DECAY IN THE OPERATING ROOM.

A. The build-up and decay of anesthesia gas in the operating room depends on the amount of anesthesia gas released, the room volume, and the number of fresh air changes per period of time.

1. The amount of anesthesia gas released into the operating room depends on the technique used to administer the gas to the patient and leakage from the anesthesia cart. Three different methods of anesthesia administration are evaluated in this report.

2. The room volume affects the anesthesia gas concentration in the operating room. For a given quantity of gas released into the room, the concentration will be less in larger rooms and greater in smaller rooms. To evaluate the effect of room volume on the build-up and decay of anesthesia gas, the volume of the smallest and largest surgical suites at David Grant USAF Medical Center at Travis AFB CA are used for each of the three anesthesia administration methods studied in this report.

3. The number of fresh air changes per period of time affect the build-up and decay of anesthesia gas in the operating room. The conventional unit of measurement is air changes per hour. Fresh air of 2, 3, 4, 5, 10, and 15 air changes per hour are used for each of the three methods and each of the two room volumes studied in this report. In addition, the gas released into the operating room is assumed to mix perfectly. Although the literature supports this assumption[3],[4] the model assumes that the operating room ventilation is not short circuited by supply and exhaust grilles located in close proximity to each other.

B. Anesthesia Administration Method #1. Anesthesia administered via a mask and endotrachael tube (a shut-off valve is not connected to the anesthesia delivery tube).

1. Anesthesia administration protocol.

a. Give sodium pentothal to make the patient lose consciousness.

b. With the patient unconscious, inject a skeletal muscle relaxant.

c. In about 10 seconds, the nitrous oxide/oxygen/halogenated agent delivery system is turned on. Assume that the gas mixture enters the room for 10 seconds.

d. Place the mask on the patient and breathe for him for about one minute. The anesthesia gas enters the room if there is poor mask fit. Assume that there is leakage during the one minute period that is equivalent to a ten second flow of gas into the room (i.e., 10 seconds of 60 seconds equals a 16.6% mask leakage rate).

e. Take the mask off the patient and hang it on the anesthesia cart. Within 30-45 seconds, intubate the patient. Since there is no shut-off valve on the delivery tube, the gas flows into the room as the patient is intubated. After patient intubation, take the mask off the cart, unhook the anesthesia delivery tube from the mask, and connect the delivery tube to the endotracheal tube.

2. Estimating anesthesia gas leakage rates.

a. Leakage prior to patient intubation. Given the above protocol, the worst case leakage would be:

10 seconds while adjusting the gas flow rates.
10 seconds (estimated leakage) of the 60 seconds that the mask is initially on the patient.
40 seconds while the transfer is made from using the mask to using the intubation tube to administer the agents to the patient.

\+

60 seconds of total gas flow prior to intubation

(1) The total gas flow rate to the patient is approximately five liters per minute (L/min) of which 3 L/min (approximately 60%) is nitrous oxide, 2 L/min (approximately 40%) is oxygen, and 0.1 L/min (approximately 2%) is the halogenated agent. During Method #1, the volume of nitrous oxide released in the room prior to intubation would be 3 Liters (60 seconds of flow at 3 L/min). The volume of halogenated agent released in the room prior to intubation would be 0.1 Liter (60 seconds of flow at 0.1 L/min).

(2) The actual time that passes from the intravenous injection of the skeletal muscle relaxant to connection of the delivery tube to the endotrachael tube will vary from patient to patient and from nurse anesthestist to nurse anesthestist. For this study, a conservative two minute estimate was chosen. This means that the 3 liters of nitrous oxide is assumed to enter the room over a two minute period (3 L per 2 minutes = 1.5 L/min) and the 0.1 liter of halogenated agent would enter the room in a similar period of time (0.1 L per 2 minutes = 0.05 L/min).

(3) Leakage from the anesthesia cart is also assumed to occur prior to intubation. NIOSH report 75-137, "Development and Evaluation of Methods for the Elimination of Waste Anesthesia Gases and Vapors In Hospitals," reports the leakage rate of 15 anesthesia carts that had been "leak" serviced one month prior. The leakage rates were 18, 27, 27, 28, 48, 57, 67, 68, 130, 140, 140, 140, 150, 160, and 320 cubic centimeters per minute (cc/min). For this USAF OEHL study, a conservative leakage of 160 cc/min (0.16 L/min) is used. Therefore, continuous nitrous oxide leakage from the cart is assumed to be 0.1 L/min (approximately 60% of 0.16 L/min) and the halogenated agent leakage is assumed to be 0.0033 L/min (approximately 2% of 0.16 L/min). It should be noted that American National Standards Institute (ANSI) Standard 79.8-1979[1] says that "the maximum permissible leakage rate on all gas services between the flow-control valves and the common gas outlet shall be 30 mL/min at 30 cm water with the vaporizer in both the ON and OFF position."

b. Leakage after patient intubation. After the anesthesia delivery tube has been switched from the mask to the endotrachael tube, the only leakage is assumed to be from the anesthesia cart. The nitrous oxide and halogenated agent leakage rates would be 0.1 L/min (approximately 60% of 0.16 L/min) and 0.0033 L/min (approximately 2% of 0.16 L/min), respectively.

c. Refer to Table 1 in Appendix A for a summary of the leakage rates.

3. Mathematical model. The mathematical model discussed in Appendix B uses the leakage rates computed above to predict the instantaneous and Time Weighted Average (TWA) concentrations for various fresh air change per hour ventilation rates.

C. Anesthesia Administration Method #2. Anesthesia administered via mask and endotracheal tube (a shut-off valve is connected to the anesthesia delivery tube).

1. Anesthesia administration protocol. The protocol for this technique is the same as for Method #1 except that a shut-off valve prevents anesthesia gas flow during the 30-45 seconds while the patient is being intubated. A shut-off valve can be located between the anesthesia delivery tube and the mask. When the mask is removed from the delivery tube, the flow of anesthesia gas is stopped. When the delivery tube is connected to the endotracheal tube, the gas can flow.

2. Estimating anesthesia gas leakage rates.

a. Leakage prior to patient intubation. The shut-off valve prevents the gas from flowing for approximately 40 seconds during patient intubation. The worst case leakage would be:

10 seconds while adjusting the cart flow rates.
10 seconds (estimated leakage) of the 60 seconds that the mask is initially on the patient.
+
20 seconds of total gas flow prior to intubation

(1) The total gas flow to the patient during Method #2 is the same as during Method #1 (i.e., 5 L/min). However, by using the shut-off valve, the time of gas flow decreases from 60 seconds to 20 seconds. Consequently, the gas volume entering the room decreases. The volume of nitrous oxide that enters the room prior to intubation would be 1 liter (20 seconds of flow at 3 L/min). The volume of halogenated agent to enter the room prior to intubation would be 0.033 liters (20 seconds of flow at 0.1 L/min).

(2) The actual time that passes from the intravenous injection of the skeletal muscle relaxant to connection of the delivery tube is again assumed to be two minutes. Therefore, the one liter of nitrous oxide is assumed to enter the room over a two minute period (1 L per 2 minutes = 0.5 L/min) and the 0.033 L of halogenated agent enters the room in a similar period of time (0.033 L per 2 minutes = 0.0167 L/min)

(3) Leakage from the anesthesia cart is assumed to be the same as discussed in Method #1: 0.1 L/min and 0.0033 L/min for nitrous oxide and the halogenated agent, respectively.

b. Leakage after patient intubation. After the anesthesia delivery tube has been switched from the mask to the endotracheal tube, the only leakage is assumed to be from the anesthesia cart. The nitrous oxide and halogenated agent leakage is assumed to be the same as discussed in Method #1: 0.1 L/min and 0.0033 L/min, respectively.

c. Refer to Table 1 in Appendix A for a summary of the leakage rates.

3. Mathematical model. The mathematical model discussed in Appendix B uses the leakage rates computed for this method to predict instantaneous and TWA concentrations for various fresh air change per hour ventilation rates.

D. Anesthesia Administration Method #3. Anesthesia delivered via a mask for the entire surgical procedure.

1. Anesthesia administration protocol.

a. Give sodium pentothal to make the patient lose consciousness.

b. With the patient unconscious, inject a skeletal muscle relaxant.

c. In about 10 seconds, the nitrous oxide/oxygen/halogenated agent delivery system is turned on.

d. Place the mask on the patient. Use the mask for the entire surgical procedure.

2. Estimating anesthesia gas leakage rates.

a. Leakage from the mask. A possible source of leakage is the mask. Gas escapes into the room if there is a poor mask fit. This leakage could occur throughout the entire surgical procedure. For this report, three mask leakage rates are assumed: 0%, 15%, and 30%. Zero percent mask leakage means that the mask fits perfectly. Fifteen percent mask leakage means that 0.45 L/min nitrous oxide (15% of 3 L/min) and 0.015 L/min halogenated agent (15% of 0.1 L/min) escape into the room. In a similar manner, 30% mask leakage means that 0.9 L/min and 0.03 L/min of nitrous oxide and halogenated agent, respectively, escape into the room.

b. Leakage from the anesthesia cart. The nitrous oxide and halogenated agent leakage from the anesthesia cart remains the same: 0.1 L/min and 0.0033 L/min, respectively.

c. Refer to Table 1 in Appendix A for a summary of the leakage rates.

3. Mathematical model. The mathematical model discussed in Appendix B uses the leakage rates computed for this method to predict the instantaneous and TWA concentrations for various fresh air change per hour ventilation rates.

V. RESULTS

A. All Tables and Figures developed for this technical report can be found in Appendix A.

B. Figures 1 to 20 are graphs of the expected instantaneous room concentration as a function of time. These results would be similar to the output of a strip chart recorder connected to a real-time concentration monitoring instrument. The FORTRAN computer program used to compute the instantaneous concentrations is included in Appendix C.

C. Figures 21 to 40 are graphs of the Time Weighted Averages of the respective data found in Figures 1 to 20 as a function of time. The term "Time Weighted Average" is frequently used in industrial hygiene work. It normally refers to an individual's exposure averaged over an eight-hour workday. Periods of exposure and nonexposure are both weighted to obtain the TWA. However, when discussing exposure to waste anesthetic gas, the TWA refers only to the period of exposure. Periods of no exposure are not included in this TWA. Figures 21 to 40 illustrate how an individual's TWA exposure would vary over the length of the surgical procedure. The FORTRAN computer program used to compute the TWA concentrations is included in Appendix D.

D. Figures 41 to 43 are graphs that compare part of Figure 21 to part of Figure 22. Their purpose is to illustrate the benefit of using a shut-off valve on the anesthesia delivery tube.

E. Figures 44 and 45 are graphs of the instantaneous concentration expected when multiple surgical procedures are performed during a 240 minute period. Figures 46 to 48 are graphs of the TWA concentration expected when multiple surgery procedures are accomplished during a 240 minute period.

F. Table 1 is a summary of the leakage rates used in the mathematical model.

G. Table 2 lists the expected equilibrium concentrations for various anesthesia cart leakage rates. The significance of these concentrations is addressed in the Discussion Section.

VI. DISCUSSION

A. Recommended anesthesia agent exposure levels.

1. There are no Occupational Safety and Health Administration Permissible Exposure Levels for nitrous oxide or the halogenated agents.

2. There are no American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) for the anesthetic agents. However, there are ACGIH Notice of Intended Changes to adopt TLVs for enflurane (75 ppm) and halothane (50 ppm).

3. HQ AFMSC/SGPA letter, "Control of Occupational Exposures to Anesthetic Gases", dated 14 Nov 80 recommends a general room concentration (not a personal air sample) of 50 ppm nitrous oxide and 2 ppm for halogenated agents as a performance standard to determine if anesthesia equipment is operating properly. The intent is for the performance standard to be a TWA over the period of anesthesia agent exposure. It would not apply to the average of both exposure and nonexposure periods.

4. The literature frequently quotes recommended exposure limits found in NIOSH publication 77-140, "Criteria For A Recommended Standard...Occupational Exposure to Waste Anesthetic Gases and Vapors." The literature normally says that the Criteria Document recommends a TWA of 25 ppm for nitrous oxide and 2 ppm for the halogenated agent. The reader should note that the NIOSH document presents the recommended exposure concentrations in a complex manner and appears to permit higher nitrous oxide concentrations in dental offices than in operating rooms. One could also infer that the 25 ppm standard only applies if nitrous oxide is delivered as the sole anesthetic agent.

5. The graphs in this report permit the reader to compare the predicted concentrations to any recommended standard.

B. The results illustrate the effect of room volume on the instantaneous room concentrations and TWA concentrations. For example, when Figure 1 is compared to Figure 6, the instantaneous concentration is much lower in the larger operating room. Also, by comparing Figure 21 to Figure 26, the TWA concentration is much lower in the larger room.

C. Essentially all of the graphs illustrate that the instantaneous and TWA concentrations eventually reach an equilibrium point. For example, in Figure 1, the room concentration for 2 ac/hr is the same at time equal to 80 minutes and at time equal to 240 minutes. Similarly, in Figure 21, the TWA concentration for 2 ac/hr does not change when the time exceeds 80 minutes. The leakage from the anesthesia cart determines the equilibrium value for the various fresh air change/hour rates and room sizes. Table 2 lists various cart leakage rates and the expected equilibrium concentration. The component leakages of 0.1 L/min for nitrous oxide and 0.0033 L/min for the halogenated agent are the cart leakages used for this report. Note how the 50 ppm nitrous oxide concentration listed on Table 2 for 2 ac/hr, 2100 cubic foot room, can be seen as the equilibrium value in Figures 1, 2, and 3. Fifty ppm is not the equilibrium concentration in Figures 4 or 5 because these cases have leakage from the mask that significantly exceed the leakage from the cart. Fifty ppm is the equilibrium point in Figure 21. However, it does not appear to be so in Figures 22 or 23. Actually, 50 ppm is the equilibrium concentration in Figures 22 and 23 also; it takes over eight hours of exposure to reach that point. By comparing Figures 21 and 22, the benefit of the shut-off valve can be determined. Figures 41 to 43 have been developed to make this comparison clear. For example, Figure 41 combines the 2 ac/hr graph from Figures 21 and 22 onto one set of axis. It can be seen that if the surgery is of short duration (e.g., one hour), the shut-off valve reduces the exposure by more than 15 ppm. However, if the surgery lasts longer than two hours, the TWA exposure is reduced to a lesser degree so that with or without the shut-off

valve, the TWA exposure is essentially the same. Figures 42 and 43 are similar graphs for 5 and 15 ac/hr, respectively. The benefit of the shut-off valve diminishes rapidly when the ventilation rate is 15 fresh ac/hr. Although the usefulness of the shut-off valve decreases with the length of surgery, it prevents a significant amount of gas from being released into the room during the intubation procedure.

D. Figures 1 to 43 assume that only one surgical procedure was performed in a 240 minute period. The effect of multiple surgical procedures on the instantaneous and TWA concentrations is addressed in Figures 44 to 48. Figures 44 and 45 illustrate the instantaneous concentration expected with and without a shut-off valve, respectively. Each "spike" represents a new procedure when the gas enters the room prior to intubation. After intubation, the concentration decays until the next case begins. Figures 46 to 48 are the nitrous oxide TWA concentrations comparing procedures performed with and without the shut-off valve. Figures 46 to 48 can be compared to Figures 41 to 43, respectively, for each air change rate. The graphs indicate that all of the TWA concentrations are higher when multiple surgeries are performed. In addition, when one surgery is performed, the value of the shut-off valve appears to diminish as time passes (i.e., the difference between the graph "with" and "without" the shut-off valve approaches zero with time). However, if multiple surgeries are performed, the value of the shut-off valve remains essentially constant (i.e., the difference between the graph "with" and "without" a shut-off valve remains essentially the same with time).

E. The results for cases in which a mask is used for the entire surgery (Method #3) illustrate the wide range of instantaneous and TWA concentrations that are possible. For example, Figures 3, 4, and 5 or Figures 8, 9, and 10 illustrate the potential instantaneous concentrations in small and large operating rooms. Leakage from the anesthesia cart is overshadowed by the leakage caused by a poor mask fit. Table 1 shows that a poor mask fit can cause up to nine times as much leakage as cart leakage (0.9 L/min vs 0.1 L/min for Method #3, 30% mask leakage). Although new masks have been developed to provide a better patient fit and thus reduce leakage, a scavenging device is needed to control this source of waste anesthetic gas. If a mask scavenging device is used, the anesthesia cart would become the predominant source of leakage and the instantaneous and TWA concentrations would be reduced to the equilibrium concentrations listed in Table 2. The zero percent mask leakage graphs (Figures 3, 8, 13, 18, 23, 28, 33, and 38) are actually plots of the instantaneous and TWA concentrations expected when cart leakage (total cart leakage of 0.16 L/min) is the only source of waste anesthetic gas in the operating room.

F. There is no support in the literature for the USAF to adopt a design ventilation rate less than 5 fresh air changes per hour. Unless the USAF is willing to undertake an expensive and legally precarious study to correlate infection rates and ventilation rates, there is no choice but to continue to use nationally recognized standards for design of new medical facilities. The use of specific design ventilation rates for new construction does not imply that once a facility is built deviations from that design rate means that a problem exists. A specific fresh air ventilation rate applicable to all operating rooms cannot be adopted since many factors can affect the anesthesia

gas TWA exposure. In addition, the unknown ventilation requirements for infection control (which can include both fresh and recirculated air) would prohibit the selection of a minimally acceptable ventilation rate that could be applied to all operating rooms.

G. This report illustrates the effect of fresh air changes per hour on the anesthetic gas instantaneous and TWA concentrations. The fresh ac/hr rate is therefore a factor to consider in evaluating semiannual air samples. Consequently, both the total and fresh air changes per hour should be measured during the semiannual surgery air sampling survey. The USAF OEHL is available to advise on measurement techniques. The bioenvironmental engineer should consult with the hospital plant management to determine room volumes and design air flow rates for the operating rooms. If the ventilation survey indicates that the total airflow is less than the design rate, plant management should investigate possible causes of the problem. If the total airflow cannot attain design rates by cleaning or replacing the filters, changing the filter from 99.9% to 95% efficiency, or by increasing the blower speed, hospital executive management should use infection rates, anesthetic agent TWA concentration survey results, and medical maintenance anesthesia cart leak servicing results to determine if corrective action is needed.

VII. CONCLUSIONS

A. Surgical cases that use anesthesia delivered via intubation (i.e., Method #1 or Method #2) can comply with the HQ AFMSC/SGPA 50 ppm nitrous oxide and 2 ppm halogenated agent TWA standards regardless of the fresh ac/hr or room volume. However, when a mask is used to deliver the anesthesia for the entire surgical procedure (i.e., Method #3), the anesthetist's technique (i.e., mask leakage) and room volume determine if the performance standards will be exceeded.

B. The anesthetic gas leakage rate is likely to vary from patient to patient when a mask is used to deliver the anesthesia. The leakage rate among intubation cases is more likely to be consistent. Therefore, to eliminate this variability from the air sampling accomplished to monitor the anesthesia delivery equipment, the bioenvironmental engineer should primarily air sample intubation cases. Surgical cases that use a mask should also be air sampled to evaluate the anesthetist's technique, but the variability of the data would not permit detection of anesthesia delivery equipment problems.

C. The use of a shut-off valve between the anesthesia delivery tube and the mask will prevent a significant amount of anesthesia gas from entering the operating room during the initial few minutes of the surgery. The elimination of this leakage reduces the TWA exposure, but the reduction becomes minimal if the surgery lasts longer than about two hours. The value of the shut-off valve increases when many surgical procedures are performed during the day.

D. The leakage from the anesthesia cart can be a significant source of waste anesthetic gas and normally determines the equilibrium gas concentration in the room. The results of periodic cart leak tests are as important as semiannual air sampling surveys.

E. Personnel familiar with a base-level respirator fit test program know that there is no mask that fits all personnel perfectly. Therefore, the use of a mask to deliver anesthesia to the patient has the potential of being a significant source of waste anesthetic gas. Although there are different sized masks available to improve the mask-to-face fit,a scavenging device is needed to control this source of gas.

F. A ventilation rate of 5 fresh air changes per hour is used by health facilities offices in designing ventilation for operating rooms in new medical facilities. If anesthesia is administered via intubation, this rate is adequate to control the TWA exposure to the anesthetic gas. However, if a mask is used to deliver the anesthesia and the anesthetist uses poor technique, 5 fresh ac/hr may not be adequate to control the TWA exposure below "acceptable" limits. In these cases, 15 fresh ac/hr would be needed to keep the waste gas TWA below 75 ppm nitrous oxide in small rooms. In larger rooms, 15 ac/hr would keep the TWA concentration well below 50 ppm even with 30% mask leakage.

G. A single, minimally acceptable fresh air change per hour cannot be adopted. The problem is complex even when examined solely from an industrial hygiene point-of-view. Room volume, anesthesia administration method, cart leakage, as well as the fresh air ventilation rate all affect the waste anesthetic gas concentration in the operating room. The effectiveness of a "minimally acceptable" fresh air ventilation rate can be nullified by any or all of the other factors. When issues such as control of infection are added to the problem, a minimally acceptable ventilation rate is essentially impossible to select. Evaluations of ventilation systems in existing medical facilities must not simply be made on the basis of the airflow into the operating room. The waste anesthetic gas concentration, infection rate, and comfort of surgical personnel must also be considered.

VIII. RECOMMENDATIONS.

A. To evaluate compliance with HQ AFMSC/SGPA policy, the bioenvironmental engineer should primarily air sample surgical cases that involve intubation. Cases that involve the use of a mask for the entire surgical procedure may have leakage rates that vary and would prevent meaningful comparison to previous air sampling data. Surgical cases that use a mask may also be air sampled to evaluate the anethestist's technique, but the likely variability of the data would not permit detection of anesthesia delivery equipment problems.

B. HQ AFMSC should direct a medical facility to procure commercially available shut-off valves for anesthesia delivery tubes and cooperate with the USAF OEHL in evaluating the device.

C. The USAF OEHL should continue to investigate possible methods to control leakage around masks.

D. Continue to use the ventilation criteria directed by U.S. Army Corps of Engineers Engineering Technical Letter 1110-3-344 (5 fresh ac/hr and 15 total ac/hr) as a design criteria for new medical facilities. If more stringent standards are adopted for waste anesthetic gas exposure and a suitable local exhaust scavenging device for masks cannot be developed, it may

be necessary to modify hospitals so that they have the capability to switch the ventilation rate in a room from 5 fresh air changes per hour for intubation cases to a greater fresh air changes per hour rate for mask cases. This technical report can help in the selection of a design rate for that purpose.

E. HQ AFMSC should reemphasize the importance of leak tests for anesthesia carts. Table 2 points out potential problems and HQ AFMSC/SGPA letter of 14 Nov 80 provides guidance to check the carts.

F. Do not adopt a specific ventilation rate as minimally acceptable for operating rooms. Once a facility is built, a ventilation rate that deviates from design criteria must not be used as the single criterion that determines if a problem exists. The waste anesthetic gas concentration, infection rate, and comfort of surgical personnel must also be considered.

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11. Personal Communication, Ms Brooks, American Hospital Association, (312)-280-6130 and Maj Gaudet, USAF OEHL/ECH, (512)-536-3214.

12. Personal Communication, Ms Harvey, Association of Operating Room Nurses, (303)-755-6300 and Maj Gaudet, USAF OEHL/ECH, (512)-536-3214.

13. Personal Communication, Mr Davis, Centers for Disease Control, (404)-329-3406 and Maj Gaudet, USAF OEHL/ECH, (512)-536-3214.

14. Personal Communication, Dr Beck, Joint Commission on Accreditation of Hospitals, (312)-642-6061 and Maj Gaudet USAF OEHL/ECH, (512)-536-3214.

15. U.S. Army Corps of Engineers, Washington DC 20314, Engineer Technical Letter, 4 Oct 83, "Interior Mechanical Design Conditions for Army and Air Force Medical Facilities."

APPENDIX A

Tables and Figures

TABLE 1

		Gas and Vapor Leakage Rates (L/min)						
		Method #1		Method #2		Method #3		
		Time (minutes)				Percent Mask Leakage		
	Type of Leakage	0-2	2-240	0-2	2-240	0%	15%	30%
Nitrous Oxide	Cart Leakage	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Other Leakage	1.50	0.00	0.50	0.00	0.00	0.45	0.90
	Total Leakage *	1.60	0.10	0.60	0.10	0.10	0.55	1.00
Hal. Agent	Cart Leakage	0.0033	0.0033	0.0033	0.0033	0.0033	0.0033	0.0033
	Other Leakage	0.0500	0.0000	0.0167	0.0000	0.0000	0.0150	0.0300
	Total Leakage *	0.0533	0.0033	0.0200	0.0033	0.0033	0.0183	0.0333

* "Total Leakage" is the value of "G" used in Equation #7 of Appendix B. For Methods #1 and #2, there are two values of "G"; one for time less than 2 minutes and one for time greater than 2 minutes. For Method #3, there is only one value of "G" for each percent mask leakage rate.

TABLE 2

	Total Leakage (L/min) *	Component Leakage (L/min) **	Equilibrium Concentration Due To Cart Leakage (ppm)											
			2100 cubic foot room						4655 cubic foot room					
			Fresh Air Changes Per Hour						Fresh Air Changes Per Hour					
			2	3	4	5	10	15	2	3	4	5	10	15
Nitrous Oxide	0.320	0.190	95	63	47	38	19	12	43	28	21	17	8	5
	0.160#	0.100	50	33	25	20	10	6	22	15	11	9	4	3
	0.080	0.048	24	16	12	9	4	3	10	7	5	4	2	1
	0.030##	0.018	9	6	4	3	2	1	4	3	2	1	1	1
	0.020	0.012	6	4	3	2	1	1	2	1	1	1	1	1
Hal. Agent	0.320	0.0064	3.2	2.1	1.6	1.2	0.6	0.4	1.4	0.9	0.7	0.5	0.2	0.1
	0.160#	0.0033	1.6	1.1	0.8	0.6	0.3	0.2	0.7	0.4	0.3	0.2	0.1	0.1
	0.080	0.0016	0.8	0.5	0.4	0.3	0.1	0.1	0.3	0.2	0.1	0.1	0.1	0.1
	0.030##	0.0006	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	0.020	0.0004	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

* "Total Leakage" is the sum of nitrous oxide, oxygen, and halogenated agent leakage from the cart.

** "Component Leakage" is 60% of the total leakage for nitrous oxide and 2% of the total leakage for the halogenated agent.

\# 0.16 L/min total cart leakage is used to construct the graphs in this report.

0.030 L/min is listed because ANSI Standard Z79.8-1979 states that the maximum leakage rate on all gas services between the flow control valves and the common gas outlet shall be 30 mL/min at 30 centimeters of water with the vaporizer in both the ON and OFF position.

FIGURES LISTED IN APPENDIX A

Instantaneous Concentration Figure	TWA Concentration Figure	Agent*	Anesthesia Method **	Room 3 Volume (ft)	Mask Leakage (%)
1	21	N_2O	1	2100	Not applicable
2	22	"	2	2100	Not applicable
3	23	"	3	2100	0
4	24	"	3	2100	15
5	25	"	3	2100	30
6	26	"	1	4655	Not applicable
7	27	"	2	4655	Not applicable
8	28	"	3	4655	0
9	29	"	3	4655	15
10	30	"	3	4655	30
11	31	Hal.	1	2100	Not applicable
12	32	"	2	2100	Not applicable
13	33	"	3	2100	0
14	34	"	3	2100	15
15	35	"	3	2100	30
16	36	"	1	4655	Not applicable
17	37	"	2	4655	Not applicable
18	38	"	3	4655	0
19	39	"	3	4655	15
20	40	"	3	4655	30
	41	N_2O	1&2	2100	Not applicable
	42	"	1&2	2100	Not applicable
	43	"	1&2	2100	Not applicable
	44***	"	1	2100	Not applicable
	45***	"	2	2100	Not applicable
	46***	"	1&2	2100	Not applicable
	47***	"	1&2	2100	Not applicable
	48***	"	1&2	2100	Not applicable

* "Agent" - Anesthesia agent, "N_2O" is nitrous oxide and "Hal." is the halogenated agent.

** "Method" - The method is the anesthesia administration method as described in the body of the report.

*** Figures 44-48 study the effects of multiple surgical procedures over a 240 minute period. All of the other Figures study a single procedure during 240 minutes.

