NATIONAL BUREAU OF STANDARDS REPORT

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VENTILATION MEASUREMENTS
(Project No. ME-14)

by

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U. S. DEPARTMENT OF COMMERCE
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to

Office of the Administrator
Housing and Home Finance Agency
Washington, D. C.

ABSTRACT

A study was made at the National Bureau of Standards of the methodsfor measuring the infiltration of air into buildings and the natural ventilation of crawl spaces and attics. This research was performed under an agreement with the Office of the Administrator, Housing and Home Finance Agency, authorized under Title III of the Housing Act of 1948, as amended, and was identified as Project No. 1950-ME-14 "Ventilation Measurement".

It was found that several tracer gas methods are available for infiltration measurement and that these methods are probably more accurate and better adapted to field use than calorimetric methods or direct air flow measurements. The more promising tracer gas methods are believed to be (a) helium gas with a katharometer, (b) ethane gas with an interferometer, (c) methane gas with an infrared gas analyzer. The use of either a radioactive gas with an electrometer or a halogenated hydrocarbon gas with a halide photometer is believed to be potentially practical but these methods involve some hazard to the personnel using them.

The heated thermocouple anemometer was found to be better suited to the measurement of very low air velocities in ducts and rooms such as those associated with natural ventilation of crawl spaces and attics than any other known instrument. A heated thermocouple anemometer and a portable helium katharometer developed at the National Bureau of Standards are described and their performance illustrated. Studies were made to determine the accuracy and lag of a commercially-made helium analyzer in measuring the absolute helium content in air and to determine the effects of pressure and sampling rate on the performance of the instrument. Infiltration measurements made simultaneously with the portable helium katharometer developed at the National Bureau of Standards and a commercially-made katharometer differed by amounts ranging from 0 to 4 percent.

A detailed study of the air exchange between the various parts of an experimental house and the outside as affected by temperature differences revealed that there was two-way flow between the basement and outside and between the living space and outside and one-way flow from attic to outside. In addition there was air movement from basement to living space, from basement to attic, and from living space to attic. All of these air exchanges were interdependent and most of them tended to increase as the indoor-outdoor temperature difference increased. This experimental house was enclosed in a larger structure and was not exposed to natural wind.

Some data are reported on the natural ventilation of a basement through foundation openings and by means of a vertical stack reaching from the basement through the roof.

This investigation reveals broad possibilities for further study of air movement into buildings and through buildings which would probably lead to revised construction for the purpose of better control of the air flow, vapor flow, and heat loss of dwellings and other structures.

I. INTRODUCTION

The computation of the heat loss of a building usually includes an item for the heat carried out of the building as a result of the infiltration of cold air. The computation of the infiltration heat loss is generally based on the length of crack around windows and doors, an estimate of the workmanship involved, and a design wind velocity or it is based on a more general estimate of the number of complete air changes that will occur in the building per hour under design weather conditions. These methods are known to be approximations, but they have received wide usage because accurate measurements of the air leakage for different kinds of structures are not available. Unknown heat losses such as that for infiltration have caused engineers to resort to the use of safety factors in the selection of heating plant capacity.

Little is known about the actual infiltration rates in existing buildings or how well the actual values compare with the values computed by the previously mentioned methods because there has been no generally accepted method of proved accuracy for measuring the infiltration rate in buildings.

The ventilation of attics and crawl spaces has likewise been based on empirical rules developed by trial and error and improved by experience because the amount of ventilation provided by any given arrangement could not readily be determined.

Attic and crawl space construction could be better protected against condensation and deterioration if ventilation rates could be more accurately evaluated for different arrangements of louvers, openings, etc. Greater precision in selecting heating equipment for houses could be attained if infiltration rates were accurately known and there would be a probable saving of materials and fuels and a greater assurance of comfort for the owner.

The present project was established to investigate various methods of measuring infiltration in buildings and to study methods for measuring the natural ventilation occurring in attics and crawl spaces with certain duct and louver arrangements. The course of the investigation was guided by the availabilities of suitable instruments for the measurements that were to be made and by the results that were observed as the investigation progressed. The kathometer used for the major portion of the infiltration measurements was loaned to the National Bureau of Standards by the American Society of Heating and Ventilating Engineers. Early investigation also showed that precise measurements of crawl space ventilation could not be made until an instrument for measurement of very low air velocities was available so a heated thermocouple anemometer was designed and constructed.

The work done under this project can be divided into five parts as follows:

1. Survey of Infiltration Measurement Methods

2. Infiltration Measurements with a Cambridge Katharometer and an Interferometer

3. Design of a Portable Katharometer

4. Measurements of Crawl Space Ventilation

5. Design and Calibration of a Heated-Thermocouple Anemometer

II. SURVEY OF INFILTRATION MEASUREMENT METHODS

The following nine methods for measuring infiltration rates were either tried or investigated sufficiently to evaluate their practicability:

a. Helium or hydrogen gas with a katharometer

b. Ethane gas with an interferometer

c. Radioactive tracer gas (ethane) with an electrometer

d. Hydrogen gas with RCA Detector tube

e. Hydrocarbon gas with an infrared gas analyzer

f. Hydrocarbon gas with a sensitive hygrometer to sense changes in the moisture content of samples after combustion of the hydrocarbon gas.

g. Halogenated hydrocarbon gas with a photometer.

h. Calorimetric determination based on the amount of additional heat required to heat the Test Bungalow with infiltration as compared to that required with no infiltration for equal temperature differences between indoors and outdoors.

i. Determination on an equivalent crack or orifice area by pressurizing the living space with an auxiliary blower and measuring the air flow and the pressure difference between indoors and outdoors.

The first two methods listed involving the use of a katharometer and an interferometer were tried and these methods will be discussed in detail later.

The use of a radioactive tracer gas[1] appeared to be practical, at first. Radioactive carbon has such a long half-life that it could be considered to be a constant source of electrons for the duration of tests such as these. Ethane gas with radioactive carbon molecules was obtainable through the Atomic Energy Commission; ethane having a density and diffusion rate closely approximating that of air. An electrometer with sufficient sensitivity to measure electron flow rates equivalent to 10^{-15} amperes was available as a recently-developed item of one manufacturer. However, calculation of the concentration of radioactive gas that would be required to produce a measurable current with this electrometer indicated that the radioactivity level would be higher than could be tolerated safety by human beings. Thus all of the observations would have to be made by remote control and the test space would remain contaminated for some time after any given test. This method might prove to be a practical one, however, if an instrument were developed that would measure lower current levels than presently available electrometers are designed for so the test space could safely be occupied by the observers.

A hydrogen detector tube with a paladium window for the detection of hydrogen gas in air was investigated for its usefulness in infiltration studies. It was found, however, that this detector apparatus was designed primarily to detect and locate leaks in vacuum tubes using hydrogen gas, and does not provide a quantitative measurement of the tracer gas.

A commercially made gas analyzer is available for the detection and measurement of carbon dioxide, carbon monoxide, methane, or other hydrocarbon gases in air based on the principle of the absorption of energy in the infrared region by these gases. The instrument uses a source of infrared energy, reflecting mirrors, sampling cells, and two bolometers as two elements in a Wheatstone bridge circuit. The amount of infrared energy absorbed from the original beam is a measure of the concentration of the tracer gas in the sample. The instrument is equipped with a recorder and is used for control and recording of gas concentration in various industrial processes.

It can be made sensitive to concentrations of less than one percent for full scale deflection and provides a printed record of the change in concentration of tracer gas with time. The analyzer is a self-contained cabinet-type unit equipped with a sampling system suited to the application. It appears to be well-suited to the purpose of infiltration measurements except for its high original cost; the selling price being approximately four thousand dollars.

A film of phosphoric acid[2] or sulfuric acid is sensitive to small changes in the water vapor content of air or other gases. The relative humidity of air can be measured by obtaining equal indications of moisture content for a sample of air with unknown moisture content and a sample of oxygen under pressure with known moisture content by passing them over a phosphoric acid film on a suitable electrode. This type of hygrometer could be used in conjunction with hydrogen or a hydrocarbon tracer gas for measuring infiltration rates. The mixture of air and tracer gas would be sampled and the tracer gas burned by means of a hot wire element after which the moisture content of the resulting gases could be determined by means of the phosphoric acid hygrometer. The concentration of tracer gas could be computed from the relative humidity data. Measurements of relative humidity of the air in the building would also have to be made without combustion of the tracer gas so corrections could be made in the results obtained from the combustion of the tracer gas. This method has some, but not all, of the disadvantages of using water vapor directly as the tracer gas in that most atmospheres have some water vapor in them; the exchange of water vapor between the materials in a building and the air inside the building probably seldom attains a steady state, and the presence of observers or other moisture-generating sources might disturb the water vapor content of any building under observation.

A portable instrument is commercially available to measure low concentrations of halogenated hydrocarbons in air. The principle of operation of this apparatus is as follows:

The intensity of the blue lines of the copper spectrum, produced in an electric arc between two electrodes, is continuously measured with an electric photometer using a blue sensitive phototube fitted with a blue glass color filter. Halide vapor coming in contact with the electrodes reacts to form a copper halide, which is carried into the arc. The intensity of the blue spectrum is proportional to the concentration of halide vapor present.

Although a full scale deflection of the indicating meter is said to be obtained at a concentration of less than 0.1% of carbon tetrachloride in air, the accuracy of the instrument is only ±10%. Because of its limited accuracy and the possible hazards to personnel working continuously in an atmosphere with halogenated compounds, this method of tracer gas detection was considered impractical.

The possibility of making a calorimetric measurement of the heat loss attributable to infiltration and from that a derived value of the quantity of air leakage was investigated. This method would involve the measurement of the heat required by the Test Bungalow for a given temperature difference with no infiltration and a comparative value of the heat loss under identical conditions except that infiltration would be permitted. It was proposed that the inside surface of the entire living space would be sprayed with one or more coats of vinal chloride acetate or polyethylene material that would reduce the air leakage and vapor transmission to a negligible value. These materials could be peeled off readily when the tests were completed without permanent damage to the interior finish of the structure.

While evaluation of the heat loss due to infiltration might be possible by this method the following practical difficulties indicated that it was not the most promising method:

(a) It would be difficult to seal all cracks and fissures in the structure especially those in the hollow studs space that permitted air leakage directly from the basement to the attic, but which removed heat from the living space by transmission through the wall surfaces.

(b) The method could not be applied to existing structures in the field.

(c) Since more heat would be required when infiltration did exist, it would be difficult, if not impossible, to attain the same temperature distribution in the building for the two cases. Consequently, a comparison of heat requirements for the two cases would probably not be devoid of all influences other than infiltration.

It had been postulated that an equivalent crack or orifice area could be established for any room or building by pressurizing the space with an auxiliary blower that would assure leakage in one direction through all the openings in the enclosing surfaces. By measuring the air delivery of the blower with a suitable orifice and determining the indoor-outdoor pressure difference with a sensitive micro-manometer an equivalent aggregate area of leakage could be computed from the orifice formula,

$$Q = KA\sqrt{\frac{h}{d}}$$

where Q = rate of air delivery by blower, cu ft/ min
h = indoor-outdoor pressure difference, in W.G.
d = density of air, lb/cu ft
A = equivalent area of all leaks, sq ft
K = combination of the orifice constant and several conversion factors for the system of units employed

However, it appears that no practical use could be made of the equivalent area A after evaluating it because the pressures causing flow through a building are a combination of wind pressure and chimney effects such that (a) the crack area serving as inlets and outlets for leakage would often be unequal (b) the neutral pressure zone in a building may shift up and down with outdoor temperature, and (c) the wind pressure causes primarily horizontal air motion through a building whereas the chimney effect produces primarily vertical movement of air through the building.

III. INFILTRATION MEASUREMENTS WITH A CAMBRIDGE KATHAROMETER AND AN INTERFEROMETER

A. Description of Ethane - Interferometer Method

Ethane has favorable characteristics as a tracer gas for air infiltration measurements because both its density and diffusion rate are very nearly equal to that of air. An interferometer provides a simple way to determine low concentrations of ethane in air.

An interferometer divides a beam of light into two or more parts that travel optical paths of different lengths and which are later recombined to form interference fringes. The optical length of path depends not only on the geometric length of path but also the refracture index of the materials through which the light beams pass. The dispersion of the interference fringes produced by passing two light beams through gases with different refractive indices can be measured by adjusting the relative angularity of identical plane-parallel plates of optical glass placed in the paths of the two beams to compensate for the dispersion. The changes in position of the optical plates can be used to evaluate the difference in refractive index of the two gases.

The instrument available at the National Bureau of Standards for making decay measurements with ethane gas was a portable interferometer with two 10 cm. chambers through which the air-ethane mixture in the room and the outside air could be passed. Because of the relatively short length of the chambers in this instrument the displacement of the fringes was small when comparing the refractive index of air and an air-ethane mixture containing less than 1 percent ethane. As a result only small adjustments of the optical plates were necessary for realigning the interference fringes and the accuracy was limited. A more elaborate instrument with longer chambers would have provided greater precision in measurement. The portable interferometer was used as a check method for comparison with the katharometer in studying infiltration of air in the north bedroom of the Test Bungalow.

B. Description of Helium Katharometer

The measurement of low concentrations of hydrogen or helium in air can be accomplished easily and with a high degree of accuracy by virtue of the difference in thermal conductivity[3] of these gases and that of air. The thermal conductivity of hydrogen is approximately 7 times that of air whereas the thermal conductivity of helium is about six times that of air. A tracer gas technique[4,5] for studying the infiltration of air in buildings was first described by Marley using a katharometer[6] (a thermal conductivity meter) to evaluate the concentration of the tracer gas in air. An instrument of this type manufactured by the Cambridge Instrument Company for use with helium as a tracer gas was purchased by the American Society of Heating and Ventilating Engineers and loaned to the National Bureau of Standards for studies of infiltration in the Test Bungalow. This instrument was equipped with three separate thermal conductivity cells so three samples of helium-air mixture could be drawn simultaneously for concentration determinations. A photograph of the Cambridge helium analyzer is shown in Fig. 1.

Each of these thermal conductivity cells contained two platinum wires that were heated by a constant electric current. The wires were installed in two cavities drilled in a single brass block so that their wall temperatures would always be equal. The wire temperature reaches a steady value when the heat generated by the electric current is equal to that dissipated by the wire to its surroundings. One cavity was closed at both ends and the tracer gas-air mixture to be analyzed was passed through the other cavity. Since the thermal conductivity of helium is roughly six times that of air, the wire in the sampler cavity was cooled more than the wire in the reference cavity. This cooling lowered the electrical resistance of the platinum wire. The two wires formed two legs of a Wheatstone bridge circuit and this change in resistance caused a bridge unbalance. The unbalance was indicated on a galvanometer calibrated directly in percent of helium in air. The instrument was equipped with a motor-driven vacuum pump to draw the helium-air mixture through the sampling cavity and these samples were bubbled through three inches of water. The samples were bubbled through water because the amount of water vapor in air has a considerable effect upon its thermal conductivity. With this arrangement, the thermal conductivity of the air in the sealed cavity serving as a reference cell was compared with the thermal conductivity of the helium-air mixture drawn through water and brought to a constant relative humidity approximating saturation.

A selector switch allowed any one of the three units to be connected to the galvanometer, which was calibrated from zero to 1.6% He and three samples could be measured in quick succession.

C. Performance Characteristics of the Cambridge Katharometer

A calibration of the Cambridge helium analyzer was made to determine how accurately it indicated the absolute volumetric concentration of helium in a mixture with air. This was done by preparing known concentrations of helium in air in glass flasks with a water seal. Several samples of each concentration were made and passed through the instrument for separate determinations. The results of this calibration, plotted in Fig. 2, show the average correction factor as a ratio of the actual concentration to the instrument reading. Fig. 2 shows considerable scattering of the individual observations for a given helium concentration. A correction factor curve has been drawn for each of the two cells used although it is recognized that the plotted observations do not define any precise line. The third cell of the instrument had become inoperative and was returned to the factory for repair.

The effect of scattering upon the correction factors determined for actual concentrations of 1.504% and 0.633% is shown in the following table which gives the number of measurements made with each cell of the apparatus and the maximum, minimum, and mean values for the correction factors.

Actual Concentration	No. of Observations Made		Correction Factors Determined					
			Maximum		Minimum		Mean	
	Cell 1	Cell 2	Cell 1	Cell 2	Cell 1	Cell 2	Cell 1	Cell 2
0.633	6	7	1.149	1.100	1.083	1.056	1.117	1.081
1.504	4	4	1.098	1.052	1.086	1.048	1.092	1.051

It will be noticed in this table that the maximum deviation of the values determined for the correction factor at an actual concentration of 0.633% was 0.066 for the first cell and 0.044 for the second cell, whereas for an actual concentration of 1.504% the corresponding deviations were only 0.012 and 0.004.

The scattering of the points in Fig. 2 for separate determinations at the same concentration is believed to have been caused principally by the drift of the zero position of the indicator over a period of time. The change in the zero position of the indicator varied as much as 1-1/2 scale divisions, 0.030% helium, over a period of seven hours. One and a half scale divisions corresponds to an error of 2% at 1.5% meter reading, 5% at 0.6% meter reading, and 15% at 0.2% meter reading. The drift of the zero point appeared to depend in part on whether or not a steady state of heat flow existed between the platinum wire heating elements in the cells and the enclosing brass block although this did not appear to be the only determining factor. When gas flow was initiated through the cells after having the heating elements ener-

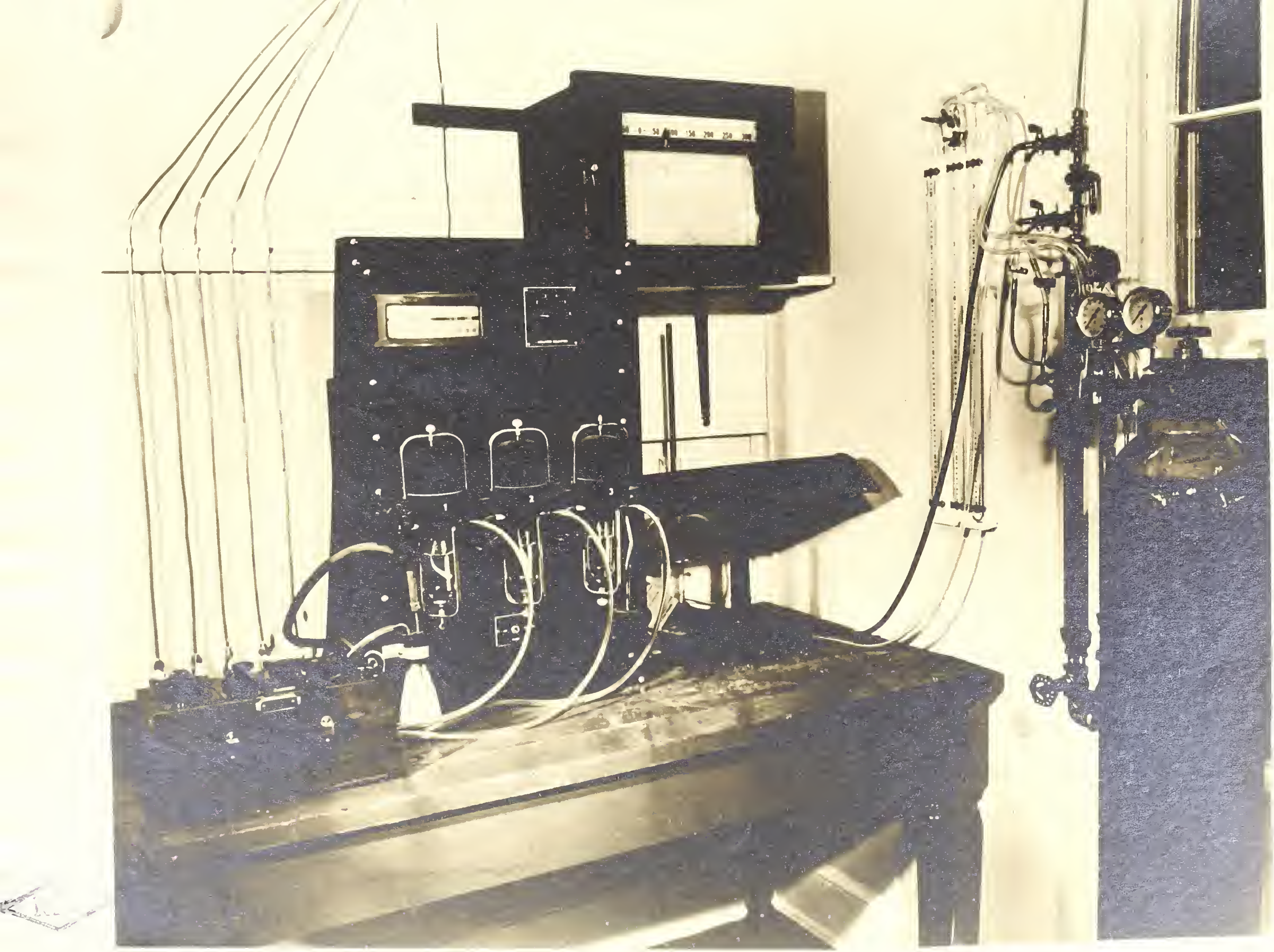


FIG. 1

CALIBRATION OF CAMBRIDGE HELIUM ANALYZER

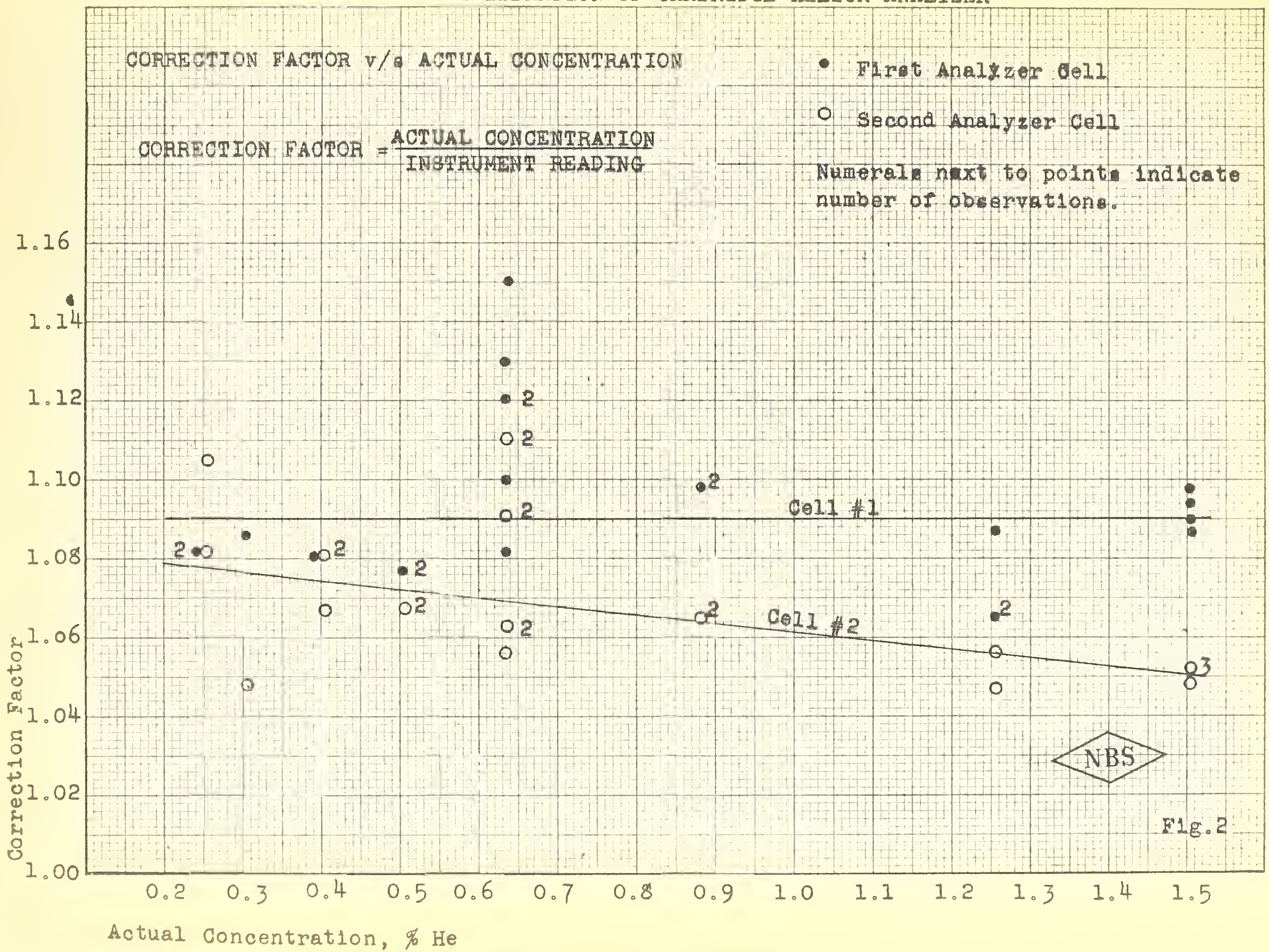


Fig. 2

gized without gas flow overnight, the zero position changed about one scale division for each cell during the first hour of operation. During the next six hours the zero position on cell No. 2 changed an additional half scale division in the same direction whereas the zero position on cell No. 1 changed a half scale division in the opposite direction.

A horizontal correction factor curve such as that shown in Fig. 2 for cell No. 1 would cause no error in infiltration measurements based on changes in concentration of helium with time assuming that the error due to scattering was not present. A correction factor curve with the slope shown for cell No. 2 in Fig. 2 would cause infiltration computations to be about 4 percent too high if no corrections were made to the observed values and there was no error due to scattering. However, the data in Fig. 2 suggest that the error resulting from the variations in indicated values at any given concentration could be greater than that resulting from the average change in correction factor from one end of the scale to the other.

Errors in reading the curved indicator scale caused by parallax are considered to be of the order of one-fourth scale division or 0.005% helium. Thus, parallax could cause a 2-1/2 percent error in the reading for a concentration of 0.2% helium.

The lag of the Cambridge device was determined by alternately introducing a helium-air mixture from a 6-gallon can and pure air into two of the test cells and averaging the readings taken during five such cycles. The results of these tests with only 3 ft of tubing between the can and apparatus are shown in Fig. 3, whereas Fig. 4 shows the results for a similar test with a sampling line consisting of 30 ft of 1/4-in. copper tubing. It will be noticed that a near balance is reached after 3.5 minutes with the 3 ft sampling line, whereas with a 30 ft line a balance of the indicator required about 5 minutes.

Some measurements were made to determine the effect of the sampling rate on the indication of the Cambridge instrument. It was found that no appreciable change of the indicator reading was noticeable if the sampling rate remained within the range from 100 to 170 cc/min. However, flow rates below 100 cc/min caused erroneous results. There was no quantitative flow rate indicator on the Cambridge instrument, but an operator with some experience could determine from the bubbling rate in the saturators when the flow rate was normal. The instrument was found to be practically insensitive to atmospheric pressure fluctuations or pressure differences that may arise from long sampling lines. A test showed that a change in pressure at the inlet of the instrument from 36 in. W. G. pressure to 36 in. W. G. vacuum increased the indicator reading by only 0.02% of helium at the middle of the scale.

The characteristics of the Cambridge katharometer described above indicate that the following precautions should be taken during use to minimize errors in the results:

(1) Gas should be drawn through the cells for at least an hour before any measurements are taken.

(2) Helium concentrations in the range from 0.4 to 1.4 percent should preferably be used to reduce the importance of the error caused by drift in the lower end of the scale and parallax at the two ends of the scale.

(3) The rate of gas flow through the bubblers should be noted to ascertain that it is normal and constant.

