

Fumes and Gases In the Welding Environment



Fumes and Gases in the Welding Environment

*A Research Report on Fumes and Gases
Generated During Welding Operations*

Research performed at Battelle-Columbus Laboratories
under contract with the American Welding Society and
supported by industry contributions

Under the direction of the AWS RESEARCH COMMITTEE ON
SAFETY AND HEALTH

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Preface

The environment presented by welding, cutting, and similar operations is a concern to industry. Management seeks to provide a safe and healthy working environment for welders, and the Occupational Safety and Health Act of 1970 has added the force of law to this desire. Although fumes and gases associated with welding and cutting are the most obvious potential hazards, other factors—radiation, heat, and noise—must also be considered.

Prior research for industry and for the American Welding Society has scarcely scratched the surface of this problem. Some work conducted has raised more questions than it has answered. Typical of these questions are the following:

- (1) Can fumes and gases be characterized on the basis of electrode classification?
- (2) Can simplified procedures be developed to evaluate the hazards presented by airborne contaminants?
- (3) What are typical noise levels associated with welding and cutting operations?
- (4) How can ozone and nitrogen dioxides be detected accurately in the presence of dense fumes?
- (5) Are fume concentrations affected in a predictable manner by the welding variables?
- (6) Can the health and safety of workers be protected without affecting productivity?

Reliable data are clearly needed to demonstrate that welding operations are safe when carried out properly and do not constitute an unusual occupational hazard.

To help industry, AWS proposed a continuing investigation at Battelle Memorial Institute-Columbus Laboratories to study the various environments to which welders are exposed, to quantify them, to demonstrate means to cope with them in a safe manner, and to correlate laboratory and shop generated data.

The processes to be studied were arc welding, oxyfuel gas welding and cutting, brazing, and thermal spraying.

The investigation required funding at a rate of \$150,000 per year for two years. Support was obtained from industry subscriptions, and progress reports were distributed to the sponsoring companies.

This report summarizes work completed to September 1978, except for studies of the noises and radiations generated in arc welding and cutting. A research report on the measurement of welding and cutting noise has been published separately as "Arc Welding and Cutting Noise" (Ref. 1)*. Two reports on radiation have been issued by the U.S. Army Environmental Hygiene Agency in cooperation with the American Welding Society and Battelle-Columbus Laboratories (Refs. 2 and 3) and a brief summary has been published in the "Welding Journal" (Ref. 4).

All measurements shown in the tables and text of this report are given in the system (U.S. customary or S.I.) in which they were made, followed by an approximate S.I. conversion in parentheses if the measurement was in U.S. units. No conversions are considered necessary for scientific measurements made directly in metric units.

*References are grouped together following the appendix.

Supporting Organizations

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AWS Detroit Section
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AWS New Jersey Section
AWS Philadelphia Section
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Mineweld Company of Indiana, Incorporated
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Rodgers Welding Supply Company
Suburban Welders Supply, Incorporated
United Association

In addition to the supporting and contributing organizations listed above, 119 other organizations contributed amounts up to \$500 each to the program. All contributions are gratefully acknowledged.

Fumes and Gases in the Welding Environment

*A Research Report on Fumes and Gases
Generated During Welding Operations*

Abstract

The environment surrounding many welding processes contains *fumes* (particulate matter) that may be harmful (toxic) or relatively harmless and *gases* that may have pulmonary or non-pulmonary effects. This report summarizes five experimental studies and several literature surveys (conducted by Battelle Memorial Institute-Columbus Laboratories for the American Welding Society) to evaluate the extent to which ventilation may control the exposure of the welder to these fumes and gases and to investigate the nature of the various fumes and gases generated in arc welding, in brazing with silver-based filler metals, in thermal spraying, and in oxyfuel gas cutting.

Comprehensive fume control requires exhaust flow rates adequate to reduce room contamination below critical levels, or cross-draft ventilation (or air-ventilated helmets) to remove fumes from the welder's breathing zone, or sometimes both.

Tables in this report show what fumes and gases are generated by fourteen types of covered electrodes for shielded metal arc welding, seven electrodes for flux cored arc welding, eleven gas metal arc solid electrodes, two BAg-class brazing filler metals, seven spraying and surfacing metals, and three thicknesses of carbon steel plate severed by oxyacetylene and oxymethane cutting under various operating conditions.

These data can be used in part to determine blower capacity and exhaust flow rates needed for ventilation.

Introduction

The American Welding Society has sponsored a two-year program, entitled "Improving the Welding Environment," conducted by Battelle's Columbus Laboratories. This book is a report of that research and consolidates the content of five topical reports on the program.

Overview of Fume Constituents

Fumes are particles formed by electrode (and base metal) constituents that are vaporized and subsequently condensed in the welding area. Because of their small size, fume particles may remain suspended in the aerosol form for long periods. Since the particles have mass and size and are affected by air movement, electrical fields, gravity, diffusional forces, and other external forces, they tend to agglomerate into clumps that gradually settle on the floor and other surfaces. While suspended, however, they are inhaled by all persons in the vicinity.

In addition to fume particles, there are also gases formed that have toxic effects. These include ozone, oxides of nitrogen, and carbon monoxide.

The presence of fumes and gases in the welding environment is a matter of concern to those responsible for the well-being of welding personnel. Some constitute a potential hazard to the health of the welder while others are merely a nuisance. Potential problems can be anticipated by estimating the concentrations of fume and gas

constituents in the welding area and comparing these data to established exposure standards.