Nitrous Oxide Instantaneous Concentration
Method #1, Mask and Intubation
Without Shut-off Valve
2100 cu ft Room

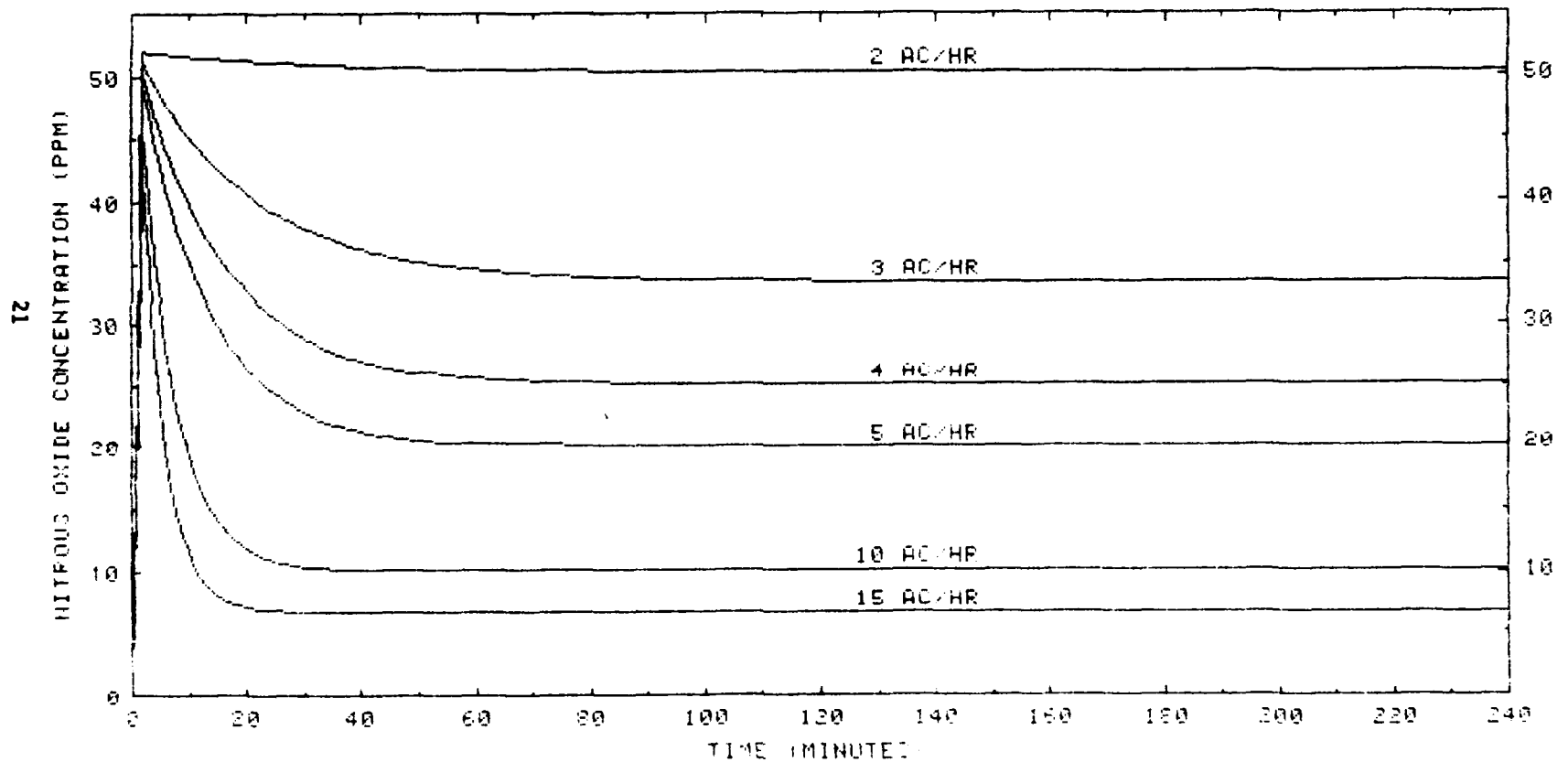


Figure 1. Nitrous Oxide Concentration vs Time, Method #1, 2100 cu ft room.

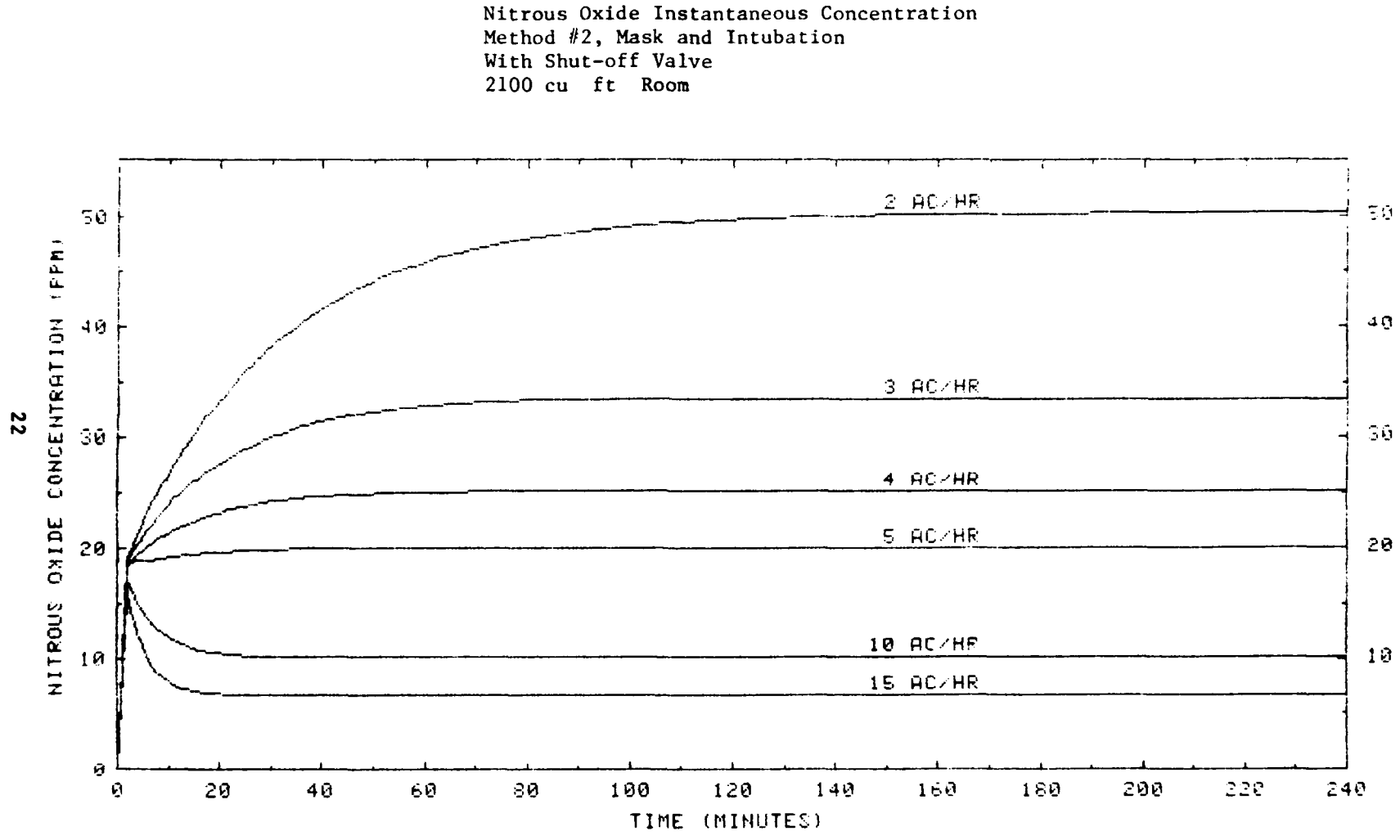


Figure 2. Nitrous Oxide Concentration vs Time, Method #2, 2100 cu ft room.

Nitrous Oxide Instantaneous Concentration
Method #3, Mask with 0% mask leakage
2100 cu ft Room

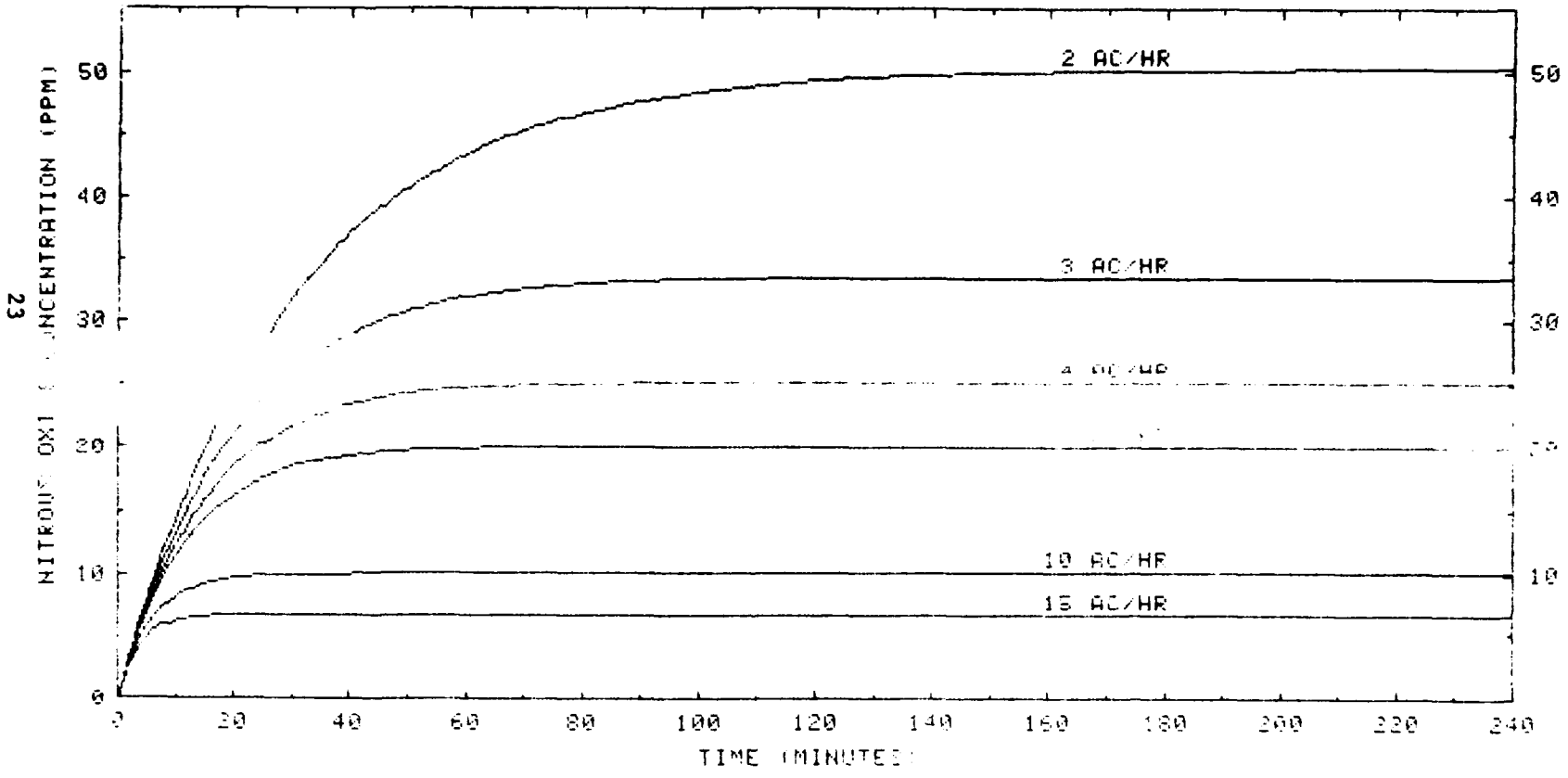


Figure 3. Nitrous Oxide Concentration vs Time, Method #3, 2100 cu ft room, 0% mask leakage.

Nitrous Oxide Instantaneous Concentration
Method #3, Mask with 15% mask leakage
2100 cu ft Room

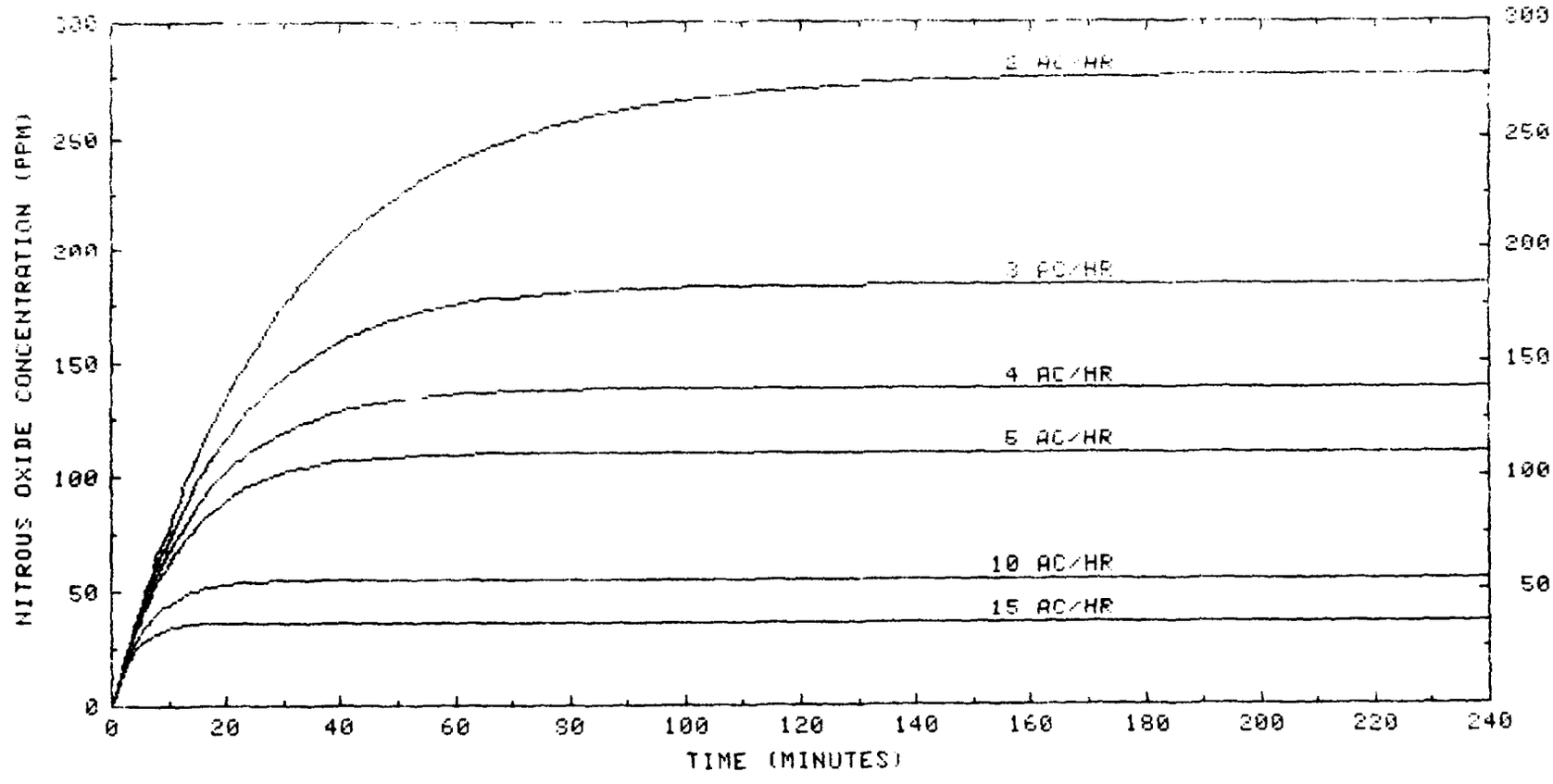


Figure 4. Nitrous Oxide Concentration vs Time, Method #3, 2100 cu ft room, 15% mask leakage.

Nitrous Oxide Instantaneous Concentration
Method #3, Mask with 30% mask leakage
2100 cu ft Room

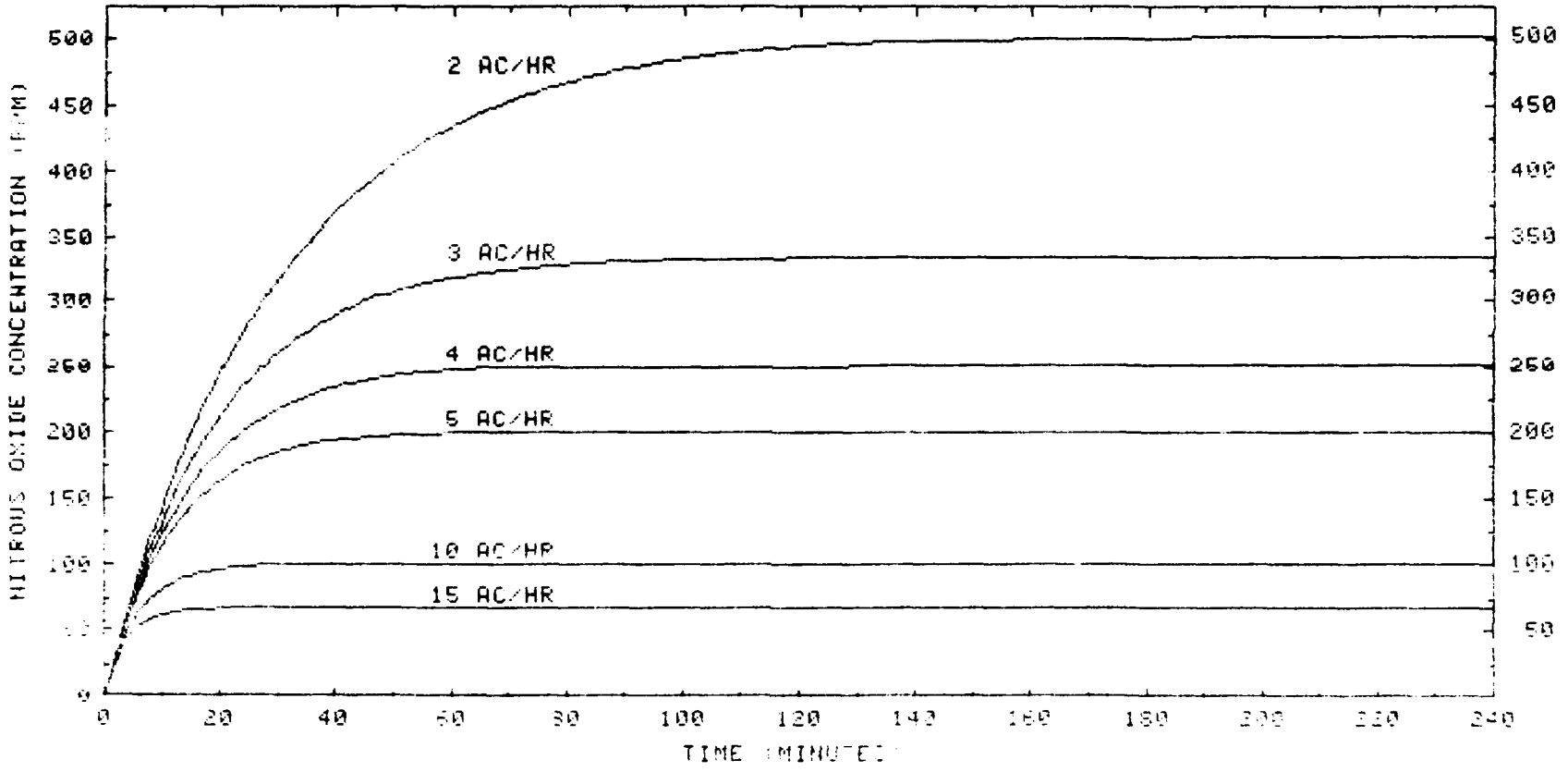


Figure 5. Nitrous Oxide Concentration vs Time, Method #3, 2100 cu ft room, 30% mask leakage.

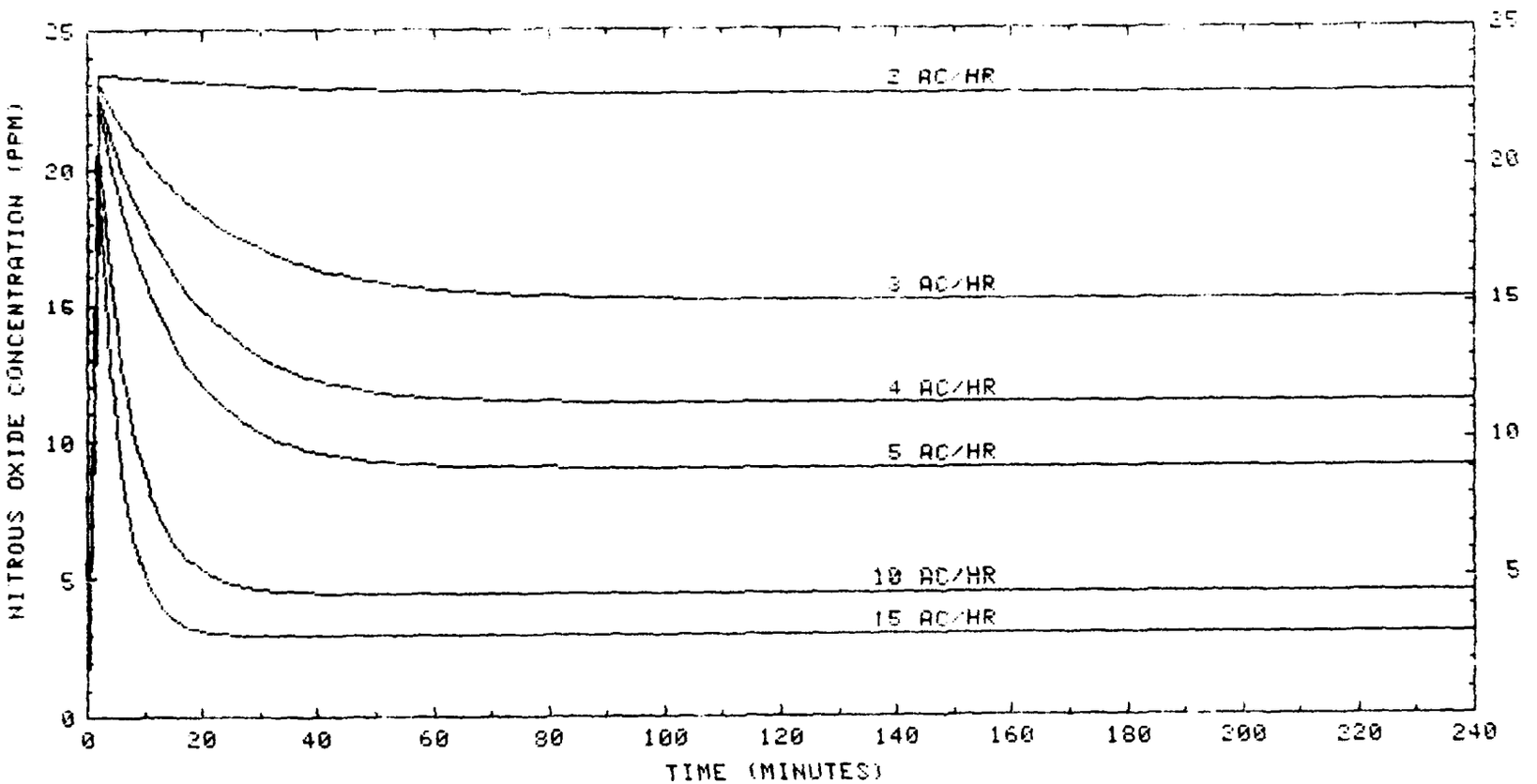


Figure 6. Nitrous Oxide Concentration vs Time, Method #1, 4655 cu ft room.

Nitrous Oxide Instantaneous Concentration
Method #2, Mask and Intubation
With Shut-off Valve
4655 cu ft Room

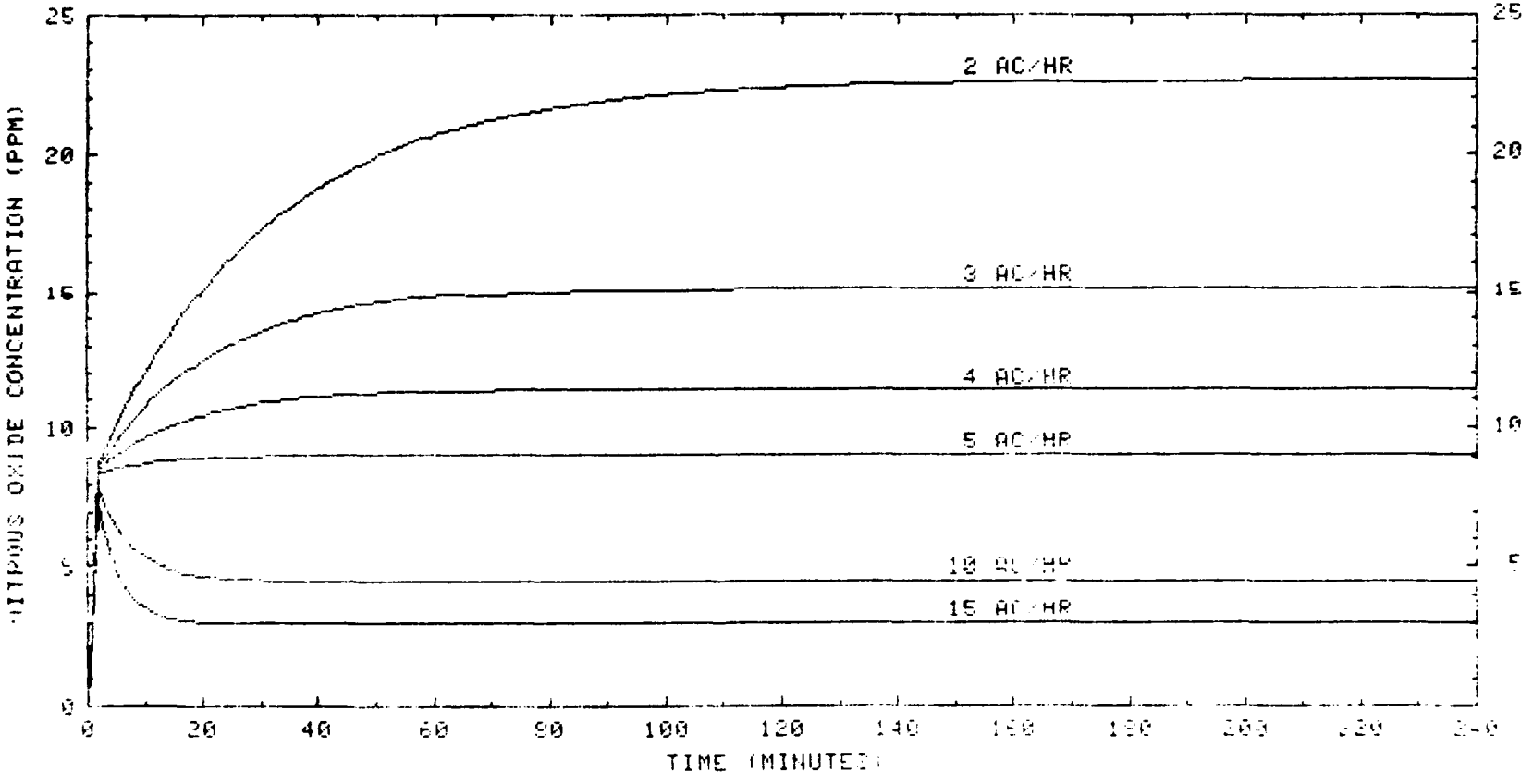


Figure 7. Nitrous Oxide Concentration vs Time, Method #2, 4655 cu ft room.

Nitrous Oxide Instantaneous Concentration
Method #3, Mask with 0% mask leakage
4655 cu ft Room

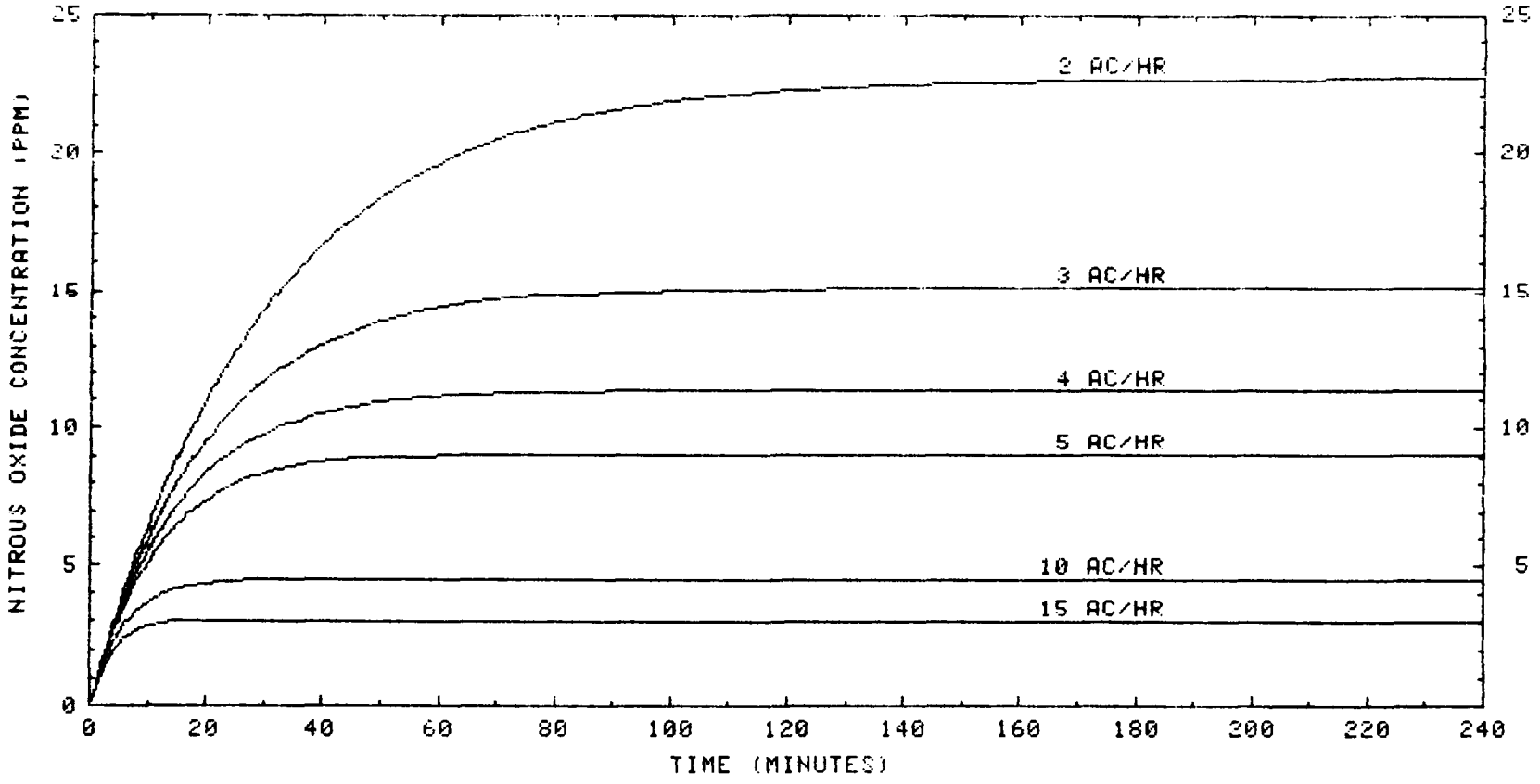


Figure 8. Nitrous Oxide Concentration vs Time, Method #3, 4655 cu ft room, 0% mask leakage.