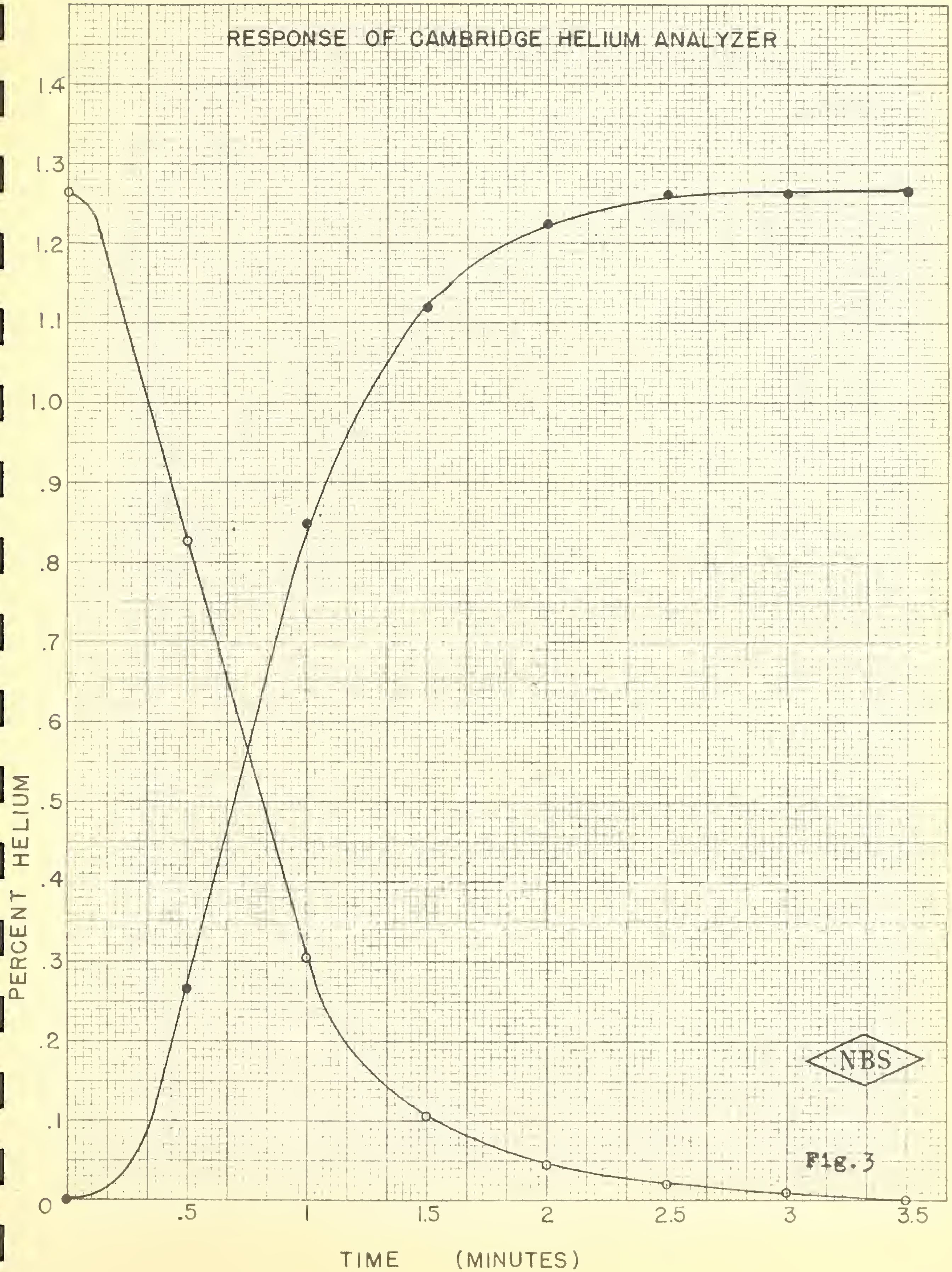
(4) The shortest possible sampling lines should be used and appropriate consideration given to the lag of the instrument at the beginning of a test.

(5) Numerous readings of concentration should be taken during any test so the errors caused by drift and parallax for a given observation would not be of such great significance.

D. Pilot Installation

A pilot installation was made in the north bedroom of the Test Bungalow to study the possibility of stratification of the tracer gas in the room and to furnish information on the best arrangement of the gas supply and sampling systems for the entire building.

Seven stations were chosen in the north bedroom to furnish data on stratification of the helium gas. These stations were near the ceiling, near the floor, midway between ceiling and floor and in upper and lower corners of the room at locations considered most likely to reveal stratification if it occurred. One-quarter inch copper tubing was run from each of these stations through the wall of the room and into the south bedroom where the helium analyzer was placed. Flexible tubing was used at one station so that, in conjunction with a pulley arrangement, it could be made to scan the wall from floor to ceiling choosing any point for sampling. An additional copper line was installed in the north bedroom to introduce the helium into the room. This line was also used as a sampling line during the test. By returning the helium-air mixture to the test room after passing it through the analyzer it was not necessary to compensate for this volume of air in the infiltration calculations. Later it was determined that the samplers only extracted about one cu. ft. of mixture per hour and this was below the precision of the infiltration measurements. The tracer


RESPONSE OF CAMBRIDGE HELIUM ANALYZER
PERCENT HELIUM
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
.5
1
1.5
2
2.5
3
3.5
TIME (MINUTES)
NBS
Fig. 3

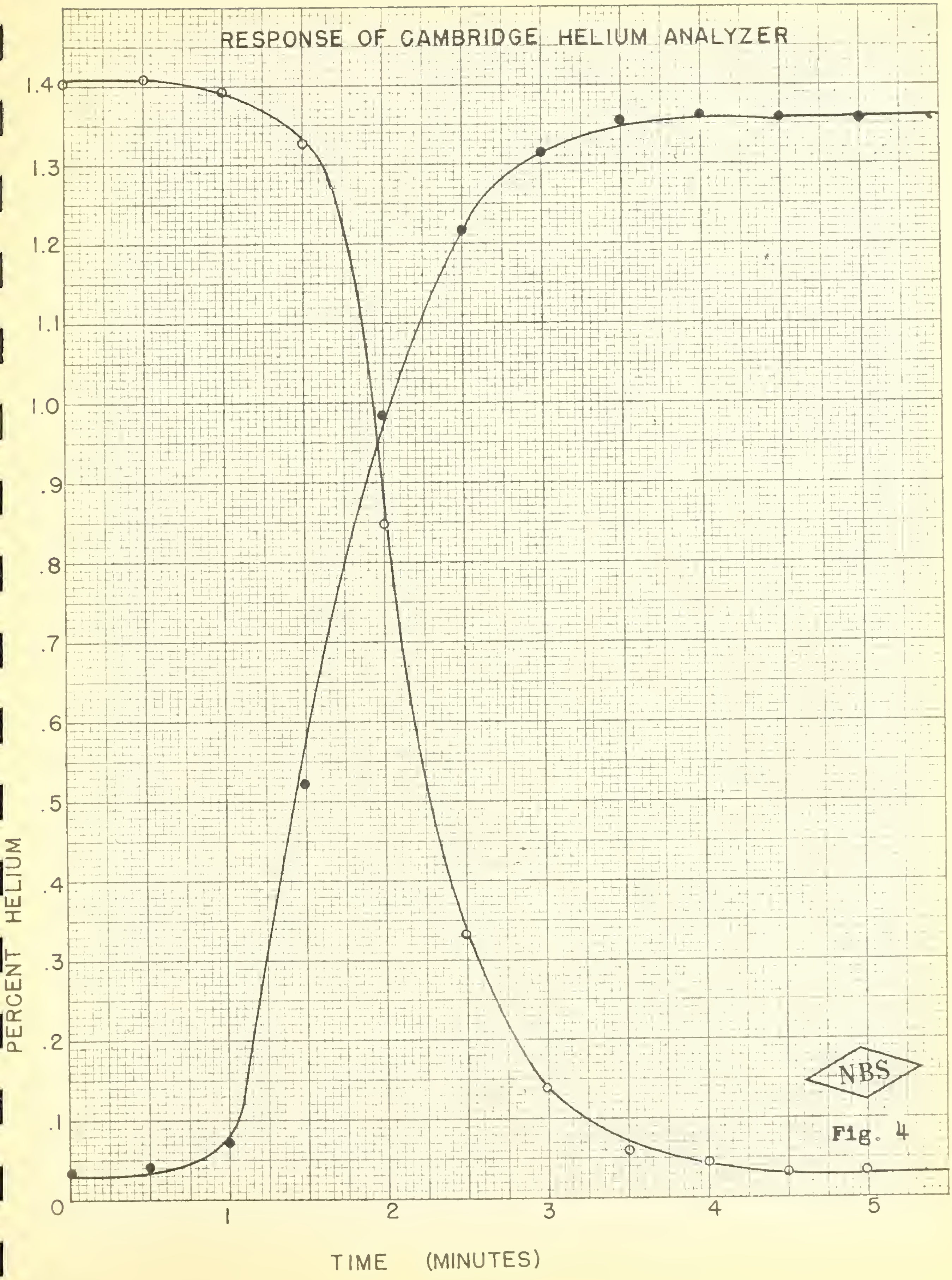

RESPONSE OF CAMBRIDGE HELIUM ANALYZER
PERCENT HELIUM
1.40
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1
2
3
4
5
TIME (MINUTES)
NBS

Fig. 4

gas was taken from compressed-gas cylinders and metered through an orifice meter. A 12" propeller type fan was operated in the room for approximately one minute after the tracer gas had been introduced to completely mix the air and helium gas. The compressed-gas cylinder and orifice meter are visible at the right of Fig. 1.

Tests were made with this pilot installation using both the helium-katharometer and the ethane-interferometer methods. In each case an initial tracer-gas concentration of approximately one percent was used. When internal and external conditions of the test room remained constant during a test the rate of fresh air leakage would be expected to remain constant with time. On this premise the graph of the volume of air infiltration versus time should be a straight line passing through the origin. Consequently, it should be possible to obtain a reasonably accurate value for the air change rate, from the slope of the line with only a few measurements.

The following formula was used to calculate the air change rate from the observed decay of the tracer gas.

$$c = c_o \, e^{-Rt} \qquad (1)$$

where

c = concentration of the tracer gas at time t

c_o = initial concentration of the tracer gas at t = o

$R = \frac{K}{V}$ = number of air changes per unit of time

K = volume of air infiltration per unit of time

V = volume of room

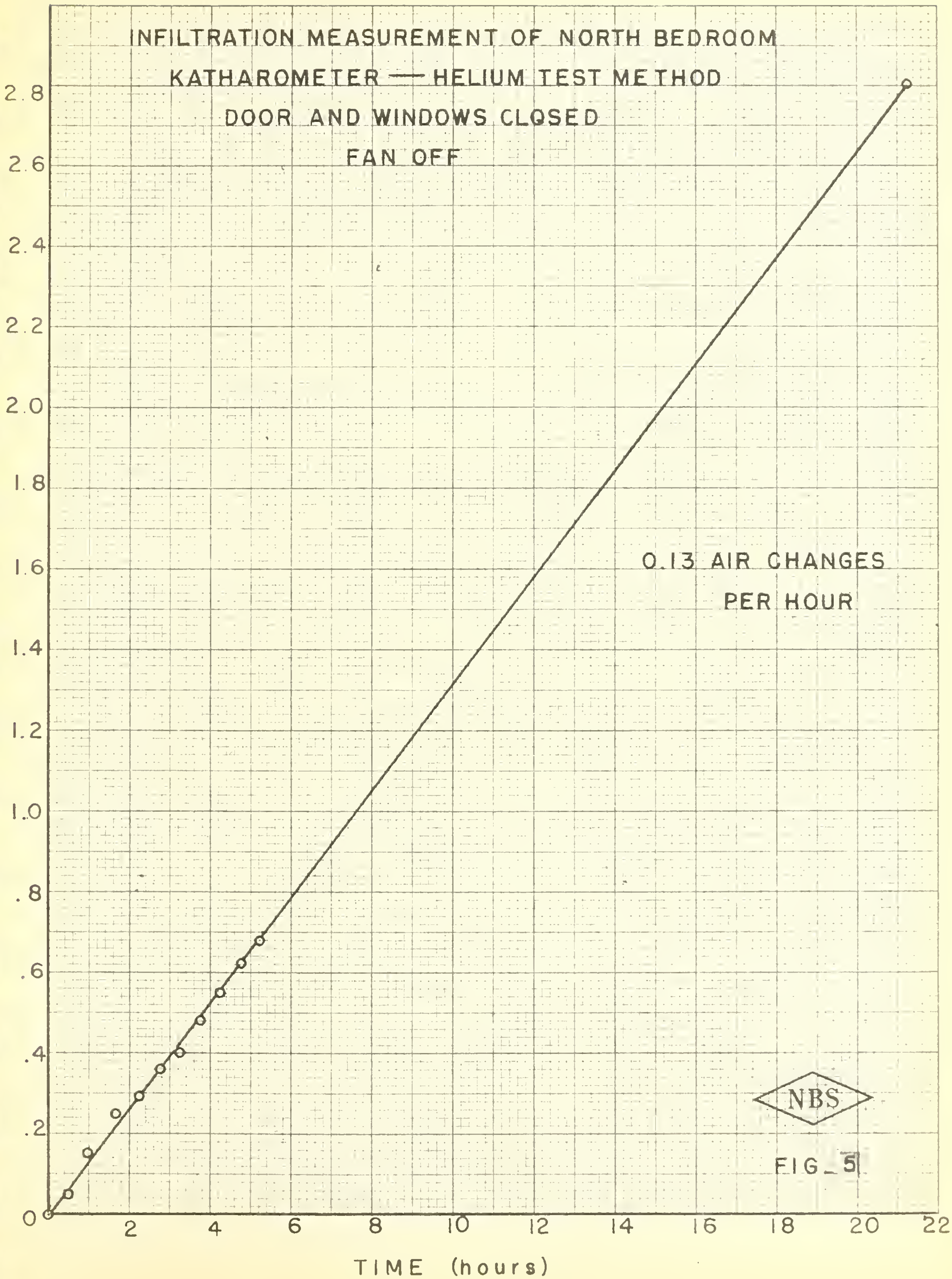
Equation (1) is obtained by integrating the following expression for the rate of loss of tracer gas per unit of time:

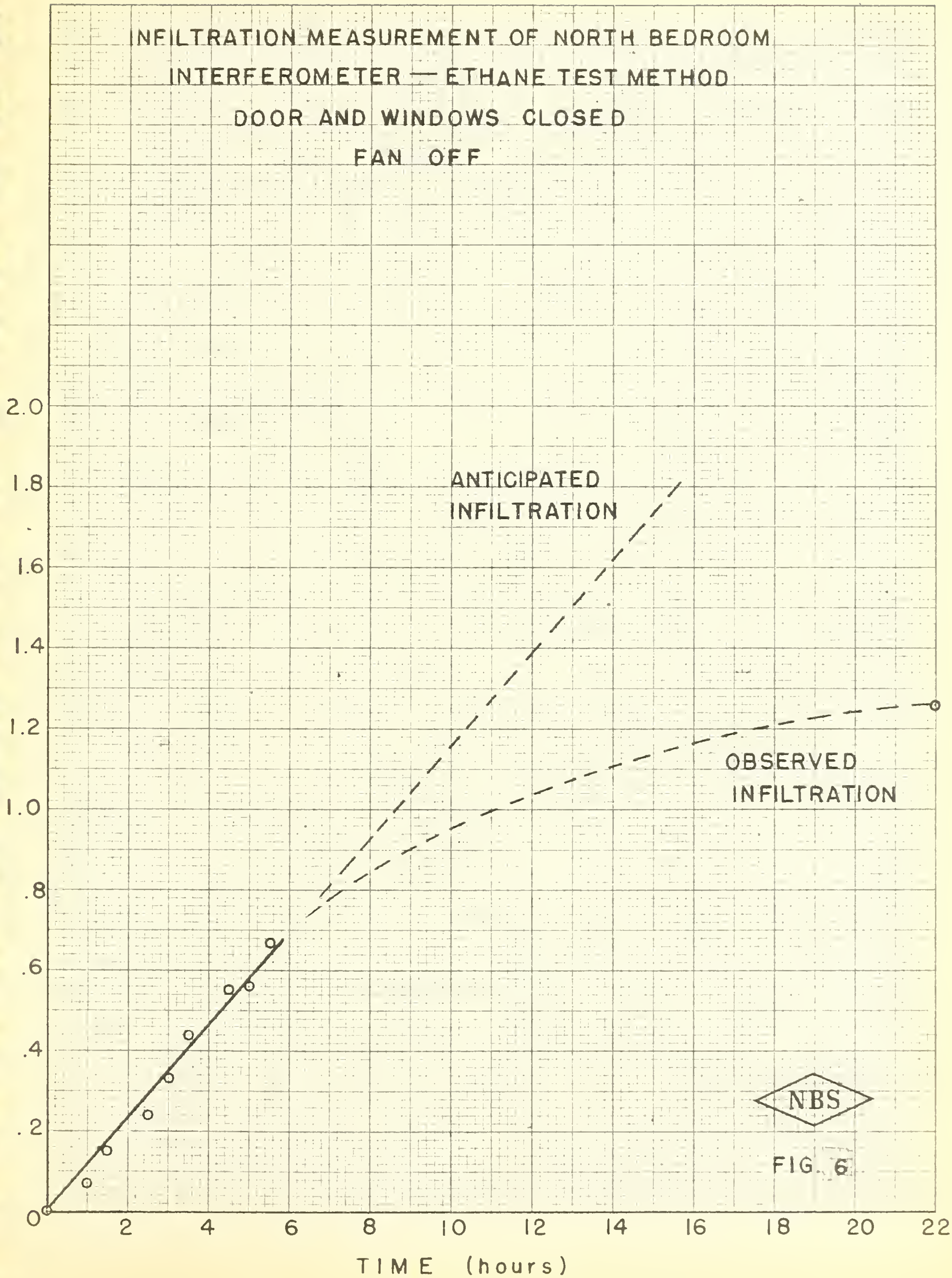
$$-V \frac{dc}{dt} = Kc \qquad (2)$$

Figures 5 and 6 show the results of infiltration tests in the north bedroom with the room closed and with no indoor-outdoor temperature difference using helium and ethane as the tracer gas, respectively. The results obtained by the two methods during separate tests under the same conditions agree quite closely during the first five and a half hours when observations were made at half-hour intervals. Based on the first 5 1/2 hours of the test the infiltration rate was 0.129 air changes per hour as measured with the katharometer and 0.125 air changes per hour as measured with the interferometer. The observations taken with the two instruments on the day following the start of the test after an elapsed time of 22 hours do not agree satisfactorily. The results obtained with the katharometer is that which would be expected if the rate of infiltration remained constant throughout the test. The result obtained with the interferometer after 22 hours was much lower. Since a period of about 16 hours elapsed, during which the test structure was unattended, between the first group of observations and the single observation taken on the next day, it is not certain that cooling of the structure or entrance by some other person did not change the infiltration into the test room.

The interferometer used for those tests had only 14 scale divisions for maximum deflection whereas the scale on the katharometer had 80 divisions for a full scale reading. Consequently, the precision of any observation with the interferometer was of a lower order than for the other instrument and it was especially difficult to read correctly at low interference ratios. For example, if the observed deflection after 22 hours had been read as 3 scale divisions instead of 4 in Fig. 6, the percent decay would have been 78.6 and the air changes 2.2 instead of 1.26. Under these conditions the agreement between the two methods after 22 hours would have been reasonably good. However, for tests of shorter duration the two instruments corroborated each other in the determination of infiltration rates. Because of its greater sensitivity the katharometer was used for all observations of infiltration after this initial comparison. An interferometer with a longer light path could be used to attain greater sensitivity than that of the instrument used for this comparison.

Studies were made to determine whether or not stratification of the tracer gas occurred in the north bedroom as air infiltration progressed in order to assist in the design of an adequate sampling system for the entire Test Bungalow. Fig. 7 shows the results of a test made with no difference in temperature between indoors and outdoors, no air circulation outdoors, and with the door and windows of the room closed. A fan in the attic was used to exchange air between the outdoors and the Test Bungalow enclosure by means of the chimney to prevent build-up of the helium concentration in the enclosure. Observations of the helium concentration were made near the floor, near the ceiling, and at the 3-foot level for 77 minutes without agitation of the air in the room. Fig. 7 shows that the tracer gas concentrations corresponded to leakage rates of 1.8, 0.88, and 0.5 air changes per hour for the first hour at the floor level, 3-foot level, and ceiling level, respectively. This stratification of helium in the room was attributed to the inward leak-


INFILTRATION MEASUREMENT OF NORTH BEDROOM
KATHAROMETER — HELIUM TEST METHOD
DOOR AND WINDOWS CLOSED
FAN OFF
0.13 AIR CHANGES PER HOUR
NBS
FIG_5
TIME (hours)
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
2
4
6
8
10
12
14
16
18
20
22



INFILTRATION MEASUREMENT OF NORTH BEDROOM
INTERFEROMETER — ETHANE TEST METHOD
DOOR AND WINDOWS CLOSED
FAN OFF
ANTICIPATED INFILTRATION
OBSERVED INFILTRATION
AIR CHANGES
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
2
4
6
8
10
12
14
16
18
20
22
TIME (hours)
NBS

FIG. 6

AIRCHANGES AT DIFFERENT ELEVATIONS DUE TO STRATIFICATION OF HELIUM.

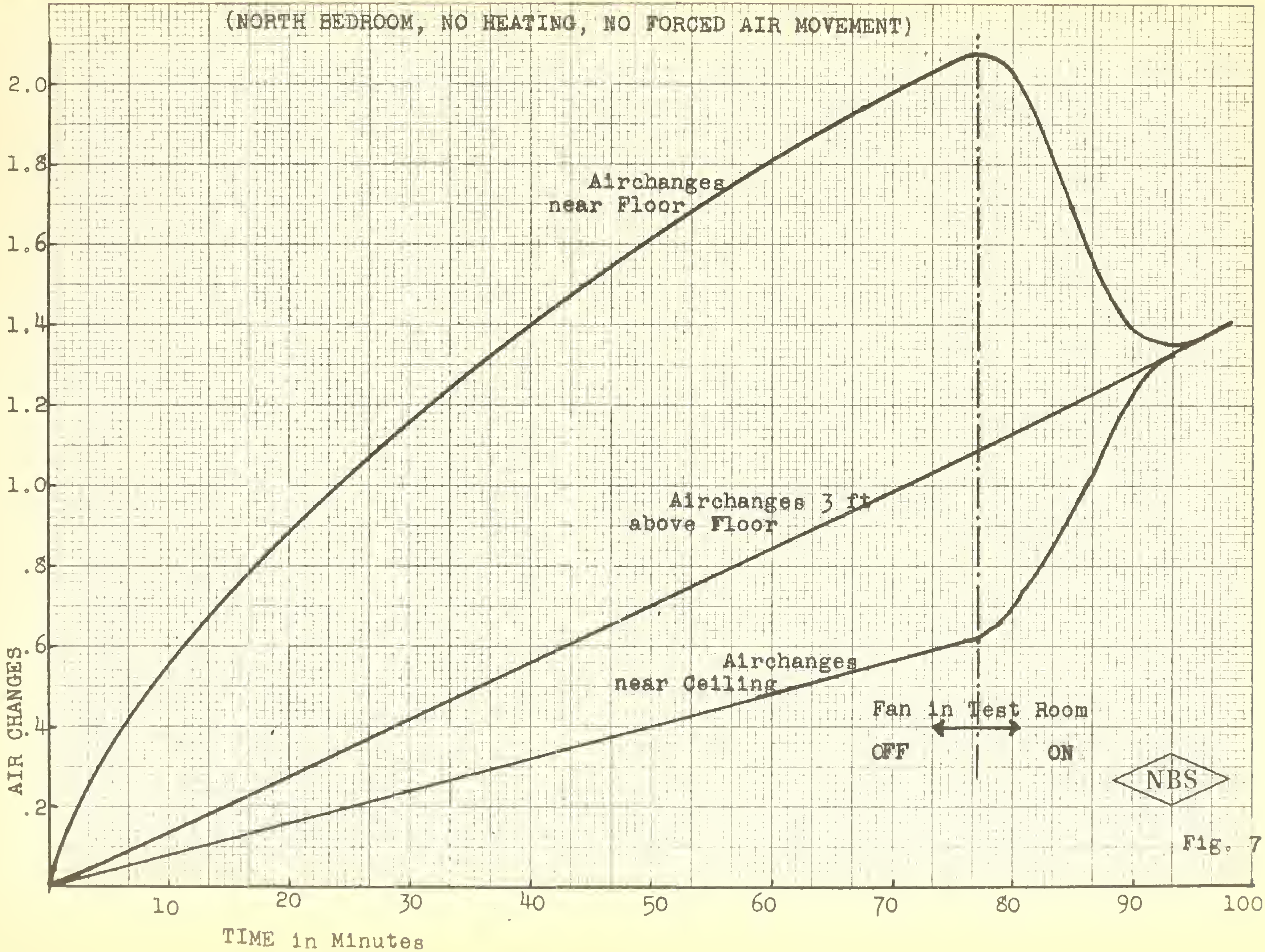


Fig. 7

age of fresh air in the lower part of the room and outward leakage of contaminated air in the upper part of the room to the attic. The attic fan reduced the pressure in the attic about 0.01 in. W. G. This pattern of air infiltration would result in more rapid dilution of the helium gas in the lower part of the room than near the ceiling. This conclusion was supported by a test which revealed no stratification of helium in air in a closed vessel as a result of the lower density of helium after the air and helium were initially well-mixed.

When a desk fan was turned on after 77 minutes of observations under still air conditions, the concentration at the ceiling decreased and that at the floor level increased until both stations indicated concentrations equal to that at the three-foot level after the fan had been operating about 15 minutes. The results in Fig. 7 indicate that for this particular building the concentration at the 3-foot level represented an average for the entire room under conditions that produced stratification of the tracer gas. The difference in infiltration rates shown in Figs. 5 and 6 as compared to Fig. 7 when there was no indoor-outdoor temperature difference in either case, was accounted for by the operation of the fan in the attic.

Subsequent tests revealed that no measurable stratification occurred when heat was being supplied to the test room. This is probably accounted for by the mixing action caused by the convection from the heater and the downdrafts near the cold walls of the room.

Preliminary tests in the north bedroom with indoor-outdoor temperature differences of 18°F and 20°F showed that the infiltration increased markedly with increase in temperature difference. The results shown in Figs. 8 and 9 can be compared with those in Figs. 5 and 6 to indicate that the infiltration with a 20 degree temperature difference was about five times as great as for the condition with no temperature difference between indoors and outdoors.

Figs. 10 and 11 show the infiltration observed in the north bedroom with no temperature difference between indoors and outdoors when a window was opened 3/8-inch from the bottom and from the top, respectively. In each case a desk fan was used to keep the air and helium gas mixed during the test. The tests indicated an infiltration rate of 0.45 air change per hour with the window opened from the bottom and 0.52 air change per hour with the window opened from the top.

In comparing the infiltration indicated in Figs. 10 and 11 with partially open windows with that indicated in Figs. 5 and 6 for a closed room, it should be pointed out that a desk fan was in steady operation in the north bedroom during the tests with the open windows whereas the fan was not in operation during the other tests. Investigation showed that the infiltration rate was approximately doubled by the operation of the desk fan inside the north bedroom for otherwise identical conditions. If it is assumed that the observed infiltration rates in Figs. 5 and 6 would have been doubled by the operation of a desk fan, it is concluded that the infiltration rate was about twice as great with a window opened 3/8-inch from top or bottom as for a closed room with no indoor-outdoor temperature difference.

E. Infiltration Measurements in a Whole House

After completing the preliminary investigation of infiltration in the north bedroom a series of tests was planned using the entire house. Based on the results obtained in the north bedroom a single sampling tube was installed in each room to withdraw gas samples 3 feet above the floor. This precaution may have been unnecessary inasmuch as it was found that no measurable stratification occurred in the north bedroom when it was heated.

Fig. 12 is a schematic drawing of the manifold installed in the south bedroom, which remained the instrument center, so samples could be taken from any part of the house. The sampling tubes also served as a distribution system for introducing helium into the five rooms of the house. The compressor shown in Fig.12 purged the lines of helium after feeding was completed so the katharometer would not be subjected to extremely high concentrations at the start of a test. Sufficient experience was obtained during the first few tests to regulate the desired concentration of tracer gas by controlling the length of time that the valve on the helium cylinder was open. The use of the orifice flow meter was then discontinued. The introduction of helium was done with all interior doors open and four fans running at appropriate places to mix the helium with the air in all the rooms. In this way all the rooms had approximately the same concentration of helium at the beginning of the test.