There are three basic ways to protect the welder from the fumes and gases generated in his or her vicinity:

(1) Isolate the welder from the fumes through the use of respirators and air supplied helmets.

(2) Remove the fumes from the welder's immediate environment by ventilation and exhaust ducts.

(3) Reduce the quantity of fumes at the source through changes in the welding process or the conditions of welding.

In the broad view, both the welder and those in the vicinity of the welding area must be protected from these fumes since no one should be exposed to accumulating concentrations of fumes and gases that are hazardous to safety and health. Accordingly, ventilation devices (method 2) are expected to become increasingly relied upon. Method 1 ignores the local environment, although it may be necessary to use it on particular tasks while keeping other personnel out of the contaminated area. Method 3 requires knowledge of the fume generating characteristics of all available processes and procedures and, in the long range, the development of fume-free processes.

The cost of operating fume control devices (method 2) will be an important factor as energy costs rise. Determining the most effective method of controlling fumes and gases generated during various welding processes will require iterative calculations of cost trade-offs that are a function of the concentration and characteristics. The level of control required will have a major effect on the cost, but in many cases more than one of the possible methods of control may need to be used in order to minimize costs.

Survey of Part I, Ventilation Studies

A major objective in studying the various welding processes was to generate data needed to design systems that will control the flow of fumes and gases. In order to meet this objective, it was necessary first to characterize the flow fields associated with fumes and gases generated by these welding processes. Then, theoretical and experimental studies were conducted to obtain the data used to define design curves for the performance of various local ventilation devices. Two series of experimental studies were conducted: local ventilation experiments were performed to define the effect that various ventilation conditions have on the welder's exposure to welding fumes, and local exhaust experiments were conducted to define the effect of various local exhaust devices on the welder's exposure to welding fumes and on the reduction in environmental contamination resulting from the collection of the fumes.

Certain welding processes were studied to provide basic information on the fume generation characteristics of commonly used arc welding electrodes as a function of welding process, electrode classification, and selected

operating variables. This task emphasizes a comprehensive laboratory investigation of arc welding fumes to determine the rate at which they were produced with selected welding conditions in order to relate the fume generation rate to various electrode characteristics. More limited studies were also conducted to detect gases in the welding area, determine fume composition, and characterize fume particles in terms of size, crystalline structure, etc. Such data will be useful to industry in planning industrial hygiene programs and determining ventilation requirements.

The technical literature of the past two decades was reviewed for references to research conducted that sampled fumes and gases in the welding area, determined individual fume and gas constituents, and calculated concentrations of these constituents for comparison with recognized allowable limits. Many of these references were included in the AWS publication, *The Welding Environment* (Ref. 5). These investigations generally had limited objectives because they were undertaken to study the fumes associated with a particular welding application, to evaluate a specific electrode, to assess the performance of a ventilation system, or for some other definite purpose. The usefulness of some of this work is questionable today because supporting data on welding procedures, sampling methods, and analytical techniques are often incomplete or totally lacking. Nonetheless, these studies are important because the results form the basis for much of today's knowledge.

The design of fume control systems was not examined during this study. The American Welding Society has identified 84 welding processes by letter designations for diverse welding applications. It is not practical (from cost and time viewpoints) to study all possible combinations of factors and develop design data specifically for each combination. The approach taken in this study was limited to experimental and theoretical efforts to generate the information needed to design systems that will control the flow of fumes and gases generated during specific welding processes.

The experiments to define the effectiveness of the exhaust devices were conducted using a simulator gas instead of the arc welding fumes and gases. The simulator gas plumes duplicated the thermal and fluid mechanic characteristics of plumes from welding operations and enabled the experiments to be conducted continuously over a long period of time under reproducible conditions. Two subsets of experiments were conducted to ensure that the pertinent thermal and fluid mechanic characteristics of the simulator plume were identical to those of the weld plume. These consisted of tests to characterize the weld plumes for various welding processes and tests to establish the simulator operating conditions required to duplicate the actual welding plumes.

Theoretical analyses were conducted to define the overall room concentration level of welding fumes and gases in terms of the ventilation and weld fume generation rates.

Survey of Part II, Arc Welding Fumes and Gases

The key task in the AWS research program, "Fumes and Gases in the Welding Environment," was an investigation of the fumes and gases associated with conventional arc welding operations. This part of the program underscored the importance of these airborne contaminants and the need to develop a comprehensive understanding of factors governing their occurrence and behavior in and around welding areas. Fumes and gases are produced during all arc welding operations. Their potential effect on the well-being of welding personnel is highly dependent upon their amount and composition. More fumes, for example, are produced when carbon steels are welded with the shielded metal arc process than when austenitic stainless steels are welded in the same manner. On the basis of fume generation rate alone, the carbon steel welding operation appears to be potentially most harmful. Such may not be the case, however, because the fumes associated with the welding of 300-series stainless steels contain nickel and chromium compounds with threshold limit values (TLV's® [Ref. 6]) much lower than that of iron oxide, the principal constituent in the fumes produced during the welding of carbon steels.

In other words, the concentrations of the nickel and chromium compounds associated with the welding of stainless steel may exceed allowable limits even though the fume generation rate is low. In evaluating problems associated with the welding environment, the following must be taken into account:

- (1) Welding process
- (2) Welding consumables
- (3) Welding conditions
- (4) Base metal
- (5) Characteristics of the welding area (size, height, air movement, etc.).