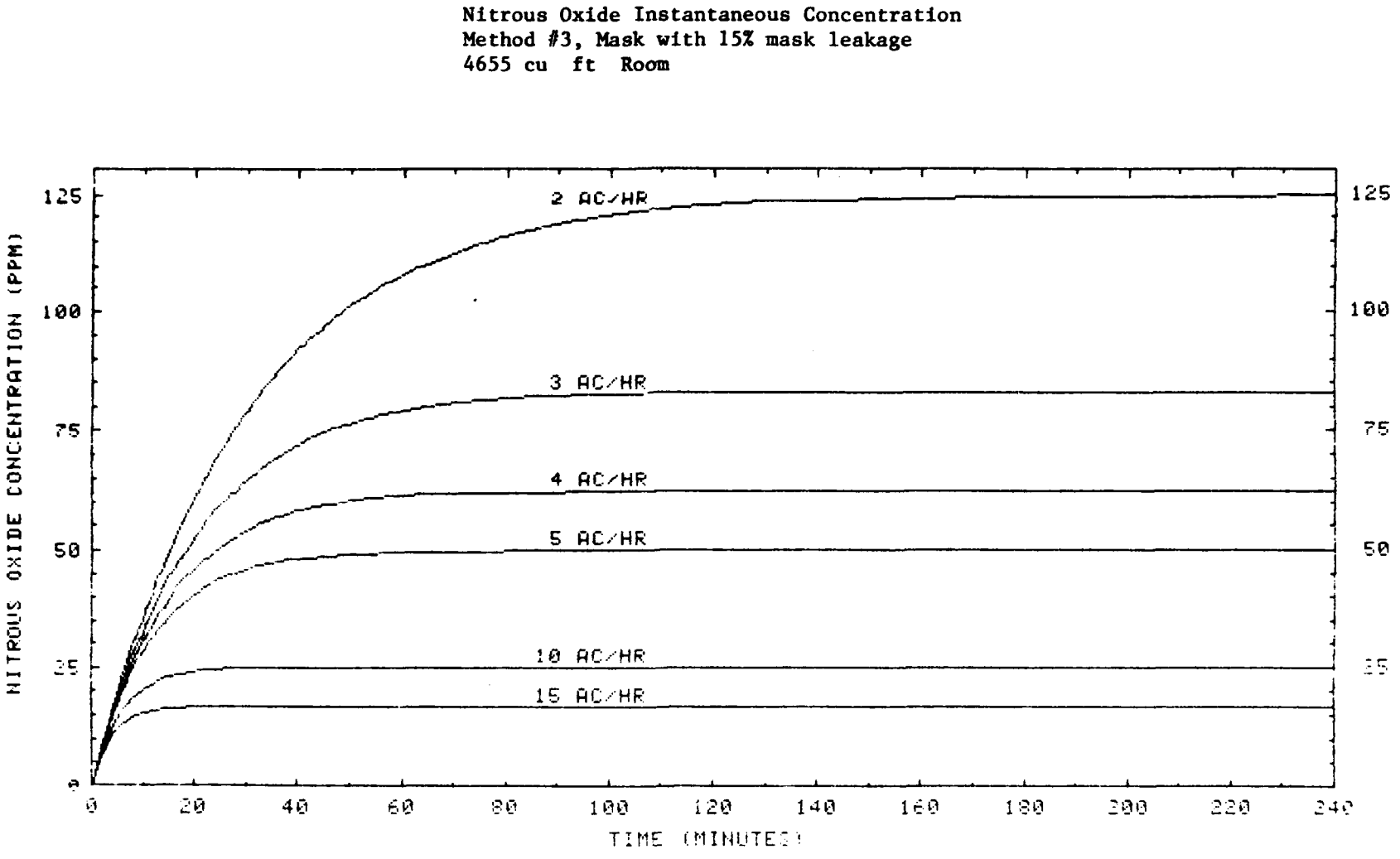


Figure 9. Nitrous Oxide Concentration vs Time, Method #3, 4655 cu ft room, 15% mask leakage.

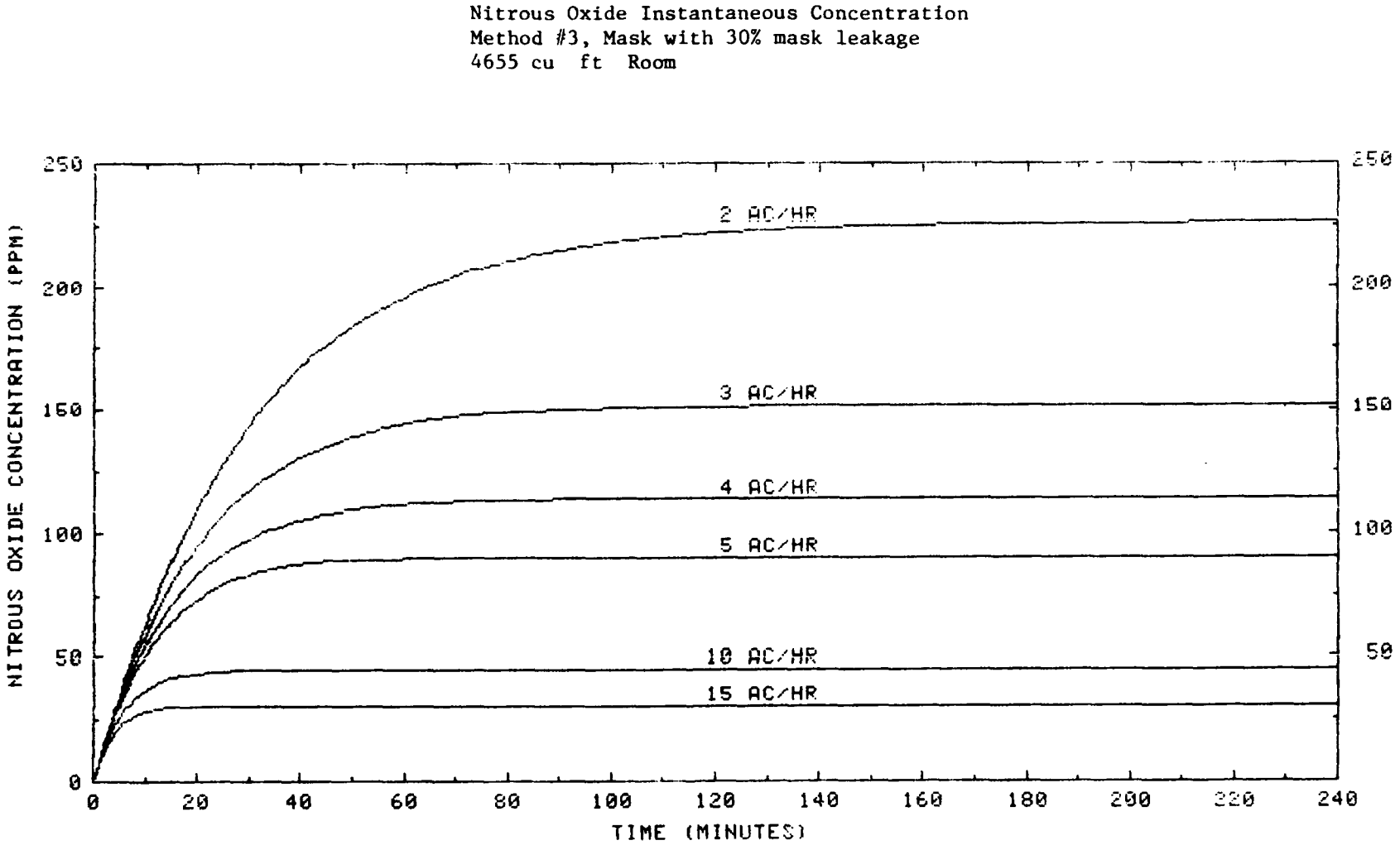


Figure 10. Nitrous Oxide Concentration vs Time, Method #3, 4655 cu ft room, 30% mask leakage.

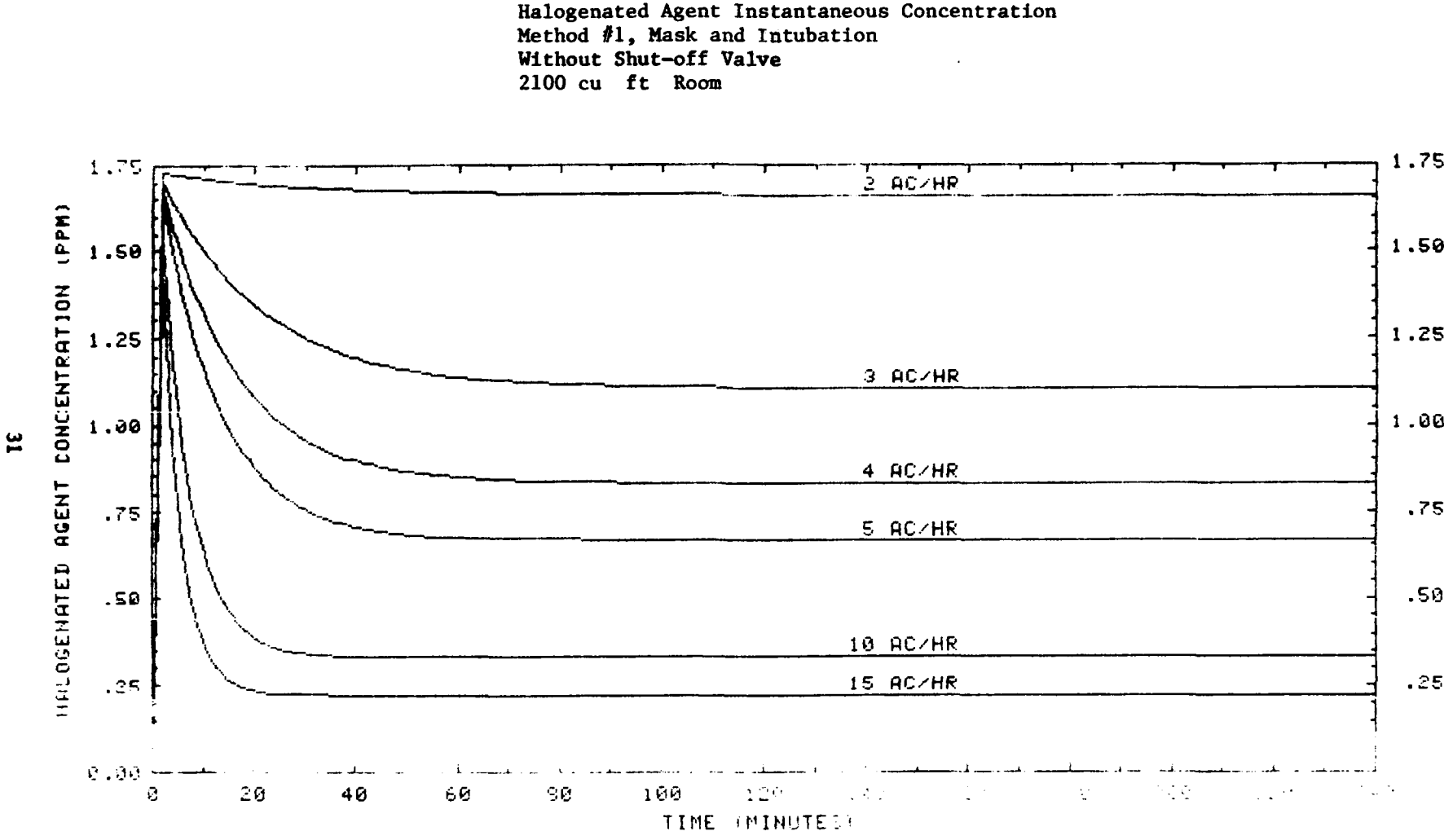


Figure 11. Halogenated Agent Concentration vs Time, Method #1, 2100 cu ft room.

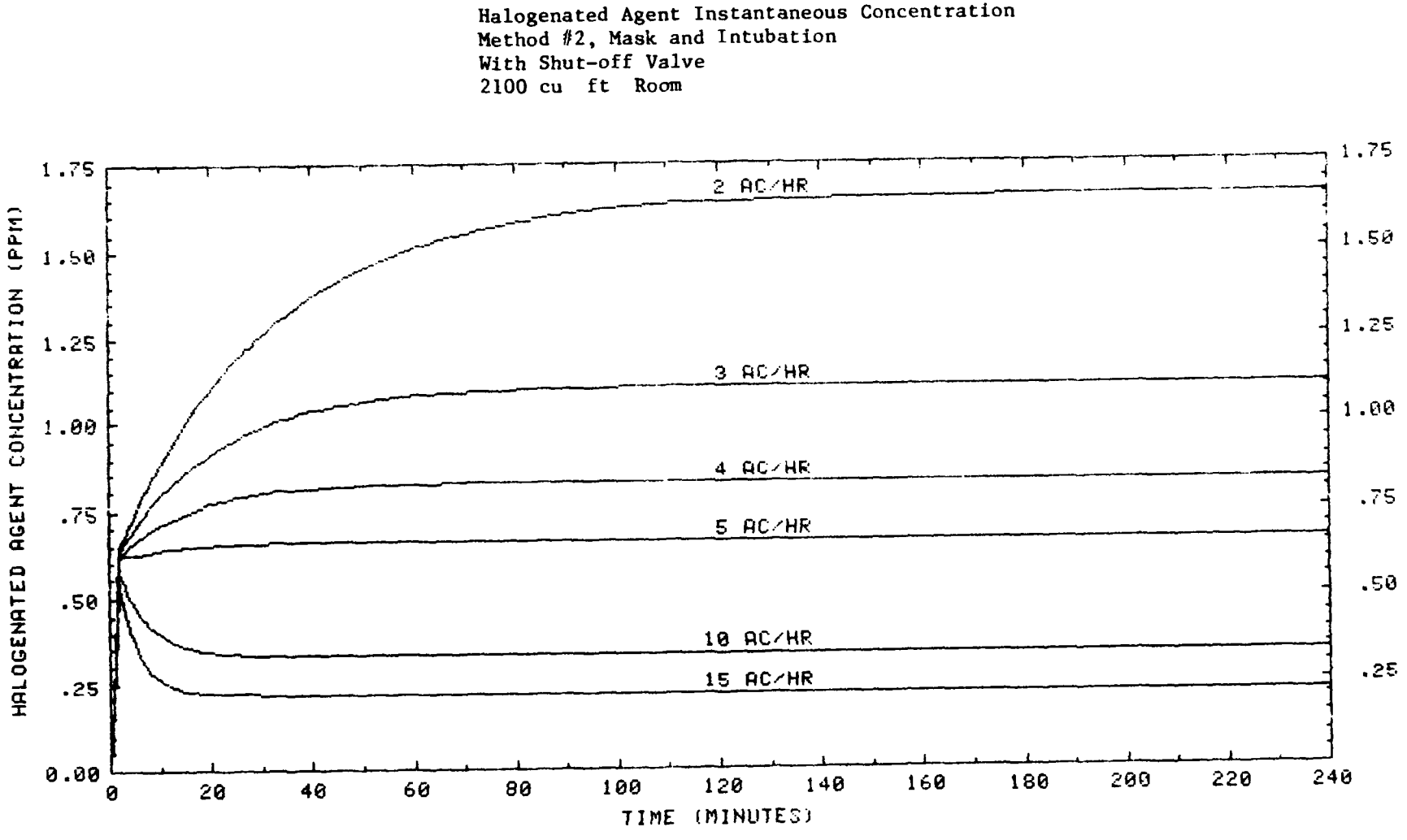


Figure 12. Halogenated Agent Concentration vs Time, Method #2, 2100 cu ft room.

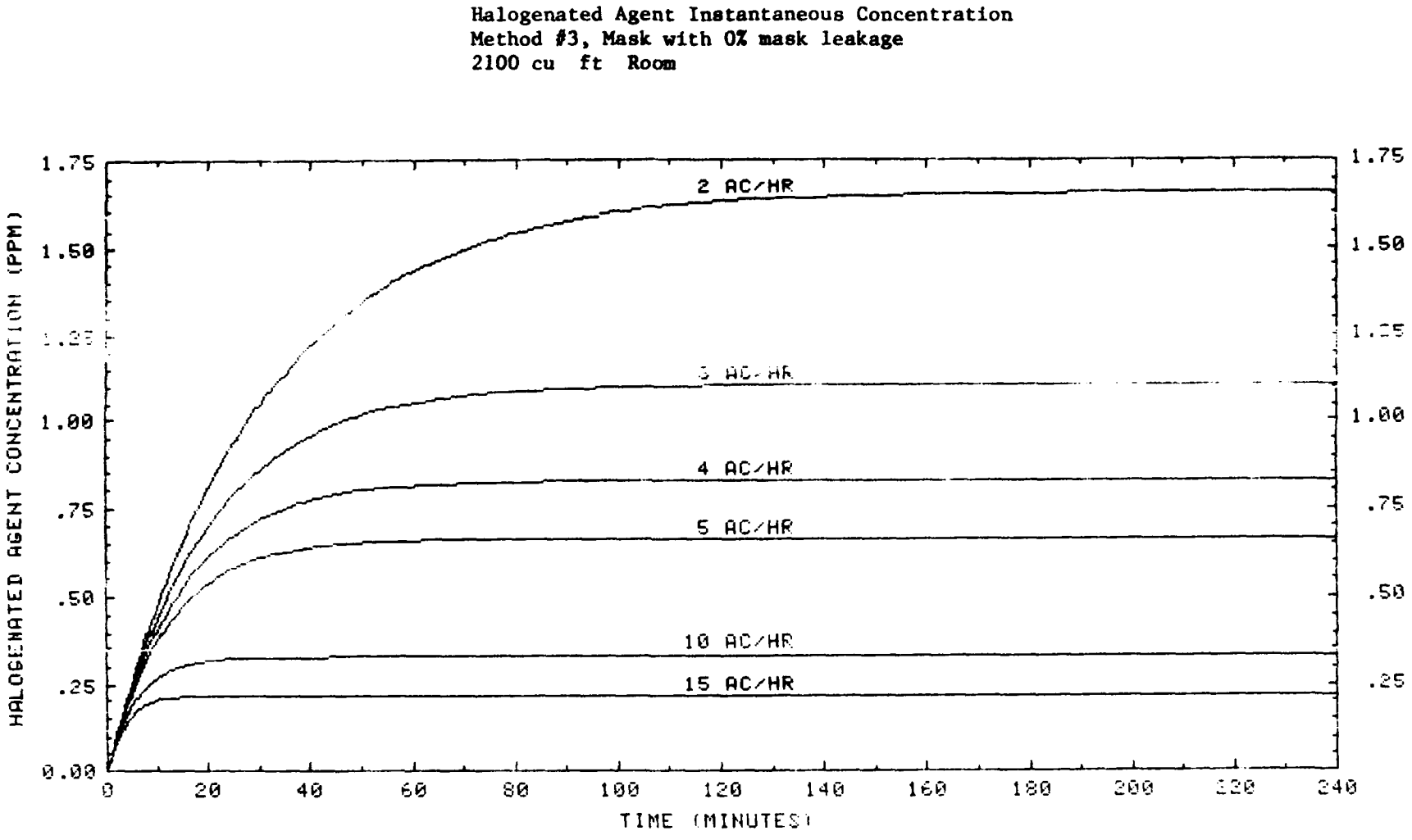


Figure 13. Halogenated Agent Concentration vs Time, Method #3, 2100 cu ft room, 0% mask leakage.

Halogenated Agent Instantaneous Concentration
Method #3, Mask with 15% mask leakage
2100 cu ft Room

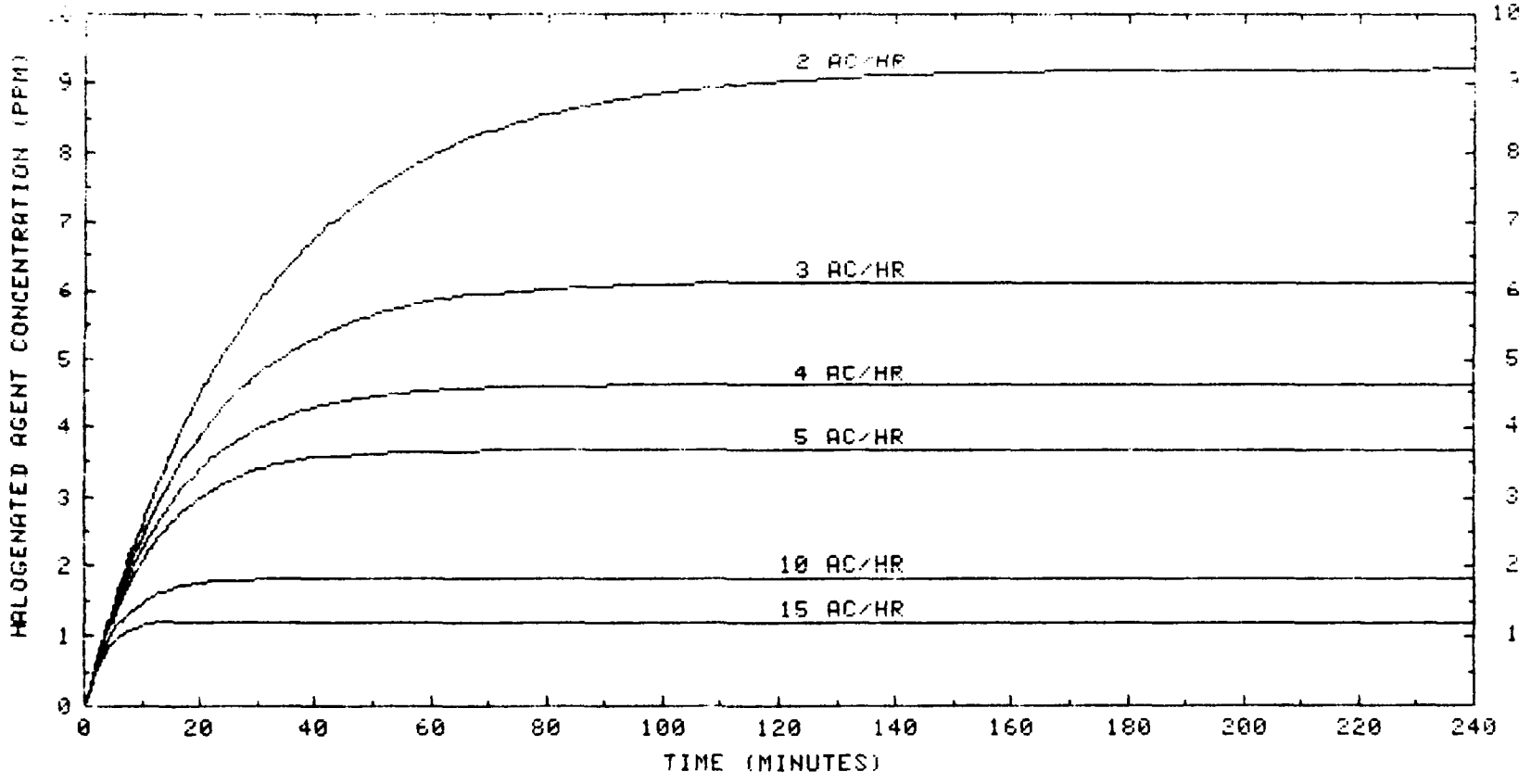


Figure 14. Halogenated Agent Concentration vs Time, Method #3, 2100 cu ft room, 15% mask leakage.

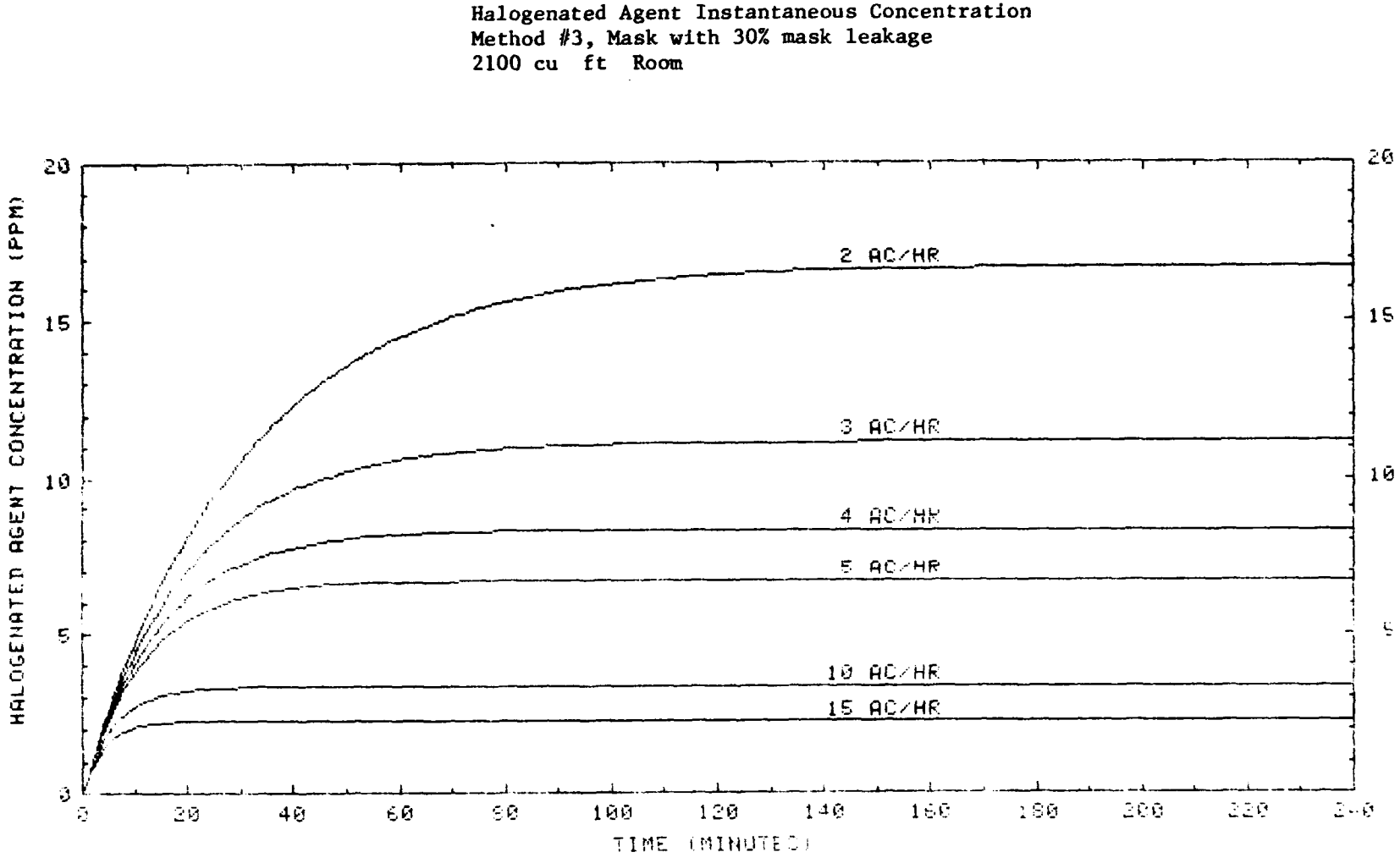


Figure 15. Halogenated Agent Concentration vs Time, Method #3, 2100 cu ft room, 30% mask leakage.