The general procedure for a test was as follows: Signs were placed outside the refrigerated enclosure requesting visitors not to enter because entrance, even into the enclosure, caused pressure changes that would disrupt the steady state conditions. All windows in the house were closed and locked and the external doors closed. The fans inside the house were turned on and operated throughout the feeding time and the time required to purge the lines of helium. Then the inside doors were all closed so the air change rate of each room could be measured individually. (It was later found that the overall air change rate of the house was the same with the inside doors open or closed.) The helium analyzer was turned on and readings commenced. Samples of gas were drawn from any three stations for five minutes, then

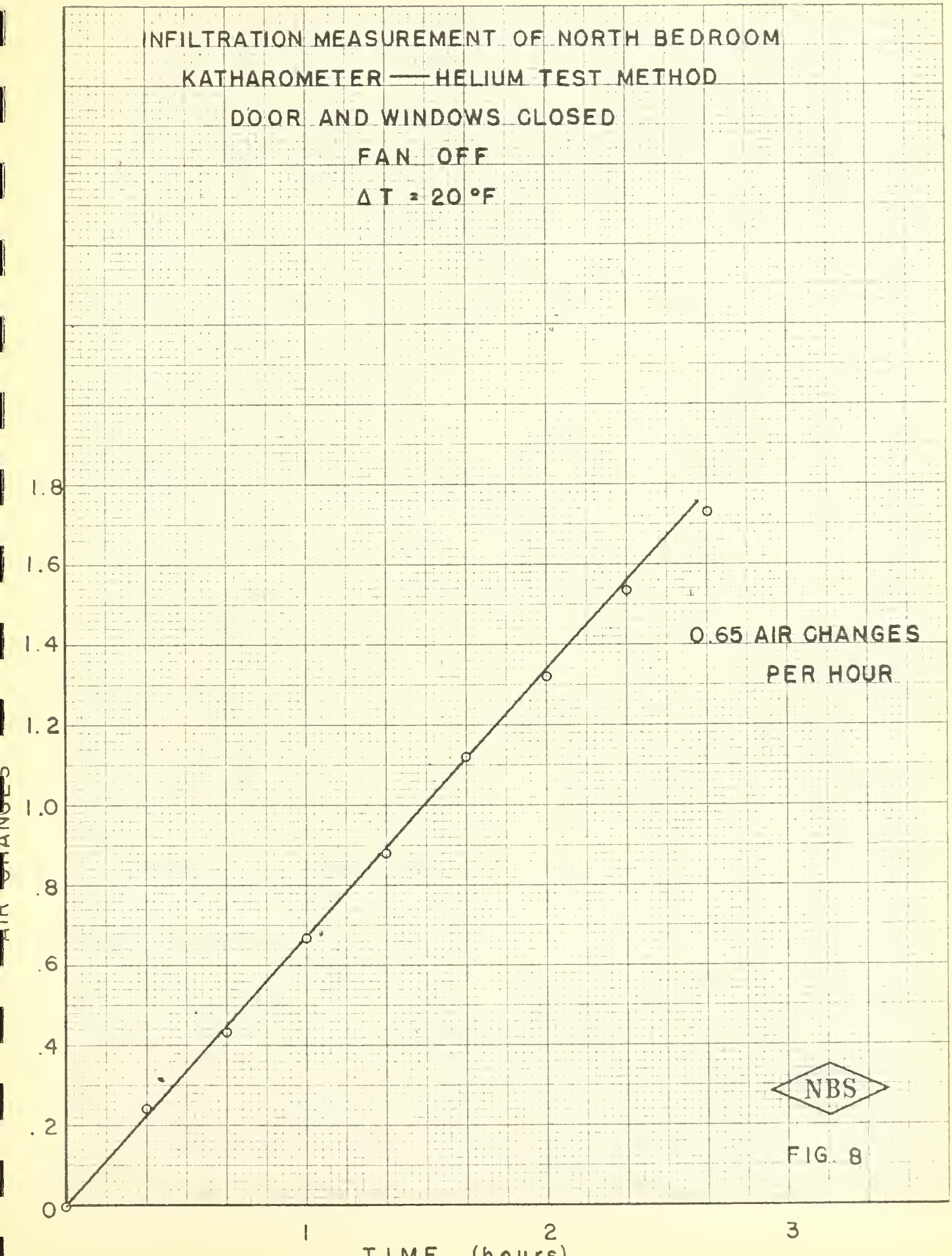
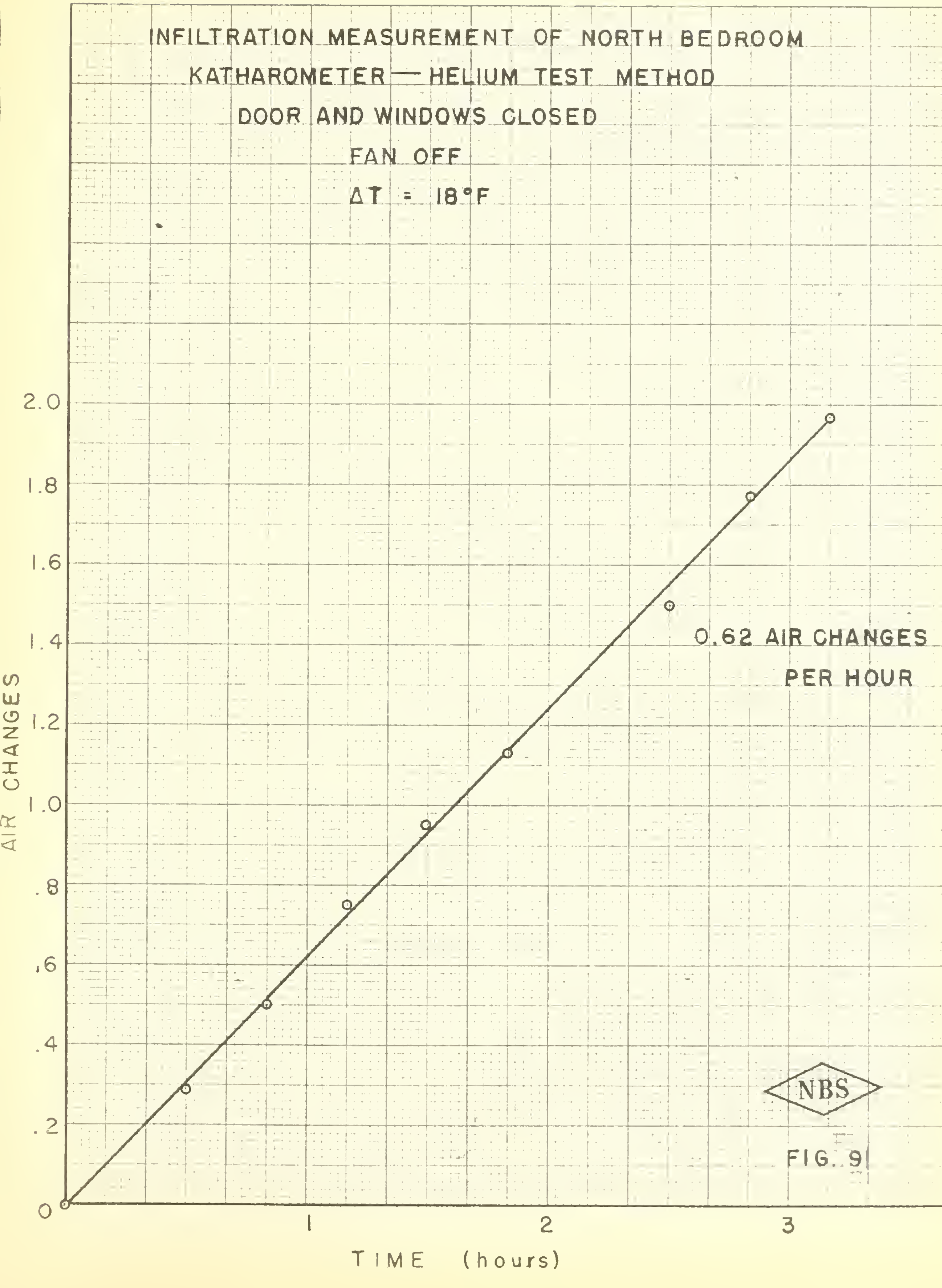

INFILTRATION MEASUREMENT OF NORTH BEDROOM
KATHAROMETER — HELIUM TEST METHOD
DOOR AND WINDOWS CLOSED
FAN OFF
ΔT = 20 °F
0.65 AIR CHANGES PER HOUR
AIR CHANGES
TIME (hours)
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
1
2
3
NBS

FIG. 8



INFILTRATION MEASUREMENT OF NORTH BEDROOM
KATHAROMETER — HELIUM TEST METHOD
DOOR AND WINDOWS CLOSED
FAN OFF
ΔT = 18°F
0.62 AIR CHANGES PER HOUR
AIR CHANGES
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
1
2
3
TIME (hours)
NBS

FIG. 9

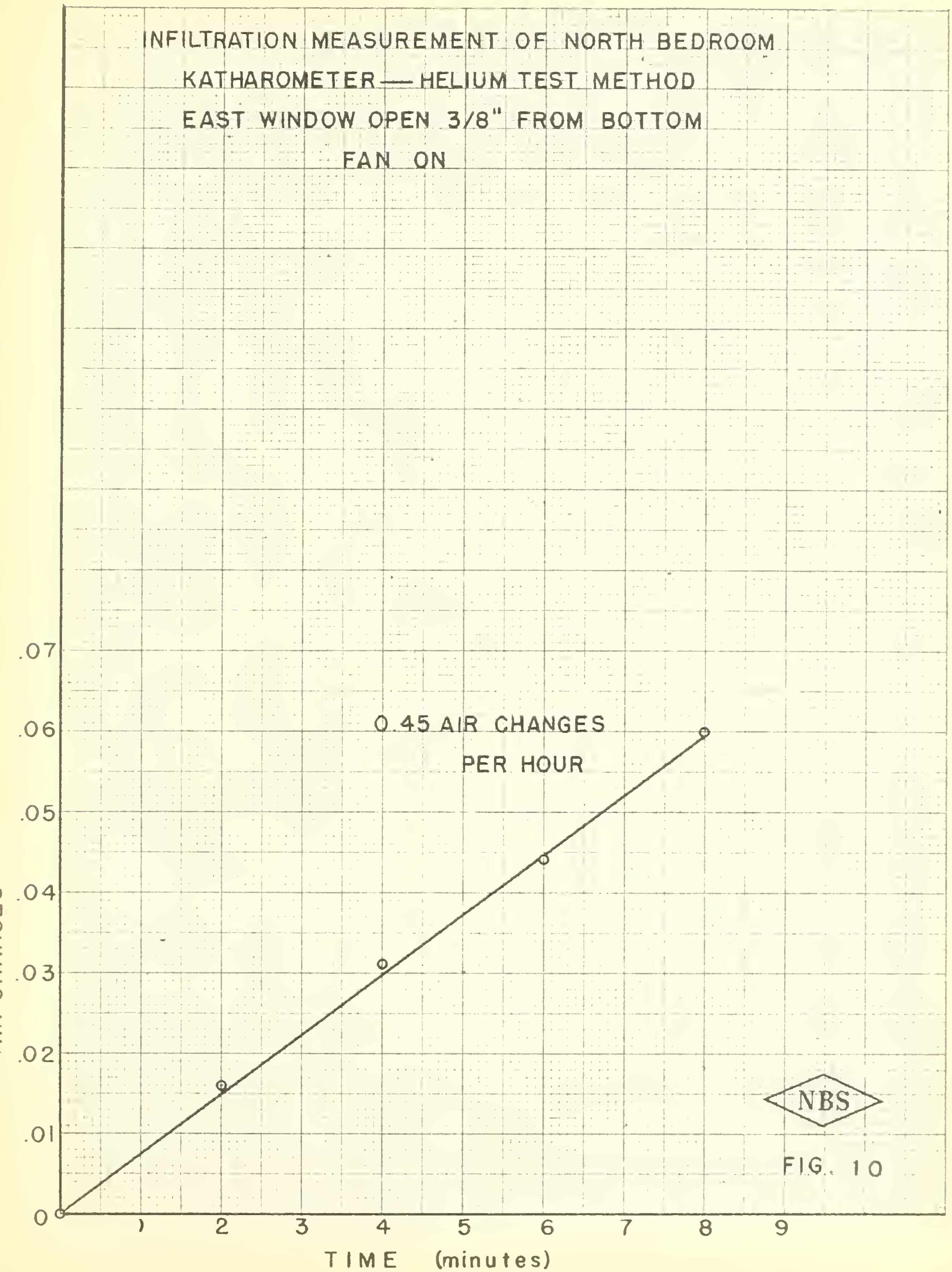
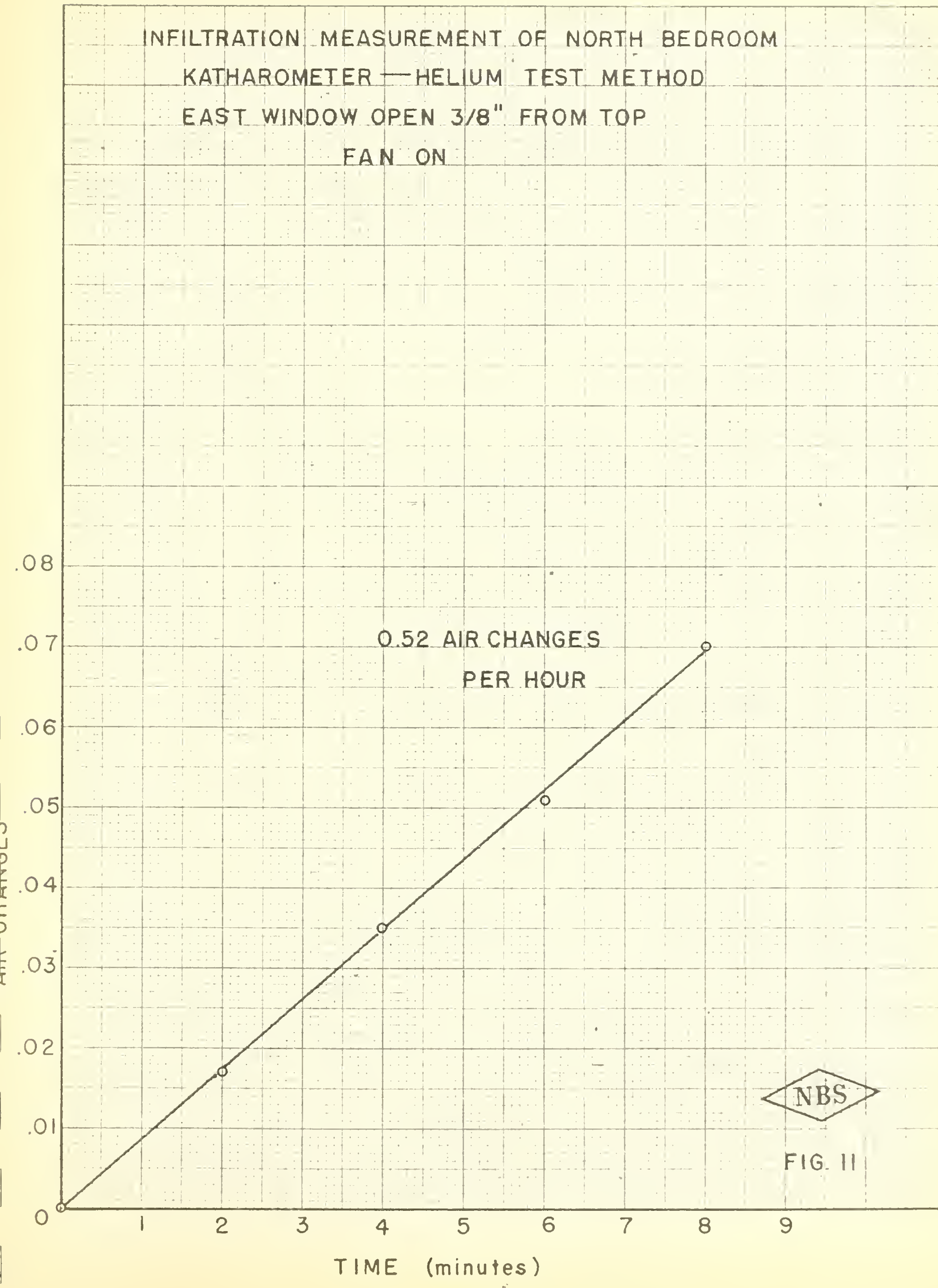
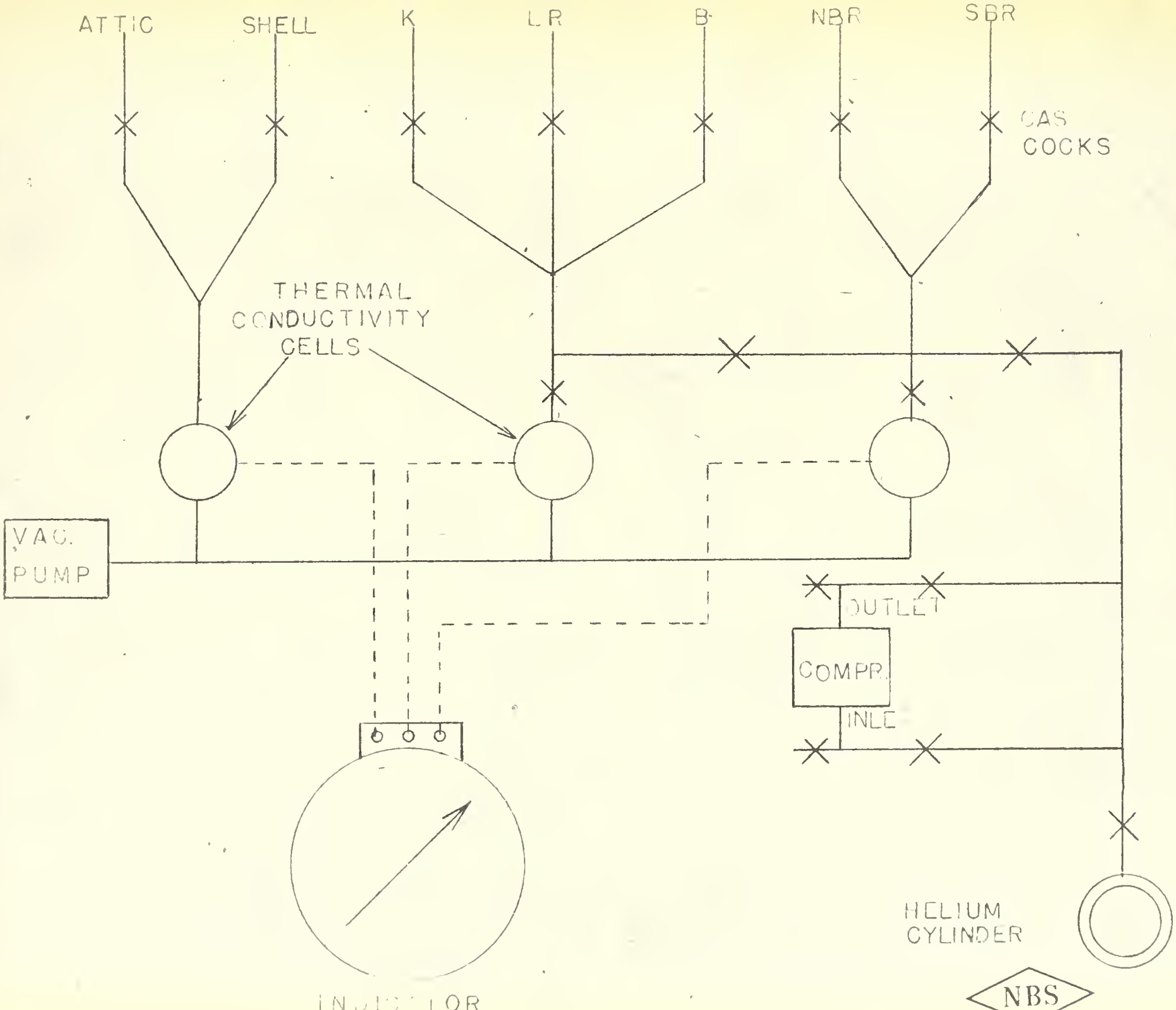

INFILTRATION MEASUREMENT OF NORTH BEDROOM
KATHAROMETER — HELIUM TEST METHOD
EAST WINDOW OPEN 3/8" FROM BOTTOM
FAN ON
0.45 AIR CHANGES PER HOUR
.07
.06
.05
.04
.03
.02
.01
0
1
2
3
4
5
6
7
8
9
TIME (minutes)
NBS

FIG. 10


INFILTRATION MEASUREMENT OF NORTH BEDROOM
KATHAROMETER — HELIUM TEST METHOD
EAST WINDOW OPEN 3/8" FROM TOP
FAN ON
0.52 AIR CHANGES PER HOUR
.08
.07
.06
.05
.04
.03
.02
.01
0
1
2
3
4
5
6
7
8
9
TIME (minutes)
NBS
FIG. 11



SCHEMATIC DIAGRAM OF HELIUM ANALYSER INSTALLATION

FIG. 12

from three other stations. The five-minute interval was used because experiment had shown that it took that long for the thermal conductivity cell to become responsive to the helium concentration at a given station. During the five minutes the galvanometer needle was moving slowly up or down the scale adjusting itself to the new sample. The tests lasted, in general, about one hour or until the concentrations were too low to give accurate readings. A disadvantage of the analyzer was found to be the curved face on the galvanometer and the absence of a parallax compensator, so readings below 0.2% and above 1.4% were considered to be less precise than those in the center of the scale when the air change rate curves were drawn.

It was planned to determine the air change rate of the Test Bungalow for a range of indoor-outdoor temperature differences so a test was made to find its infiltration with no temperature difference and no wind. Fig. 13 shows the results of this test. Fig. 14 represents the air change rate with no temperature difference but with the refrigeration blowers running and creating the equivalent of approximately a two mile per hour wind. This was actually the average air motion around the house in a circular pattern in a vertical plane and was constant for all tests since the blowers were operated at constant speed. All of the remaining tests were made with the blowers running.

In Figs. 13 and 14 the air change rate is reported as a weighted average, which was arrived at in the following manner: Since the rooms were of different sizes, it would not be correct to merely calculate the air change rate of each room and average the rates of the individual rooms because the small rooms would affect the average air change rate of the entire house disproportionately under such a procedure. Therefore, the air change rate of each room was multiplied by its fractional part of the entire volume of the house. The sum of these products was called the "weighted air change rate" of the house and is indicated by a dotted line in Fig. 13.

It will be noted in Figs. 13 and 14 that some of the curves showing the relationship between air infiltration and time are not straight lines whereas in Figs. 5, 6, 8, 9, 10, and 11 this relationship is best represented by a straight line. Later observations led to the conclusion that the curvature of the air leakage lines obtained from these early tests using all rooms of the house was probably caused by inadequate mixing of the helium and air or inadequate purging of the sampling lines after using them to introduce helium into the rooms.

Before additional infiltration measurements were made it was found desirable to modify the basic air change rate formula (1) discussed earlier in this report. It was observed during the tests of the entire Test Bungalow that the concentration of helium in the enclosure increased enough, due to leakage of the contaminated air from the house, to affect the results in the house. Because the air infiltrating into the house was not pure air, but air with helium in it, formula (1) no longer described the conditions of the test. Since the enclosure surrounding the house had a volume of only about 5 times that of the living quarters of the house the concentrations of helium in the enclosure sometimes reached 0.25%. For this reason the following formula was derived to represent the actual conditions that prevailed.

If c_1 = helium concentration in the house at time t_1, %

c_2 = " " " " " " " t_2, %

C_1 = " " " " enclosure " " t_1, %

C_2 = " " " " " " " t_2, %

v = volume of the living space, cu. ft.

V = volume of the enclosure, basement and attic, u.ft.

M = total helium in the system, cu. ft.

K = infiltration rate into house, cu. ft/hr

then $$V \frac{dc}{dt} = -K (c - C) \qquad (3)$$

$$M = v\,c + V\,C \qquad (4)$$

These formulae could have been combined and integrated, if M were a constant, and then solved for K. However, the enclosure had an air change rate with the outside atmosphere as high as 0.15 air changes per hour. Thus M was not a constant and the equation cannot be integrated.

Since the interval between readings of the helium concentration in the enclosure was expected to be ten minutes, the change in helium concentration in the enclosure would be very small during that interval. If the concentration of helium in the enclosure is considered to be constant between consecutive readings ten minutes apart equation (3) can be integrated and the definite integral used to evaluate K, the infiltration rate of the living space, for any short interval with very little error.