In addition, some knowledge concerning the relative hazards of specific fume and gas constituents is needed.

A limited number of welding processes was selected to represent the family of welding processes because of their common use and their wide range of fume generation rates. The selected processes included shielded metal arc welding (SMAW), flux cored arc welding (FCAW), gas metal arc welding (GMAW), and gas tungsten arc welding (GTAW) operations. Commercially-available electrodes were used in this study at manufacturer-specified arc voltage and current conditions.

A comprehensive matrix of tests was selected and followed to ensure versatility in the application of the results. Relationships were established between fume generation rate and various electrode characteristics (melting rate, metal deposition rate, etc.) to obtain data that could be used effectively by welding engineers, industrial hygienists, ventilation specialists, and others concerned with the health and safety aspects of arc welding. Research was also conducted to investigate the fume

generation characteristics of selected electrodes as a function of various process variables such as current, voltage, and arc length.

During the course of this investigation, limited research on fume particle characterization, fume analysis, and gas detection during welding was included. No determination of the oxidation state of chromium in the fumes was attempted, however. Although fume characterization was an objective of the original program, budget limitations (especially in view of the expense of sophisticated analytical research) precluded a thorough analytical program, even though the need is recognized. A NIOSH criterion document issued in 1975 and the recent indictment of hexavalent chromium by OSHA identify certain compounds of chromium of value +6 as being carcinogenic (cancer-causing). It remains for some future program to determine the oxidation state of chromium in fumes from welding stainless steel. The concentrations of Cr given in this report must be identified as total Cr. Possibly two-thirds of the total Cr may be hexavalent, of which 95 percent may be water-soluble and, therefore, noncarcinogenic; the remaining 5 percent of that two-thirds would be presumed to be insoluble and carcinogenic.

Analytical research coupled with fume and gas studies could improve our ability to reduce the quantity of fumes and gases generated at the source by varying the process conditions. A limited amount of such research was included in this program. The results are sufficiently useful to indicate the value of further study.

Survey of Part III, Brazing Fumes and Gases

Another purpose of the American Welding Society research program was to examine the fumes generated during brazing. The broad objective of this task was to show experimentally the relationship of the fumes given off to the brazing filler metal used.

A literature search on brazing references was conducted to learn the extent and usefulness of the bibliographic data available. Study of this literature revealed the adequacies and deficiencies of the available information.

The experimental research program was developed without benefit or knowledge of any published prior experience by other investigators. Its magnitude and scope were restrained by the availability of funds assignable for brazing fume studies.

The investigation was limited to the BAg-class filler metals which are predominantly silver but contain copper, zinc, and cadmium. It was directed toward determining the fume generation characteristics of two filler metals having widely different cadmium contents: Ag-15Cu-16Zn-24Cd (BAg-1) and Ag-22Cu-20Zn-7Cd-1Sn. These filler metals have similar melting characteristics and are used extensively in industry for torch brazing.

The research plan was designed to minimize the variables caused by changes in flame shape, character, and position that occur during torch brazing. Therefore, procedures similar to those used during welding fume studies were suggested. Total fume samples collected in the AWS-Battelle welding fume collection chamber were used to find the influence of brazing variables on the fume generation rates and quantities. The fume samples were analyzed by atomic absorption methods to determine how brazing variables affect fume compositions. Unfortunately, it became increasingly evident, as the program progressed, that the procedures chosen did not provide the precision required for accurate measurement of brazing filler metal fumes.

In the brazing studies, the small quantities of fume produced and its apparent extremely small particle size presented problems in filter choice, chamber design, sample weight-analysis balance, and sampling environments. To minimize these problems, a fume collection chamber having the least volume possible, containing an atmosphere that is inert or readily controllable, and which can be made part of a closed system is advised. Filters or fume collection media must be capable of collecting very fine particles ($<1\mu\text{m}$) and should be small enough to avoid masking of actual fume weights by large blank filter weights. Continuous sampling through an atomic absorption type of analytical system appears worthy of consideration instead of filter sampling systems.

Attention to the details of actual filler metal melting and fluxing practices is also required. Melt sizes, quantities of flux used, exposed melt surface areas, and heating and cooling rates need attention. Melt size, particularly with respect to exposed areas, may alter fume generation rates because of flux cover variation. Crucibles should be a metal that is wet by the filler metal to avoid flux collection around the melt. This implies combined weight determination that includes the crucible. Weighing exercises should include checks of flux losses in addition to filler metal losses. Ideally, all tests should begin in a cool chamber and heating furnace to minimize differences in heating and cooling rates. The closed chamber already suggested should eliminate any influence of humidity in the test area.

Analytical procedures for fume analysis should be validated for the tests being conducted. An early phase of any analytical work should be directed toward determining the chemical character of the fume (metal, oxides, soluble, insoluble, etc.). Early analytical work should include complete analyses. Subsequent analyses requirements may be relaxed when the whole story is known.

Survey of Part IV, Thermal Spraying Fumes and Gases

As another part of the program, Battelle investigated the fumes and gases produced by thermal spraying opera-

tions and the manner in which the nature of the spraying process and the type of metal being sprayed affect their characteristics and the rate at which they are generated.