Halogenated Agent Instantaneous Concentration
Method #1, Mask and Intubation
Without Shut-off Valve
4655 cu ft Room

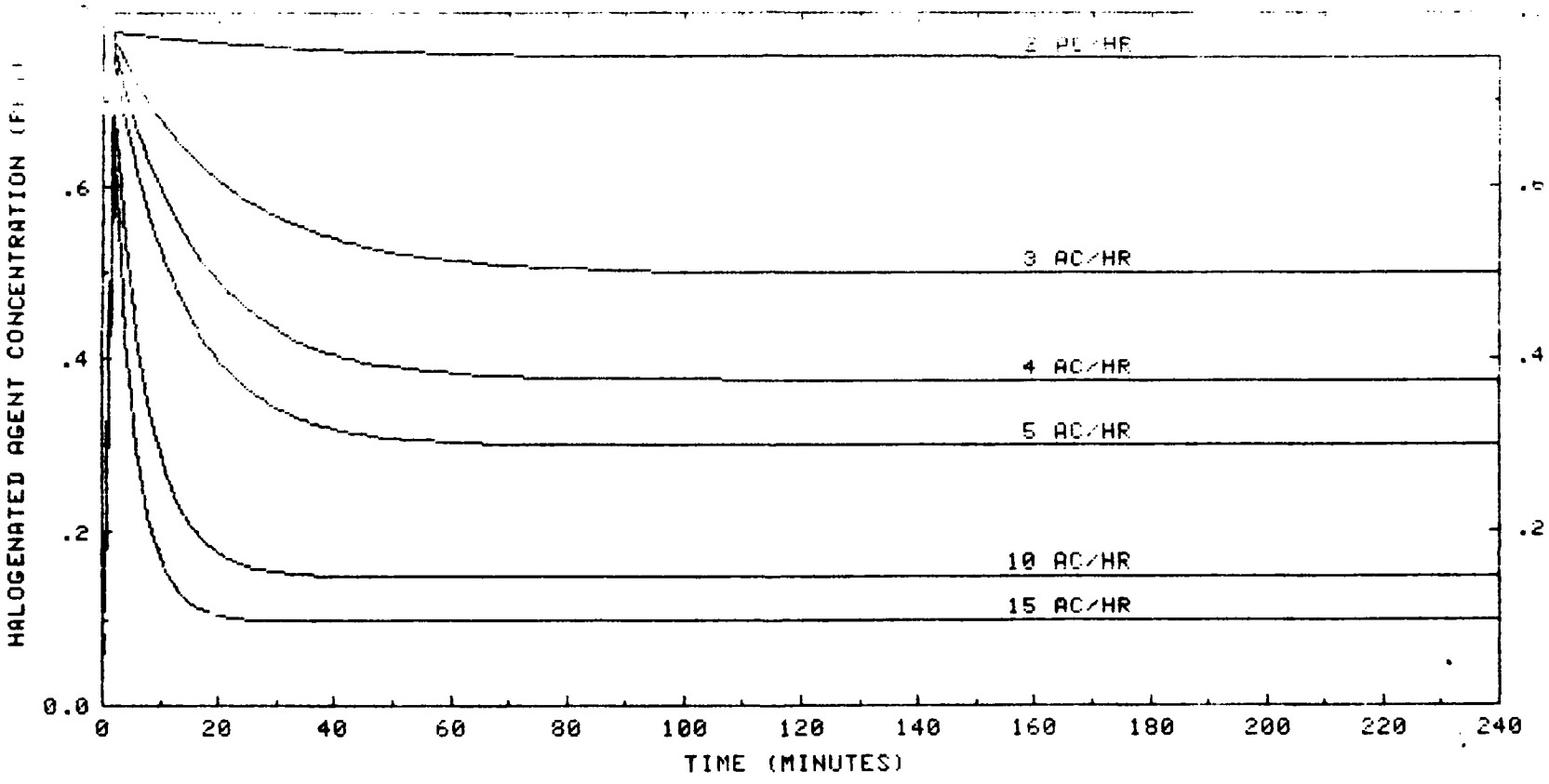


Figure 16. Halogenated Agent Concentration vs Time, Method #1, 4655 cu ft room.

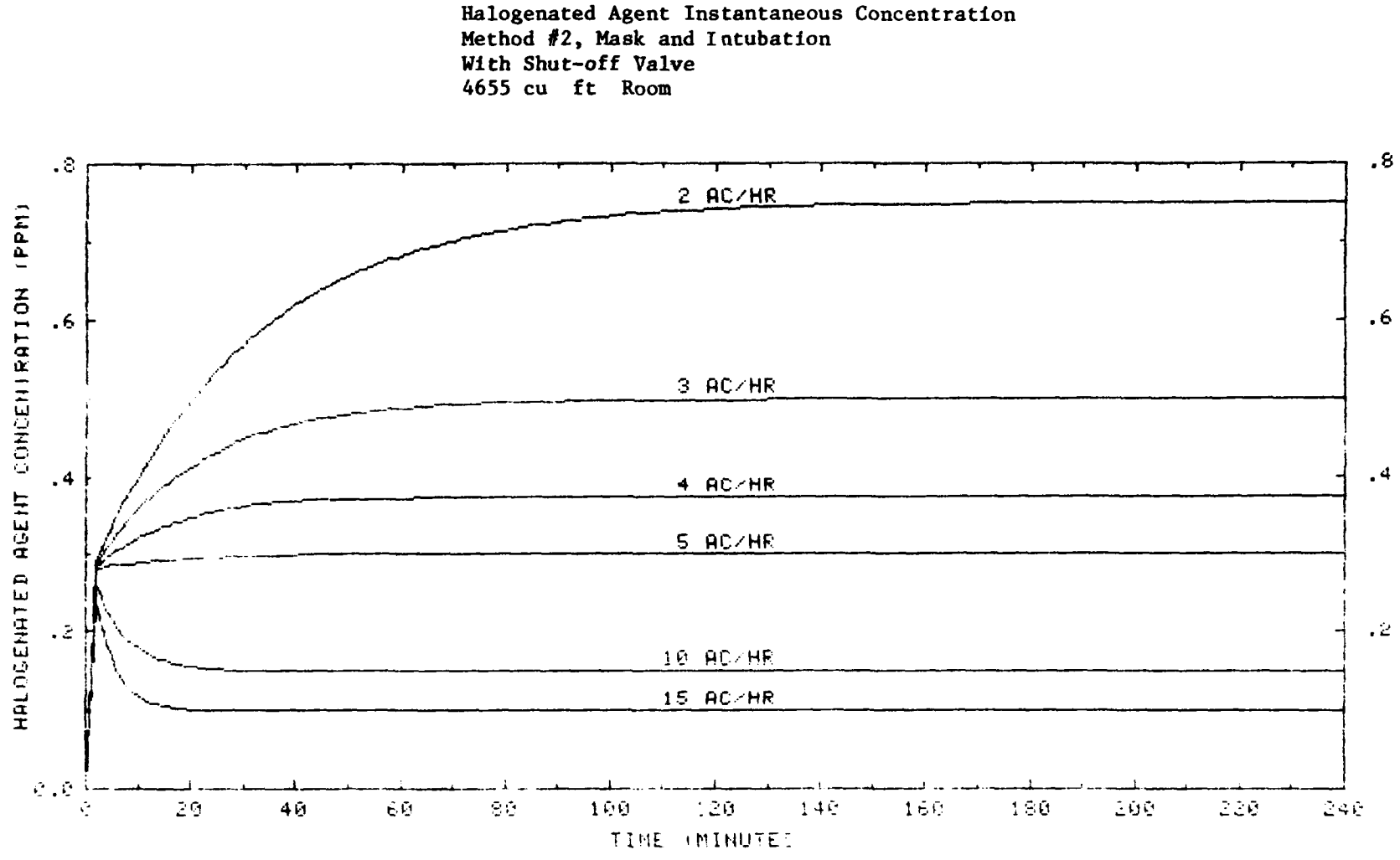


Figure 17. Halogenated Agent Concentration vs Time, Method #2, 4655 cu ft room.

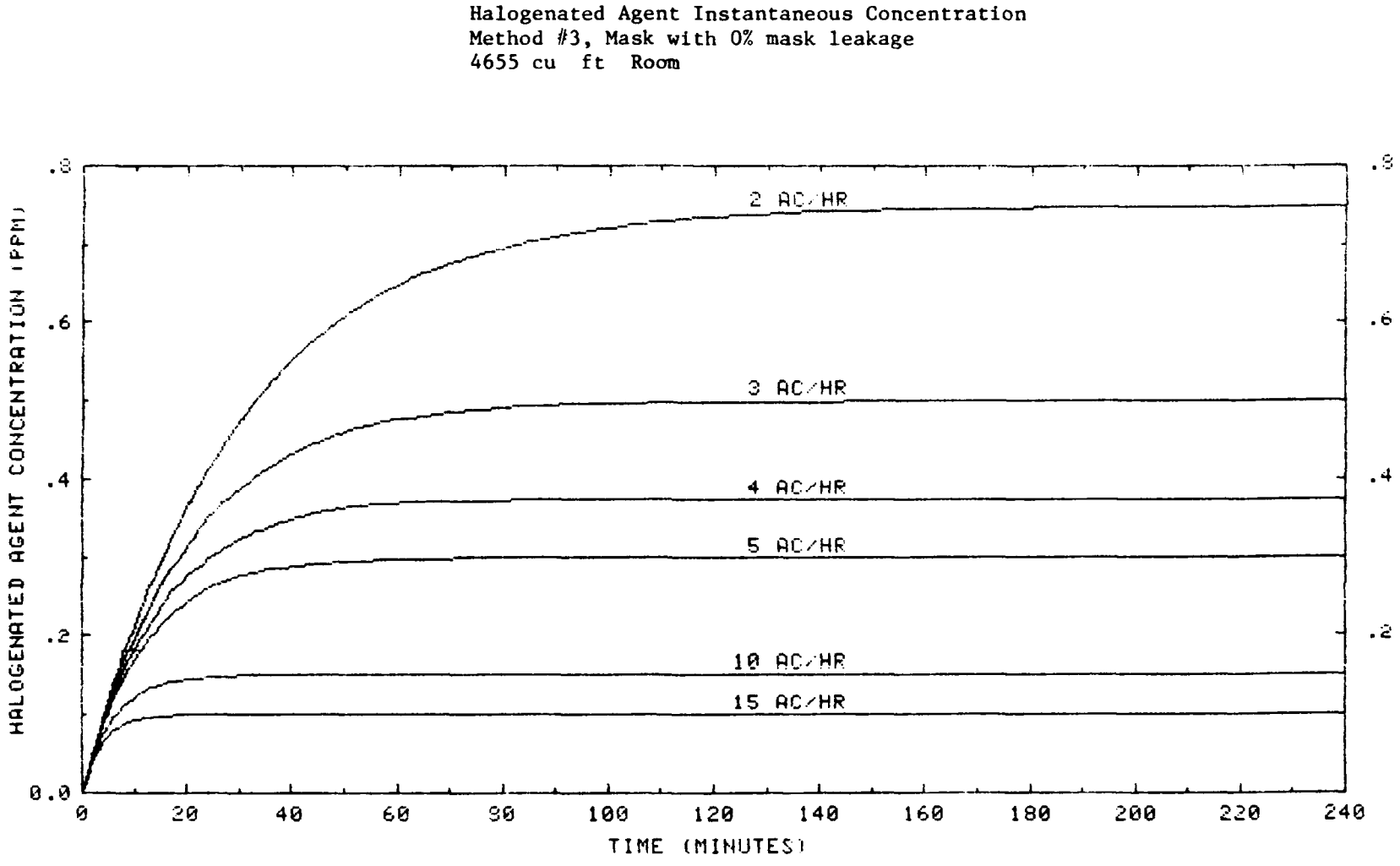


Figure 18. Halogenated Agent Concentration vs Time, Method #3, 4655 cu ft room, 0% mask leakage.

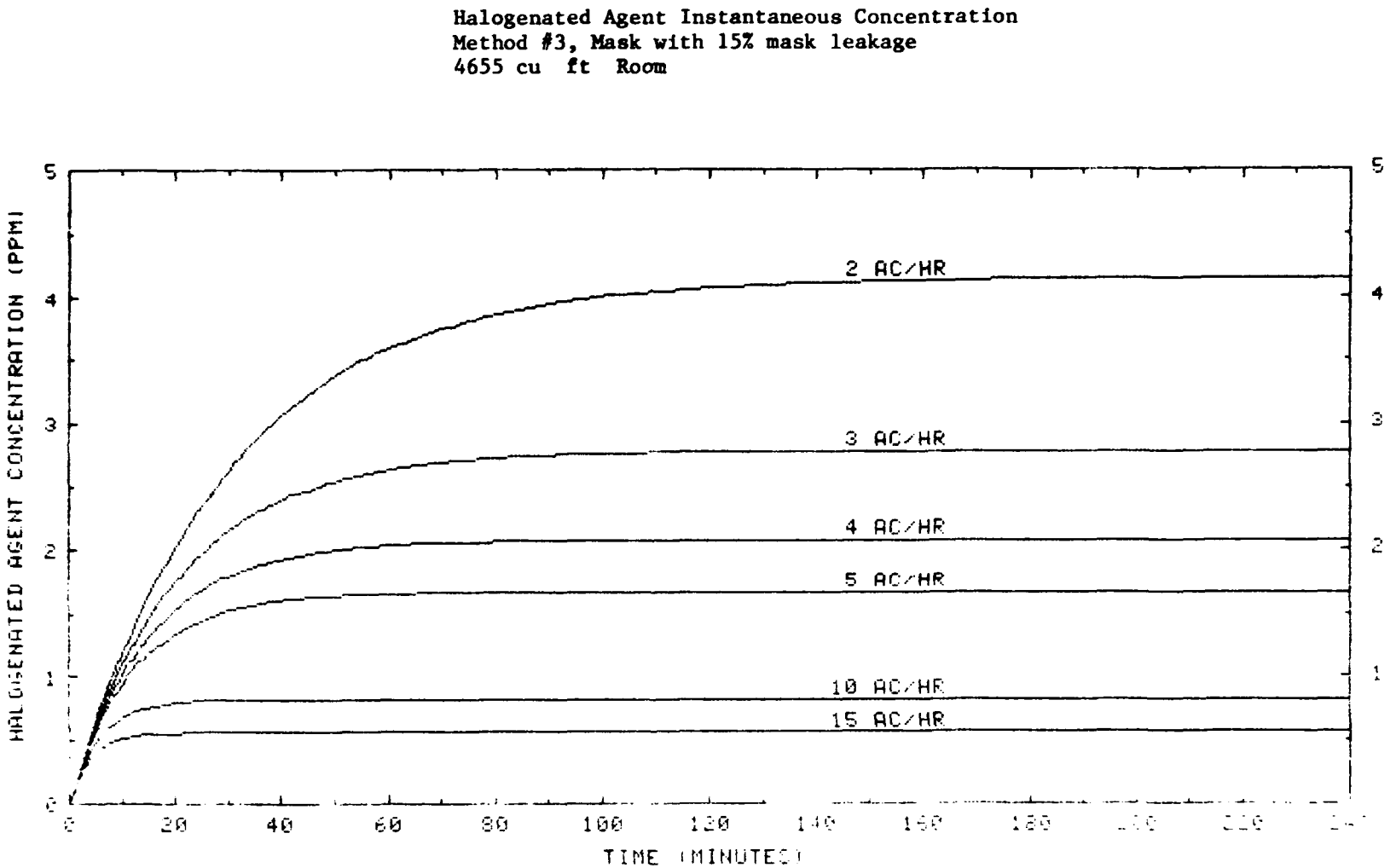


Figure 19. Halogenated Agent Concentration vs Time, Method #3, 4655 cu ft room, 15% mask leakage.

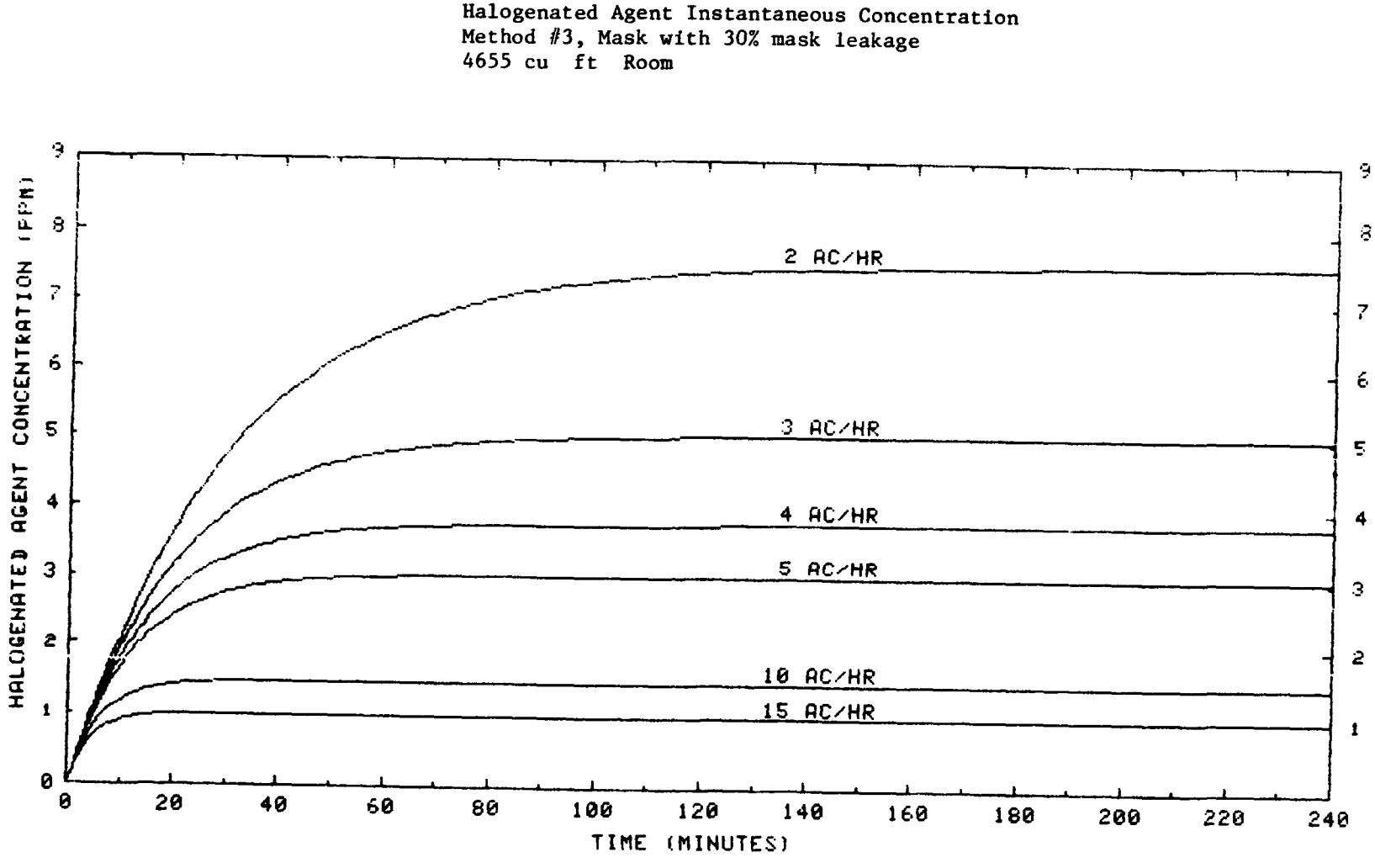


Figure 20. Halogenated Agent Concentration vs Time, Method #3, 4655 cu ft room, 30% mask leakage.

Nitrous Oxide TWA Concentration
Method #1, Mask and Intubation
Without Shut-off Valve
2100 cu ft Room

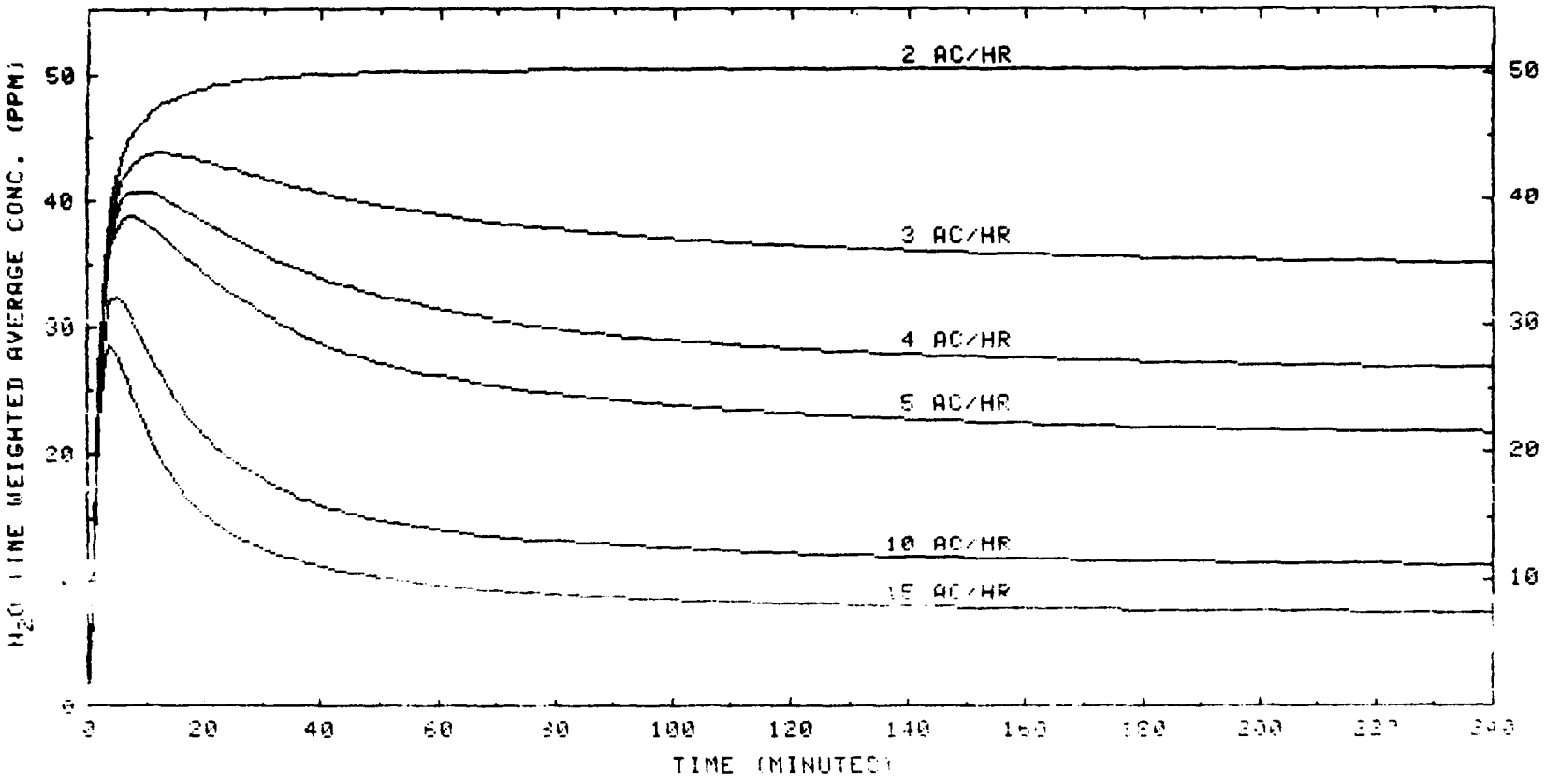


Figure 21. Nitrous Oxide TWA Concentration vs Time, Method #1, 2100 cu ft room.

Nitrous Oxide TWA Concentration
Method #2, Mask and Intubation
With Shut-off Valve
2100 cu ft Room

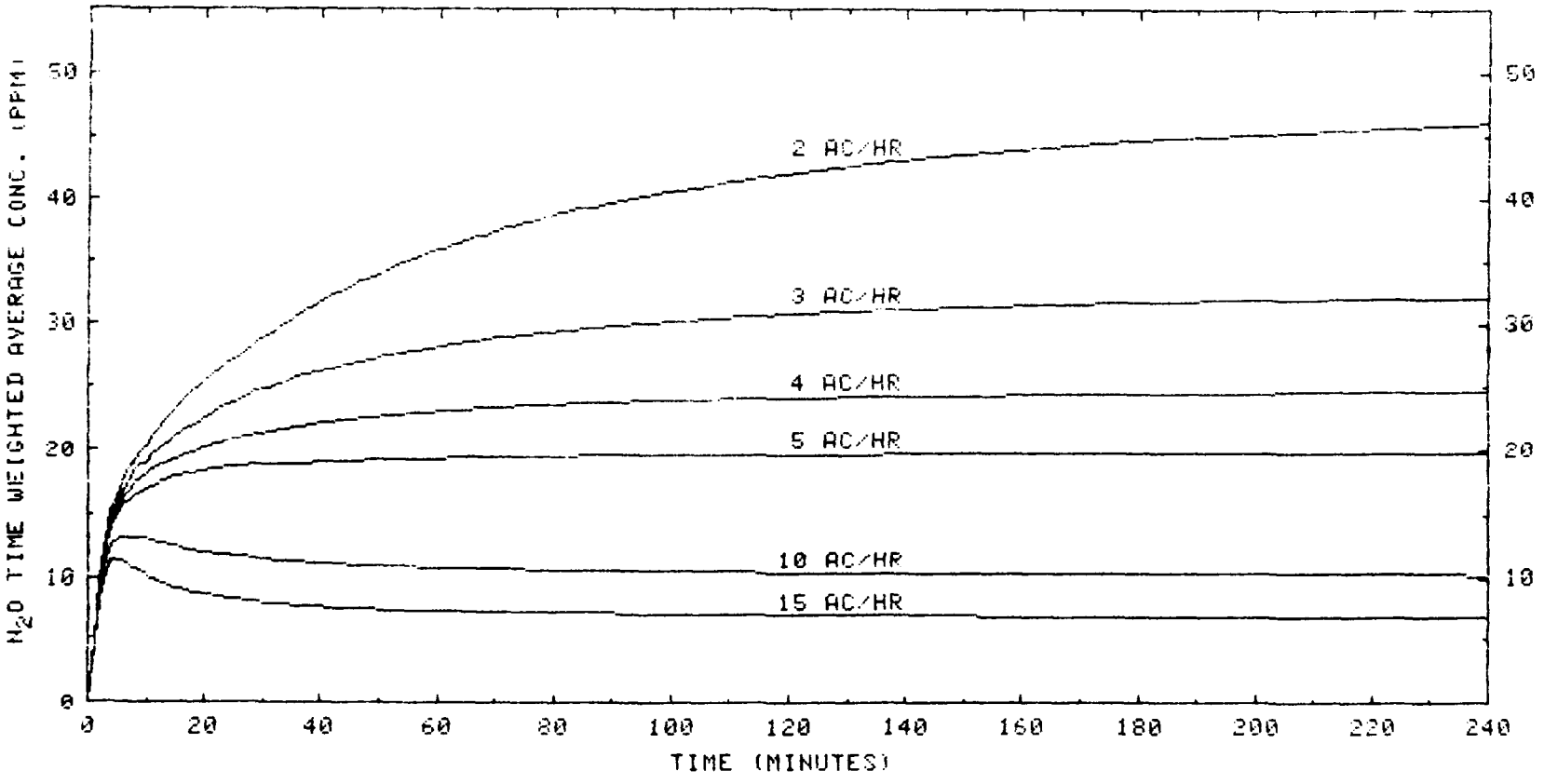


Figure 22. Nitrous Oxide TWA Concentration vs Time, Method #2, 2100 cu ft room.