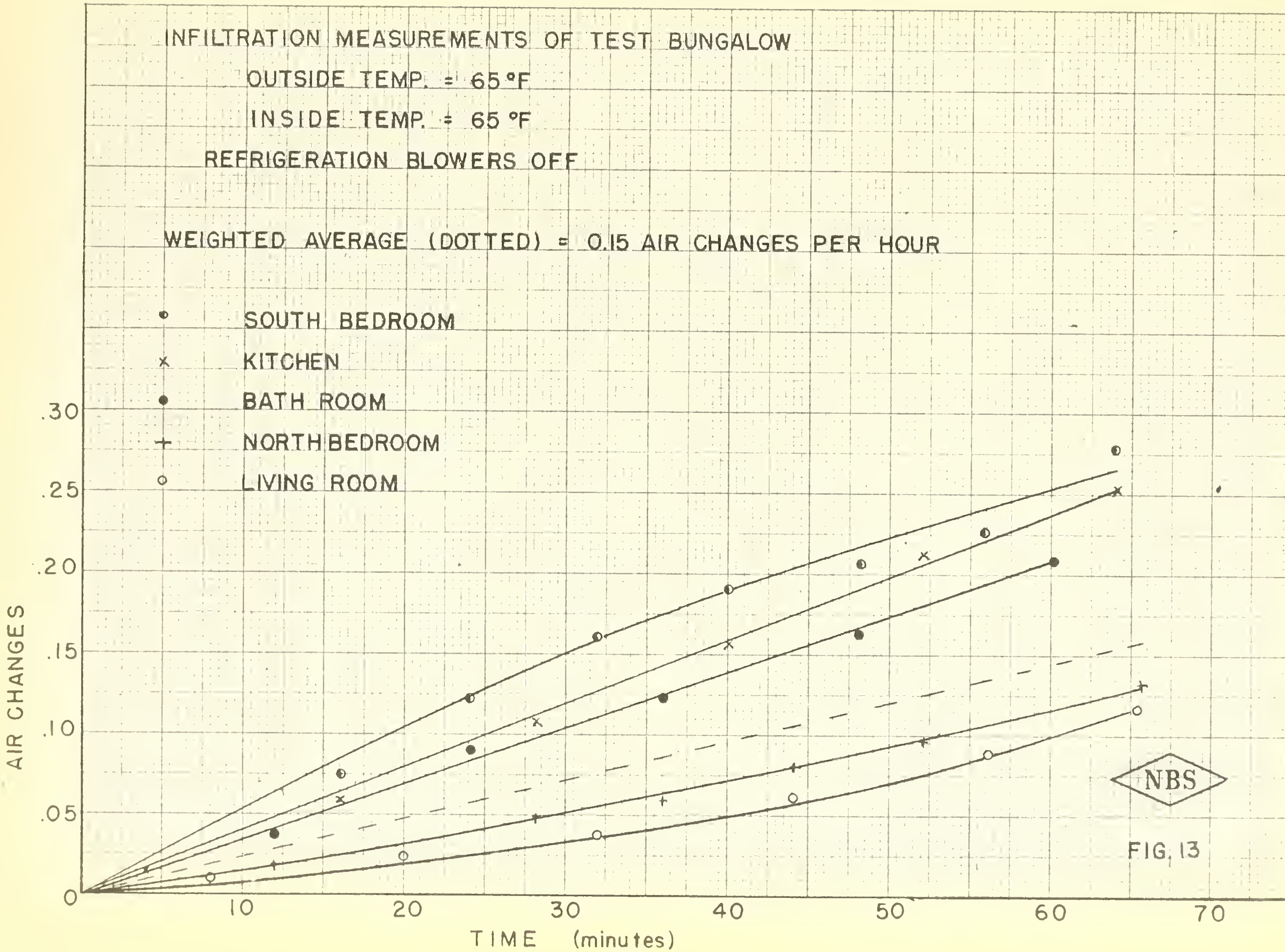

INFILTRATION MEASUREMENTS OF TEST BUNGALOW
OUTSIDE TEMP. = 65 °F
INSIDE TEMP. = 65 °F
REFRIGERATION BLOWERS OFF
WEIGHTED AVERAGE (DOTTED) = 0.15 AIR CHANGES PER HOUR
SOUTH BEDROOM
KITCHEN
BATH ROOM
NORTH BEDROOM
LIVING ROOM
AIR CHANGES
0
.05
.10
.15
.20
.25
.30
10
20
30
40
50
60
70
TIME (minutes)
NBS

FIG. 13

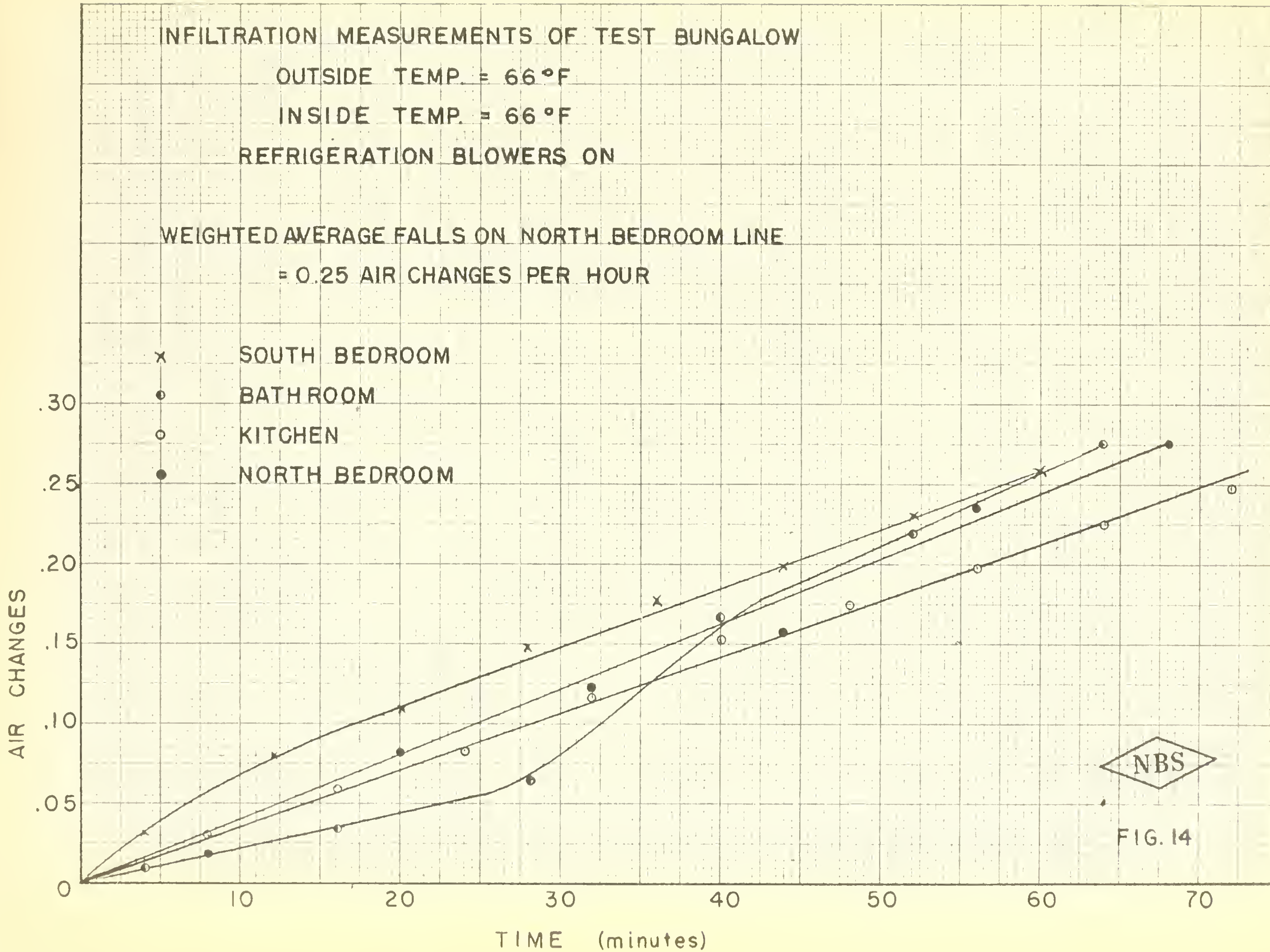

INFILTRATION MEASUREMENTS OF TEST BUNGALOW
OUTSIDE TEMP. = 66 °F
INSIDE TEMP. = 66 °F
REFRIGERATION BLOWERS ON
WEIGHTED AVERAGE FALLS ON NORTH BEDROOM LINE
= 0.25 AIR CHANGES PER HOUR
SOUTH BEDROOM
BATHROOM
KITCHEN
NORTH BEDROOM
AIR CHANGES
0
.05
.10
.15
.20
.25
.30
10
20
30
40
50
60
70
TIME (minutes)
NBS

FIG. 14

Integrating equation (3)

$$\log (c - C) = \frac{-Kt}{V}$$

or

$$\log \frac{c_1 - C_1}{c_2 - C_2} = \frac{K}{V} (t_2 - t_1)$$

Where $\frac{K}{V} (t_2 - t_1)$ = infiltration from time t_1 to time t_2

and

$$\frac{c_1 - C_1}{c_2 - C_2} = e^{\frac{K}{V} (t_2 - t_1)}$$

where t_2 and t_1 are the times corresponding to two consecutive observations of the helium concentration. Equation (5) can be solved for values of $\frac{K}{V}$, which is the number of air changes per hour based on observations taken at ten-minute intervals more or less. By computing the logarithmic mean value of C_1 and C_2, the concentration in the enclosure, during the time interval under consideration from katharometer measurements, the computed values of $\frac{K}{V}$ would be quite accurate for short time intervals. This method of calculation was used for all subsequent tests.

At first, observations of helium concentration were taken in all five rooms and the infiltration rate for each room computed individually as described previously for the weighted average method. However, it was noted that the average of the concentrations in the north bedroom, living room and bathroom was, in almost every case, very close to the average of the five rooms so measurements were made only in these rooms and sampling stations were added in the attic and basement. All the rooms were still contaminated with helium so the exchange of air between rooms would result in representative concentrations in the three sample rooms as before and give true indications of the total air changes. Under this procedure the actual concentrations, in percent helium, of the north bedroom, living room, and bathroom at each time interval, were averaged and then computed for air change rate in the manner just described using equation (5). The results of this simple method checked well with those of the more elaborate method. For example, Fig. 15 shows the infiltration computed for each of the five rooms based on a single sampling station in each room and also the weighted average of the five rooms as a dotted line. The infiltration rates for the north bedroom, living room, and bath were 0.55, 0.86, and 0.69 air change per hour, respectively, resulting in a three-room average of 0.70. This three-room average is very close to the weighted average of 0.71 for the five rooms.

The results of a number of infiltration tests in the Test Bungalow for a range of indoor-outdoor temperature differences are plotted in Fig. 16 to 18, inclusive. Duplicate tests are plotted on Fig. 16, 17, and 18 for indoor-outdoor temperature differences of 20°F, 55°F, and 70°F, respectively, in addition to other test data. The observations for each test are quite consistent and all lie very close to a straight line. A single curve represents the infiltration for each test because the infiltration rates for the north bedroom, living room and bath were averaged to obtain a weighted average in accordance with the procedure described above. It will be noted in Figs. 16 to 18 that the infiltration rates during duplicate tests were very consistent in some cases and deviated by as much as 10 percent in other cases. Some of the inconsistencies can be traced directly to differences in the basement temperature during comparable tests. The effect of basement temperature on infiltration will be discussed in more detail later. The relation of air change rate in the living quarters to indoor-outdoor temperature difference is also summarized in Table 1.

<u>Table 1</u>

AIR CHANGE RATES IN THE LIVING QUARTERS FOR
A RANGE OF INDOOR-OUTDOOR TEMPERATURE DIFFERENCE

INDOOR-OUTDOOR TEMPERATURE DIFFERENCE						
0°F	20°F	38°F	55°F	70°F	85°F	90°F
AIR CHANGES PER HOUR						
.245	.500	.792	1.15	1.31	1.60	1.64
.230	.540	.780	1.05	1.19	1.62	--

F. Infiltration in Basement, Attic, and Living Space

It is generally accepted that the infiltration into a building caused by the difference of the indoor and outdoor temperatures is the result of the chimney effect. In a closed building with the ordinary amount of air leaks suitably distributed, a neutral zone [7,8] exists at about midheight when the building is heated above the outdoor temperature. At the neutral zone the internal and external pressures are equal. Below the neutral zone a negative pressure exists in the building and air will leak inward whereas above the neutral zone the internal pressure is positive and the air leakage will be outward. Pressure measurements in the Test Bungalow with a sensitive differential

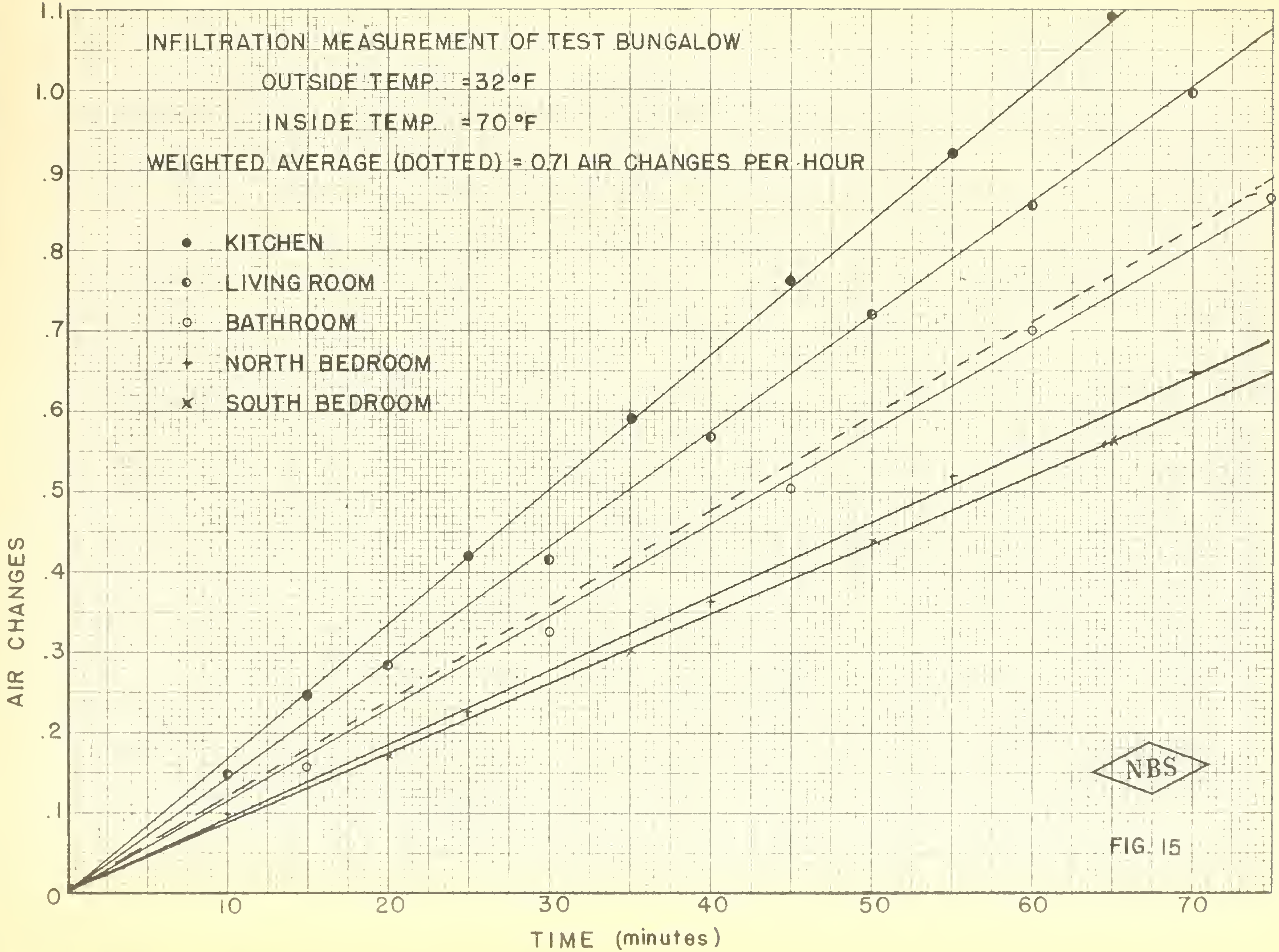
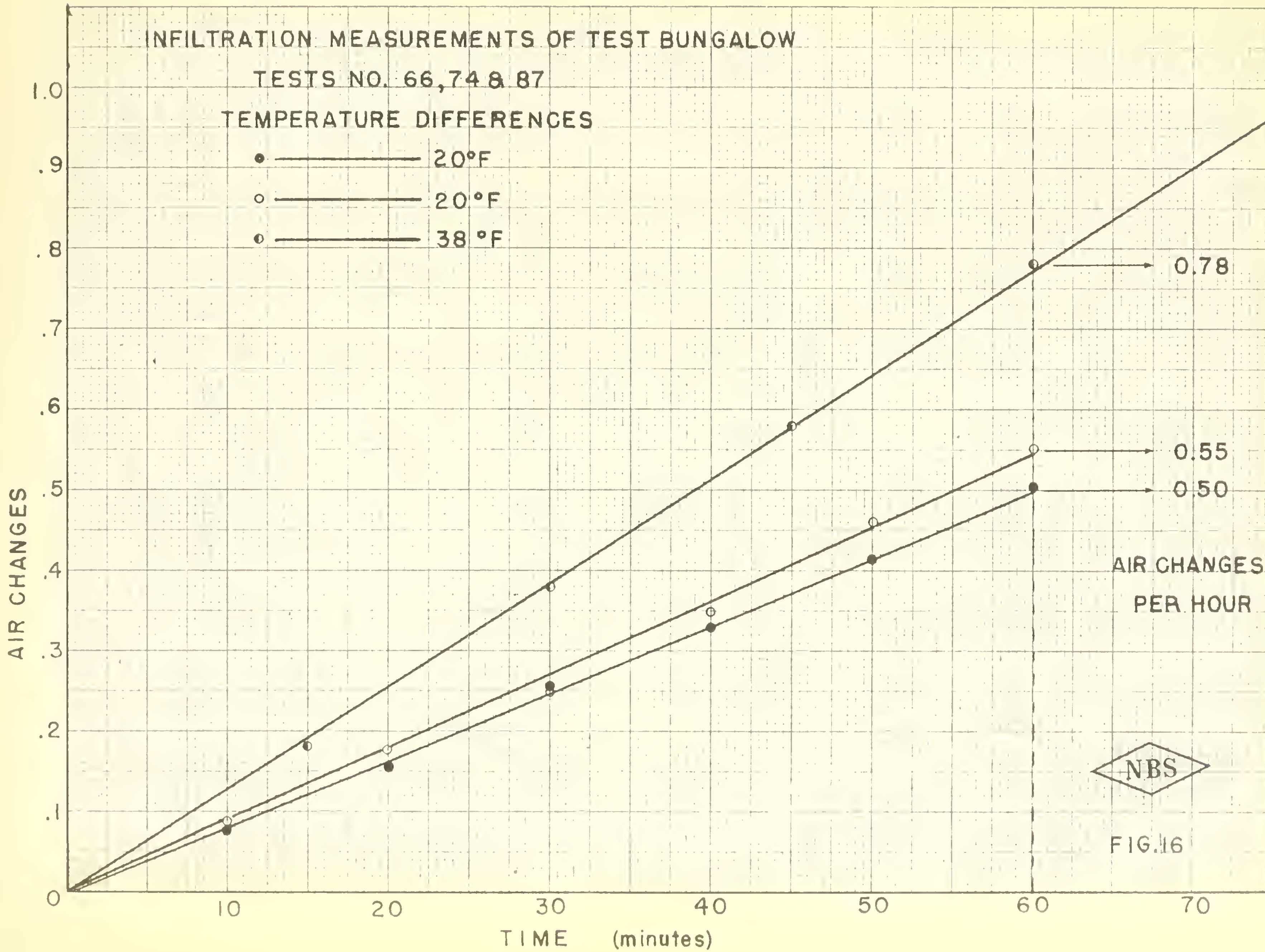
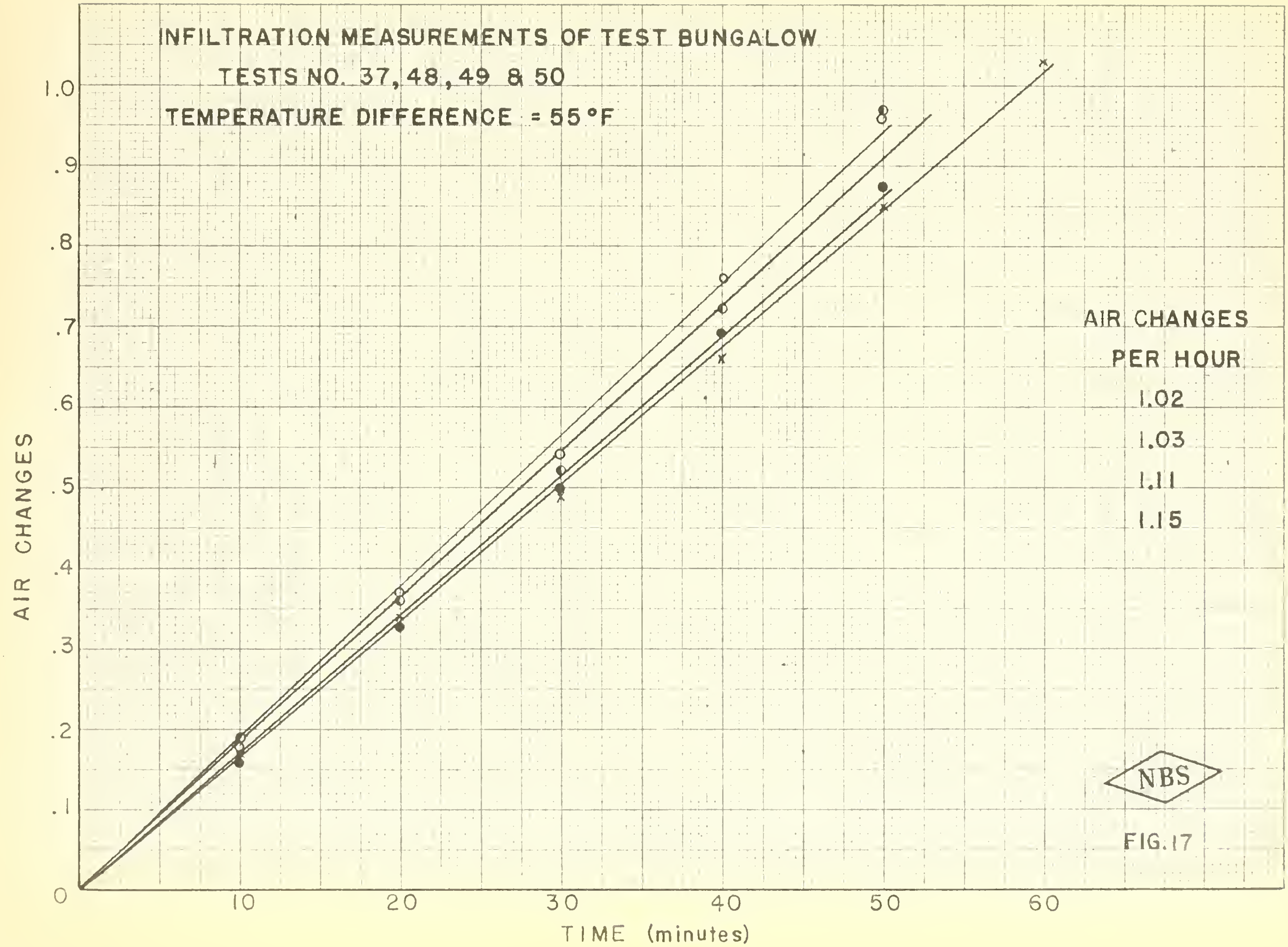

INFILTRATION MEASUREMENT OF TEST BUNGALOW
OUTSIDE TEMP. = 32 °F
INSIDE TEMP. = 70 °F
WEIGHTED AVERAGE (DOTTED) = 0.71 AIR CHANGES PER HOUR
KITCHEN
LIVING ROOM
BATHROOM
NORTH BEDROOM
SOUTH BEDROOM
AIR CHANGES
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
10
20
30
40
50
60
70
TIME (minutes)
NBS

FIG. 15



INFILTRATION MEASUREMENTS OF TEST BUNGALOW
TESTS NO. 66, 74 & 87
TEMPERATURE DIFFERENCES
20°F
20°F
38°F
0.78
0.55
0.50
AIR CHANGES PER HOUR
NBS
AIR CHANGES
TIME (minutes)
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
10
20
30
40
50
60
70

FIG. 16


INFILTRATION MEASUREMENTS OF TEST BUNGALOW
TESTS NO. 37, 48, 49 & 50
TEMPERATURE DIFFERENCE = 55°F
AIR CHANGES
PER HOUR
1.02
1.03
1.11
1.15
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
10
20
30
40
50
60
AIR CHANGES
TIME (minutes)
NBS
FIG. 17

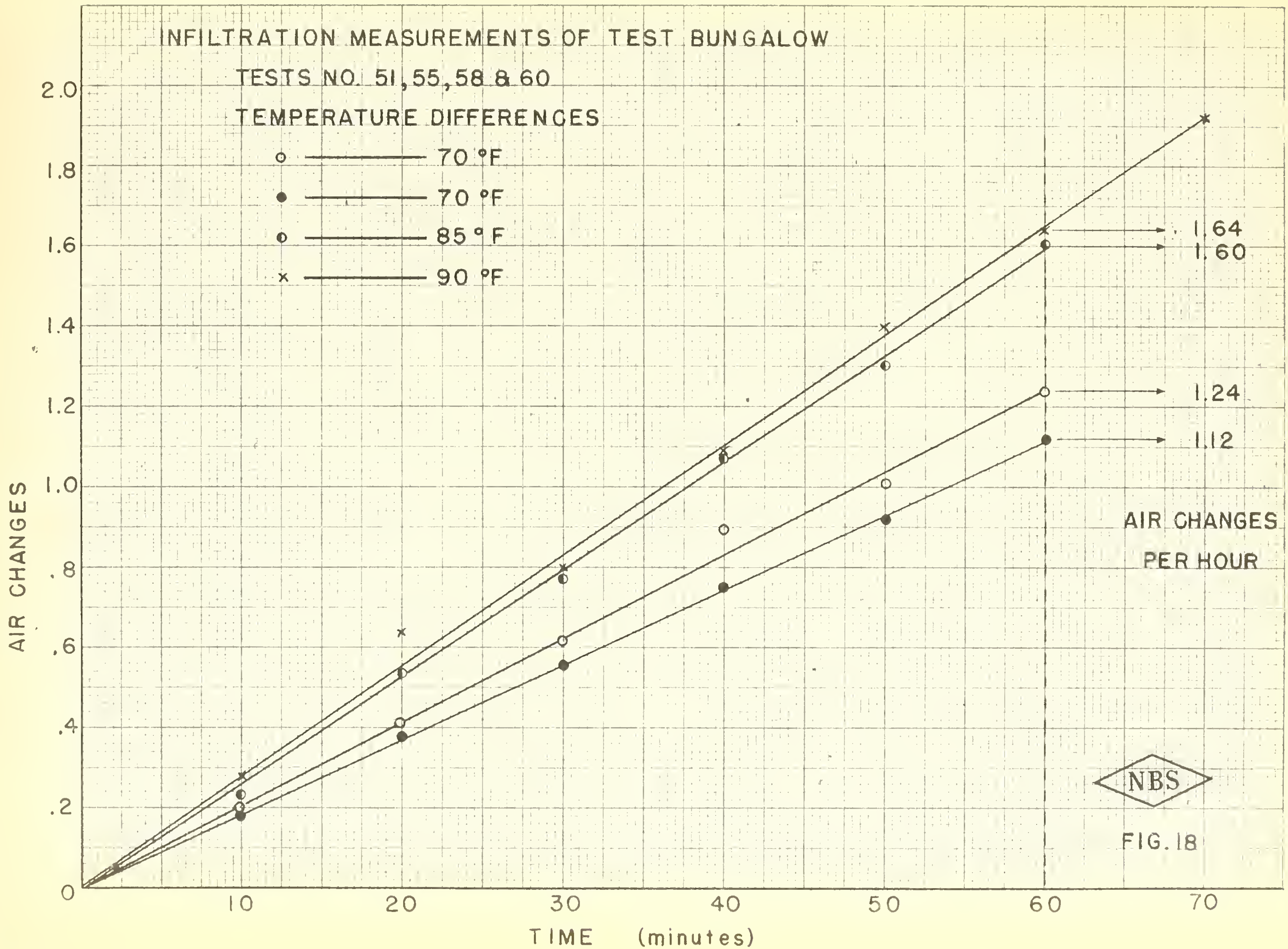

INFILTRATION MEASUREMENTS OF TEST BUNGALOW
TESTS NO. 51, 55, 58 & 60
TEMPERATURE DIFFERENCES
70 °F
70 °F
85 °F
90 °F
1.64
1.60
1.24
1.12
AIR CHANGES PER HOUR
AIR CHANGES
TIME (minutes)
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
10
20
30
40
50
60
70
NBS

FIG. 18

manometer showed that this neutral zone existed somewhere between floor and ceiling of the living quarters for certain test conditions. Based on these pressure measurements it was assumed that air exchange took place in both directions between the basement and the Bungalow enclosure and that there was no infiltration from the enclosure to the attic when the attic louvers were closed, but only exfiltration from the attic to the enclosure.

With these assumptions the air movement between enclosure, basement, living space, and attic was determined by the following procedure:

(a) The basement was contaminated with helium and the rate of air flow from the enclosure into the basement was determined.

(b) The attic was contaminated and its exfiltration to the enclosure was determined.

(c) The living space was contaminated and its total exfiltration to attic and enclosure measured.

(d) The increasing concentration of helium in the attic during step (c) was observed. The infiltration rate of the attic from the living space was computed taking into account the measured exfiltration from attic to enclosure.

(e) The difference between the attic exfiltration determined from step (b) and its infiltration from the living space is its infiltration from the basement.

(f) The decreasing concentration of helium in the living space during step (c) was observed. The rate of air movement from basement to living space was computed from the decrease in helium in the living space, the known total air motion from living space to attic and enclosure and the mean concentration of helium in the basement and enclosure during the test.

(g) The difference between the total infiltration into the basement measured in step (a) and the sum of the air exchange from basement to attic determined in step (e) and the air exchange from basement to living space determined in step (f) is the exfiltration from basement to enclosure.

(h) The difference between the infiltration from basement to living space determined in step (f) and the total exfiltration from the living space measured in step (c) is the infiltration from enclosure to living space.

(i) The difference between the total exfiltration from the living space determined in step (c) and the exfiltration from the living space to the attic determined in step (d) is the exfiltration from the living space to the enclosure.