Thermal spraying processes are used by industry to repair or build up worn parts and to produce coatings that resist oxidation, corrosion, wear, erosion, abrasion, or impact. In practice, finely divided metallic or non-metallic particles in the molten or semimolten state are sprayed on a suitable substrate to produce a dense, adherent deposit or coating. Thermal spraying encompasses three distinct processes that are differentiated mainly by the manner in which the particles are produced and heated: (a) gas combustion spraying, (b) electric arc spraying, and (c) plasma arc spraying. These processes are characterized by relatively low deposition efficiencies, moderate-to-high fume levels, and moderate-to-high noise levels.

In the area of thermal spraying, research efforts were directed toward a study of the fumes associated with the most commonly used processes: gas combustion spraying and electric arc spraying. In each instance, the metal being sprayed was in the form of wire. The metals included in the investigation were mutually agreed upon by the AWS Research Committee and Battelle.

Fume collection studies for thermal spraying were limited to those conducted at recommended spraying conditions. No work was done on detonation spraying, which is also included among the thermal spraying processes; it is a proprietary process and little is known about its characteristics.

Survey of Part V, Fumes and Gases from Oxygen Cutting

Finally, the fumes associated with oxygen cutting operations were investigated. These fumes occur as the result of the chemical reaction between iron and high purity oxygen and the process through which molten oxides and unoxidized metal are removed from the kerf by the cutting jet. Fume quantities are dependent upon the cutting process variables, base metal thickness, base metal composition, surface contaminants, and other factors. Fume compositions are governed by the composition of the metals being cut and any coating that may be on the surface of the metal.

To study the fumes associated with oxygen cutting operations, total fume samples were collected to accumulate data for use in determining fume generation rates and quantities relating fume generation rates to important process variables.

Research was directed toward a study of the fumes produced during oxyacetylene and oxynatural gas (methane) cutting of carbon steel plate in thicknesses of 1/2, 1, and 2 in. (12.7, 25.4, and 50.8 mm) at conditions recommended by the cutting torch manufacturer. Also included were studies of the effect of selected process variables on fume formation rates.

Although the potential problems presented by oxygen cutting fumes have long been noted, there are few references to this subject in the technical literature on safety and health. There is little information on the rate at which fumes are produced during oxygen cutting operations. The data obtained in the course of this investigation only partially fill this void.

Additional research would be needed to more fully characterize cutting fumes. Such research should include studies to determine the distribution of fume particles by size and examination of fume deposits with the scanning electron microscope.

In this study, concentrations of major elements could not be determined accurately because of difficulty in interpreting the spectrographic record and because of the lack of suitable standards. As a result, concentrations of such elements are expressed in a range of weight percentages instead of discrete weight percentages. If more accurate compositional data are needed, optical emission spectroscopy should be supplemented by other analytical techniques such as atomic absorption analyses or wet chemistry methods.

No study of arc cutting was made, although that was an original aim of the research program: Suitable equipment was not available at Battelle, and alternative loca-

tions at which tests could run could not be identified by the Committee.

Organization of This Report

Each of the five sections of the body of this report is organized in the following format:

- Introduction
- Scope
- Limitations
- Background (Part II only)
- Program
- Equipment, Materials, Procedure
- Description of Work (Organized under Section A, Section B, etc.)
- Discussion
- Summary

Appendixes have been included at the end of the report which present the tabular data for Parts II, III, IV, and V in sequence.

The references cited in the Preface, Introduction, and Parts I, II, III, and V have been grouped together following the appendixes.

An index completes this compilation.

Part I. Ventilation Studies

Introduction

The research performed by Battelle-Columbus Laboratories for this portion of the American Welding Society program obtained ventilation design data for use in controlling welding plumes. The study was conducted over a 6-month period that began in May, 1977. The plume control study was monitored by a committee appointed by the AWS Research Committee.

About 250 tests were carried out in the course of this study. The results of the study show that various ventilation methods can be used effectively to reduce the welder's exposure to fumes and, conversely, that certain ventilation conditions can result in higher welder fume exposures than those experienced with no ventilation. Operating conditions for various local exhaust devices are specified in terms of a welder exposure factor and a room contamination factor which make them easy to use.

The report is divided into three major subsections paralleling the three main areas of investigation: "General Room Ventilation," "Local Ventilation," and "Local Exhaust Studies." Included in each subsection, where appropriate, is a description of the test apparatus and procedures and a discussion of test results. These subsections are followed by a summary. The references are found following the appendixes at the end of this report compilation.

An example problem is included in the report to show how the study results can be used. The example outlines one possible application of the results; it should be kept in mind that the results have a wide scope of application toward designing devices that can be used to control welding fumes and gases. Familiarity with the various experiments conducted during this study and the associated results will enable the reader to apply the results to a variety of welding problems in order to achieve cost-effective and environmentally acceptable control of welding plumes.

Scope

Theoretical and experimental studies were combined to generate data on the effect of ventilation air currents on fume concentrations in the welder's breathing zone and to define the effectiveness of exhaust devices in reducing environmental contamination.

One major series of experiments defined the fume concentration level in the breathing zone as a function of ventilation velocity and relative orientation of the ventilation source with respect to the welder using a large flow area source (4 x 4 ft. [1.2 x 1.2 m]).