Nitrous Oxide TWA Concentration
Method #3, Mask with 0% mask leakage
2100 cu ft Room

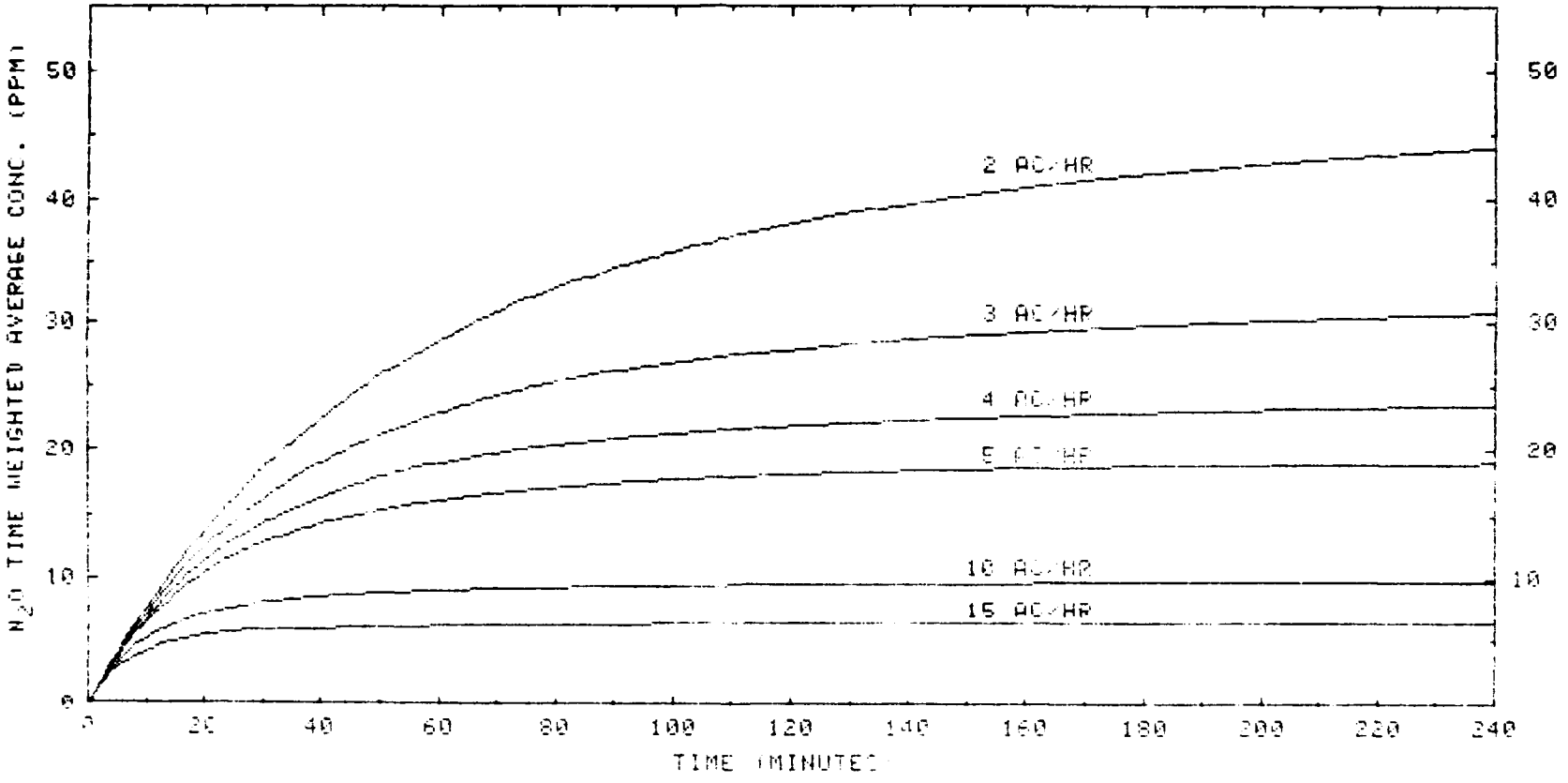


Figure 23. Nitrous Oxide TWA Concentration vs Time, Method #3, 2100 cu ft room, 0% mask leakage.

Nitrous Oxide TWA Concentration
Method #3, Mask with 15% mask leakage
2100 cu ft Room

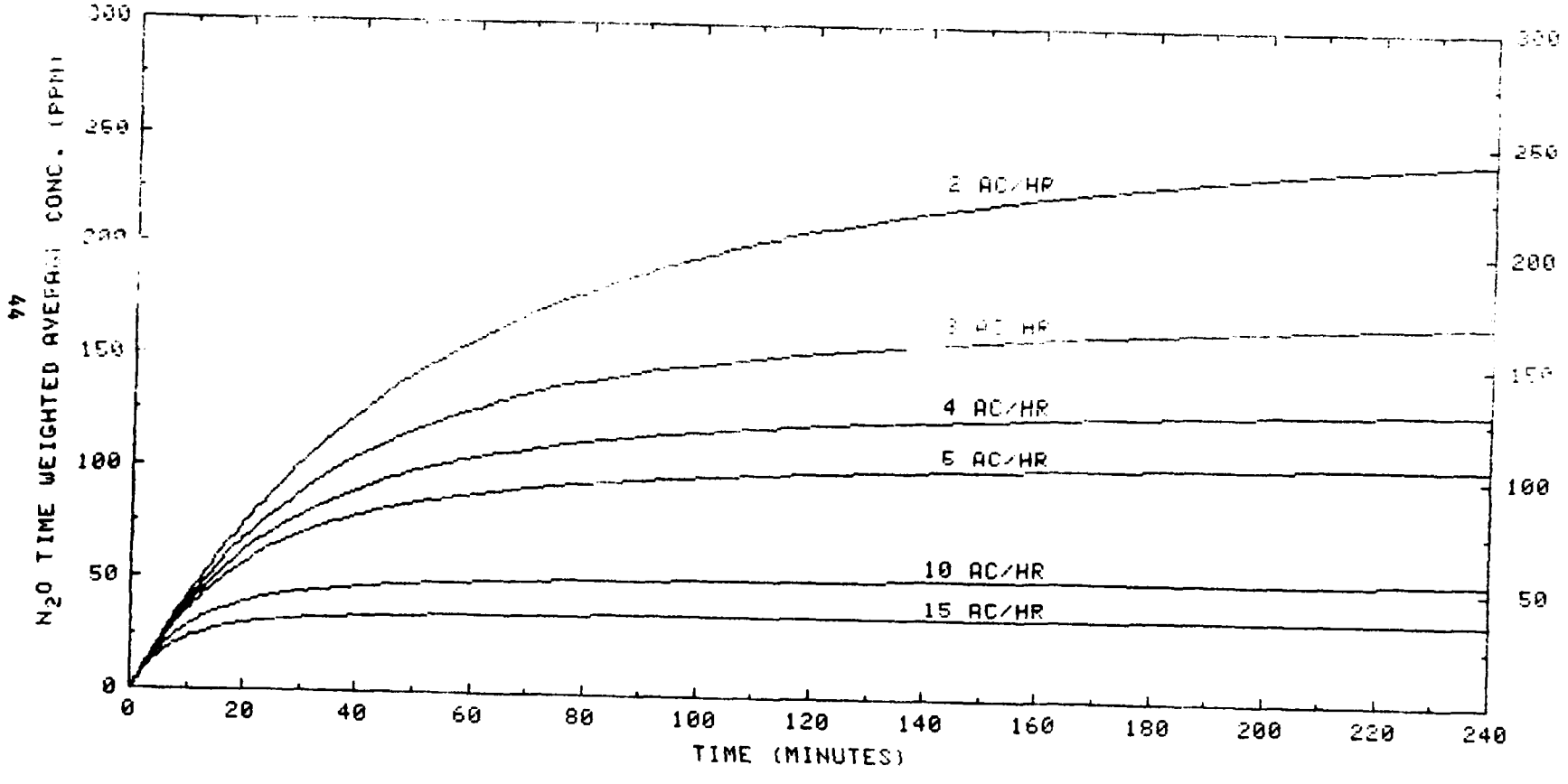


Figure 24. Nitrous Oxide TWA Concentration vs Time, Method #3, 2100 cu ft room, 15% mask leakage.

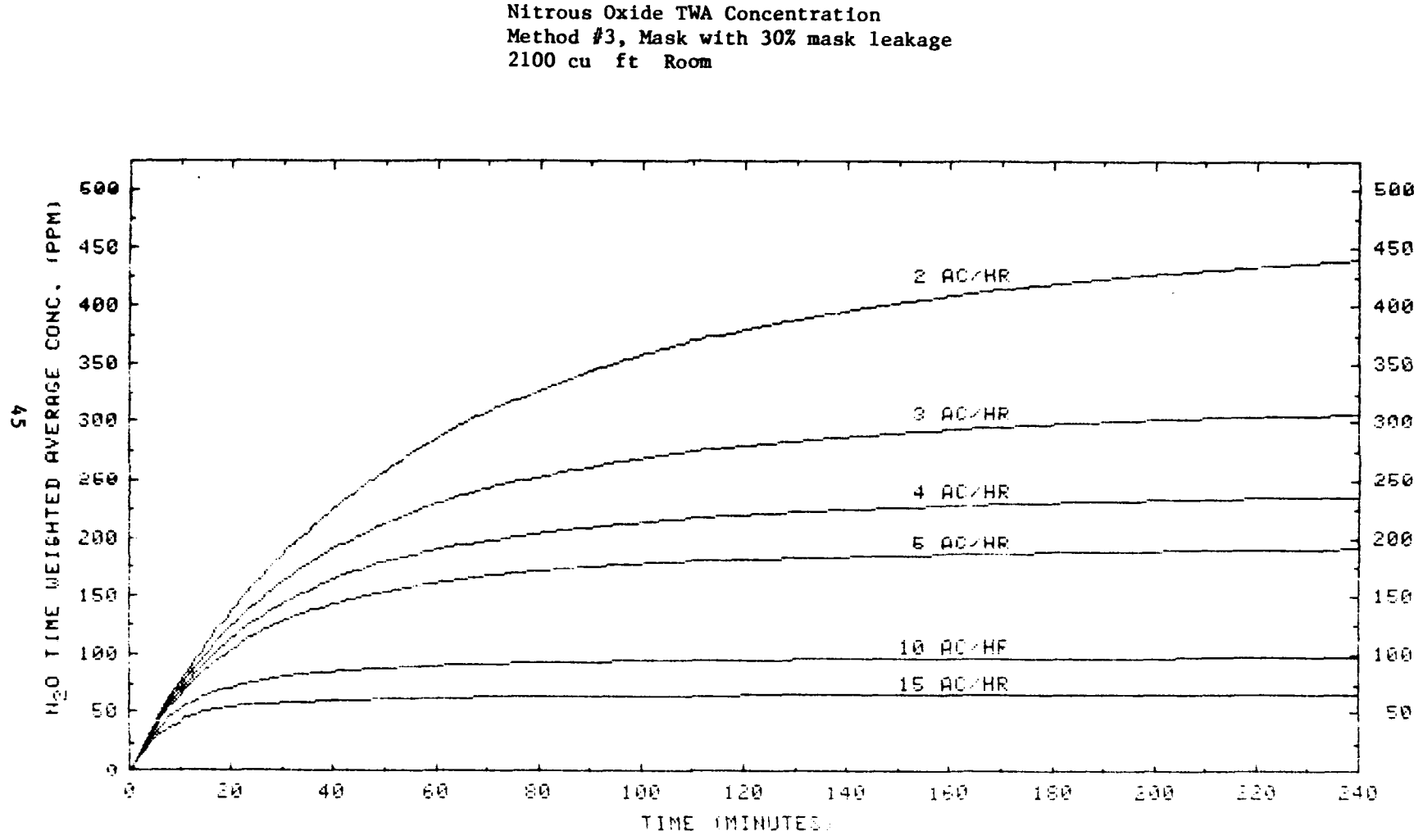


Figure 25. Nitrous Oxide TWA Concentration vs Time, Method #3, 2100 cu ft room, 30% mask leakage.

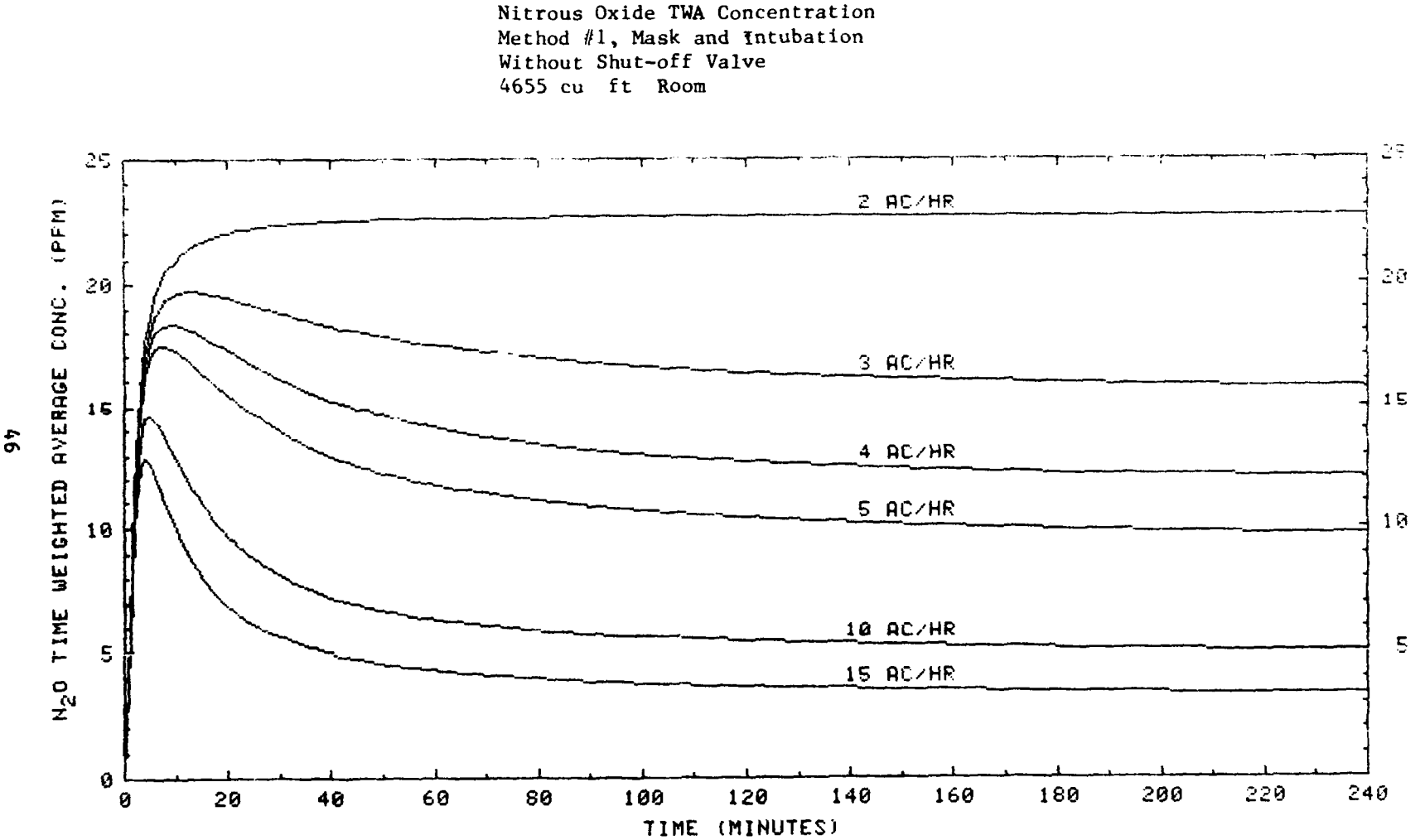


Figure 26. Nitrous Oxide TWA Concentration vs Time, Method #1, 4655 cu ft room.

Nitrous Oxide TWA Concentration
Method #2, Mask and Intubation
With Shut-off Valve
4655 cu ft Room

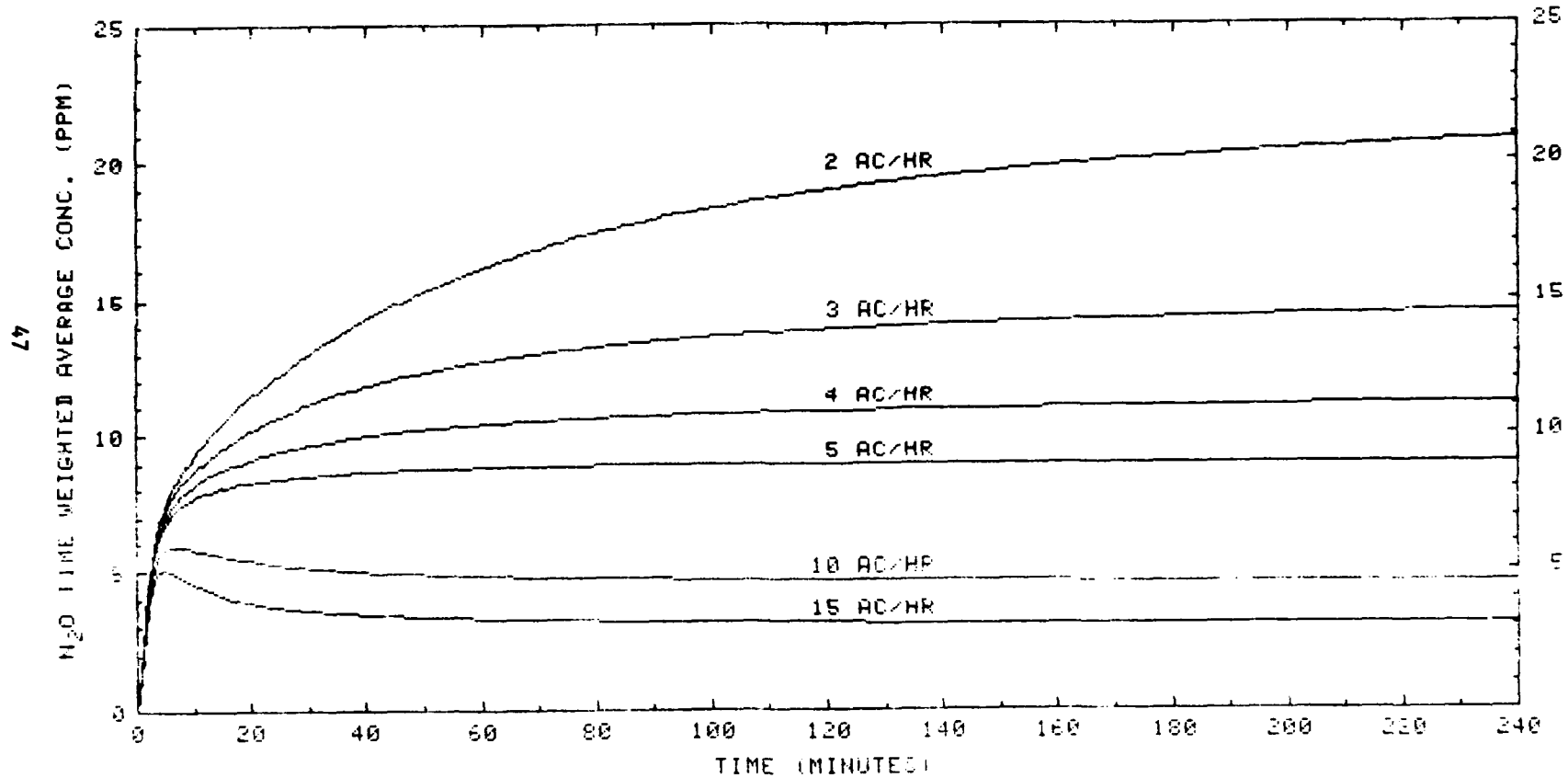


Figure 27. Nitrous Oxide TWA Concentration vs Time, Method #2, 4655 cu ft room.

Nitrous Oxide TWA Concentration
Method #3, Mask with 0% mask leakage
4655 cu ft Room

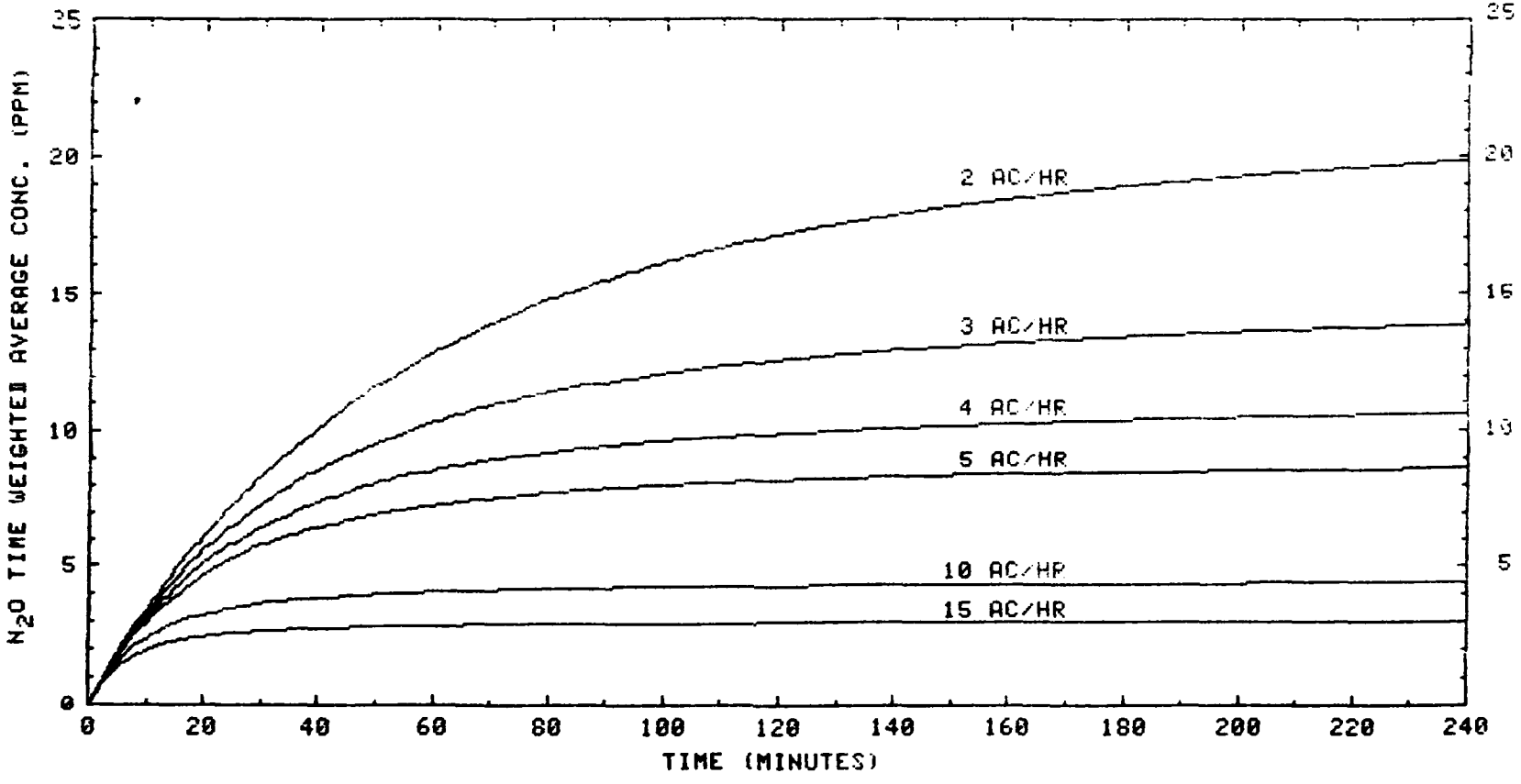


Figure 28. Nitrous Oxide TWA Concentration vs Time, Method #3, 4655 cu ft room, 0% mask leakage.

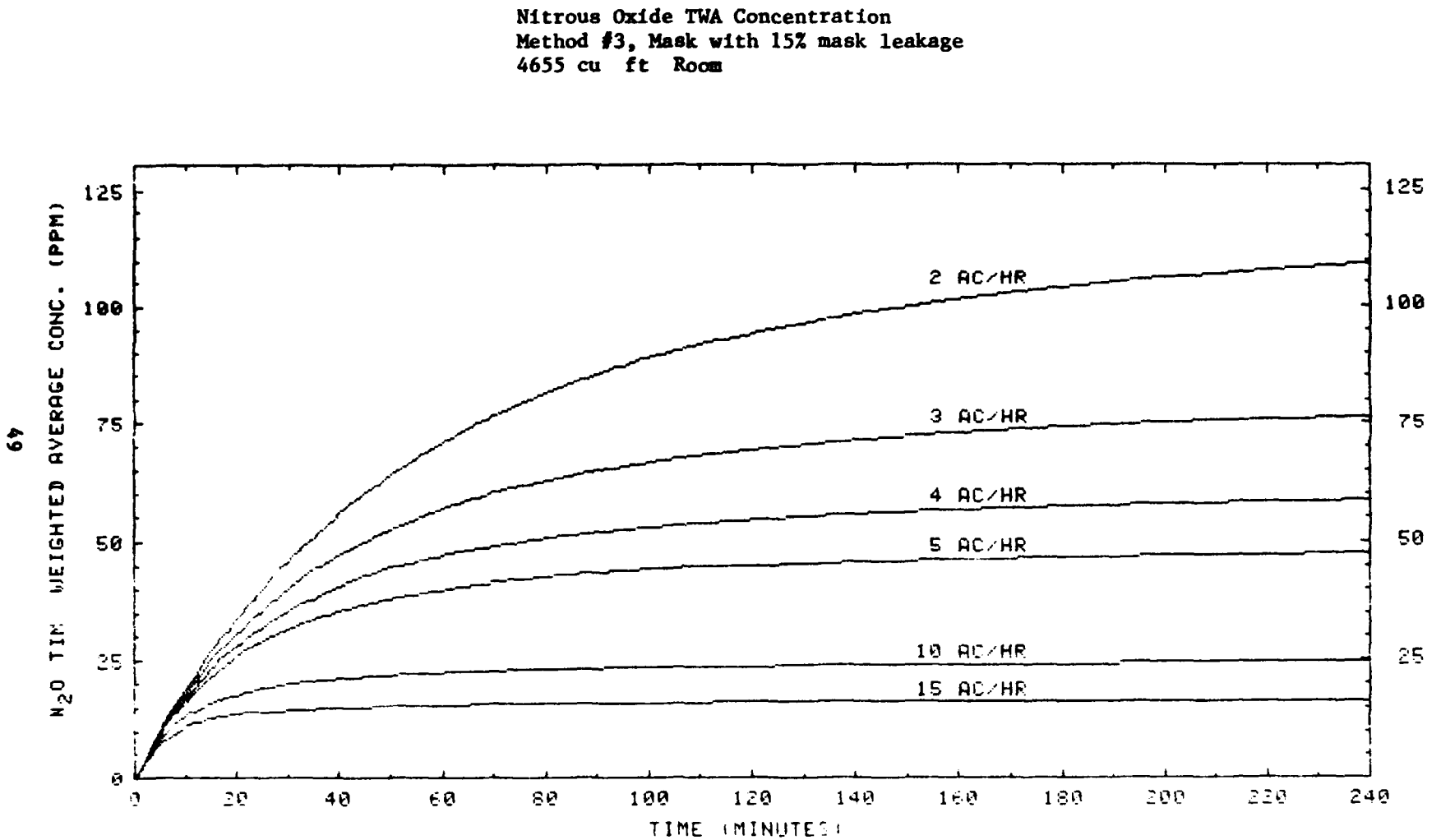


Figure 29. Nitrous Oxide TWA Concentration vs Time, Method #3, 4655 cu ft room, 15% mask leakage.

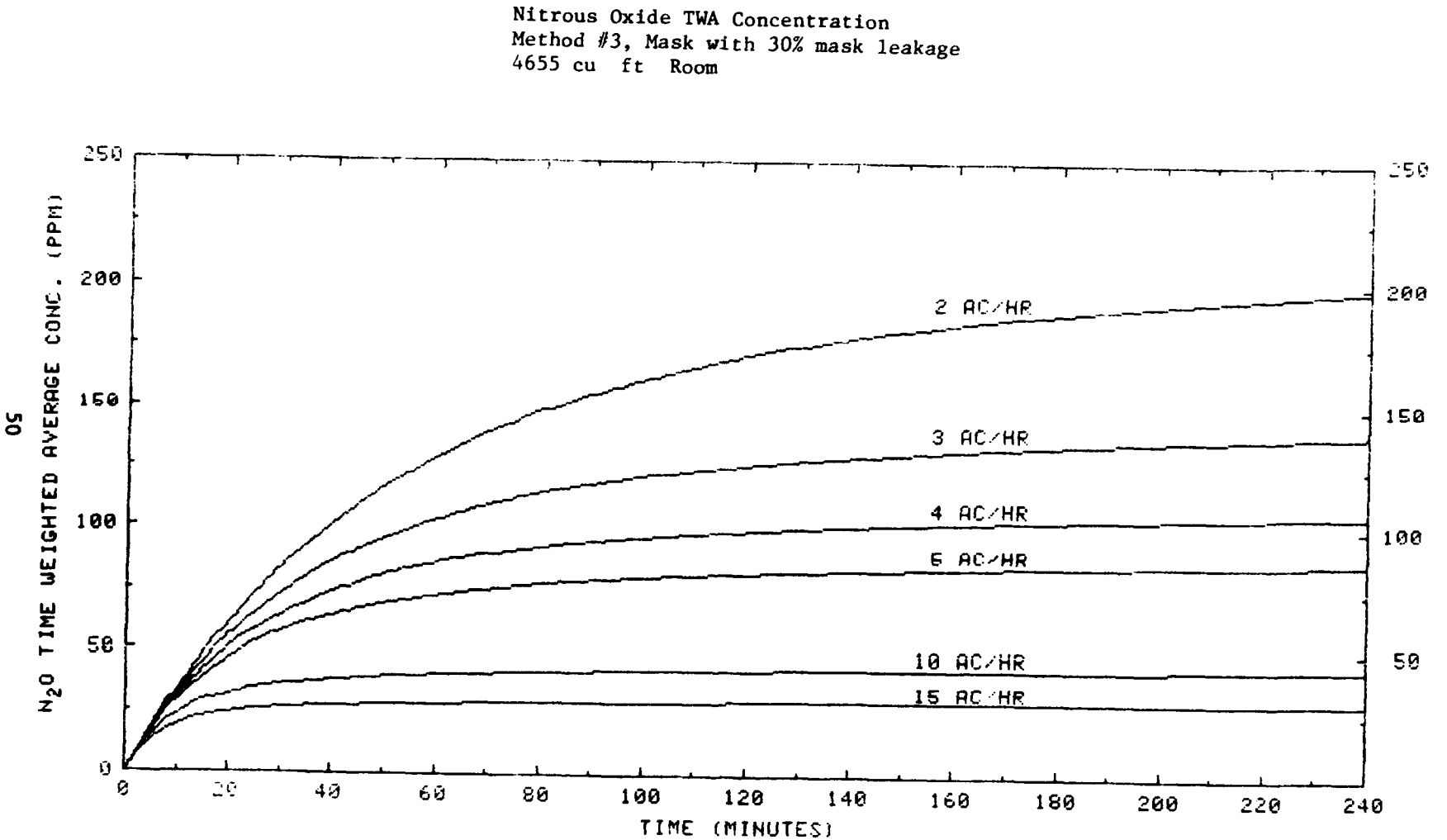


Figure 30. Nitrous Oxide TWA Concentration vs Time, Method #3, 4655 cu ft room, 30% mask leakage.