If BE = the air flow from the basement to enclosure

BL = the air flow from the basement to living space

BA = the air flow from the basement to attic

EB = the air flow from the enclosure to basement

LA = the air flow from the living space to attic

LE = the air flow from the living space to enclosure

EL = the air flow from the enclosure to living space

AE = the air flow from the attic to enclosure

K_L = log mean average of concentration in living space during test

K_A = log mean average of concentration in attic during test

K_A' = concentration in attic at start of test

K_A'' = concentration in attic at end of test

V_A = volume of attic

K_E = log mean average of concentration in enclosure during test

K_B = log mean average of concentration in basement during test

K_L' = concentration in living space at start of test

K_L'' = concentration in living space at end of test

V_L = volume of living space

then

1. $BL + BA + BE = EB$
2. $LA + LE = BL + EL$
3. $BA + LA = AE$
4. $EL + EB = AE + LE + BE$
5. $LA = \frac{1}{K_L}\left[K_A''V_A + K_A + AE - K_A' \times V_A\right]$
6. $BL = \frac{1}{K_B}\left[V_L(K_L'' - K_L') + (LE + LA)K_L - EL \times K_E\right]$

Formula 5 is derived from the fact that the helium present in the attic at the start of the test plus that flowing into the attic during the test must equal the helium present in the attic at the end of the test plus that which leaked into the enclosure during the test. That is,

$$K'_A V_A + K_L \times LA = K''_A V_A + K_A \times AE$$

Formula 6 is derived from the fact that the helium present in the living space at the start of the test plus that flowing into it from the basement and enclosure during the test must equal the helium in the living space at the end of the test plus that flowing from it to the enclosure and attic during the test. That is,

$$V_L K'_L + BL \times K_B + EL \times K_E = V_L K''_L + (LE + LA) K_L$$

The quantities EB, AE, and LA + LE can be determined by conducting infiltration tests of the basement, attic, and living quarters, respectively and

$$K_L,\ K_A,\ K'_A,\ K''_A,\ K_B,\ K_E,\ K''_L,\ K'_L$$

will be known by observing concentrations in the attic, basement, enclosure, and living space during these tests. There will remain six unknowns in the above six equations which can readily be determined by computation.

Infiltration tests were made of the attic, basement and living space at various indoor-outdoor temperature differences so the patterns of air movement could be determined. These tests revealed the aforementioned inconsistency in the original tests of the living space. It was found that small changes in the basement temperature, when the temperature difference between living space and enclosure was constant, had considerable effect on the air change rate of the basement which in turn affected the air change rate of the living space. Since the basement temperatures were not too carefully regulated during the original tests of the living space there were some variations in results for duplicate tests as shown in Figs. 16 to 18.

Figs. 19, 20, and 21 show the air change rate vs. temperature difference curves for the house, basement, and attic, respectively. These curves are based on actual infiltration tests and form the basis for the calculations of the air flow patterns in the entire structure. It is noted that the variation of infiltration in the living space and attic with temperature difference between indoors and outdoors is linear whereas the basement infiltration is proportional to a power of the temperature difference greater than one. The relation between infiltration and temperature difference could not readily be predicted because the chimney effect of the entire structure depends on the temperature differences between enclosure and basement and between enclosure and attic as well as that between the enclosure and living space.

Figs. 22, 23, and 24 are graphical representations of the air flow to and from the living space, to and from the basement, and to and from the attic, respectively, for a range of temperature difference between living space and enclosure from 20 to 90 degrees F. The upper curve in each figure is plotted from direct measurements made with the katharometer. The other curves in each figure are derived from the relationships in the six simultaneous equations shown earlier.

All of the infiltration curves show consistent trends with variation of indoor-outdoor temperature difference except curves F and H in Fig. 22 and curves F and G in Fig. 23. All of these four curves depend on the evaluation of equation 6 of the group of simultaneous equations and involve several measurements of helium concentration in the basement, living space, and enclosure during a given test. It is believed that the results plotted for these curves at a temperature difference of 55°F are in error and that there should not be a radical change of curvature at this temperature difference.

The air exchange rates that involved measurements in the basement are not considered as accurate as the other results because considerable equipment was stored in the basement. This condition made the basement volume somewhat indeterminate and hindered good mixing of the helium and fresh air initially and during the progress of the tests. More reliable data could be obtained in the basement, if it were empty.

The leakage indicated from basement to attic presumably occurred through the hollow stud spaces in the walls without entering the living space. Filling the stud spaces with insulation would close this path of air flow.

It is not known whether or not the air movements between the enclosure, basement, living space, and attic that are shown in Figs. 22, 23, and 24 are typical for frame houses of similar construction. The Test Bungalow had a plastered ceiling and was finished with gypsum wallboard with nailing strips at the joints of the wall surfaces at the time of these tests. It is probable that there were some cracks for air leakage between the stud spaces and the living space. A number of openings had been made through the double wood floor for tests of heating equipment prior to the infiltration tests, but these were carefully rebuilt, sealed with building paper between sub-flooring and finish flooring and caulked at the edges before starting the infiltration tests.

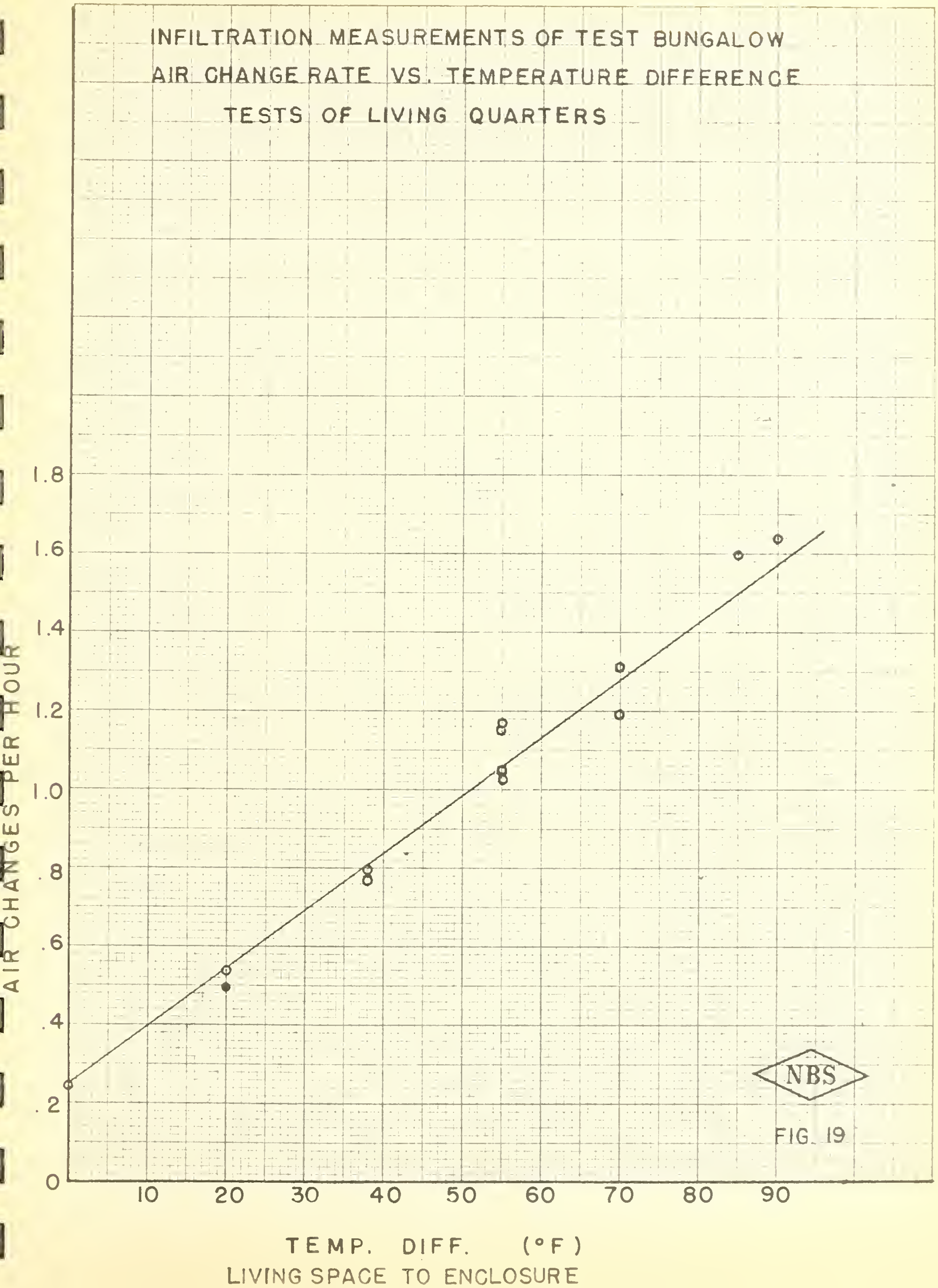

INFILTRATION MEASUREMENTS OF TEST BUNGALOW
AIR CHANGE RATE VS. TEMPERATURE DIFFERENCE
TESTS OF LIVING QUARTERS
AIR CHANGES PER HOUR
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
10
20
30
40
50
60
70
80
90
TEMP. DIFF. (°F)
LIVING SPACE TO ENCLOSURE
NBS

FIG. 19

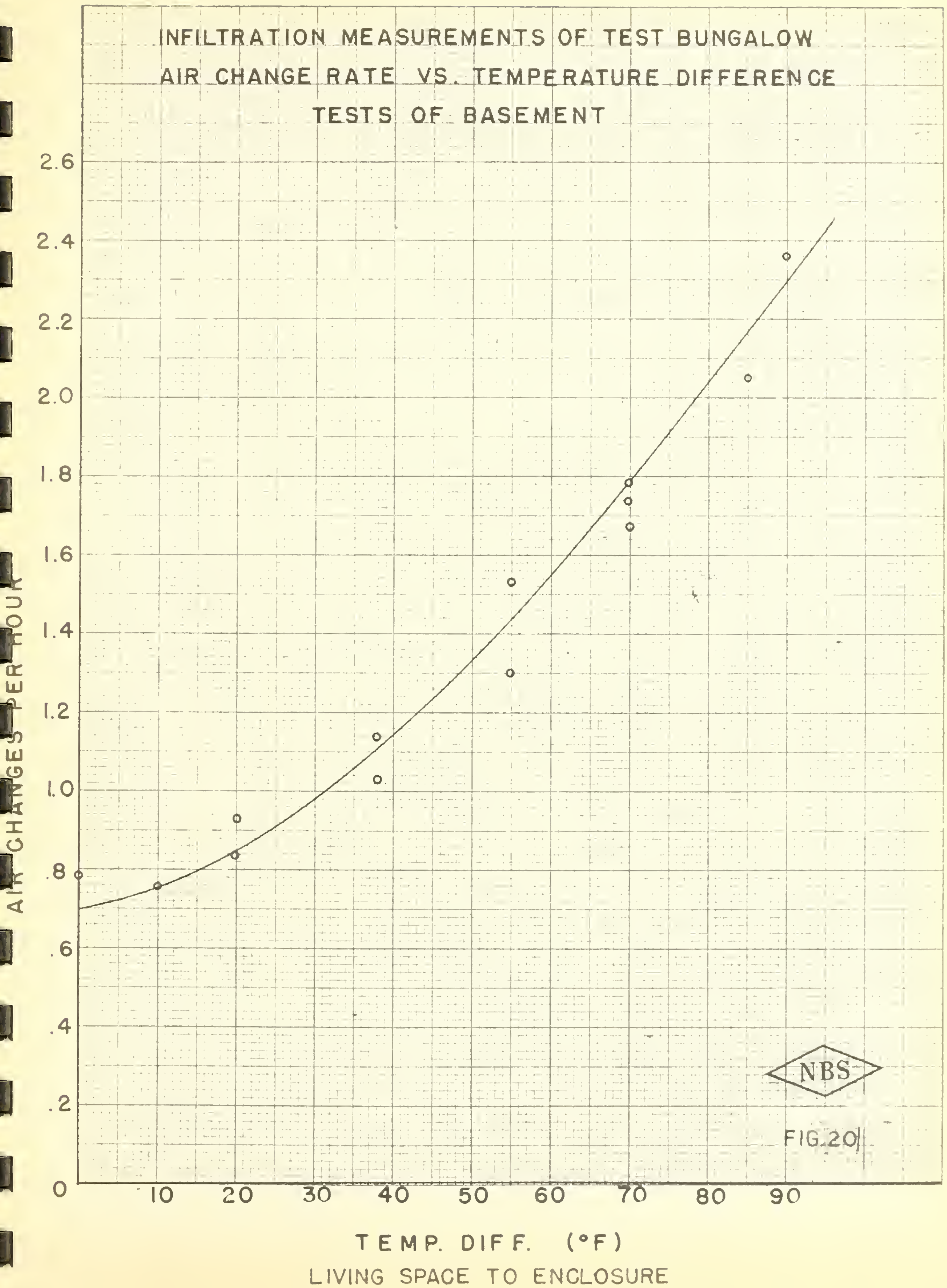
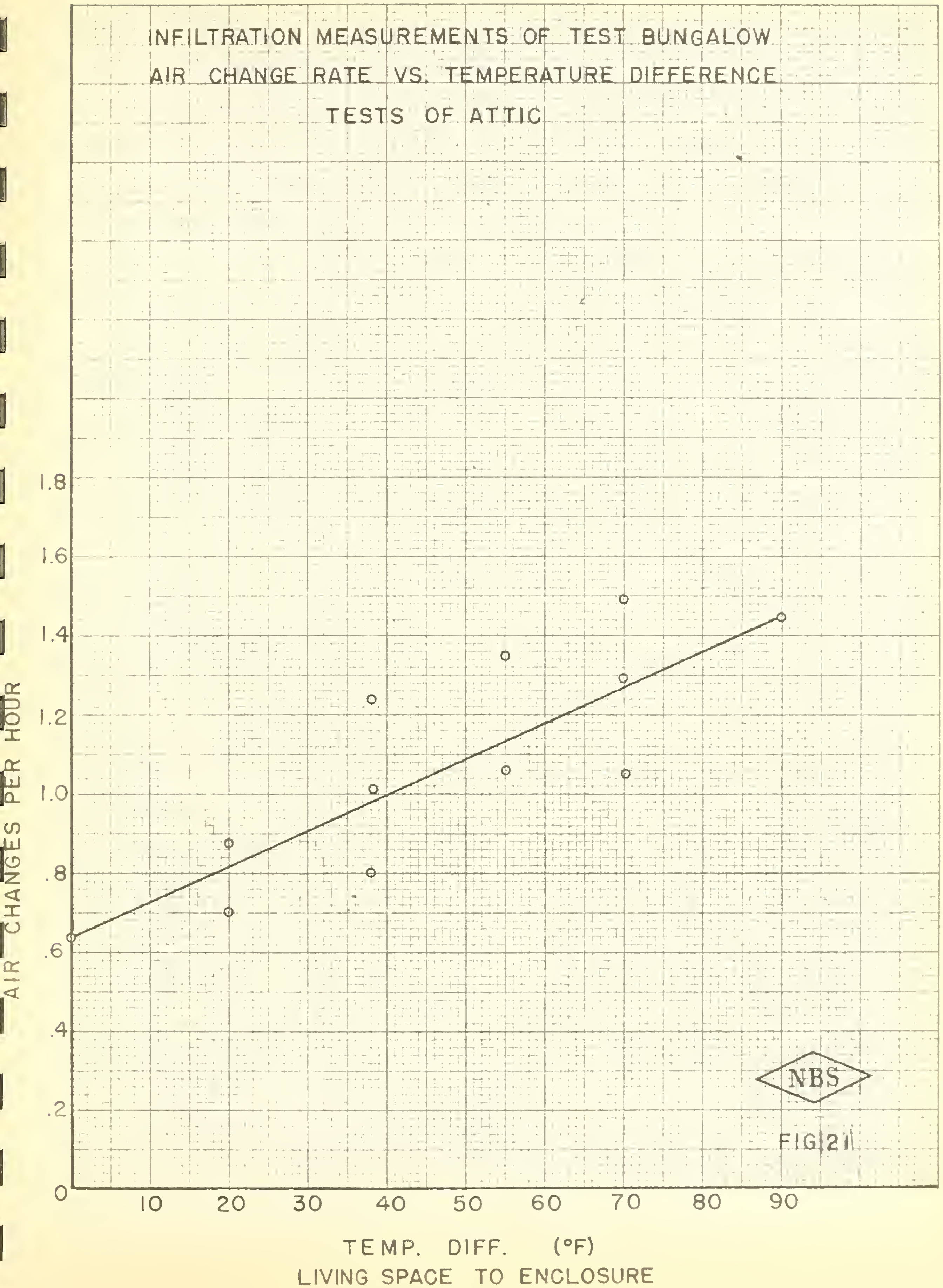
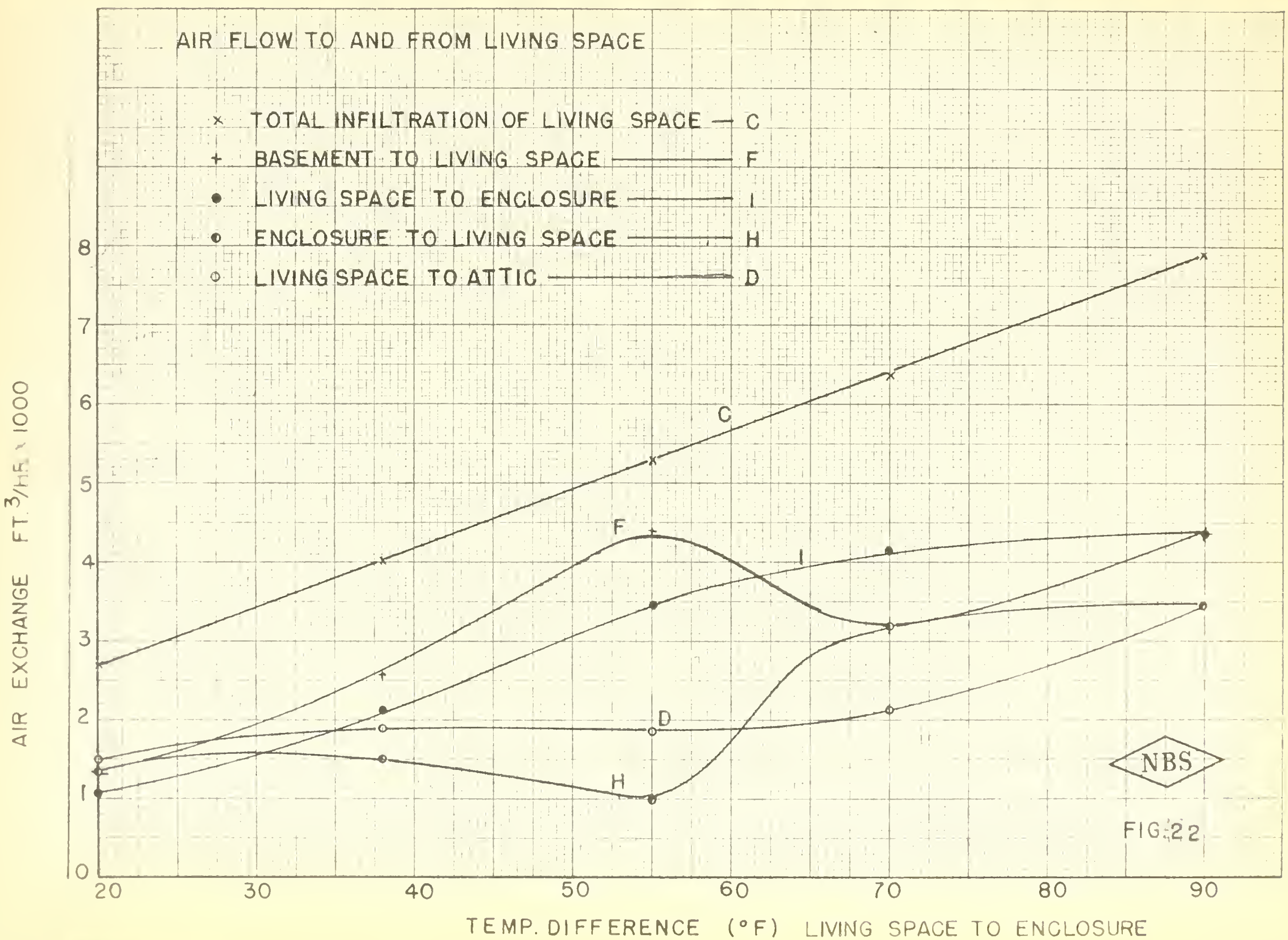

INFILTRATION MEASUREMENTS OF TEST BUNGALOW
AIR CHANGE RATE VS. TEMPERATURE DIFFERENCE
TESTS OF BASEMENT
AIR CHANGES PER HOUR
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
10
20
30
40
50
60
70
80
90
TEMP. DIFF. (°F)
LIVING SPACE TO ENCLOSURE
NBS

FIG. 20


INFILTRATION MEASUREMENTS OF TEST BUNGALOW
AIR CHANGE RATE VS. TEMPERATURE DIFFERENCE
TESTS OF ATTIC
AIR CHANGES PER HOUR
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
10
20
30
40
50
60
70
80
90
TEMP. DIFF. (°F)
LIVING SPACE TO ENCLOSURE
NBS
FIG. 21


AIR FLOW TO AND FROM LIVING SPACE
× TOTAL INFILTRATION OF LIVING SPACE — C
+ BASEMENT TO LIVING SPACE — F
● LIVING SPACE TO ENCLOSURE — I
◉ ENCLOSURE TO LIVING SPACE — H
○ LIVING SPACE TO ATTIC — D
C
F
I
D
H
NBS
0
1
2
3
4
5
6
7
8
20
30
40
50
60
70
80
90
AIR EXCHANGE FT.^{3}/HR × 1000
TEMP. DIFFERENCE (°F) LIVING SPACE TO ENCLOSURE
FIG. 22

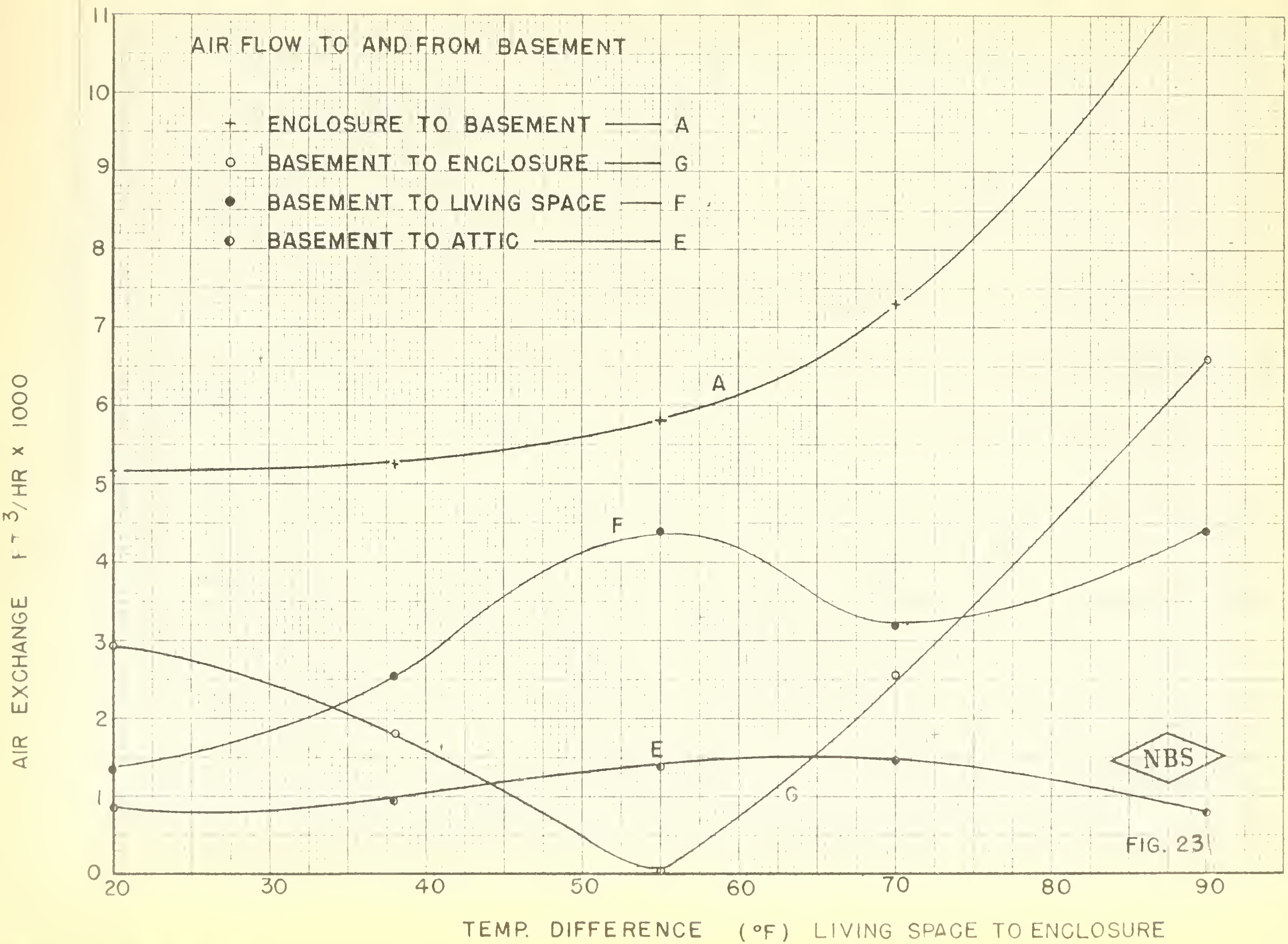

AIR FLOW TO AND FROM BASEMENT
ENCLOSURE TO BASEMENT — A
BASEMENT TO ENCLOSURE — G
BASEMENT TO LIVING SPACE — F
BASEMENT TO ATTIC — E
A
F
E
G
NBS
AIR EXCHANGE FT 3/HR x 1000
TEMP. DIFFERENCE (°F) LIVING SPACE TO ENCLOSURE
0
1
2
3
4
5
6
7
8
9
10
11
20
30
40
50
60
70
80
90

FIG. 23

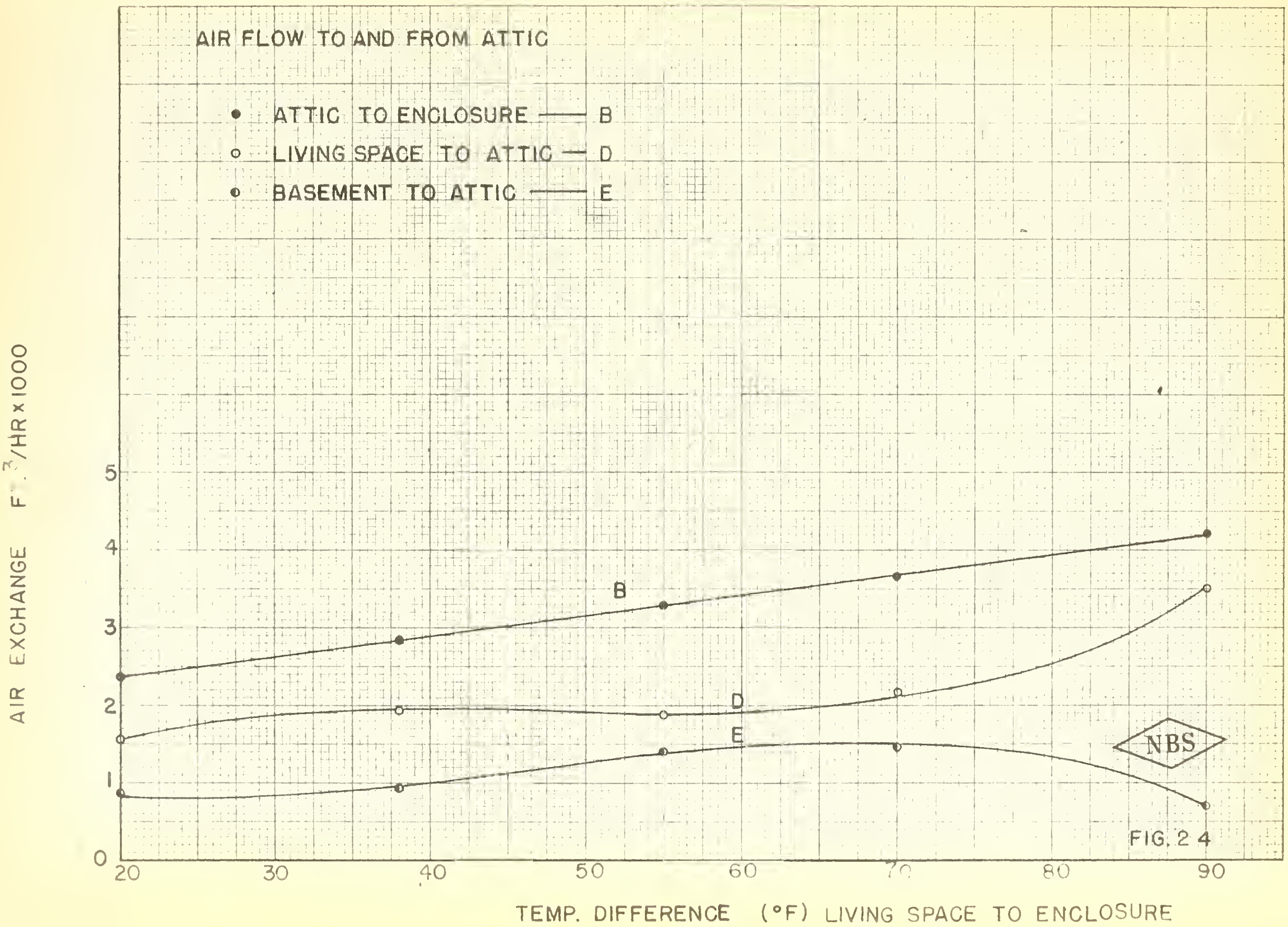

AIR FLOW TO AND FROM ATTIC
ATTIC TO ENCLOSURE — B
LIVING SPACE TO ATTIC — D
BASEMENT TO ATTIC — E
B
D
E
NBS
0
1
2
3
4
5
20
30
40
50
60
80
90
TEMP. DIFFERENCE (°F) LIVING SPACE TO ENCLOSURE
AIR EXCHANGE

FIG. 2 4

G. Effects of the Opening of the Attic Louvers

During all the tests previously discussed in this report the louvers of the attic were packed with insulation to prevent air circulation. The Test Bungalow was normally kept in this condition for tests of heating equipment. However, since attic ventilation is often recommended for winter conditions a short series of tests was made, for comparison, with the attic louvers open. Figs. 25 and 26 show the results for two of these tests. A comparison of these results with those summarized in Table 1 indicates that opening the attic louvers increased the infiltration in the living space from 30 to 35 percent. The infiltration was also increased in the basement, and of course, the ventilation in the attic was very much higher when the louvers were open than when they were closed.