A second major test series used a simulator gas instead of the arc welding fumes and gas. The simulator gas plumes were identical to the weld plumes in thermal and fluid mechanic characteristics and enabled the experiments to be conducted continuously over a long period of time under reproducible conditions. Two subsets of experiments were conducted to ensure that the pertinent thermal and fluid mechanic characteristics of the simulator plume were identical to those of the weld plume: tests to characterize the weld plumes for various welding processes, and tests to establish the simulator operating conditions required to duplicate the actual welding plumes.

Theoretical analyses were conducted to define the overall room concentration level of welding fumes and gases in terms of the ventilation and weld fume generation rates. The results of these analyses combined with the results of the experimental studies provide the information needed to design effective systems for control of welding fumes and gases.

Limitations

The design of fume control systems was not examined during this study.

Previous application of fume control methods to specific welding processes has been limited because sufficient data are not available. Most of the quantitative information in the literature is very general, having been obtained at a time when the need to conserve energy and to control the welder and plant environments was not so acute as it is today. However, in view of the large number of recognizable welding processes and variations of them, it was not practical for this study to consider more than a few representative combinations of factors which may influence the ultimate design of ventilation equipment. A limited number of welding processes was selected as being representative of the family of welding processes because of their common use and their wide range of fume generation rates. The selected processes included shielded metal arc welding (SMAW), flux cored arc welding (FCAW), and gas metal arc welding (GMAW) operations. Commercially-available electrodes were used in this study at manufacturer-specified arc voltage and current conditions.

Program

Ventilation provides a means for reducing to an acceptable level the hazardous and noxious fumes and gases to which a welder may be exposed. Many techniques are available for controlling welding fumes and gases. These range from systems that employ natural convection to localized devices such as air-ventilated helmets. Examples of methods for controlling the welder's exposure to fumes and gases include:

- (1) General room ventilation
- (2) Overhead exhaust hoods
- (3) Portable local exhaust devices
- (4) Down-draft tables
- (5) Cross-draft tables
- (6) Extractors built into the welding equipment
- (7) Air-ventilated helmets

Fluid dynamics were applied to the theory of the welding plume. The governing differential equation for the contamination level in a closed room was integrated to obtain an expression for the room contamination level as a function of time. Steady-state fume concentration levels were calculated for rooms of all sizes. Transient concentration levels were calculated for times prior to achieving steady-state conditions.

Experiments were performed to determine the effect of air currents on these theoretical fume concentrations in the welder's breathing zone (local ventilation). Apparatus was developed to measure the reduction in operator exposure to contaminants, using two methods to measure the fume concentration level: weighing a filter and counting condensation nuclei. Sampling probes inside the welding helmet collected fumes at the level of the welder's mouth. Sampling efficiency of the probe was measured over a range of particle diameters.

An air current generator was devised. Data were then

obtained with no ventilation and with variations in air speed and direction.

Local exhaust studies evaluated the effect of collector configuration, collector location, and exhaust flow rate. Three types of experiments were conducted:

- (1) Welding fume characterizations
- (2) Simulator characterizations
- (3) Inlet configuration studies

Equipment, Materials, Procedure

Experimental apparatus

The experimental apparatus used to measure the reduction in operator exposure to contaminants resulting from the use of local ventilation included fume sampling equipment, an air current generator, and welding equipment consisting of a power supply, arc voltage and current instrumentation, and a welding table. The apparatus was set up in an area having a high ceiling and no natural drafts. Figure 1.1 is a schematic diagram of the experimental setup viewed from above the apparatus.

Fume Sampling Equipment. Two methods were used to measure the fume concentration level in the welder's breathing zone: the filter weighing method, and the condensation nuclei counter method.

The fume sampling system used in the filter weighing method of analysis is shown schematically in Fig. 1.2. The sampling technique was specified by the American Welding Society (AWS) as a standard procedure when using the filter weighing method (Ref. 1.1). The sampling system consisted of sampling probes, a filter and filter holder, a critical flow orifice, a pressure gage, and a vacuum pump. Essential features of the present sampling system are described below.

Two sampling probes were installed inside the welding helmet, positioned at the level of the welder's mouth 1-1/2 in. (38 mm) on either side of the vertical centerline of the helmet. Two probes were used to obtain a less biased sample from the welder's breathing zone by halving the sample flow rate, thus reducing interference effects caused by the welder's breathing. Figure 1.3 is a photograph of the helmet showing the sampling ports. These sampling probes were connected to the filter holder mounted on the outside of the helmet using a standard Y connector. In order to minimize any possible particulate losses through the sampling system, the inlet end of the probes was sharply machined, and relatively large tubing (1/4 in. [6.4 mm diameter]) was used. The distance between the inlet ends of the probes and the filter holder was about 4 in. (100 mm). Measurements of the sampling efficiency of this system showed it to be essentially 100 percent efficient when collecting particles below approximately 0.05 micron (μm) in diameter and 97.0 percent efficient with 2 μm diameter particles.