Halogenated Agent TWA Concentration
Method #1, Mask and Intubation
Without Shut-off Valve
2100 cu ft Room

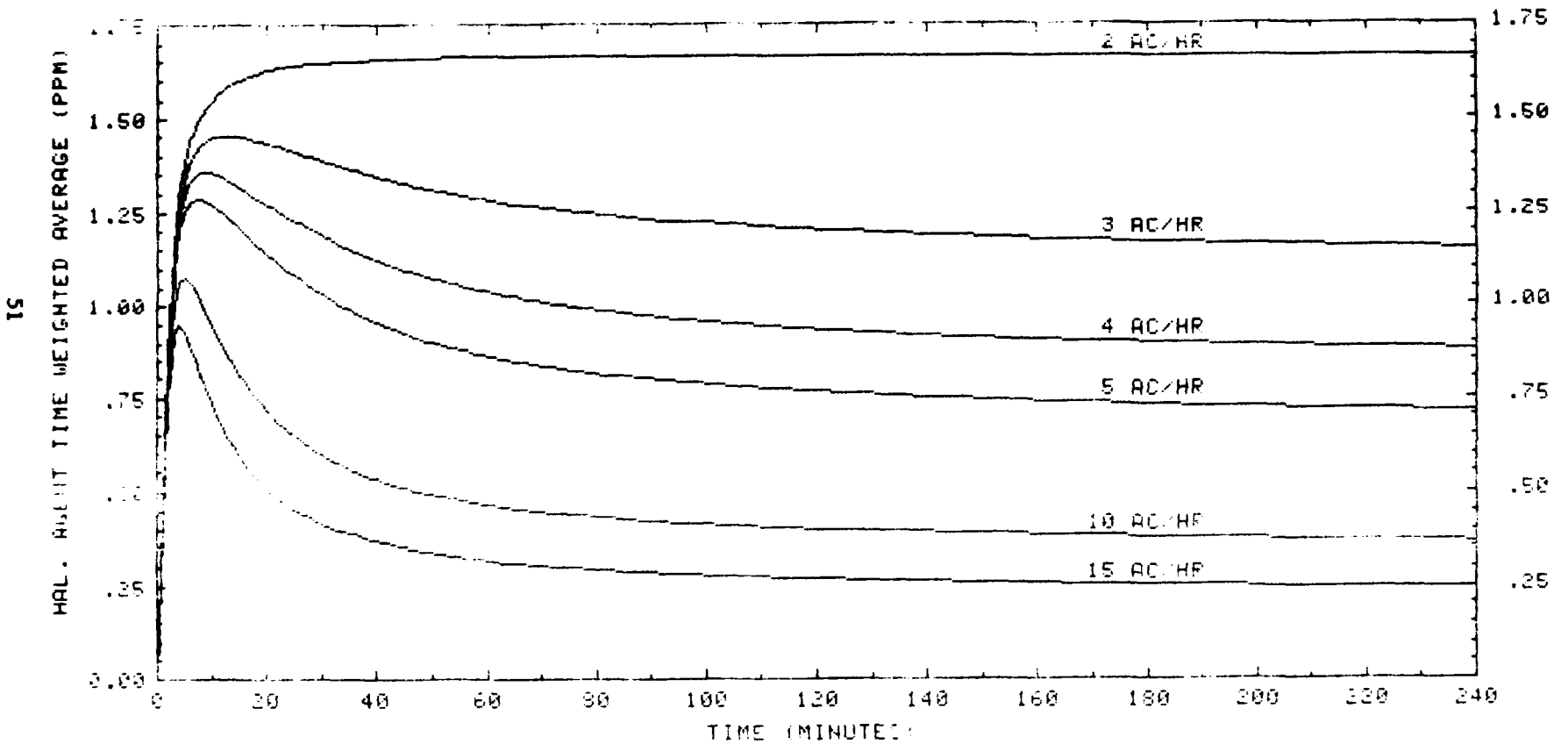


Figure 31. Halogenated Agent TWA Concentration vs Time, Method #1, 2100 cu ft room.

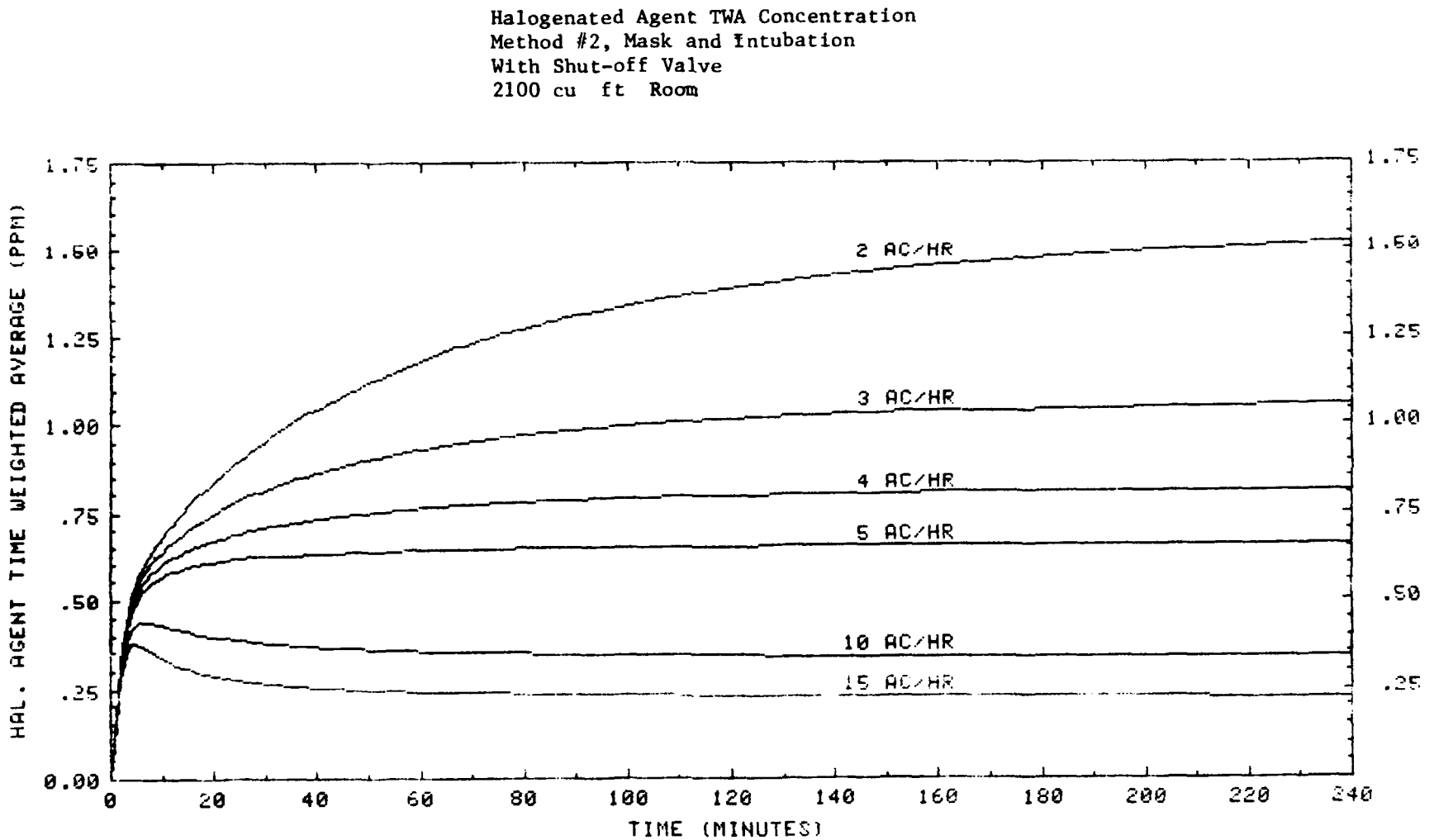


Figure 32. Halogenated Agent TWA Concentration vs Time, Method #2, 2100 cu ft room.

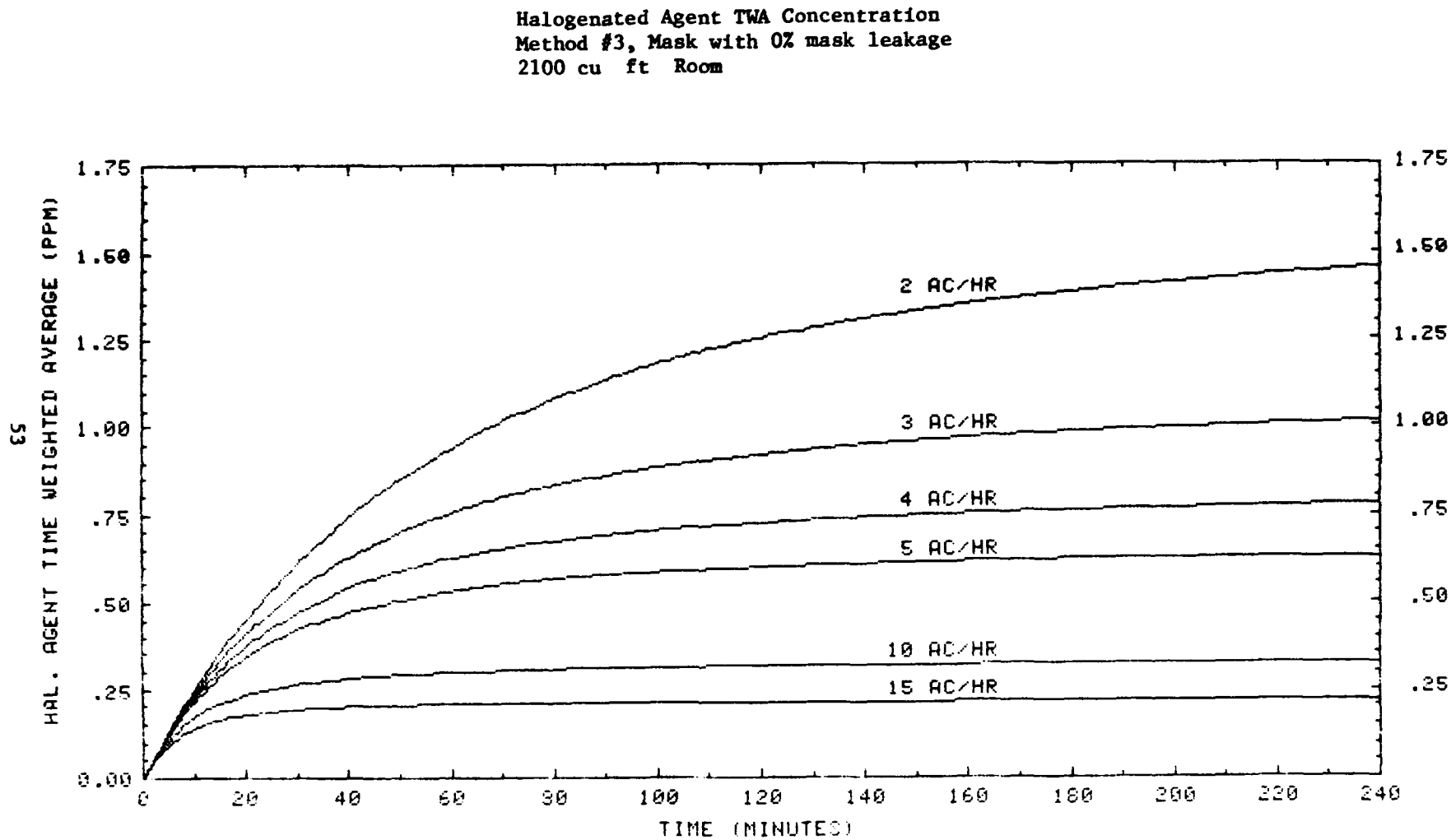


Figure 33. Halogenated Agent TWA Concentration vs Time, Method #3, 2100 cu ft room, 0% mask leakage.

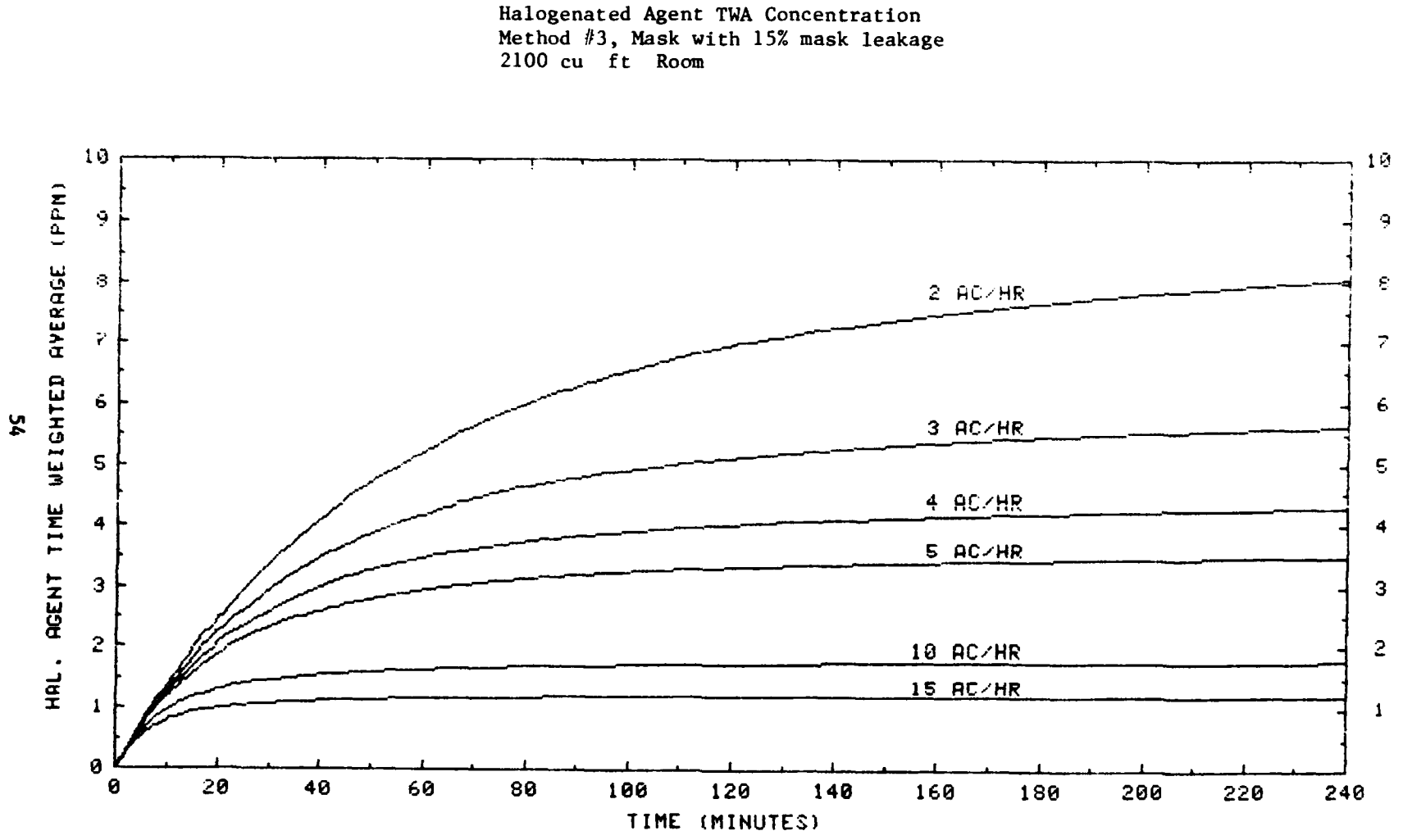


Figure 34. Halogenated Agent TWA Concentration vs Time, Method #3, 2100 cu ft room, 15% mask leakage.

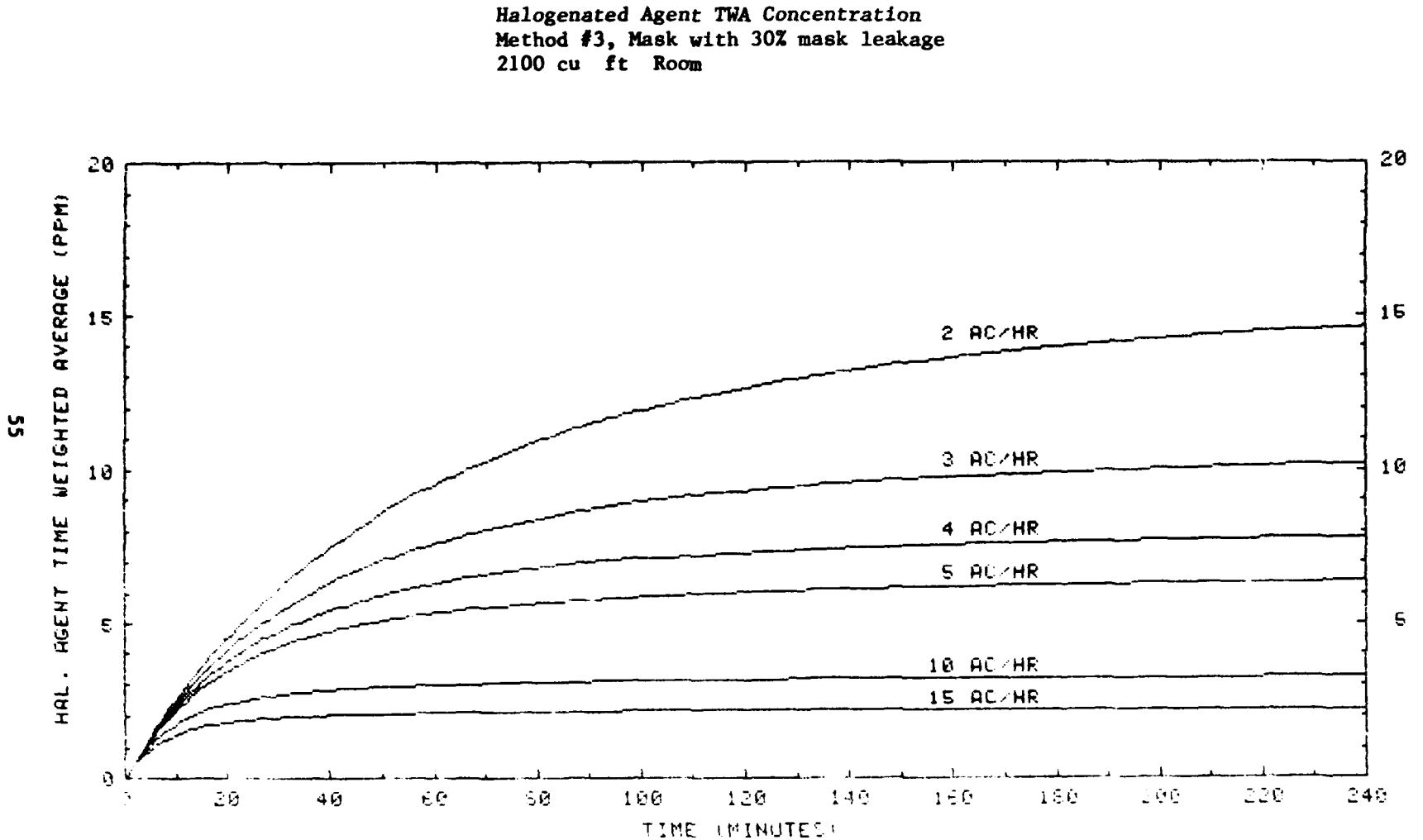


Figure 35. Halogenated Agent TWA Concentration vs Time, Method #3, 2100 cu ft room, 30% mask leakage.

Halogenated Agent TWA Concentration
Method #1, Mask and Intubation
Without Shut-off Valve
4655 cu ft Room

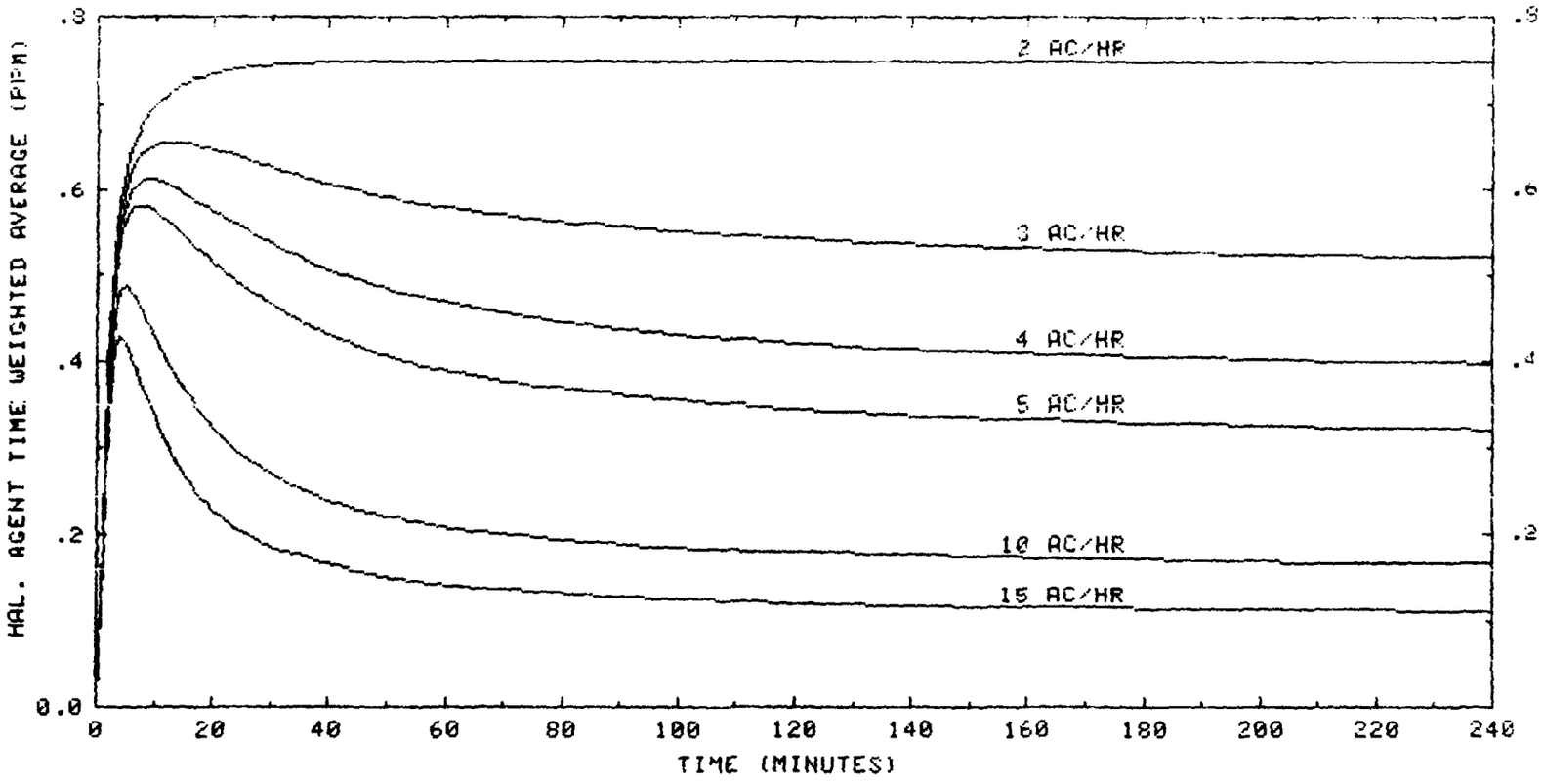


Figure 36. Halogenated Agent TWA Concentration vs Time, Method #1, 4655 cu ft room.

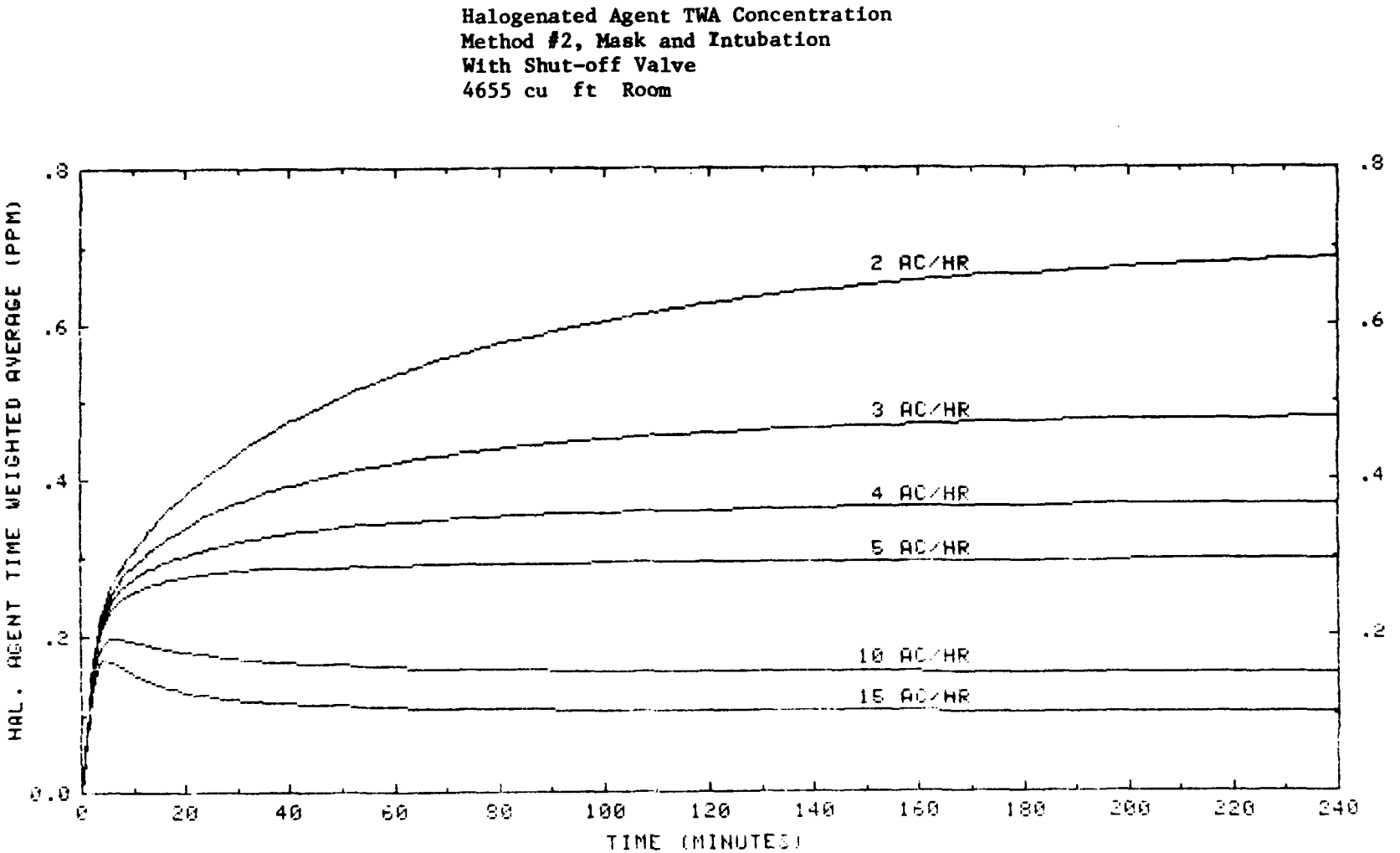


Figure 37. Halogenated Agent TWA Concentration vs Time, Method #2, 4655 cu ft room.