H. Door Tests

Tests were also made to determine the amount of air infiltration when a person opens and closes an interior door to enter a room or an exterior door to enter a house. An opening time of 4 seconds and an opening width of 28 inches were found to be representative values, and these values were used in the following tests. There was no temperature difference between the spaces connected by the doors for these tests.

After mixing the room air with about 0.5% of helium a series of concentration measurements was made. The door was then opened and closed as described above ten times at one minute intervals to obtain a significant change of concentration in the room. Before continuing with the concentration measurements it was necessary to thorughly mix the infiltrated air in the room with the helium-air mixture by operating a circulating fan in the room for 30 seconds, after which another series of concentration measurements was made. Previous tests had shown that the infiltration rate of a room was appreciably increased by a forced air movement in the room. Therefore, the fan was operated again for another 30 seconds with the door closed before taking a third series of concentration measurements to evaluate the effect of the fan operation. The air changes were then calculated and plotted against time. As the three groups of measurements were taken with the doors and windows of the room in the same condition the air change rate should have been constant, i.e., the air change curves should be straight and parallel lines. The vertical distances between pairs of curves were a measure of the air changes caused by the door openings and fan operation. Fig. 27 shows the test results obtained when opening the interior door between the north bedroom and the hall of the Test Bungalow without heating or forced air circulation around the building. Tests were made under the same conditions with the outside doors of the living room and the kitchen and the following values were obtained for the air infiltration for one opening of the door in each case.

Room	Door Size, in.	Infiltration, cu ft
North bedroom	30 x 78	17.4
Living room	36 x 78	36.5
Kitchen	30 x 78	32.4

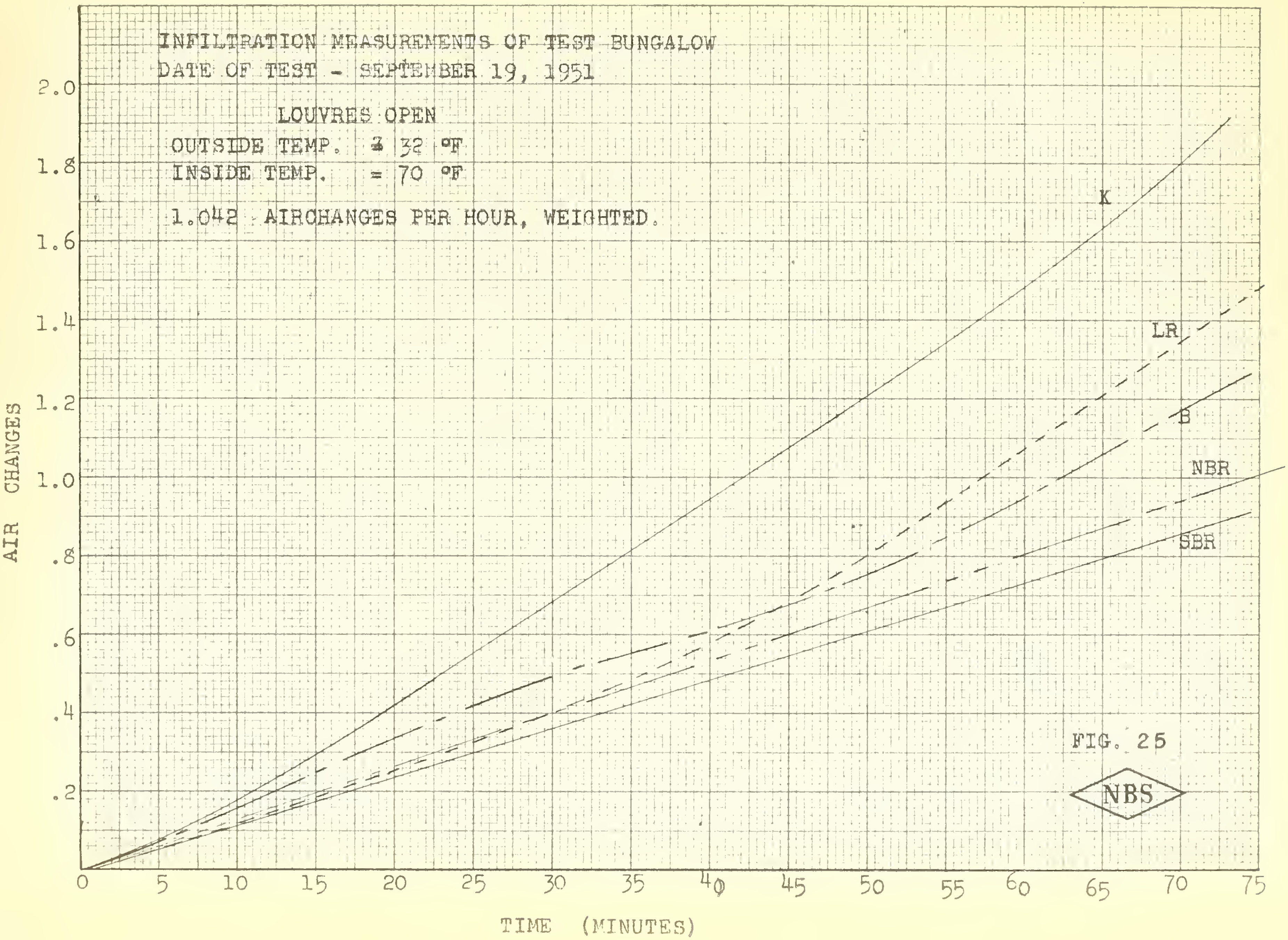
It is probable that the observed value of air infiltration for each door opening was a little lower than the actual value because of rebreathing during every opening of the door after the first. That is, with no forced air motion either inside or outside the room near the door, the air would be contaminated with helium on the outside and the room air-helium mixture near the door on the inside would have a helium concentration lower than the room average after the first few door openings. Consequently, the air entering the room would not be pure and the air leaving the room would not be representative of the average in the room. Although there was no temperature-difference between outdoors and living space during these tests, it would be expected that the basement caused some chimney effect and that this chimney effect would cause greater infiltration through an outside door than was observed for an interior door.

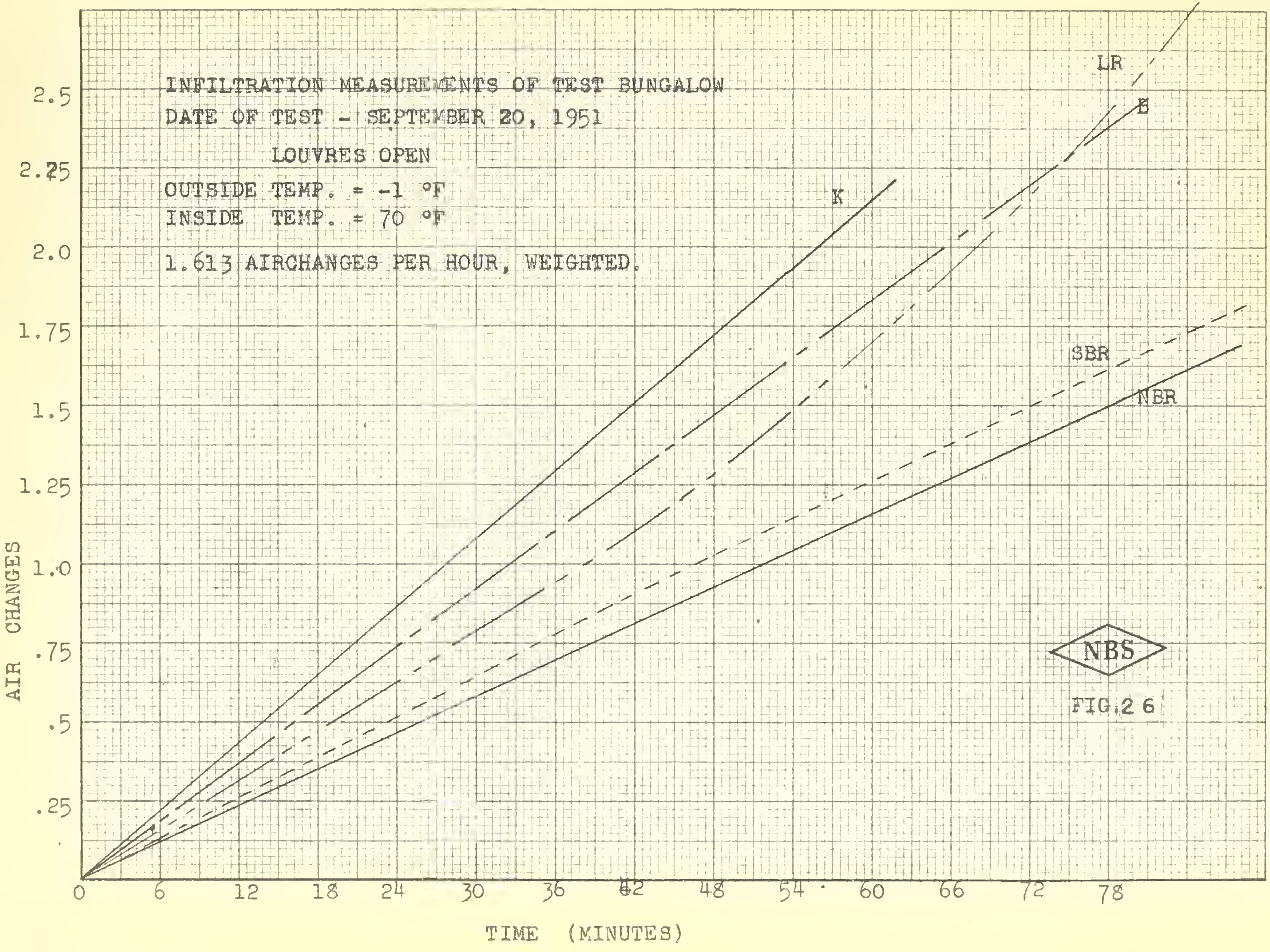
I. Effect of an Open but Unheated Fireplace

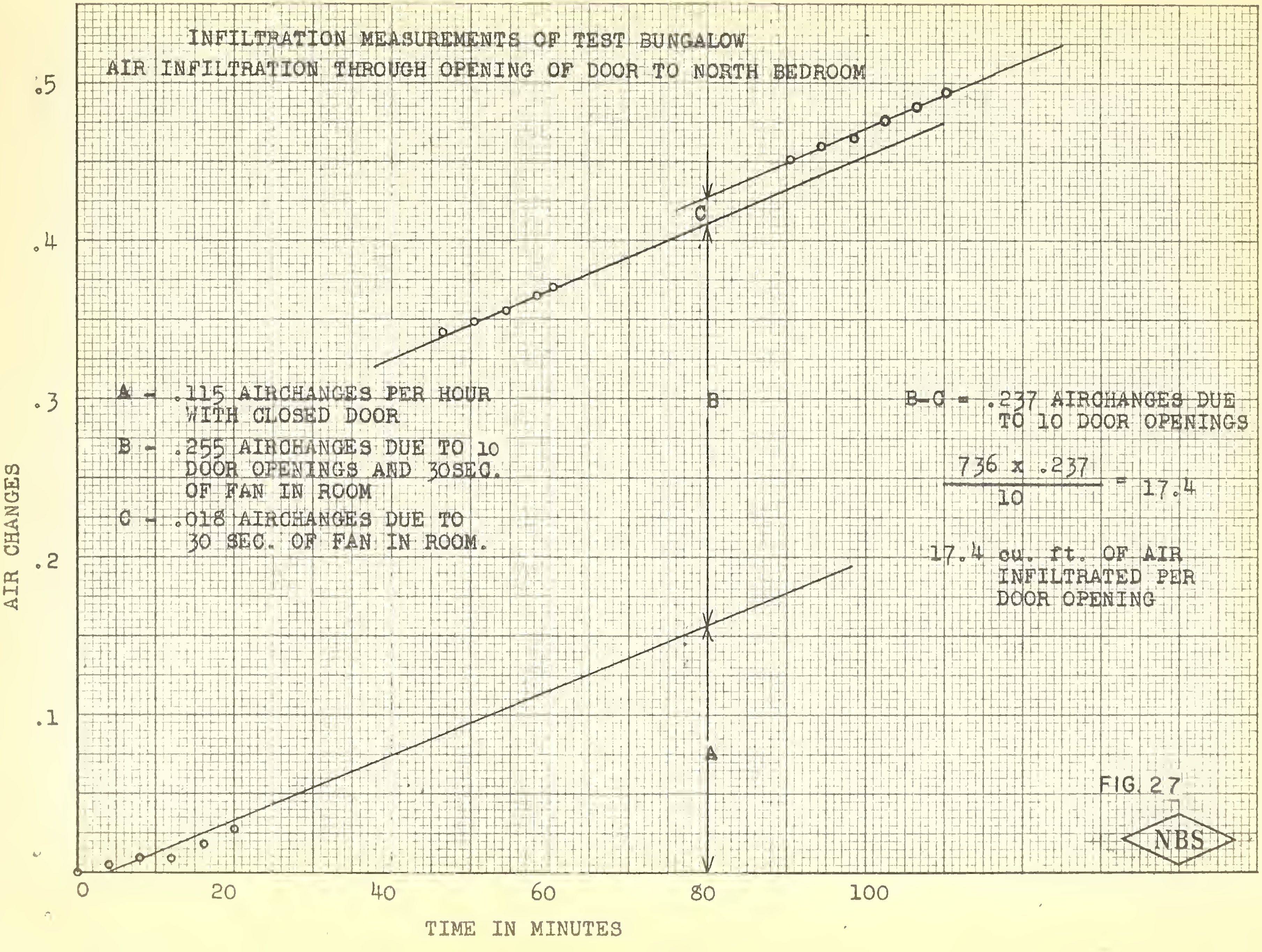
Two tests were made to determine the effect of an open fireplace flue on the infiltration rate of the Test Bungalow. The flue of the fireplace was generally kept closed with a steel plate during all tests. When this plate was removed the air change rate of the living space with all inside doors kept open and with an outside temperature of 32°F increased from 0.78 to 1.99 per hour, i.e. by 1.21 air changes per hour. With a house volume of 4,900 cu. ft, this means that the volume of air removed from the house through the unheated fireplace flue every hour approximated 6,000 cu ft.

IV. DESIGN OF A PORTABLE KATHAROMETER

The Cambridge helium indicator appeared to be quite satisfactory for measurement of infiltration in the Test Bungalow. However, the lag in response of the instrument was some disadvantage in attempting to observe the helium concentration at a number of stations. This lag was related to and dependent in part upon the length of the sampling lines. It was also observed by trial that the instrument was too cumbersome and heavy for field use.


INFILTRATION MEASUREMENTS OF TEST BUNGALOW
DATE OF TEST - SEPTEMBER 19, 1951
LOUVRES OPEN
OUTSIDE TEMP. = 32 °F
INSIDE TEMP. = 70 °F
1.042 AIRCHANGES PER HOUR, WEIGHTED.
K
LR
B
NBR
SBR
AIR CHANGES
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
TIME (MINUTES)
NBS
FIG. 25


INFILTRATION MEASUREMENTS OF TEST BUNGALOW
DATE OF TEST - SEPTEMBER 20, 1951
LOUVRES OPEN
OUTSIDE TEMP. = -1 °F
INSIDE TEMP. = 70 °F
1.613 AIRCHANGES PER HOUR, WEIGHTED.
LR
B
K
SBR
NBR
NBS
AIR CHANGES
TIME (MINUTES)
0
6
12
18
24
30
36
42
48
54
60
66
72
78
.25
.5
.75
1.0
1.25
1.5
1.75
2.0
2.25
2.5
FIG. 26


INFILTRATION MEASUREMENTS OF TEST BUNGALOW
AIR INFILTRATION THROUGH OPENING OF DOOR TO NORTH BEDROOM
A - .115 AIRCHANGES PER HOUR WITH CLOSED DOOR
B - .255 AIRCHANGES DUE TO 10 DOOR OPENINGS AND 30SEC. OF FAN IN ROOM
C - .018 AIRCHANGES DUE TO 30 SEC. OF FAN IN ROOM.
B-C = .237 AIRCHANGES DUE TO 10 DOOR OPENINGS
736 x .237 / 10 = 17.4
17.4 cu. ft. OF AIR INFILTRATED PER DOOR OPENING
AIR CHANGES
.5
.4
.3
.2
.1
0
20
40
60
80
100
TIME IN MINUTES
A
B
C
NBS
FIG. 27

Consideration of the operating principle of the helium katharometer led to the conclusion that a simpler portable instrument could be designed using the same principle, but depending on natural convection rather than a vacuum pump for sampling the air-tracer-gas mixture. Such an instrument was designed, constructed, and preliminary tests completed. A photograph of the pilot instrument is shown in Fig. 28.

The helium indicator designed at the National Bureau of Standards was comprised of a portable amplifier the size of a small table radio and a sensitive cell consisting of a metal block with two cylindrical cavities in which thermistors were installed. The thermistors were arranged in a Wheatstone bridge circuit with the two reference resistors placed in the metering box which could be connected to the cell by a cable of any desired length. For testing, the cell was placed in the room whose infiltration was to be determined and the operator with the metering box could be in close proximity or outside the building.

One thermistor cavity was continuously ventilated by a natural convection air movement resulting from the heated thermistor and passing through small holes at the top and at the bottom of the cavity. The other thermistor cavity was tightly sealed during the test after having been opened before the tracer gas was introduced into the room to assure that the tracer gas itself was the only difference between the air in the two cavities. The equality of the air temperature in the cavities was assured by the enclosing metal block.

The thermistors were heated with alternating current and the bridge circuit was balanced before tracer gas was introduced into the room. The off-balance potential, resulting from the presence of tracer gas in only one cavity, was electronically amplified. The output current of the amplifier was adjusted to be directly proportional to the concentration of the tracer gas. An amplifier gain control made it possible to read either the absolute tracer gas concentration, to provide a full scale deflection for any helium concentration between 0.4% and 1.5% or to observe the concentrations of any other tracer gas having similar thermal conductivity that is convenient for the particular study to be undertaken. By adding a selector switch to the metering box of the instrument, any number of test cells could be used thus permitting as many observation stations during one test as desired.

Several comparison tests were made using the new instrument and the Cambridge helium indicator in the Test Bungalow. Figs.29 and 30 show comparisons between the airchanges calculated from decay measurements made at the same time in the same space with the two analyzers. These curves show substantial agreement between the two instruments for infiltration rates of 1.1 and 2.4 airchanges per hour. There was some small scattering of the points for both instruments but the data indicate a straight line infiltration rate for each. The same line best represents the data for both instruments in Fig. 29 whereas in Fig. 30 the best line for each set of points indicates a difference in infiltration rate of about 4 percent, the Cambridge instrument indicating the higher value. The low initial concentration of 0.24% used for the test represented by Fig. 30 was probably disadvantageous to the Cambridge instrument because of parallax and drift errors in reading the lower end of the scale.

When considering the results in Fig. 29 and 30 along with the correction factors determined for the Cambridge instrument and shown in Fig. 2, it is concluded that the NBS katharometer indicated infiltration rates that were higher than the true values by amounts ranging from 0 to 4 percent. The NBS instrument was not graduated in percent helium so a calibration of this instrument in terms of absolute concentrations could not be made.

In preparing for the comparison of the performance of the two helium indicators the following test procedure was used.

Helium gas was fed into the North Bedroom of the Test Bungalow for a period of one minute during which the air and helium were being mixed by means of a 16-inch desk fan. This mixing continued for one minute after ceasing to inject helium gas into the room. Separate copper tubes were used for injecting the helium gas into the room and for sampling the mixture, since earlier tests revealed some difficulties in purging the helium from such a line promptly after injection.

Following the one-minute injection period the gas mixture was drawn through the sampling lines for 5 minutes before any observations were taken. At the end of this 5-minute period the indicator on the Cambridge instrument had reached the maximum, and it was at this time that the decay measurements commenced as shown in Figs. 29 and 30.

The thermal conductivity cell of the NBS instrument was in the room to be investigated all during the above procedures with the ports to the sampling cylinder open to the atmosphere in the room. The zero point on the time scale for the NBS instrument was the same clock time as for the other instrument in Figs. 29 and 30. The concentrations observed at zero time on both instruments were considered 100% concentration for comparison with later readings on the same instrument. Thus, the curves shown on the attached figures really represent rates of dilution relative to the concentration that existed at zero time. It is probable that the absolute concentrations of helium in the thermal conductivity cells of the two instruments were actually a little different at the zero point on the time scale.

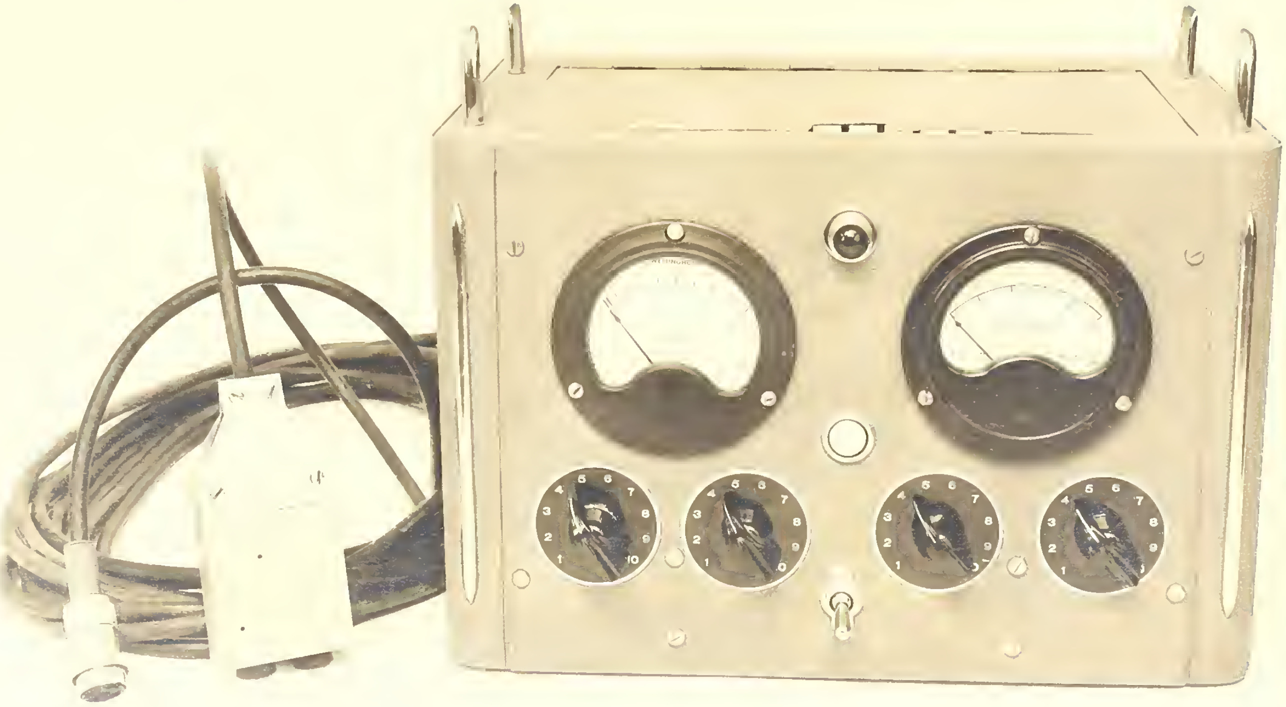


FIG. 28

COMPARISON BETWEEN CAMBRIDGE INSTRUMENT CO. AND N.B.S. HELIUM INDICATORS.

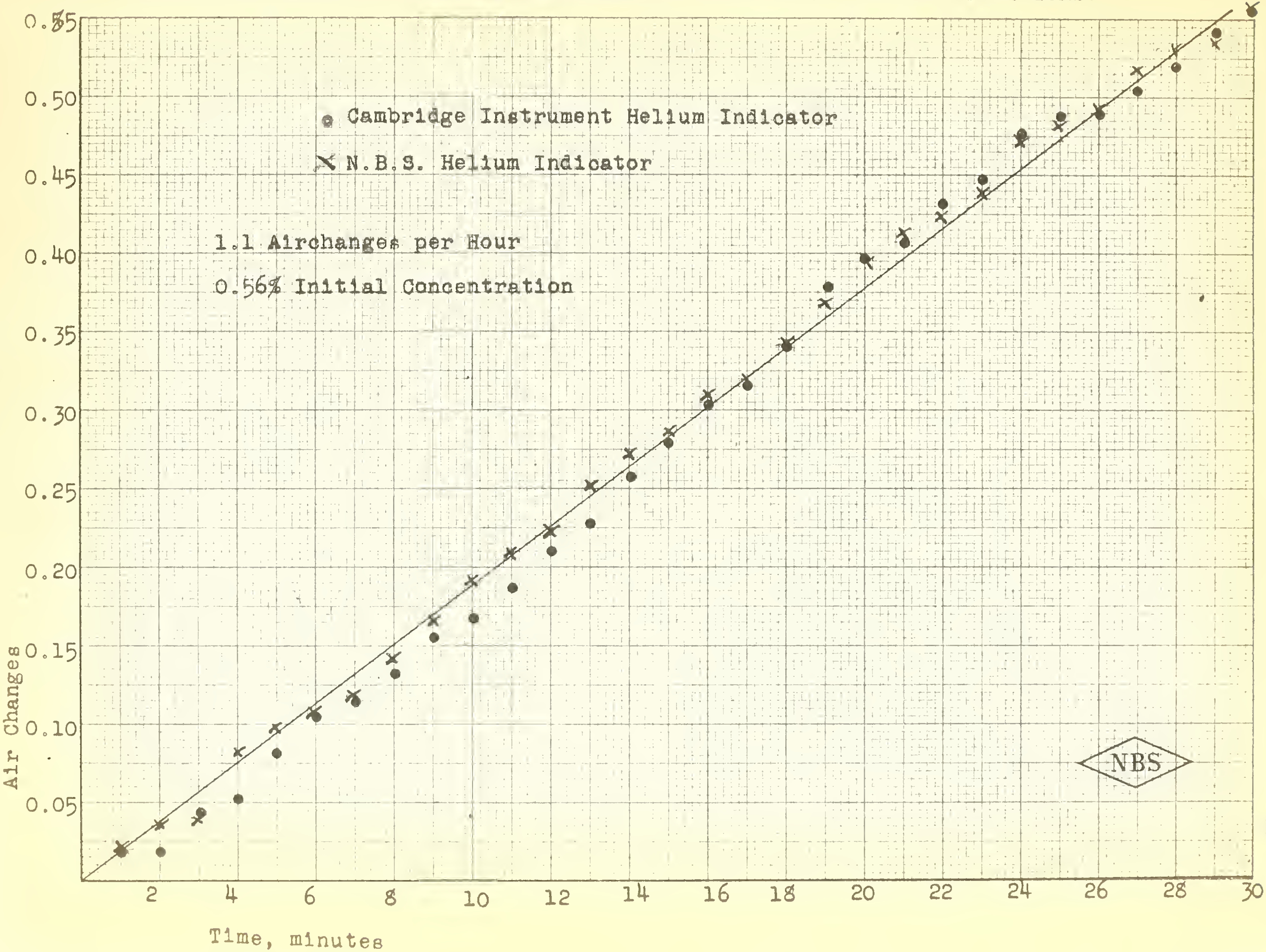


Fig.29

COMPARISON BETWEEN CAMBRIDGE INSTRUMENT COMPANY AND N.B.S. HELIUM INDICATORS.