The filter holder used was a standard 25 mm in-line holder (Model 1109, Gelman Instrument). Millipore

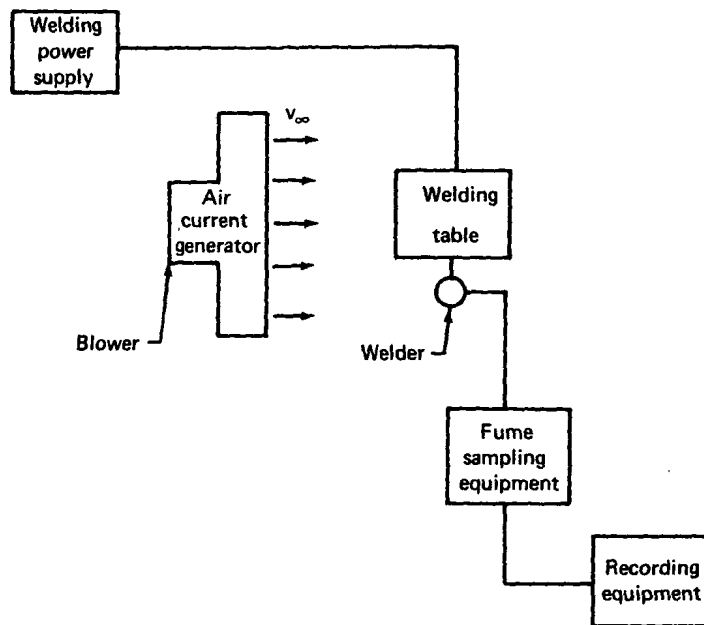


Fig. 1.1–Schematic of experimental setup

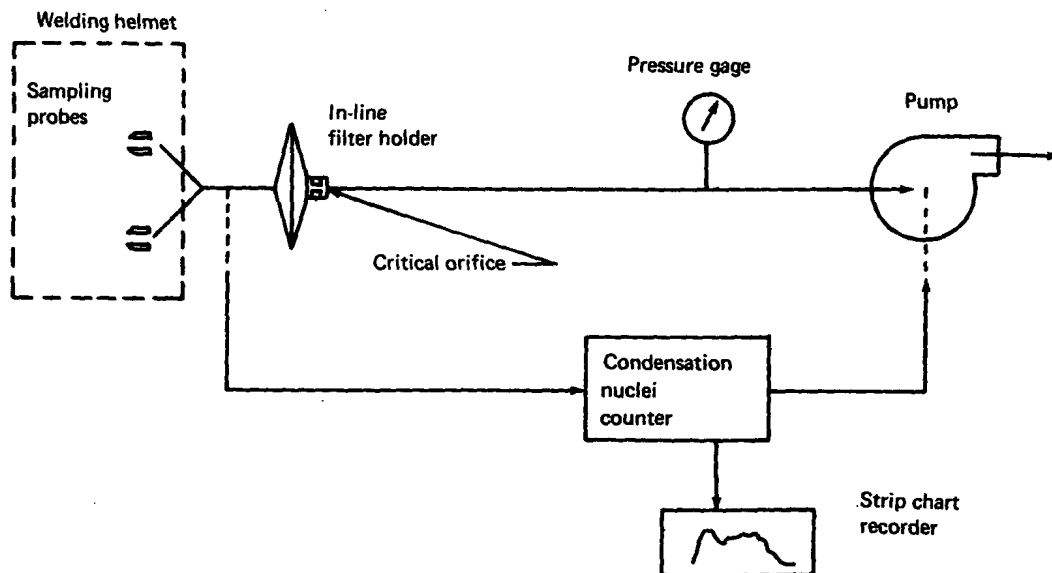


Fig. 1.2–Schematic of fume sampling system used in the filter weighing method

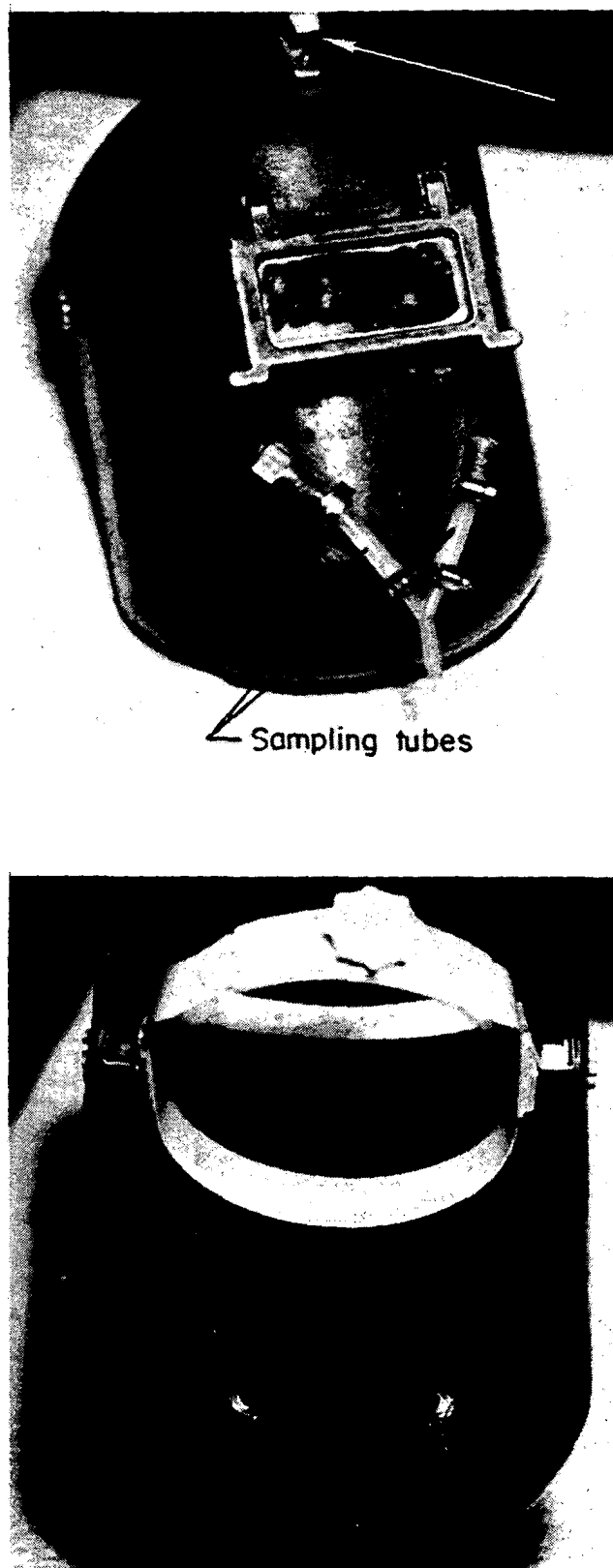


Fig. 1.3—Photograph of modified welding helmet

membrane filters (Model HA, Millipore Corporation [Ref. 1.2]) were used to collect the fume samples. The HA Millipore filter has a nominal pore size of $0.45\ \mu\text{m}$ which meets the AWS specification. In addition, a previous study (Ref. 1.3) showed that the filtration efficiency of a comparable filter (Model FH, pore size $0.5\ \mu\text{m}$) was essentially 100 percent for all particle sizes. An analytical balance (Model M5, Mettler Instrument) with a nominal sensitivity of $0.001\ \text{mg}$ was used to weigh the filters before and after use. A simple repeatability check showed that the actual accuracy was about $0.005\ \text{mg}$. In order to avoid any moisture absorption or chemical reaction effects on the filter and sample weight, the filters were kept in a constant temperature, constant humidity room for at least one hour prior to weighing. When a blank filter was kept under this environment and the weight was measured, the data were repeatable within $0.015\ \text{mg}$ over 24 hours. A similar experiment using a filter-plus-fume sample showed that the measurement was repeatable within $0.020\ \text{mg}$. Since the collected sample weight was always higher than $5\ \text{mg}$, the above variations were considered acceptable.