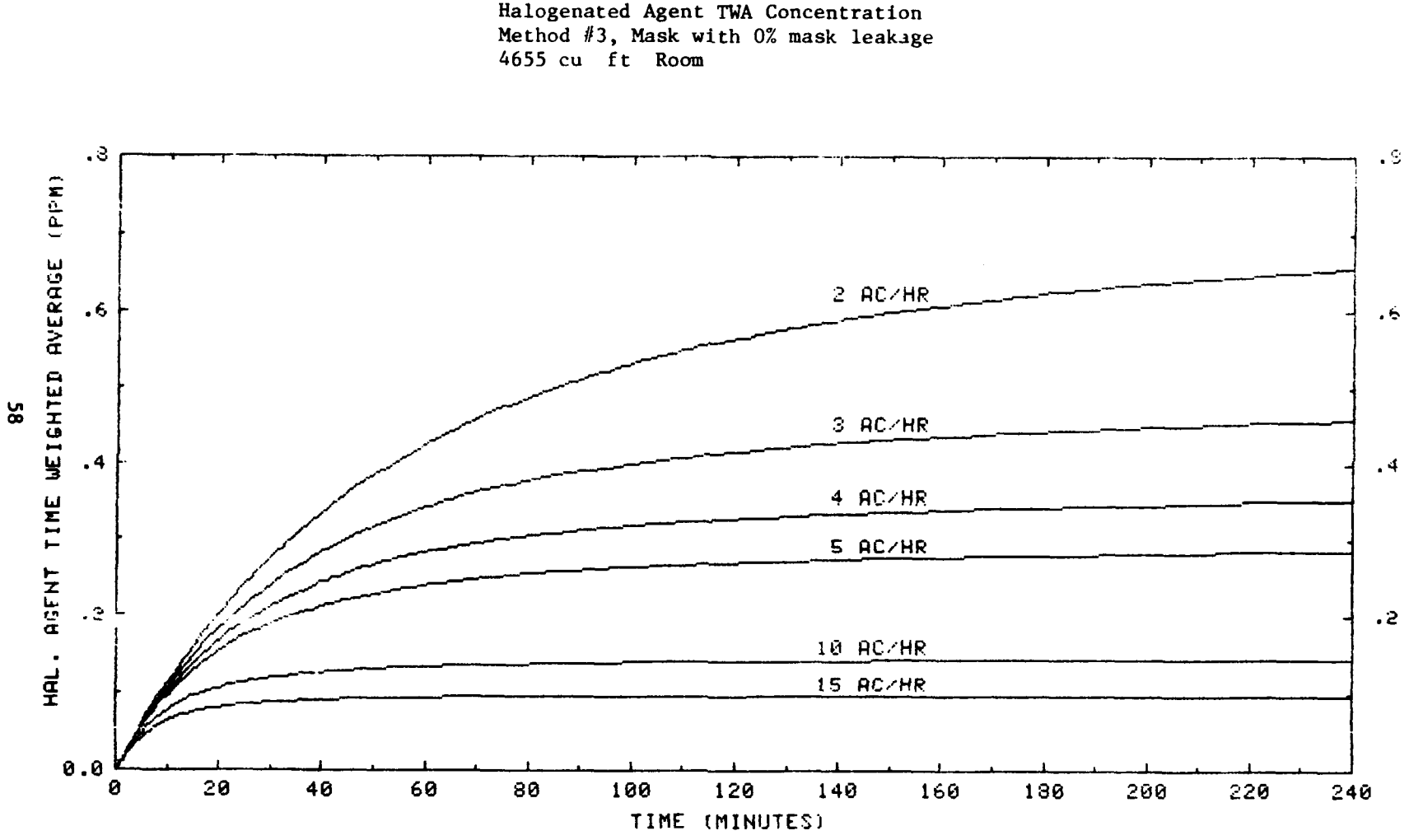


Figure 38. Halogenated Agent TWA Concentration vs Time, Method #3, 4655 cu ft room, 0% mask leakage.

Halogenated Agent TWA Concentration
Method #3, Mask with 15% mask leakage
4655 cu ft Room

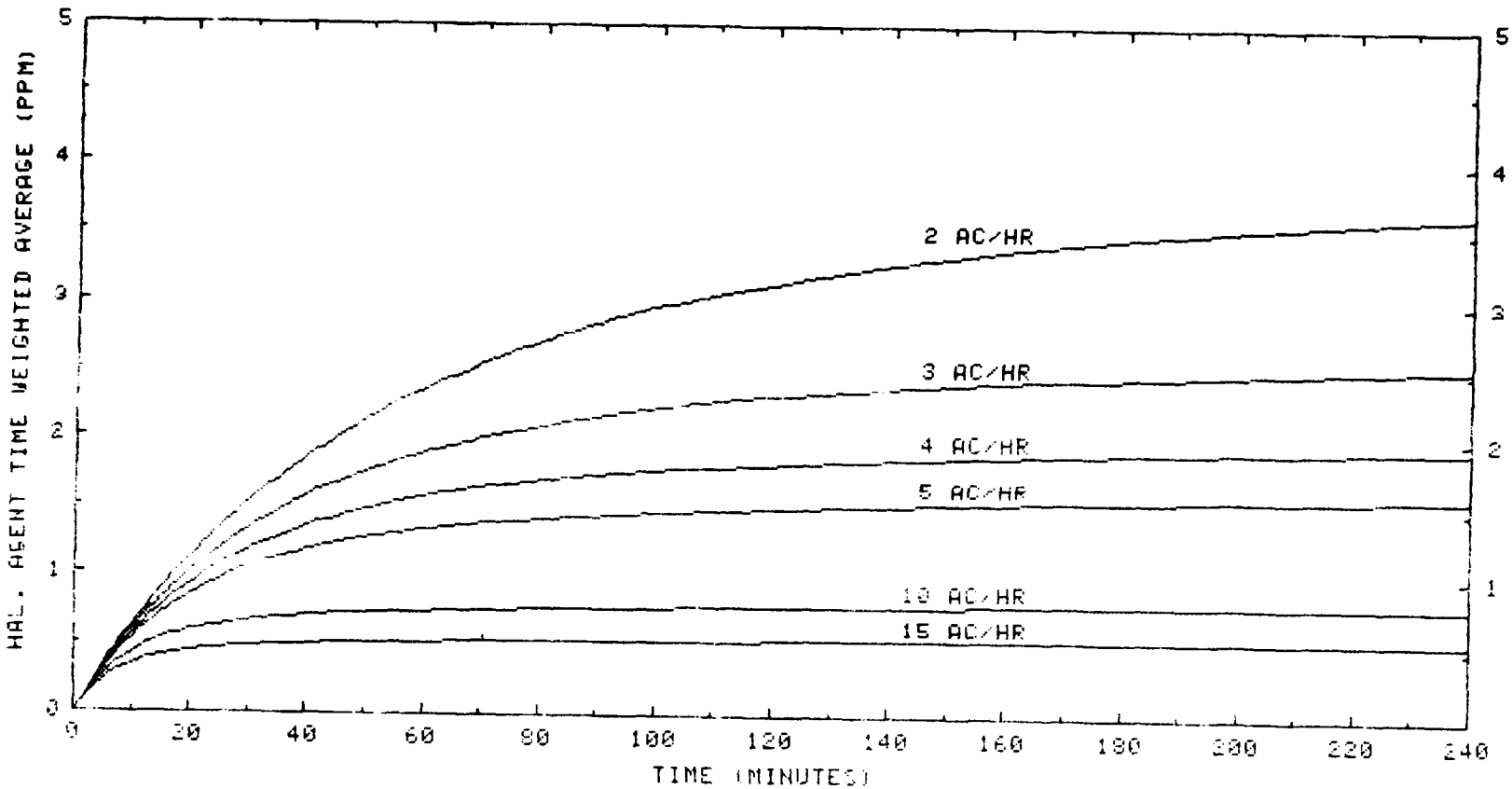


Figure 39. Halogenated Agent TWA Concentration vs Time, Method #3, 4655 cu ft room, 15% mask leakage.

Halogenated Agent TWA Concentration
Method #3, Mask with 30% mask leakage
4655 cu ft Room

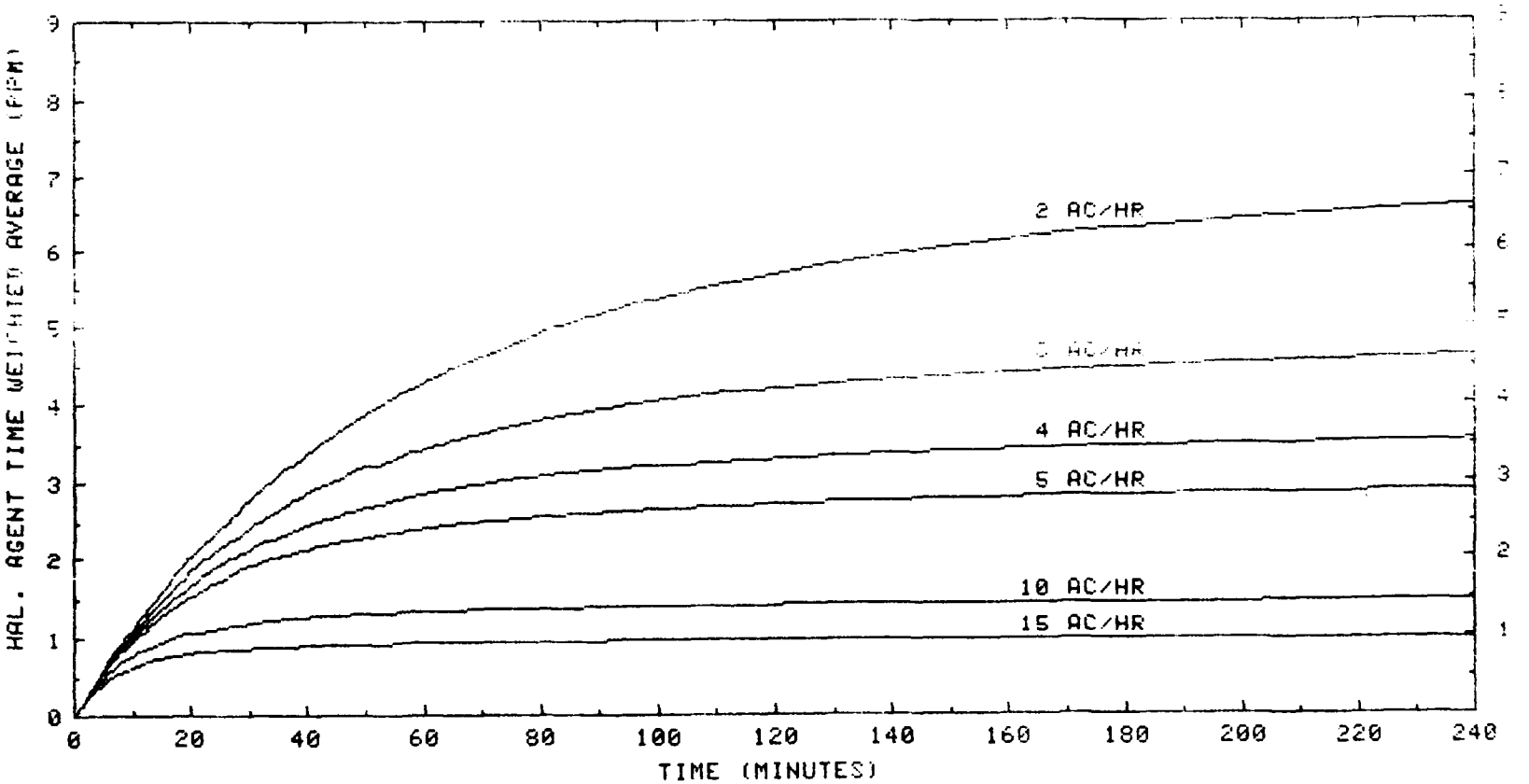


Figure 40. Halogenated Agent TWA Concentration vs Time, Method #3, 4655 cu ft room, 30% mask leakage.

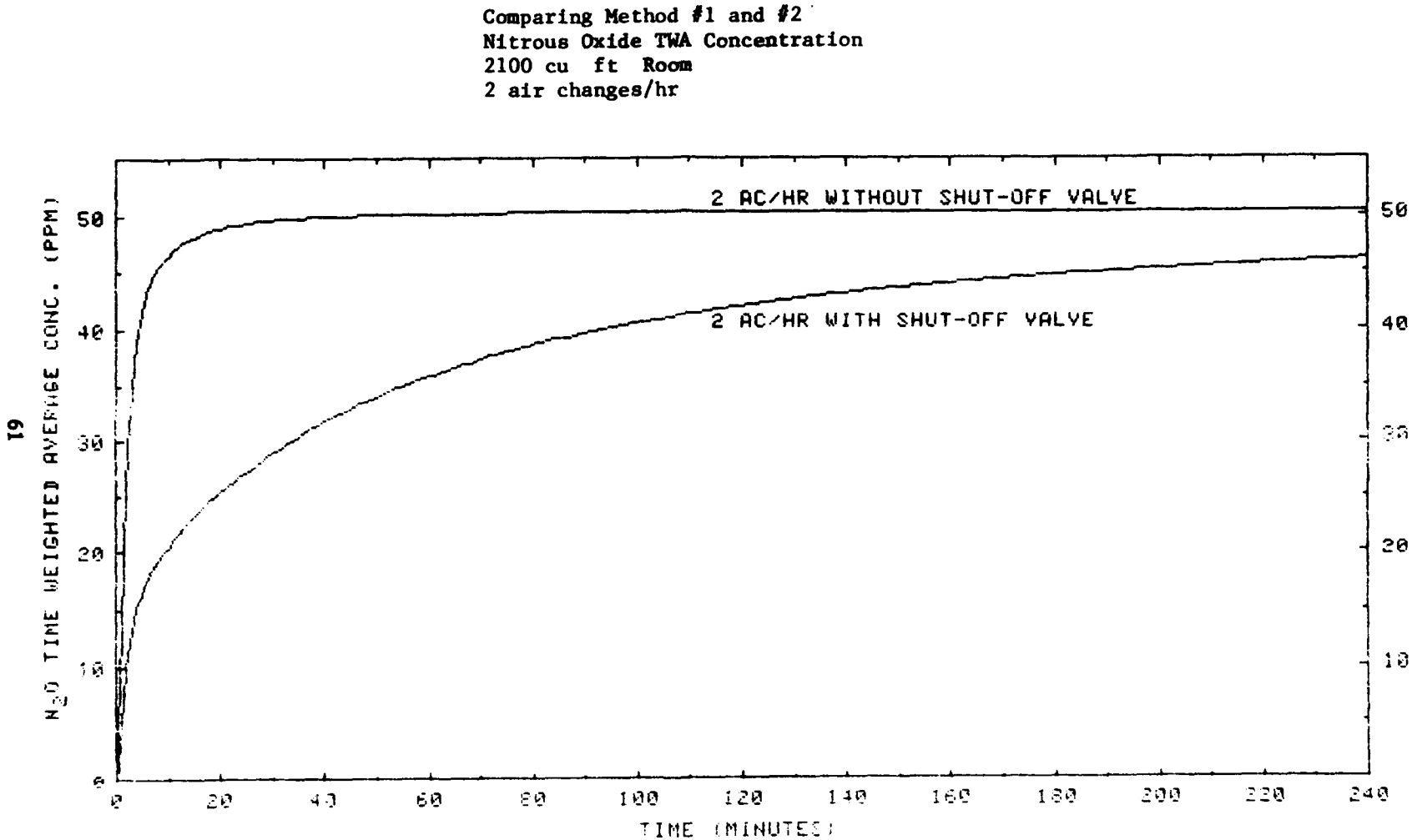


Figure 41. Graph comparing Method #1 and #2, Nitrous Oxide TWA Concentration vs Time, 2 air changes/hr, 2100 cu ft room.

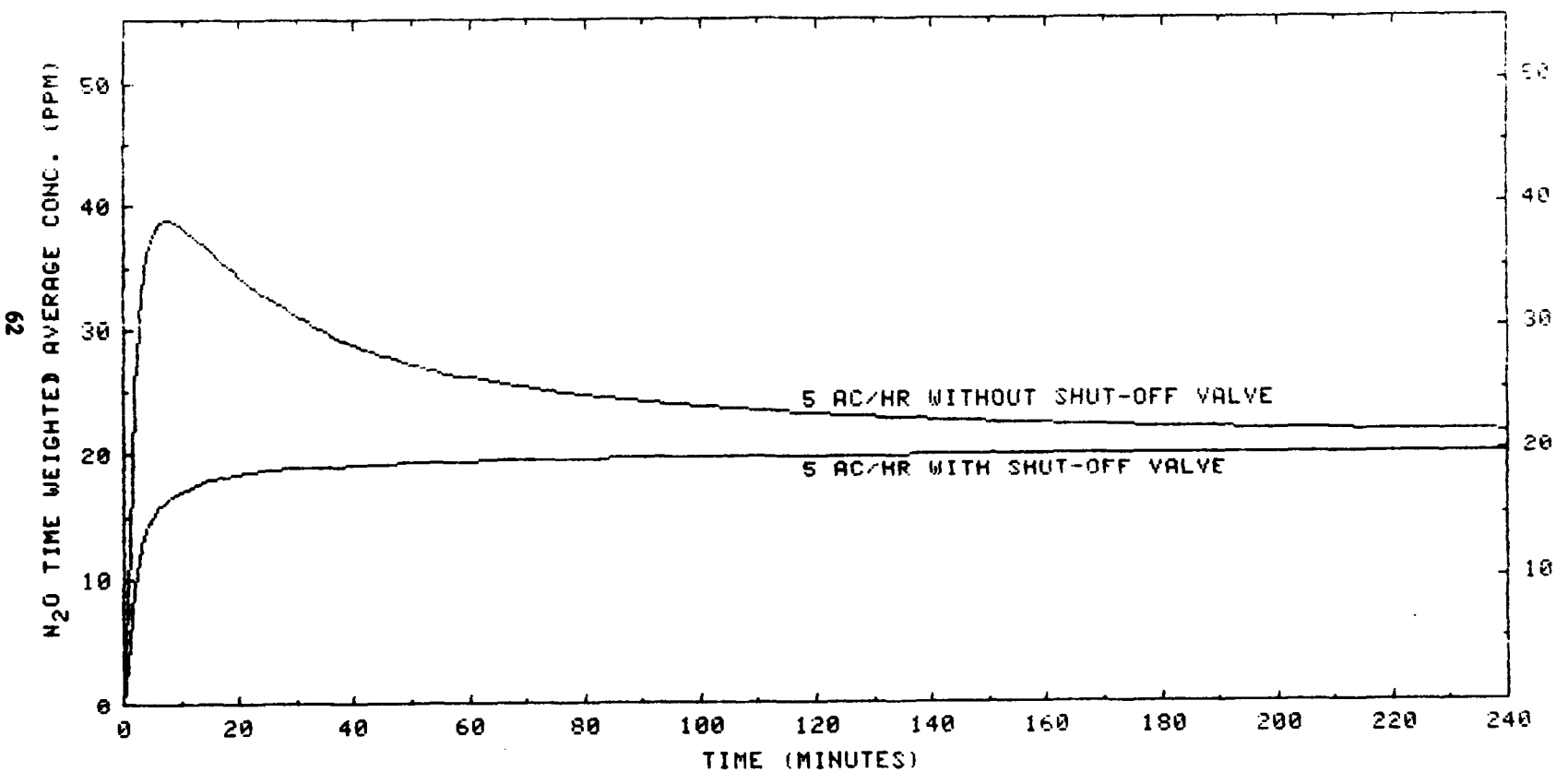


Figure 42. Graph comparing Method #1 and #2, Nitrous Oxide TWA Concentration vs Time, 5 air changes/hr, 2100 cu ft room.

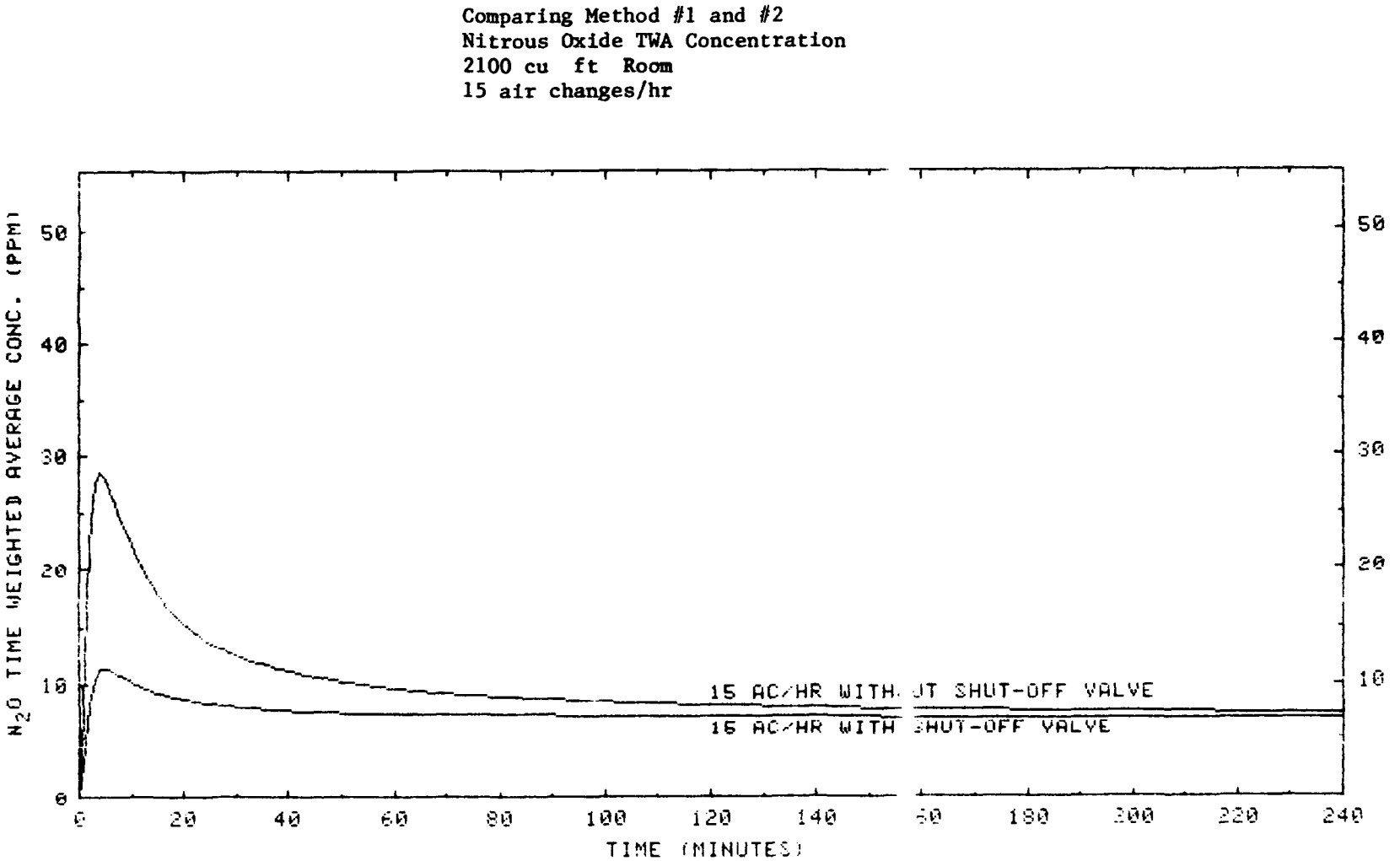


Figure 43. Graph comparing Method #1 and #2, Nitrous Oxide TWA Concentration vs Time, 15 air changes/hr, 2100 cu ft room.

Multiple Surgical Procedures
Method #1
Nitrous Oxide Instantaneous Concentration
2100 cu ft Room

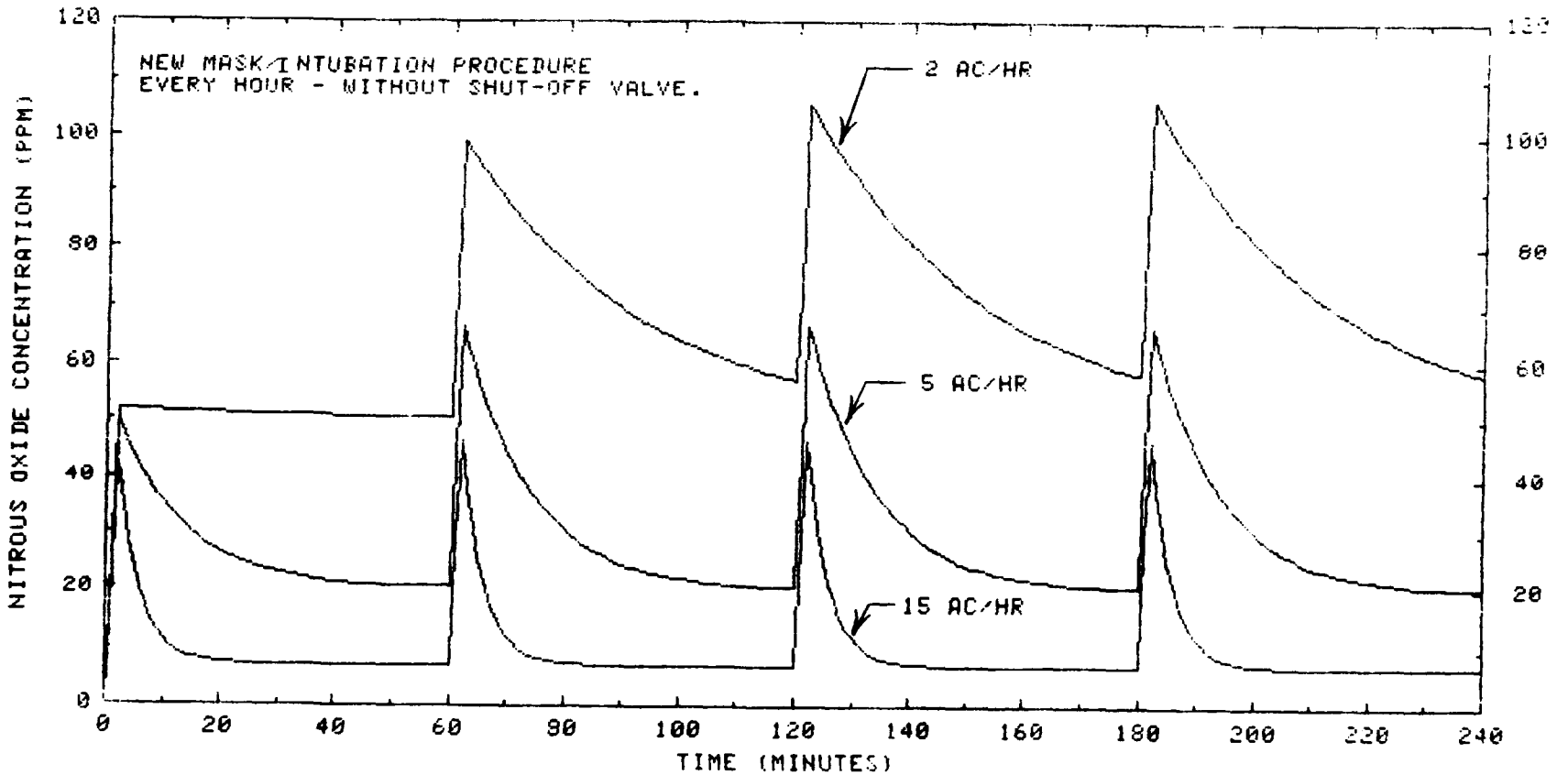


Figure 44. Multiple Surgical Procedures, Nitrous Oxide Concentration vs Time, Method #1, 2100 cu ft room, 2, 5, and 15 AC/Hr.

Multiple Surgical Procedures
Method #2
Nitrous Oxide Instantaneous Concentr. tion
2100 cu ft Room

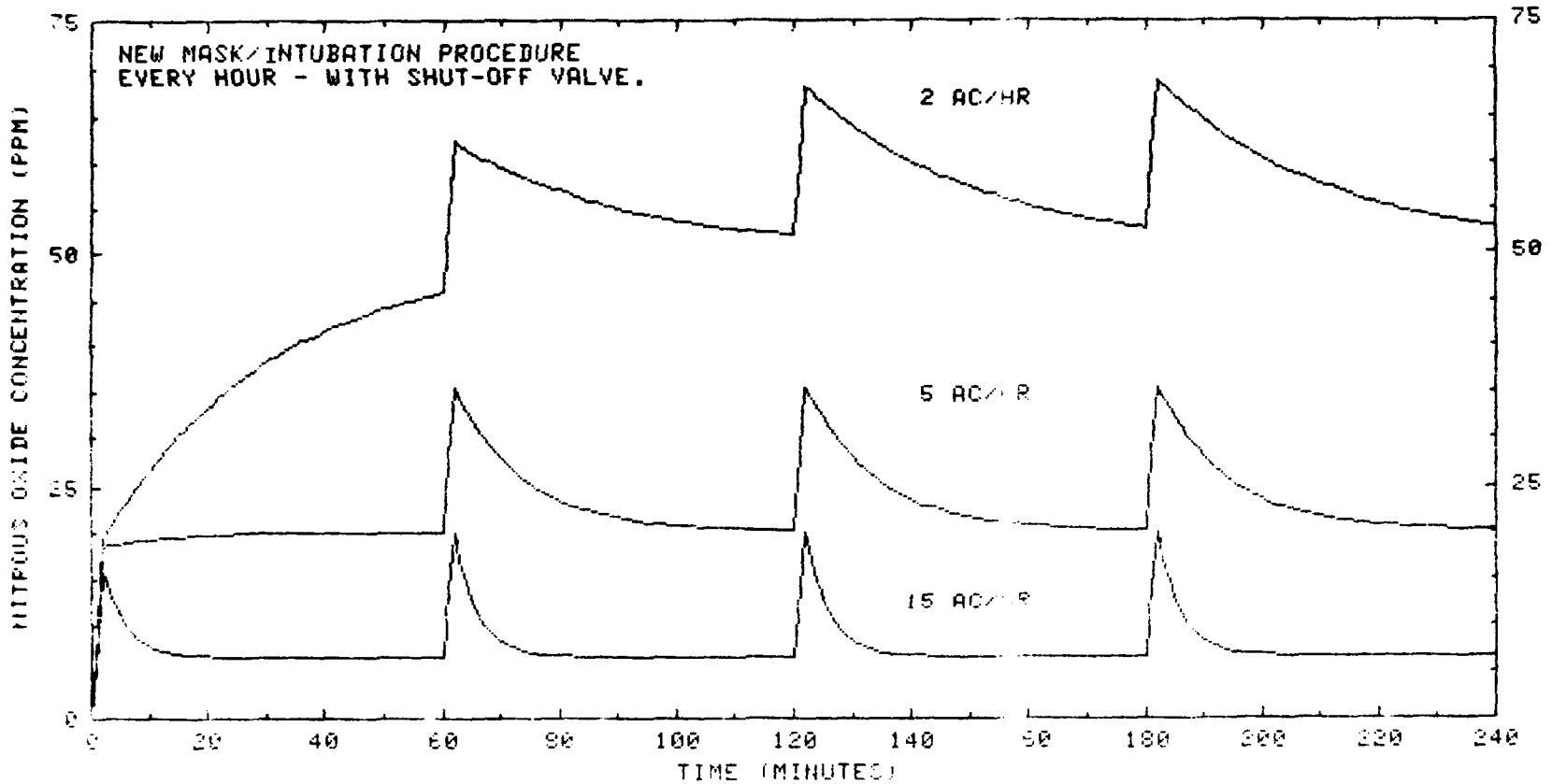


Figure 45. Multiple Surgical Procedures, Nitrous Oxide Concentra on vs Time, Method #2, 2100 cu ft room, 2, 5, and 15 AC/Hr.