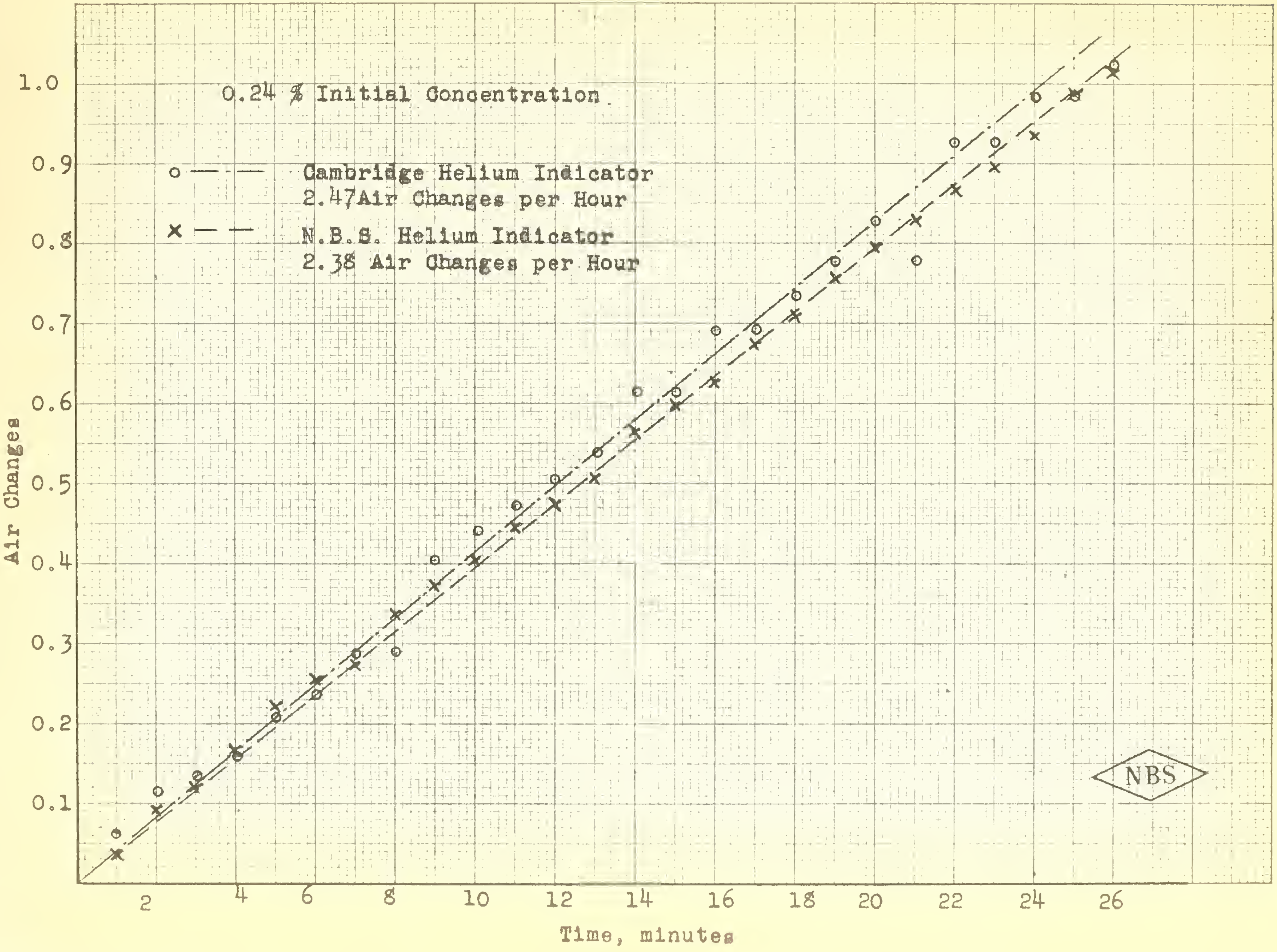


Fig. 30

V. MEASUREMENTS OF CRAWL SPACE VENTILATION

A. Ventilation through Foundation Louvers

Prior to the investigation of infiltration by means of a tracer gas and the katharometer a study was made of several methods of ventilating crawl spaces for dwellings. It is generally accepted that the crawl space of houses should be ventilated during the summer in most parts of the United States east of the Mississippi River where high humidity occurs during the summer to minimize condensation and rot of floor and foundation constructions. The usual method used is to provide openings in the foundation wall on all or several sides of a house so natural convection and wind forces can ventilate the space under the floor. However, very little is known about how much air exchange occurs through such foundation louvers, probably because instruments for measurement of very low air velocities have not been available.

Tests were made to determine the amount of ventilation provided for a crawl space beneath a house by openings in the foundation walls. The Test Bungalow was used for this purpose and observations were made with still air surrounding the house and with the blowers of the refrigerating units circulating approximately 20,000 cfm around the structure. Observations were taken for outdoor temperatures of 0°F, 50°F and 85°F with the indoor temperature being maintained at about 70°F in the living space. The area of the foundation ventilators was determined by the following formula: Area = 2 sq ft per 100 linear feet of perimeter plus 1/300 of the crawl space area. For the Test Bungalow the formula indicated a total of 4.17 sq ft of ventilator area.

For the tests six of the panes were removed from the basement windows; two each on the east and south exposures and one each on the north and west exposures. The total area of the six openings was 4.08 sq ft. Metal ducts about two feet in length were installed in the openings to streamline the air flow somewhat and facilitate air velocity measurements. For these tests all of the visible cracks and openings in the floor construction were sealed and all visible cracks in the subfloor duct system of the warm air heating plant were sealed to minimize air exchange between the basement and living space. Observations of air velocity were made with a pitot tube and differential manometer when the blowers were in operation whereas the rate of air motion was determined by timing the travel of visible smoke in the metal ducts through the foundation for the still air condition around the house. The latter method was not considered to be very precise but was used because the delivery of the commercial thermocouple-anemometer ordered for this purpose was delayed several times. The results of these observations are shown in Table 2.

The data in Table 2 show that air flowed into the basement through a part of the openings and out through others when the blowers were in operation, but the net flow was inward for all three outdoor temperatures tried. The amount of air flowing into the basement and out again ranged from 300 to 400 cfm whereas the amount that entered the basement through the foundation ventilators and then passed upward through the floor ranged from 86 to 244 cfm. The results indicate that the natural chimney effect of the house assisted the flow of air upward through the house construction because the net inward flow increased as the outdoor temperature decreased. Test 3 indicates that the blowers used for circulating air around the Test Bungalow created a lower pressure at the roof than at the basement level. With the outdoor temperature higher than the temperature of either the living space or the basement as in Test 3 the chimney effect of the house should have been reversed and the net flow of ventilating air should have been from basement to enclosure instead of vice versa. This result was observed in Tests 9-11 when the blowers were not running. It is apparent that the blowers counteracted the chimney effect and produced an upward flow through the floor of 86 cfm. A comparison between Test 1 in Table 2 and tests with the katharometer for the same indoor-outdoor temperature difference shows that the net air leakage into the basement and up through the house was about twice as great with the foundation ventilators open as when they were closed.

For still air conditions around the house as in Tests 4-11 of Table 2 the chimney effect of the house predominated and the direction of flow of air between basement and outdoors was determined by the relation between the temperature indoors and the outside temperature. As the outside temperature was lowered from 50°F to 0°F the net inward flow of outside air to the basement increased from 111 cfm to 366 cfm. For three tests with the outside air 10 to 15 degrees F warmer than the living space the net flow of air from the basement to outside ranged from 119 cfm to 152 cfm. If the Test Bungalow were assumed to have a crawl space two feet high the rates of air exchange reported for still air conditions would range from one air change in eleven minutes for Test 8 to one air change in 3.4 minutes for Test 5.

An apparent inconsistency is indicated by a comparison of the net flow of air into the basement in Test 1 with that observed for Tests 4 and 5. This comparison shows greater ventilation with still air than with forced air circulation around the bungalow for the same outdoor temperature. This would appear to contradict the indication in Test 3 that the blower operation provided an upward air movement through the structure in opposition to the chimney effect. It is quite probable that air

Table 2

Ventilation of Crawl Space
by
Openings in Foundation Walls

Forced Air Circulation Around Test Bungalow

Test No.	Outdoor Temp.	Temp. Difference Basement to Outdoors	Air Movement Through Foundation Opening						Total Inward Flow	Total Outward Flow	Net Flow
			A	B	C	D	E	F			
	°F	°F			CFM				CFM	CFM	CFM
1	0	+25	+127[b]	-141[b]	-161[b]	+139[b]	+136[b]	+144[b]	546	302	+244[b]
2	50	0	+126	-214	-180	+170	+158	+149	603	394	+209
3	80	-10	- 44	-176	-156	+171	+169	+122	462	376	+ 86
Still Air Around Test Bungalow											
4	0	+25	+57	+66	+71	+39	+37	+47	317	0	+317
5	0	+25	+68	+71	+86	+42	+58	+41	366	0	+366
6	48[a]	+ 7	+62	+61	+53	+17	+12	+18	-	-	+223
7	48[a]	+ 9	+50	+48	+41	+11	+12	+19	-	-	+181
8	50	0	+17	+20	+19	+19	+17	+19	111	0	+111
9	80	-13	-34	-23	-23	-17	-17	-19	0	133	-133
10	85[a]	-16	-36	-26	-28	- 9	- 9	-11	-	-	-119
11	85[a]	-21	-47	-32	-28	-14	-15	-16	-	-	-152

[a]Two-way flow was observed in some of the ducts during these tests.

[b]Positive sign indicates inward flow; negative sign, outward flow.

entered the basement from the enclosure through cracks and fissures as well as through the foundation ventilators and that the effective area of such cracks and fissures was not the same for the conditions of natural and forced circulation.

The measurements in still air are not considered precise within ±20 percent because of the extremely low air velocities and because flow occurred in both directions simultaneously in the same duct in some cases. Ventilation measurements made with a katharometer would probably be more accurate provided the tracer gas could be kept adequately mixed and the response of the cell were fast enough.

In a typical occupied house under still air conditions the air entering the crawl space would come predominantly from the living space when the outside air was warmer than the living space and it would come predominantly from outside when the outside air was colder than the living space. In an actual house in the summer time the direction of air movement would probably reverse at least twice in twenty-four hours under still air conditions due to the change in relation of indoor and outdoor temperatures. During the late hours of darkness and the early forenoon the outside air would often be cooler than the indoor air so the air motion would be upward through the house and the outdoor air would enter the crawl space. The air at this time would have the lowest moisture content and would have a drying effect in the crawl space. During the afternoon and evening hours the outside air would often be warmer than the indoor air so the air motion would be downward through the house and air from the living space would leak into the crawl space. The air at this time would probably have its highest moisture content which would tend to add moisture to the crawl space.

B. Ventilation by an Unheated 6-in. Vertical Duct

The ventilation of the basement achieved by a 6-in. vertical duct extending from the basement to a level about one foot above the roof was measured for several different conditions. The vertical duct had a cross section area of 0.196 sq ft and a total length of 17.54 ft. It had been suggested that such a vertical stack in a house might be used to ventilate a crawl space through openings in the floor and thus avoid the need for foundation ventilators. Advantages claimed for such an arrangement were that the annoyance of closing the foundation louvers in the winter time and opening them in the summer time would be avoided, or the chilling effect on the floor in the winter that resulted from leaving the foundation louvers open all the year around would be avoided.

For this test the basement windows and basement door were sealed and all visible cracks at the sill of the house were caulked. A 6 by 14 inch register that connected the basement and living space in each room was left open. For some of the tests the attic was heated to simulate solar effects on the roof.

The results observed with no heat in the 6-in. vertical duct are summarized in Table 3. Tests 1-3 show that the air flow rate up the duct ranged from 8 to 14 cfm when the temperature in the living space was from 12 to 16 degrees warmer than the outdoors. The higher rate was observed when the attic was heated to a temperature 40 to 45 degrees F higher than the outdoors to simulate solar effects. When the indoor and outdoor temperatures were about equal as for Tests 4 and 7, the quantity of air flowing in the vertical stack was very small, sometimes changed direction, and sometimes was too small to be measured. Heating the attic to temperatures ranging from 118°F to 128°F as in Tests 5 and 6 created enough chimney effect in the duct to cause an air flow rate of about 5 cfm with no temperature difference between living space and outdoors. Table 3 shows that the movement of air through the floor registers was predominantly upward even though the basement was sealed at all noticeable cracks.

C. Ventilation by a Heated 6-in. Vertical Stack

The ventilation provided in the basement of the Test Bungalow by a 6-in. vertical stack, heated in a manner simulating that which might occur when the flue gases from a gas water heater were discharged into the stack, is summarized in Table 4. For these observations an electric cone heater was inserted into the 6-in. stack about 6 feet above the floor level through the side outlet of a tee and the side outlet covered to prevent entry of air at that place. The voltage on the electric heater was adjusted to heat the air to a temperature ranging from 150°F to 200°F simulating the flue gas temperature of a gas water heater beyond the draft diverter.

The ventilation of the basement and the air flow in the stack were measured for the following two test conditions:

(a) Basement sealed insofar as possible and with the floor registers that connected the basement and living space open. The attic was heated to simulate solar effects and the vertical duct was heated to simulate the heat provided by the flue gases from a gas water heater.

(b) Same as (a) except that the foundation ventilators were open.

Table 3

Crawl Space Ventilation with a Vertical Stack (Unheated)
Still Air Outdoors

Test No.		1	2	3	4	5	6	7
Outdoor Air Temp.	°F	62	64	59	80	81	81	77
Basement Air Temp.	°F	68	70	66	77	73	77	71
House Air Temp.	°F	74	80	75	79	83	81	77
Attic Air Temp.	°F	72	105	106	105	128	118	103
Temp. of Air Entering Stack	°F	66	68	64	76	71	75	71
Ventilation Rate Provided by Stack	cfm	8.4	13.8	13.8	*	5.3	5.6	4.2*
Air Velocity in Stack,	fpm	42.8	70.6	70.2	*	26.8	28.8	21.6*
Air Motion through Floor Registers								
Living Room		Upward	not observed	upward	upward	upward	upward	upward
Kitchen		"	"	"	"	"	"	"
North Bedroom		"	""	"	down	"	none	"
South Bedroom		"	"	"	upward	"	upward	"

* Direction of flow irregular - changing from upward to downward and vice versa.

Table 4

Crawl Space Ventilation with a Heated Vertical Stack

Test No.	1	2	3	4	5	6	7	8	9	10
Outdoor Air, Temp. °F	65	68	68	69	67	64	63	66	64	66
Basement Air Temp. °F	68	69	69	69	70	70	70	70	70	70
House Air Temp. °F	75	76	76	76	78	77	78	78	79	79
Attic Air Temp. °F	102	102	103	103	104	104	102	102	103	103
Air Temp. in Stack										
At Entrance °F	66	67	67	66	67	67	66	67	67	67
After Heater °F	145	145	179	181	178	177	176	176	175	174
At Outlet °F	105	103	115	110	a	a	a	a	a	a
Blowers Used Outdoors	no	yes	no	yes	no	yes	no	yes	no	yes
Ventilation Rate Provided by stack, cfm	16.8	20.6	23.7	25.5	29.2	33.7	31.1	32.8	30.0	34.4
Air Velocity in Stack, fpm	85.6	105.2	121.0	130.0	149.0	172.0	159.0	167.0	153.0	175.0
Air Motion Through Floor Registers										
Living Room	upward	upward	upward	upward	a	a	sealed	sealed	sealed	sealed
Kitchen	"	"	"	"	a	a	"	"	"	"
North Bedroom	"	"	"	"	a	a	"	"	"	"
South Bedroom	"	"	none	"	a	a	"	"	"	"
Flow Rate Through Foundation Ducts										
South cfm	sealed	sealed	sealed	sealed	sealed	sealed	sealed	sealed	36.8	*
West cfm	"	"	"	"	48.5	*	32.1	41.8	21.0	41.9
North cfm	"	"	"	"	sealed	sealed	sealed	sealed	25.2	*
East cfm	"	"	"	"	50.5	*	29.3	45.0	21.2	50.5
Static Press Difference, in W.G.										
House - Stack	0.004	0.0045	0.0055	0.006	0.007	0.009	0.0065	0.007	0.007	0.0085
Basement - House	0.001	0.0005	0.0005	0.0005	a	a	a	a	a	a
Outdoors - Basement	0.0073	0.0082	0.0073	0.0082	b	b	b	b	b	b

* In excess of 80 cfm. Not observable with smoke method.

a Not observed

b Not measurable

The air flow in the 6-in. duct ranged from 17 to 26 cfm for the first four tests summarized in Table 4 when the foundation ducts were sealed and the basement was sealed up at all visible cracks. However, the air flow through the open floor registers was also upward indicating that more air was entering the basement from outside than was flowing up the 6-in. stack. The stack reduced the pressure in the basement from 0.007 to 0.008 in W.G. below the outdoor pressure and the living quarters near the floor were at a pressure just slightly below the basement pressure in Tests 1 to 4. The flow of air up the 6-in. stack was from 50% to 100% greater with the stack heated as in Tests 1 to 4 of Table 4 than was observed with the stack unheated as in Tests 2 and 3 of Table 3. Operating the blowers in the space between the Test Bungalow and its enclosure appeared to increase the flow up the stack slightly.

When the foundation ventilators were open as in Test 5-10 of Table 4, the flow of air up the 6-in. stack increased from 20 to 40 percent. The flow up the stack was not much different when four ventilators were open than that observed when only two were open, but the total air flow into the basement was increased significantly. More air entered the foundation ventilators than traversed the stack by a ratio of 4 to 1 in some cases and as high as 6 to 1 in other cases indicating that more air was passing upward through the floor construction than was moving up the stack. Comparing the air movement through the foundation ventilators in Tests 5 and 6 with that in Tests 7 and 8 of Table 4, it will be noted that sealing the floor registers reduced the basement ventilation appreciably. However, opening all of the foundation ducts as for Tests 9 and 10 more than offset the effect of sealing the floor registers.

The air flows up the vertical stack for Tests 1 to 4 in Table 4 ranged from 1/2 to 1/3 that observed as total basement infiltration for the same indoor-outdoor temperature difference with the katharometer. This indicates that the vertical duct was only conveying a part of the total air through the house construction.

The infiltration in the basement with the foundation louvers open and with the blowers outside running as in Tests 8 and 10 of Table 4 ranged from nearly twice to about 5 times that observed with the katharometer for the same indoor-outdoor temperature difference, but without the louvers open in the basement. However, the attic was not heated and there was no heated vertical duct extending up through the structure for the tests using the katharometer.

In no case did the 6-in. stack cause air to move from the living space through the floor registers into the basement even though the windows and the door in the basement were caulked and the sill plate was sealed. Of course, a full basement wall presents more area and more joints for air leakage than would crawl space foundation walls, but it is concluded from these tests that special measures would have to be taken to seal such a wall sufficiently to ventilate the crawl space through floor registers from the living space above by the use of a vertical stack such as that tried for these experiments.

VI. THE DESIGN AND CALIBRATION OF A HEATED THERMOCOUPLE ANEMOMETER

A. Introduction

For investigating the ventilation of house attics, basements and crawl spaces as well as for measuring air motion in the proximity of heated and cooled walls, windows, grilles, etc., a device was required that would measure air velocities as low as 5 ft/min non-directionally and omni-directionally with reasonable precision and which was easy to operate and was portable. Since all known commercial apparatus was either inaccurate or of too low sensitivity at the desired air flow rate, the design and construction of a suitable instrument was undertaken.

A study of the literature [9, 10, 11] on this subject indicated that the required results were most likely to be achieved with a heated thermocouple anemometer if reproducible measurements could be obtained at temperature differences between the hot thermo-junction and the ambient air low enough to prevent self-generated natural convection currents from distorting the readings at very low air velocities.

The differential electromotive force in a thermocouple anemometer is provided by one or more electrically-heated thermojunctions and an equal number of unheated junctions connected in series and placed in the same air stream. The magnitude of this electromotive force can be related to the air velocity by calibration. It was found that the heat loss by free convection, radiation, and conduction from a horizontal wire of 0.004 in. to 0.005 in. diameter heated 3°F above room temperature was about equal in magnitude to the additional increment of heat loss caused by a superimposed forced convection of 5 ft/min for the same temperature difference. Therefore, to prevent the effects of free convection from being predominant or equal to the effect of a forced convection of the order of 5 ft/min it was necessary to design the heated thermojunctions for a temperature rise of less than 3°F.

B. Design of the Instrument

The thermocouple anemometer was built in the form of a probe for portable application in ducts and rooms. The probe was designed with two pairs of thermojunctions in series to double the differential electromotive force (EMF) and also to obtain a symmetrical design pattern. Chromel-P and constantan junctions were selected for their high electric resistance and also for their relatively high EMF output of 33 microvolts per degree Fahrenheit. Availability determined the use of 0.004 in. chromel and 0.005 in. constantan wires for the heated junctions and 0.040 in. wires for the cold junctions which were arranged as shown in Fig. 31. It seems obvious that the electric current which heated the smaller wires a maximum of 3°F would not cause a significant temperature increase of the larger wires having a cross section area one hundred times as great. It will be noticed that the potential of the two hot junctions is opposed by the cold junction potential so that the total EMF at the ends equals twice the potential difference between one pair of junctions.

The schematic diagram in Fig. 31 shows the alternating current heating circuit divided into two parts with one side of the line connected to the center of the thermocouple circuit and with the other side of the line connected to its extreme ends so that a zero A.C. potential could be made to exist across the entire thermocouple circuit. A variable resistor, R_1, between lines 1 and 3 in the diagram was provided to compensate for differences in the resistances of the two parts of the thermocouple circuit and for differences in the series resistances, R_2, in lines 1 and 3. A zero A. C. potential difference between terminals 1 and 3 was obtained by adjusting resistance R_1 until there was no noticeable vibration of the D.C. microammeter needle. Resistors, R_2, each contained 1500 ohms resistance as compared to a resistance of 3.5 ohms for the D.C. microammeter. Thus, only about one tenth of one percent of the thermoelectric current generated by the thermocouple circuit was not registered on the D.C. microammeter.

Fig. 32 is a photograph of the thermocouples at the end of the probe showing the symmetrical arrangement of the two pairs of thermocouple junctions which resulted in essentially an omnidirectional design for air-velocity measurements. Fig. 33 is a photograph of the entire prototype thermocouple anemometer.

C. Calibration of Thermocouple Anemometer

The thermocouple anemometer was calibrated in a small wind tunnel designed for isothermal conditions and using a compressed air supply. The compressed air was brought to the tunnel through a 100 gallon surge tank to reduce pressure variations. The air flow rate was measured with an orifice flow meter constructed in accordance with the ASME Research Publication entitled "Fluid Meters, Their Theory and Application" Fourth edition and calibrated with a gas meter for rates below the range covered by this publication. The pressure drop across the orifice was observed on two U-tube manometers, one filled with water and the other with mercury, which permitted the use of the same orifice plate for pressure drops ranging from 1 cm of water to 60 cm of mercury, corresponding to average air velocities in the wind tunnel from 4.8 ft/min to 129.2 ft/min. A cone-shaped adapter connected the pipe downstream from the orifice meter and the wind tunnel. A cloth screen was installed at the entrance of the wind tunnel to equalize and streamline the air flow over the full area of the wind tunnel. The probe was attached to the end of a piece of 5/8-inch steel tube and placed in the center of the tunnel, 12 inches above the cloth screen. The wind tunnel consisted of an 8-inch stainless steel tube, 4 feet long installed in a vertical position.

During the initial calibration of the prototype instrument a semi-precision portable potentiometer was used to measure the EMF produced by the thermocouple circuit. The relation between the terminal EMF of the thermocouple circuit and the air flow rate in the wind tunnel is shown in Fig. 34. A heater current of 75 milliamperes was used for the air velocity range from 0 to 35 ft/min and a heater current of 120 milliamperes was used for the air velocity range from 20 to 130 ft/min. The use of two different heater currents provided greater sensitivity over the entire range of air flow rates. The upper part of the curve for a heater current of 75 milliamperes shows a change of only 10 microvolts in EMF for the range of flow rates from 21.5 to 33.4 ft/min whereas the other curve shows a change of 22 microvolts in EMF for the same range of flow rates when a heater current of 120 milliamperes was used. The change in curvature of the curve for the lower heater current for flow rates below 5 ft/min is believed to have been caused by the increasing effect of free convection around the heated thermocouple junctions.

The curves in Fig. 34 apply to air at a temperature of 70°F and at approximately standard barometric pressure. Tests at high and low values of relative humidity showed that the effect of humidity on the electromotive force developed by the heated thermocouple probe could not be detected. The difference in density between dry air and saturated air at 70°F is slightly over 2 percent, so the difference in EMF caused by a change of relative humidity less than 100 percent could hardly be measured reliably with a semi-precision potentiometer.