In addition to the filter weighing method, a particle counter was also used to determine fume particle concentrations in the breathing zone. The particular instrument used was a condensation nuclei counter, Model E-1033A-001G1, manufactured by the Environment One Corporation, designed for real time measurements of airborne particle number concentrations. In this instrument the particulate-laden air sample is saturated with water vapor and then adiabatically expanded to a low pressure, causing the water vapor to condense on the particles (which, in this case, serve as condensation nuclei) and form relatively large droplets. The concentration of these large droplets is then measured optically by light transmission. The instrument can measure fume particles in the size range of $0.002\ \mu\text{m}$ and larger in diameter. The standard operating flow rate for the instrument is 3 liters per minute, which was only 10 percent higher than the filter sampling rate, as will be shown. The advantage of using this instrument was that it gave real time measurements while filter measurements only provide time average values. The counter was used because it provided information on changes in particle concentration as a function of time. Of particular interest was the rate at which the fume concentration behind the helmet varied.

Air Current Generator. The air current generator was used to produce air currents or local ventilation across and around the table where the welding experiments were performed. Details of the air current generator plenum are shown in Fig. 1.4. The plenum was a plywood box, $4\ \text{ft} \times 4\ \text{ft} \times 1.5\ \text{ft}$ ($1.2\ \text{m} \times 1.2\ \text{m} \times 0.45\ \text{m}$), containing a thick, packed bed. A blower was mounted on the back side to force air through the assembly. The bed was filled with a foamed plastic packing material held in place with perforated plates. Measurements showed that the generator produced a uniform velocity