Multiple Surgical Procedures
Comparing Method #1 and #2
Nitrous Oxide TWA Concentration
2100 cu ft Room
2 air changes/hr

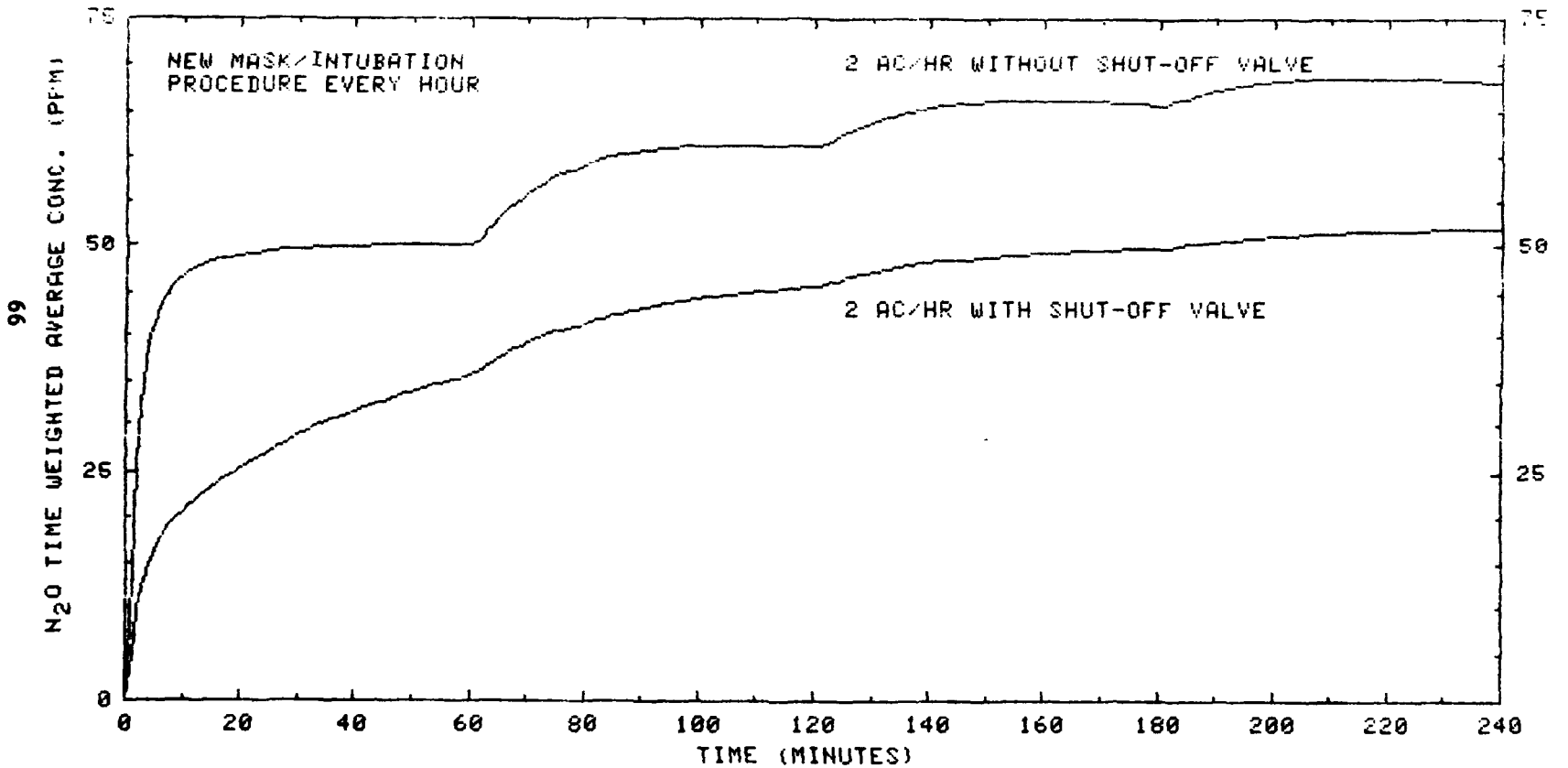


Figure 46. Multiple Surgical Procedures, Graph comparing Method #1 and #2, Nitrous Oxide TWA Concentration vs Time, 2 AC/Hr.

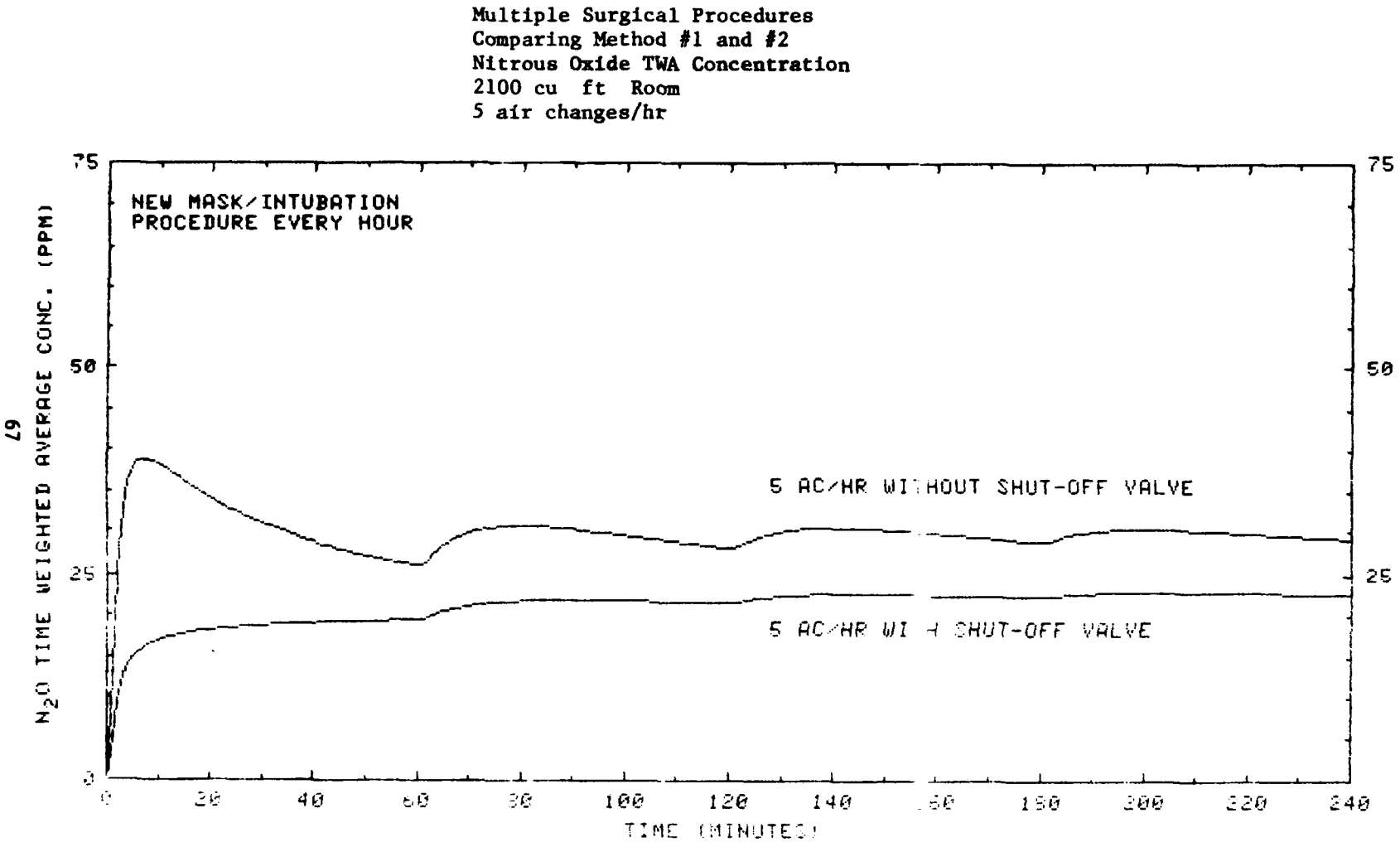


Figure 47. Multiple Surgical Procedures, Graph comparing Method #1 and #2, Nitrous Oxide TWA Concentration vs Time, 5 AC/Hr.

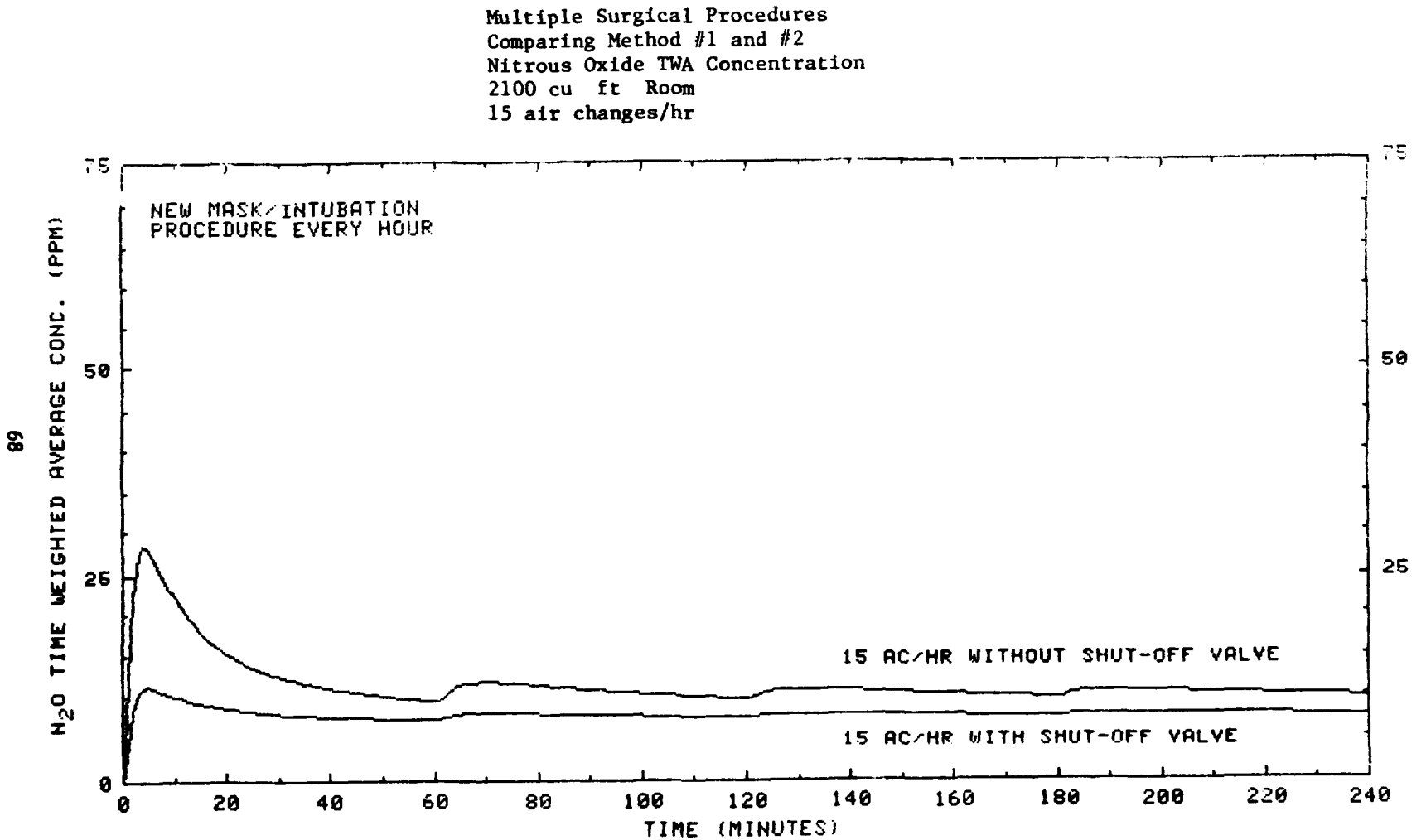
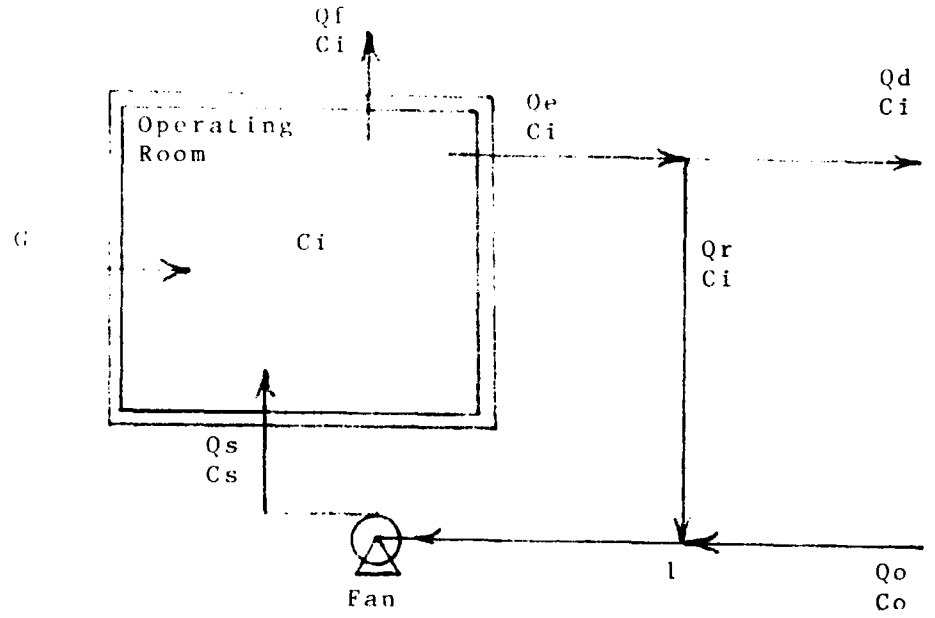


Figure 48. Multiple Surgical Procedures, Graph comparing Method #1 and #2, Nitrous Oxide TWA Concentration vs Time, 15 AC/Hr.

APPENDIX B

Mathematical Model

Mathematical model to predict anesthesia gas/vapor concentration in the operating room.



Where: Qo = Airflow from outdoors (CFM).

Qs = Airflow of the supply grille entering the operating room (CFM).

Qf = Airflow that escapes from the room via cracks, doors, etc. (CFM).

Qe = Airflow that departs the room via the exhaust grille(s) (CFM).

Qd = Airflow that is discharged from the building (CFM).

Qr = Airflow that is recirculated (CFM).

G = Vapor and gas generation rate (leakage) (CFM).

Co = Concentration of anesthetic gas/vapor in the outdoor air (ppm).

Cs = Concentration of anesthetic gas/vapor in the air entering the room (ppm).

Ci = Concentration of anesthetic gas/vapor in the room, exhaust, recirculated, and discharge airstreams (ppm).

Step A. Perform a material balance around point #1 on the schematic diagram.

$$(Qr * Ci) + (Qo * Co) = Qs * Cs \qquad \text{Eqn \#1}$$

Since the outdoor air is assumed to be free of anesthetic gas/vapor, Co = 0.

Therefore, Eqn #1 becomes: $Qr * Ci = Qs * Cs$

$$Cs = (Qr * Ci)/Qs \qquad \text{Eqn \#2}$$

Step B. Perform a material balance around the entire operating room.

$$\frac{VdCi}{dt} = G + (Qs*Cs) - (Qe*Ci) - (Qf*Ci) \qquad \text{Eqn \#3}$$

Use Eqn #2 for the term "Cs" in Eqn #3. Eqn #3 then becomes:

$$\frac{VdCi}{dt} = G + (Qs*(Qr*Ci/Qs)) - (Qe*Ci) - (Qf*Ci)$$

$$= G + (Qr*Ci) - (Qe*Ci) - (Qf*Ci)$$

Combining terms:

$$\frac{VdCi}{dt} = G + (Qr - Qe - Qf)*Ci \qquad \text{Eqn \#4}$$

To simplify the solution of Eqn #4,

Let $Qp = (Qr - Qe - Qf)$

Equation #4 then becomes:

$$\frac{VdCi}{dt} = G + Qp*Ci \qquad \text{Eqn \#5}$$

Solving Eqn #5:

$$\frac{dCi}{G+Qp*Ci} = \frac{1}{V}\,dt \qquad \text{Eqn \#6}$$

Integrating the left side of the equation #6:

let $u = G + Qp*Ci$

$du = Qp\ dCi$

$$\frac{du}{u} = \ln u$$

$$\int \frac{dCi}{G+Qp*Ci} \qquad \frac{1}{Qp}\int \frac{Qp\ dCi}{G+Qp*Ci} = \frac{1}{Qp}\int \frac{du}{u} = \frac{1}{Qp} * \ln u \Big|_{C1}^{C2}$$

$$= \frac{1}{Qp} * \ln (G+Qp*Ci) \Big|_{C1}^{C2}$$

$$= \frac{1}{Qp} * \ln \frac{(G+Qp*C2)}{(G+Qp*C1)}$$

Integrating the right side of the equation #6:

$$\int \frac{1}{V}\, dt = \frac{1}{V} * t \Big|_{T1}^{T2} = \frac{1}{V} * (T2-T1)$$

Combining the results of both integrations:

$$\frac{1}{Qp} * \ln \frac{(G+Qp*C2)}{(G+Qp*C1)} = \frac{1}{V} * (T2-T1)$$

$$\ln \frac{(G+Qp*C2)}{(G+Qp*C1)} = \frac{Qp}{V} * (T2-T1)$$

Solving in terms of C2,

$$C2 = (e^{(Qp*(T2-T1)/V)} * (G+Qp*C1) - G) / Qp \qquad \text{Eqn \#7}$$

where: $Qp = (Qr - Qe - Qf)$

$$Qp = (Qr - (Qe+Qf)) \qquad \text{Eqn \#8}$$

Step C. Perform a volumetric flow balance around the entire operating room.

$$(Qe + Qf) = (Qs + G) \qquad \text{Eqn \#9}$$

Equation #9 can be substituted into Equation #8 so that,

$$Qp = Qr - (Qs + G) \qquad \text{Eqn \#10}$$

Step D. Perform a volumetric flow balance around point #1 on the schematic diagram.

$$Qs = Qr + Qo$$

$$Qr = Qs - Qo \qquad \text{Eqn \#11}$$

Substitute Equation #11 into Equation #10

$$Qp = ((Qs - Qo) - (Qs + G))$$

$$= Qs - Qo - Qs - G$$

$$Qp = - Qo - G \qquad \text{Eqn \#12}$$

Step E. Use Eqn #7 and #12 to solve for concentration C2 as a function of time.

V = Room volume (cubic feet)
G = Rates obtained from Table 1 (L/min)

$$Qo = \frac{\text{Room Volume * Fresh air changes/hr}}{\text{60 minutes/hr}} \quad \text{(cfm)}$$

C2 = Concentration at time T2 (ppm)
C1 = Concentration at time T1 (ppm)
T2 = Final time (minutes)
T1 = Initial time (minutes)

APPENDIX C

FORTRAN COMPUTER PROGRAM TO PREDICT INSTANTANEOUS CONCENTRATIONS

Appendix C

The following FORTRAN computer program was used to compute the instantaneous concentrations illustrated in Figures 1 to 20.

```
FTN7X
      PROGRAM RPT
      DIMENSION T(610), C2(610), A(610), TWA(610)
C
C     Input the fresh ac/hr (FAC).
C
    1 WRITE(1,2)
    2 FORMAT(1,"FRESH AC/HR =")
    3 READ(1,*)FAC
C
C     The Total Air Change/Hr (TAC) does not affect the
C     computation.  The value later drops out of the equation.
C     (Refer to Eqns #11 and #12 in Appendix B to see how the
C     value "QS" (the total air flow entering the room)
C     drops out of the equation).  For clarity, the TAC rate
C     is kept in this program.  The TAC was selected as
C     equal to the Fresh Air Change/Hr (FAC) rate.  However,
C     any other value for the TAC would have worked equally
C     as well.
C
    4 TAC=FAC
C
C     The initial concentration (RC) is 0 ppm.
C
    5 RC=0.
C
C     Input the room volume (RV).
C
    6 WRITE(1,7)
    7 FORMAT(1,"ROOM VOLUME IN CUBIC FEET=")
    8 READ(1,*)RV
C
C     Input the first value of "G".  See Table 1 in
C     Appendix A.
C
    9 WRITE(1,10)
   10 FORMAT(1,"FIRST G VALUE IN L/MIN=")
   11 READ(1,*) GV1
C
C     Convert liters/min to cubic feet/min.
C
   12 G1=GV1*.0351851
C
```

```
C     Input the second value of "G".  See Table 1 in Appendix A.
C     If the anesthesia administration method is Method #1 or
C     #2, the second value of "G" will differ from the first
C     value.  If Method #3 is used, the second value of "G" is the
C     same as the first value of "G".
C
   13 WRITE(1,14)
   14 FORMAT(1,"SECOND G VALUE IN L/MIN=")
   15 READ(1,*) GV2
C
C     Convert liters/min to cubic feet/min.
C
   16 G2=GV2*.0351851
C
C     Change supply (QS) and outdoor (QO) air changes/hr to CFM.
C
   17 QS=RV*TAC/60.
   18 QO=RV*FAC/60.
C
C     Q recirculated is equal to Q supply minus Q outdoors.
C
   19 QR=QS-QO
C
C     Q prime (QP) is used beginning after Eqn #4 in
C     Appendix B to simplify the equation.
C
   20 QP=QR-(QS+G)
C
C     Compute the concentration (C2) at times (T) equal to 0,
C     1, and 2 minutes.
C
   21 DO 26 Y=0,2
   22 T(Y)=Y
   23 C2(Y)=((2.718**(QP*T(Y)/RV)*(G1+QP*RC)-G1)/QP)*1000000.
C
C     Print out the data (time and concentration).
C
   24 WRITE(1,25) T(Y),C2(Y)
   25 FORMAT(1,F10.1,F10.3)
   26 CONTINUE
C
C     The value of RC used for T>2 minutes is the value
C     of C2 at T = 2 minutes.
C
   27 RC=C2(2)/1000000.
C
C     Compute the concentration (C2) at times (T) equal to 3,
C     4, 5, ..., 239, and 240 minutes.
C
   28 DO 34 Y=3,240
C
```

```
C     The second equation (line 30) is "shifted" in real time
C     by 2 minutes.  Time = 0 is really 2 minutes after the
C     procedure has begun.  Therefore, 2 minutes is
C     subtracted from T(Y) so that T(3) = 1, T(4) = 2, etc.
C
   29 T(Y)=Y-2.
   30 C2(Y)=((2.718**(QP*T(Y)/RV)*(G2+QP*RC)-G2)/QP)*1000000.
C
C     To print the "correct" Time (T), 2 minutes are added to
C     the time used in the equation of line 30.
C
   31 T(Y)=T(Y)+2.
C
C     Print out the data (time and concentration).
C
   32 WRITE(1,33) T(Y), C2(Y)
   33 FORMAT(1,F10.1,F10.3)
   34 CONTINUE
   35 STOP
      END
```

APPENDIX D

FORTRAN COMPUTER PROGRAM TO PREDICT TWA CONCENTRATIONS

Appendix D

The following FORTRAN computer program was used to compute the Time Weighted Average (TWA) concentrations illustrated in Figures 21 to 40.

```
FTN7X
      PROGRAM TWA
      DIMENSION T(610), C2(610), A(610), TWA(610)
C
C     Input the fresh ac/hr (FAC).
C
    1 WRITE(1,2)
    2 FORMAT(1,"FRESH AC/HR =")
    3 READ(1,*)FAC
C
C     The Total Air Change/Hr (TAC) does not affect the
C     computation.  The value later drops out of the equation.
C     (Refer to Eqns #11 and #12 in Appendix B to see how the
C     value "QS" (the total air flow entering the room)
C     drops out of the equation).  For clarity, the TAC rate
C     is kept in this program.  The TAC was selected as
C     equal to the Fresh Air Change/Hr (FAC) rate.  However,
C     any other value for the TAC would have worked equally
C     as well.
C
    4 TAC=FAC
C
C     The initial concentration (RC) is 0 ppm.
C
    5 RC=0.
C
C     Input the room volume (RV).

    6 WRITE(1,7)
    7 FORMAT(1,"ROOM VOLUME IN CUBIC FEET=")
    8 READ(1,*)RV
C
C     Input the first value of "G".  See Table 1 in
C     Appendix A.
C
    9 WRITE(1,10)
   10 FORMAT(1,"FIRST G VALUE IN L/MIN=")
   11 READ(1,*) GV1
C
C     Convert liters/min to cubic feet/min.
C
   12 G1=GV1*.0351851
C
```

```
C     Input the second value of "G".  See Table 1 in Appendix A.
C     If the anesthesia administration method is Method #1 or
C     #2, the second value of "G" will differ from the first
C     value.  If Method #3 is used, the second value of "G" is the
C     same as the first value of "G".
C
   13 WRITE(1,14)
   14 FORMAT(1,"SECOND G VALUE IN L/MIN=")
   15 READ(1,*) GV2
C
C     Convert liters/min to cubic feet/min.
C
   16 G2=GV2*.0351851
C
C     Change supply (QS) and outdoor (QO) air changes/hr to CFM.
C
   17 QS=RV*TAC/60.
   18 QO=RV*FAC/60.
C
C     Q recirculated is equal to Q supply minus Q outdoors.
C
   19 QR=QS-QO
C
C     Q prime (QP) is used beginning after Eqn #4 in
C     Appendix B to simplify the equation.
C
   20 QP=QR-(QS+G)
C
C     Compute the concentration (C2) at times (T) equal to 0,
C     1, and 2 minutes.
C
   21 DO 24 Y=0,2
   22 T(Y)=Y
   23 C2(Y)=((2.718**(QP*T(Y)/RV)*(G1+QP*RC)-G1)/QP)*1000000.
   24 CONTINUE
C
C     The value of RC used for T>2 minutes is the value
C     of C2 at T = 2 minutes.
C
   25 RC=C2(2)/1000000.
C
C     Compute the concentration (C2) at times (T) equal to 3,
C     4, 5, ..., 239, and 240 minutes.
C
   26 DO 30 Y=3,240
C
C     The second equation (line 28) is "shifted" in real time
C     by 2 minutes.  Time = 0 is really 2 minutes after the
C     procedure has begun.  Therefore, 2 minutes is
C     subtracted from T(Y) so that T(3) = 1, T(4) = 2, etc.
C
```

```
   27 T(Y)=Y-2.
   28 C2(Y)=((2.718**(QP*T(Y)/RV)*(G2+QP*RC)-G2)/QP)*1000000.
C
C     To print the "correct" Time (T), 2 minutes are added to
C     the time used in the equation of line 30.
C
   29 T(Y)=T(Y)+2.
   30 CONTINUE
C
C     Compute the area (A(Y)) under the curve for each time
C     increment (T(Y)-T(Y-1)).  A(Y) is the sum of an area of a
C     triangle and the area of a rectangle.  "AMIN1" is the
C     command to use the lesser of C2(Y) and C2(Y-1).  "ABS"
C     is the command to use the absolute value of C2(Y)-C2(Y-1).
C
   31 DO 33 Y=1,240
   32 A(Y)=ABS(C2(Y)-C2(Y-1))*(T(Y)-T(Y-1))/2+(AMIN1(C2(Y),
     1C2(Y-1)))*(T(Y)-T(Y-1))
   33 CONTINUE
C
C     Begin to add up each area under the curve segment.
C
   34 SUM=0.0
   35 DO 38 Y=1,240
   36 SUM=SUM+A(Y)
   37 TWA(Y)=SUM/T(Y)
   38 CONTINUE
   39 DO 42 Y=1,240
C
C     Print out the data (time and TWA)
C
   40 WRITE(1,41) T(Y), TWA(Y)
   41 FORMAT(1,F10.1,F10.3)
   42 CONTINUE
      STOP
      END
```