SCHEMATIC DIAGRAM OF HEATED THERMOCOUPLE ANEMOMETER

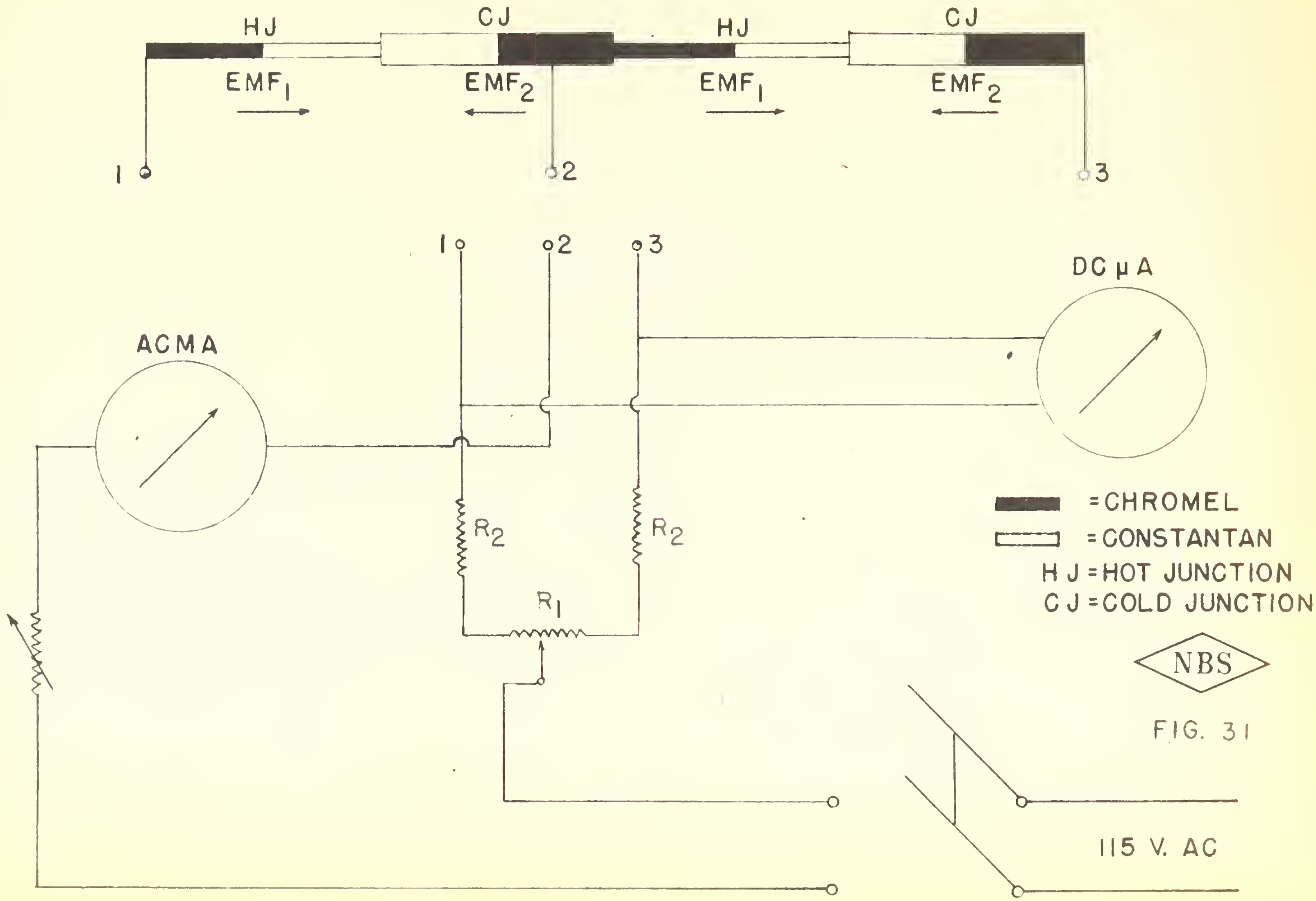


FIG. 31

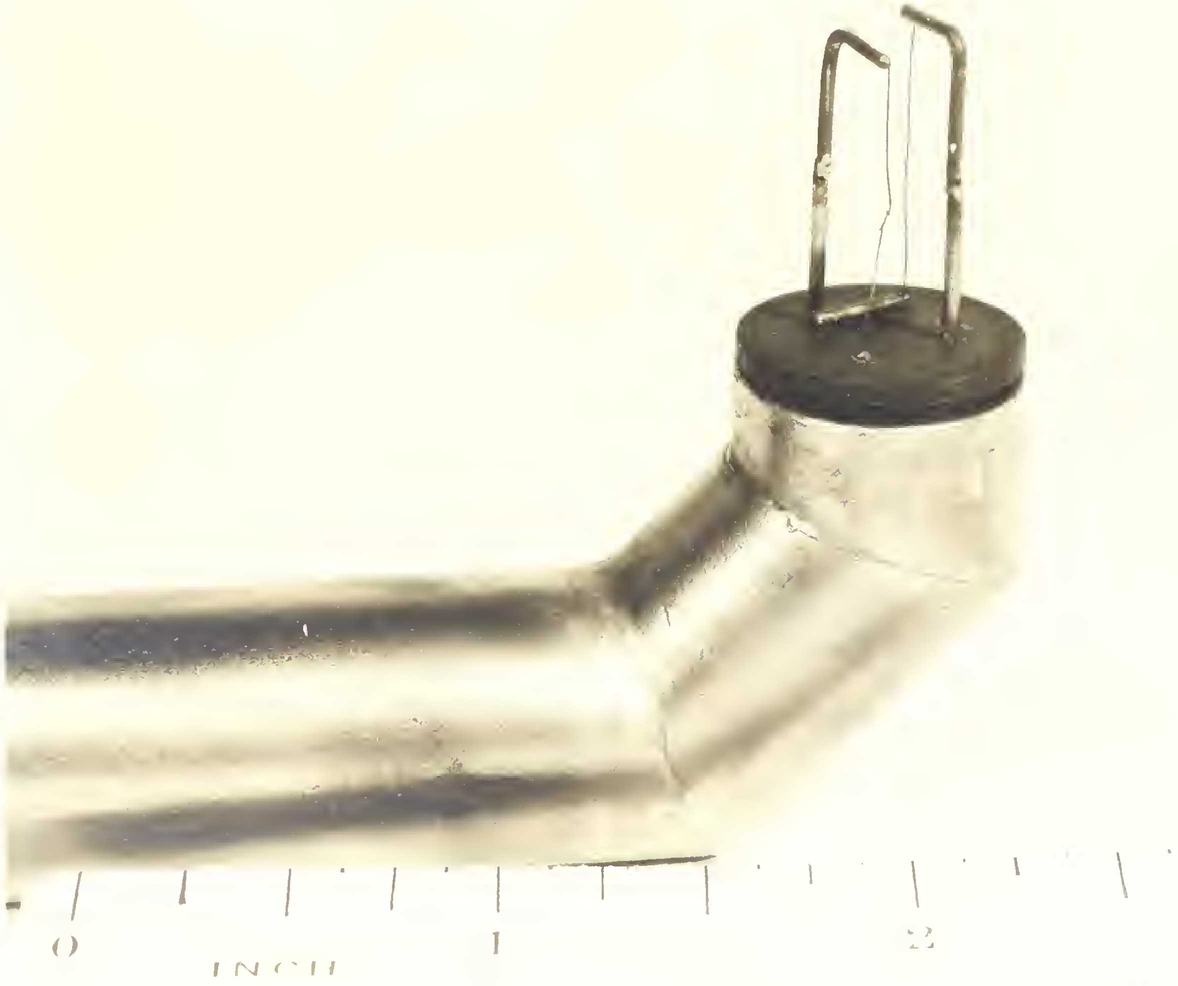


FIG. 32

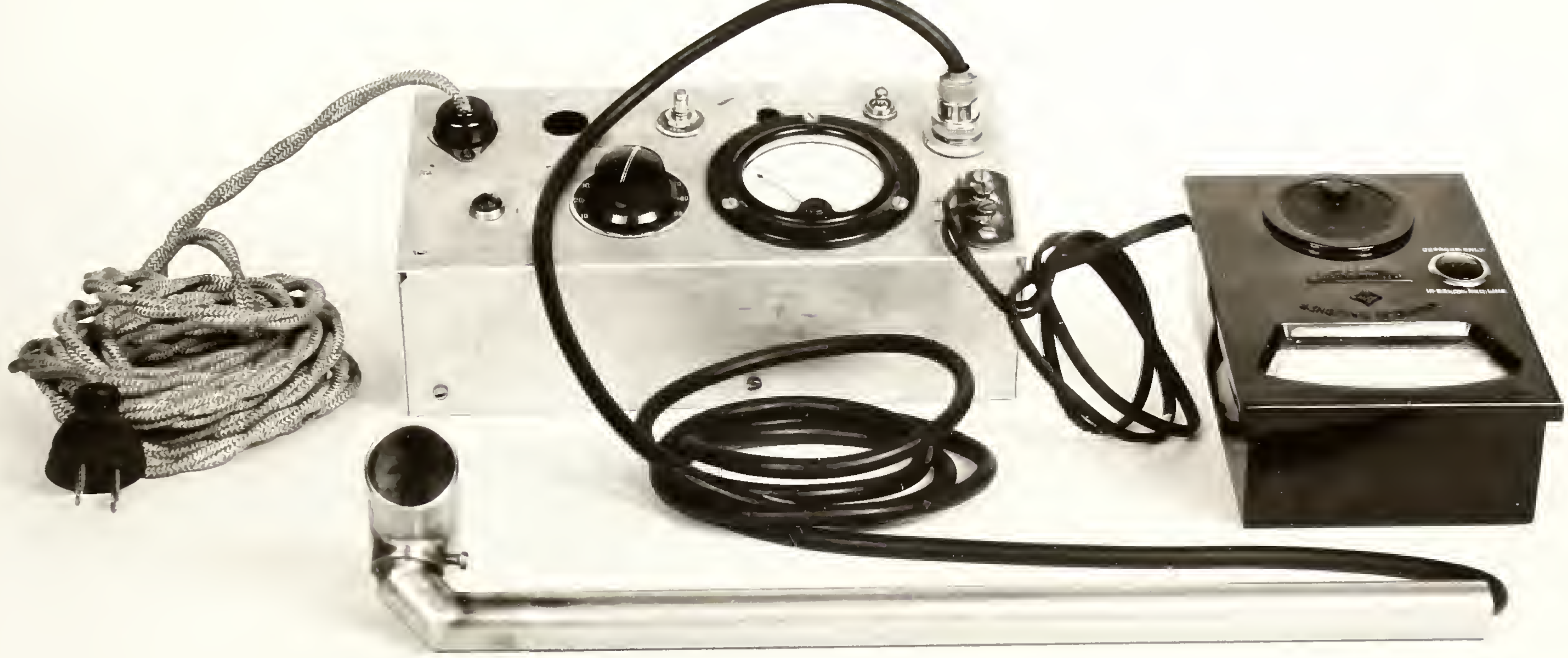


FIG. 33

THERMOCOUPLE ANEMOMETER, CALIBRATION CURVES

Tabulation of Values:

Airflow Rate ft/min	E.M.F., microvolts Heater Current 75 m.amp.	E.M.F., microvolts Heater Current 120 m.amp.
0	144	
5.00	123	
7.07	111	
8.59	102	
10.85	93	
13.77	86	
16.65	80	
21.47	74	189
25.3	70	180
30.2	66	172
33.4	64	168
43.2		156
55.6		144
70.4		131
86.1		120
105.4		107
124.0		95
135.8		86

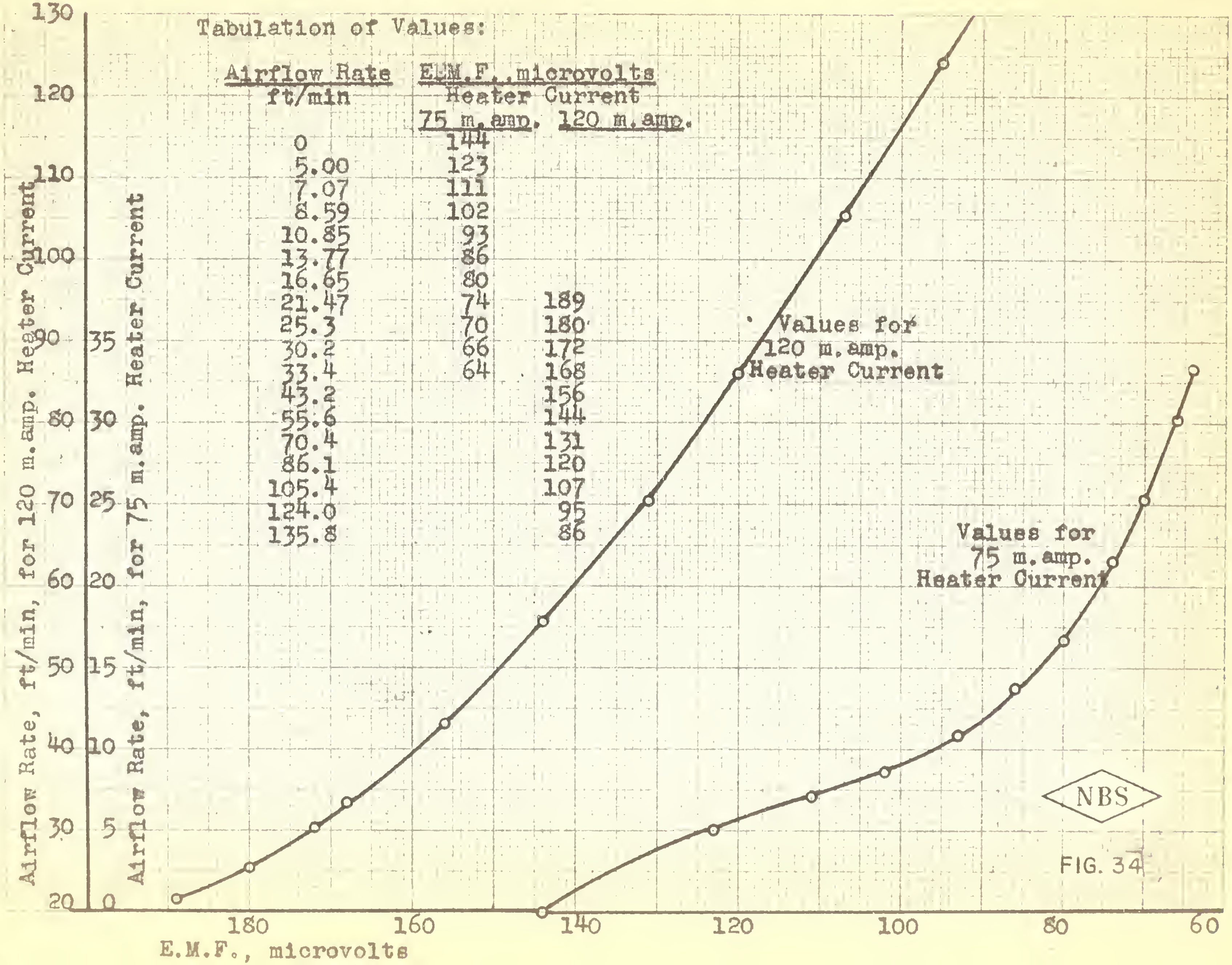


FIG. 34

The heat transfer from a heated wire by convection is approximately proportional to the density of the fluid circulated over it. That is, for a given total heat transfer rate from the wire to ambient air the temperature difference would be inversely proportional to the density of the air. Thus, for small variations in air temperature, the EMF produced by the heated thermocouple anemometer would be inversely proportional to the air density.

The use of a semi-precision potentiometer for observations of the EMF of the heated-thermocouple anemometer greatly reduced its portability so the apparatus was modified to use a microammeter to observe the thermoelectric current of the probe. A microammeter with a resistance of 3.5 ohms, and a full scale of 100 microamperes was found to give suitable readings.

The heated-thermocouple anemometer was recalibrated using this microammeter and the results are plotted in Fig. 35. Two values of heater current were again used to obtain suitable values of thermoelectric current for a range of air flow rates.

The results in the wind tunnel were checked by installing the anemometer on the carriage of the Current Meter Rating tank at this Bureau. By adjusting the velocity of the carriage, the desired values of air velocity were obtained. These results verified those obtained in the wind tunnel.

A computation can be made of the probable thermoelectric current that would flow through the microammeter circuit for any given heater current and air flow rate by computing the electric energy dissipated in the thermocouple wires and the probable temperature difference required between the hot junctions and the air to transfer this heat to the air stream.

The total heat dissipated by the heated wires equals the heat input after reaching a steady state condition. The overall resistance of the probe was 2.4 ohms. As the resistance of the smaller wires was one hundred times that of heavier ones, the resistance of the entire probe was used to compute the heat input. The electric energy converted into heat in the thermocouple wires would be

$$Q_I = I^2R \times 3.415 \text{ Btu/hr} \qquad (1)$$

Since the heater current was divided equally between the two halves of the thermocouple circuit the total heat input would be as follows:

For $I_1 = 0.075$ amp $\qquad Q_{I_1} = 0.01152$ Btu/hr

For $I_2 = 0.150$ amp $\qquad Q_{I_2} = 0.0461$ Btu/hr

The heat loss by radiation would be almost negligible since the temperature difference between the hot wires and the surroundings was small and the emissivity of the constantanand chromel wires was of the order of 0.05. Using the radiation equation with a 2°F temperature difference and an emissivity of 0.05 the heat loss by radiation was as follows:

$$Q_R = 1723\ Ae \left[\left(\frac{T_w}{1000}\right)^4 - \left(\frac{T_f}{1000}\right)^4 \right] \qquad (2)$$

or $$Q_R = 1723 \times 1.47 \times 10^{-4} \times .05 \left[\left(\frac{532}{1000}\right)^4 - \left(\frac{530}{1000}\right)^4 \right]$$

$$Q_R = 0.0000153 \text{ Btu/hr}$$

By comparison with the total heat dissipation Q_R was negligible.

The conduction of heat from the thermocouples was unknown, but was small because the three leads connecting the probe to the power supply was brought through a hard rubber mounting about 5/8 inch in diameter and 3/4 inch long.

The heat transfer due to forced convection can be expressed by equation (3).

$$Q_c = f_c \times A \times \Delta t, \text{ Btu/hr} \qquad (3)$$

where A = surface area of the wire, sq ft

Δt = temperature difference between wire and air, °F

f_c = surface film coefficient, Btu/(hr)(sq ft)(°F)

$$f_c = N_{nu} \times \frac{k}{d}$$

where N_{nu} = Nusselt Number

k = thermal conductivity of air, Btu/(hr)(sq ft)(°F/ft)

d = diameter of wire, ft

Hilpert[12] gives the following relationship between the Nusselt number, N_{nu}, and the Reynolds number, R_e, for forced convection around heated wires and cylinders.

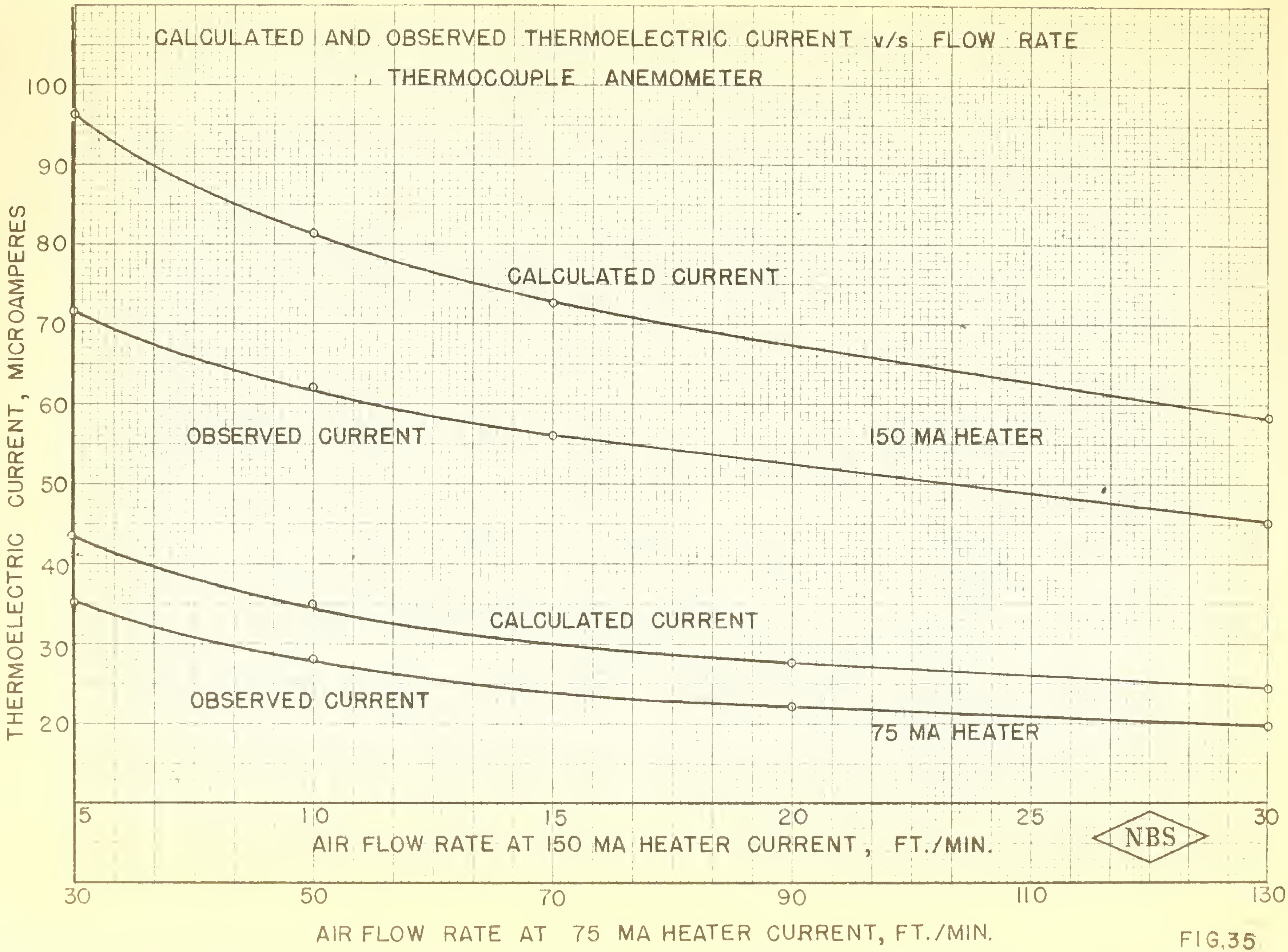

CALCULATED AND OBSERVED THERMOELECTRIC CURRENT v/s FLOW RATE
THERMOCOUPLE ANEMOMETER
CALCULATED CURRENT
OBSERVED CURRENT
150 MA HEATER
CALCULATED CURRENT
OBSERVED CURRENT
75 MA HEATER
THERMOELECTRIC CURRENT, MICROAMPERES
100
90
80
70
60
50
40
30
20
5
10
15
20
25
30
AIR FLOW RATE AT 150 MA HEATER CURRENT, FT./MIN.
NBS
30
50
70
90
110
130
AIR FLOW RATE AT 75 MA HEATER CURRENT, FT./MIN.

FIG.35

$$N_{nu} = B\ R_e^{\ n} \qquad (4)$$

where the values of B and n are selected from the following table for the appropriate Reynolds number.

R_e	n	B
1-4	0.330	0.891
4-40	0.385	0.821
40-4000	0.466	0.615
4000-40,000	0.618	0.179
40,000-250,000	0.805	0.0239

The Reynolds Number for the air flow was

$$R_e = \frac{V \times d \times \rho}{\mu} \qquad (5)$$

where: V = air flow rate, ft/sec

d = diameter of wire, ft

ρ = density of air, lb/ft^3

μ = absolute viscosity of air, lb/ft sec

The thermoelectric current flowing in a circuit of 5.9 ohms total resistance (2.4 ohms probe resistance plus 3.5 ohms meter resistance) with 2 x 33 = 66 microvolts EMF per degree temperature difference would be

$$I_o = \frac{66}{5.9} \times \Delta t = 11.20 \times \Delta t, \text{ microamperes} \qquad (6)$$

By solving for Δt in equation (3) and inserting its value in equation (6)

$$I_o = 11.20 \times \frac{Q_c}{A \times f_c} \qquad (7)$$

$$I_o = 76{,}100 \times \frac{Q_c}{f_c} \qquad (8)$$

Neglecting the heat transfer from the thermocouple wire by radiation and conduction the heat input calculated from equaltion (1) equals the heat dissipated by the forced convection.

$$Q_I = Q_c$$

Therefore, for

$$I_1 = 0.075 \text{ amp}, \quad I_o = \frac{76{,}100 \times 0.001152}{f_c} = \frac{875}{f_c}$$

$$I_2 = 0.150 \text{ amp}, \quad I_o \doteq \frac{76{,}100 \times 0.0461}{f_c} \doteq \frac{3500}{f_c}$$

Table 5 shows the calculated values of the Reynolds and Nusselt numbers for a range of air flow rates from 5 ft/min to 130 ft/min and also the resulting values for the coefficient f_c. The calculated and the observed values of the thermoelectric current I_o in microamperes for heater currents of 75 and 150 milliamperes are also shown in Table 5.

Table 5

Airflow Rate, ft/min	R_e	N_{nu}	f_c	I_o for 75 MA		I_o for 150 MA	
				calculated	observed	calculated	observed
5	0.189	0.513	20.1	43.5	35		
10	0.378	0.646	25.4	34.4	28		
20	0.756	0.813	31.8	27.6	22		
30	1.134	0.930	36.4	24.1	19	96.2	76
50	1.890	1.101	43.2			81.1	62
70	2.646	1.229	48.2			72.6	56
130	4.914	1.518	59.6			58.8	45

A comparison of the observed and calculated values of the thermo-electric current of the heated thermocouple anemometer is shown in Fig. 35 for air flow rates from 5 ft/min to 130 ft/min. This figure shows that the slopes of the curves for the observed and calculated currents were very nearly equal for the same flow rate, but the calculated values were from 23 to 31 percent higher than the observed values. This discrepancy is accounted for in part by the radiation and conduction of heat from the smaller thermocouple wires and by the convection heat transfer that occurred from the larger wires where they joined the smaller wires. That is, the effective area for convective heat transfer was somewhat greater than the area of the smaller wires and this effective area, if it could be evaluated, should have been used in equation (7) for computing the thermoelectric current.

In addition, the values of B and n selected for use in equation (4) may not have been entirely suited to the conditions of heat transfer that existed, but appeared to be the best available in the literature.

It is expected that the sensitivity of the heated thermocouple anemometer could be increased by adding a small electronic amplifier to the output. Operating on the EMF output of the anemometer, only a small rate of amplification would be required and a less delicate indicator could be used. Another advantage of amplification would be that a suitable gain control could be used to obtain a full scale measurement for both air velocity ranges.

VII. DISCUSSIONS AND CONCLUSIONS

This investigation of the infiltration in the Test Bungalow and of various methods for the measurement of infiltration reveals first, that the air movement through the various parts of a frame building are quite complicated and second, that instruments are now available for reasonably precise measurement of air infiltration rates. The present study is considered to be only a preliminary exploration of the subject of infiltration but it reveals broad possibilities for the development of new and reliable information on the air leakage into buildings under the influence of wind and temperature difference and how it is affected by building design and construction practices.

The results of the measurements in the Test Bungalow show that the rate of infiltration increased as the indoor-outdoor temperature difference increased and that under this influence alone a number of interdependent air flows took place between attic, living space, and basement and between these spaces and the outside air. The large amount of basement infiltration in the Test Bungalow suggests that houses without basements or crawl spaces would probably have appreciably less infiltration. The air movement through the stud spaces in the Test Bungalow would not be present in a building with solid walls or one in which the stud spaces were filled with granular or fibrous insulation. The measurements in the Test Bungalow showed that opening louvers in the attic increased the ventilation through the entire structure and that considerable air leaked into the basement through the concrete block foundation walls even when the basement door and windows and the sill were caulked. These observations indicate that considerable variation in air leakage values are to be expected in houses of different construction.

Before any reliable estimates could be made of the absolute values of the infiltration for particular types of construction, field surveys of a number of houses of each construction would be necessary. Field surveys of this type might suggest how building construction could be changed and improved to provide better control of air movement, vapor movement, and heat loss than is now possible. The exact effects of weather stripping and storm windows on air leakage could be evaluated by tracer gas methods of infiltration measurement. A study of exposure factors and the effect of house orientation on air leakage is also possible.

The use of the heated-thermocouple anemometer and the helium katharometer or other tracer gas technique together could provide valuable information on attic and crawl space ventilation for condensation control which might result in the development of construction criteria for the ventilation of these spaces.

The investigation of methods of infiltration measurement described in this report indicated that a number of tracer gas methods are available and that these methods are probably more accurate and better adapted to field use than calorimetric methods or direct air flow measurements. The more promising tracer gas methods are believed to be (a) helium gas with a katharometer (b) ethane gas with an interferometer, (c) methane gas with an infrared gas analyzer. Suitable measuring techniques are possible using either a radioactive gas with an electrometer or a halogenated hydrocarbon gas with a halide photometer. However, these latter two methods present some hazard to the personnel using them or to the occupants of the building being tested.

The Cambridge katharometer loaned to the National Bureau of Standards by the American Society of Heating and Ventilating Engineers for this investigation appeared to provide a better means for measuring infiltration rates than other methods previously used for this purpose. A calibration of the instrument showed that the indicated values of concentration were subject to some errors caused by parallax and drift at the zero setting, but that on the average the error in infiltration measurements would not exceed 4 percent if some precautions were taken in operating the instrument. The instrument was not sufficiently portable for field use and it had a lag in response ranging from 3.5 minutes with no sampling line to about 5 minutes with a sampling line 30 ft long.

A katharometer based on the same principle as the Cambridge instrument was designed and built by the National Bureau of Standards. It was portable and employed natural convection rather than a pump for circulating the tracer-gas-air mixture through its thermal conductivity cells. It was shown to have an accuracy equal or slightly better than the Cambridge instrument.

The heated thermocouple anemometer appeared to be the type of instrument best suited to measuring air velocities below 100 ft/min. It can be made with sufficient sensitivity and accuracy to measure streamlined air flow rates as low as 5 ft/min. Turbulence in an air stream would probably alter its accuracy at the lower end of the velocity range. Such an instrument seems to be well-suited to measurements of the air flow rates associated with natural ventilation of attics and crawl spaces through louvered openings.

VIII. References

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