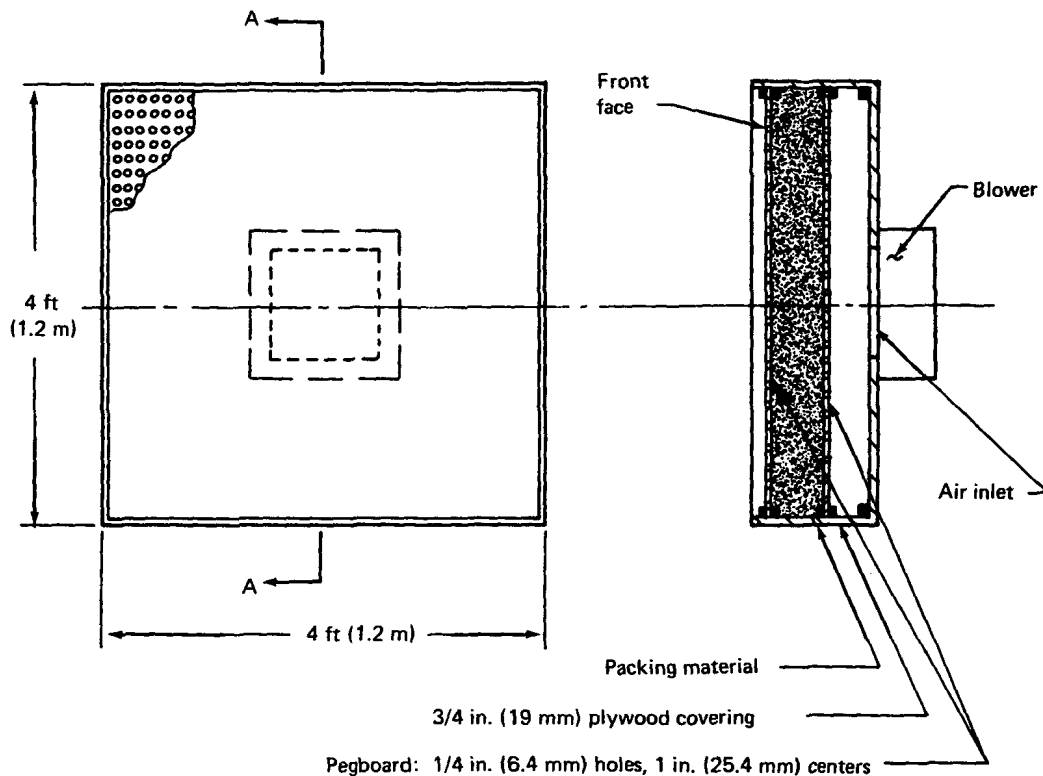


Fig. 1.4—Details of the air current generator

profile at the outlet face and over the welding area.

The air velocity in the welding zone was measured during the calibration tests using a hot wire anemometer (Thermo-System, Inc., Model No. 1050). The variation in the velocity profile at a distance of 42 in. (1.07 m) from the outlet face of the generator was ± 15 percent of the average velocity at 50 ft/min (15.24 m/min) and ± 5 percent at 200 ft/min (61.0 m/min). The air velocity was varied by varying the blower speed, which made it possible to obtain any velocity between 30 and 250 ft/min (9.14 and 76.20 m/min). Flow direction relative to the welder's normal welding position was obtained by rotating the working table relative to the generator.

Welding Equipment. Welding equipment used during these experiments included a dc power generator, a shunt bar to measure arc voltage and current, and a welding table. The electrical output of the power supply was monitored using a shunt bar arrangement which made it possible to record electrical signals (mV) that were proportional to arc voltage and current. The data signals were recorded on a Honeywell Electronic 19 Strip Chart Recorder. Welding was performed using 5/32 in. (4 mm) diameter E6013 shielded metal arc electrodes.

A working table surface of 24 in. x 24 in. (0.61 m x 0.61 m) at a height of 28 in. (0.71 m) was used in the studies. In order to maintain a consistent welder head

position, a horizontal bar was set up 14 in. (0.36 m) above the table and a guide hanger was attached to the welder's helmet 4 in. (0.10 m) above the viewing window, as shown in Fig. 1.5. With this apparatus, the welder could move his head smoothly along the horizontal bar as the weld bead was made, but he could not move up and down or in and out. When the welder was in a welding position and his helmet was attached to the horizontal bar, his ear position was 13 in. (0.33 m) above the arc and 10 in. (0.25 m) away from the arc (horizontal distance).

Local Exhaust Apparatus

The test apparatus used to conduct the local exhaust experiments included: (a) local exhaust configurations, (b) fume simulator, (c) exhaust vacuum supply system, (d) welding setup, and (e) instrumentation. Components of the apparatus used in the local ventilation experiments that were also used in the local exhaust experiments are not discussed in this section; these include the air generator and components associated with the welding setup.

Local Exhaust Configurations. A number of local exhaust configurations were examined, including flanged ducts (3, 6, and 8 in. [76, 152, and 203 mm] diameters),

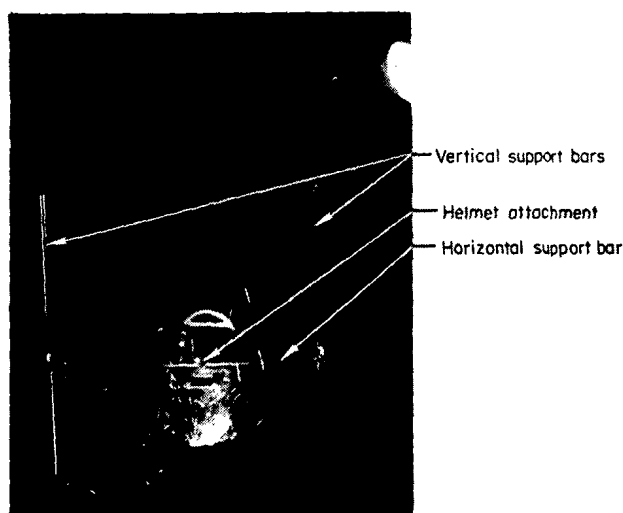


Fig. 1.5—Photograph of the helmet support mechanism

slots (single and double configurations), and two overhead hood configurations. The inlet configurations of the flanged duct exhaust systems are shown in Fig. 1.6 for the 3, 6, and 8 in. (76, 152, and 203 mm) diameter ducts. The flange size that was used is a recommended configuration set forth in Ref. 1.4. A section of sheet metal ducting was used for the exhaust inlet; the sheet metal section was connected to a flexible tube that was, in turn, connected to the vacuum supply plenum. The flanges were attached to the sheet metal ducts and sealed to

eliminate air leaks between the flange and the metal duct.

Single- and double-slot exhaust configurations were examined during this study. Fig. 1.7 is a schematic of the slot configuration. Included in the drawings are the controlling dimensions for the two configurations examined (slot dimensions were obtained from Ref. 1.4). The single-slot size was 1.20 x 24 in. (30.5 x 610 mm), which is approximately equal in area to a 6 in. (152 mm) diameter circular duct. The double-slots were each 0.6 x 24 in. (15.2 x 610 mm), having a total area equivalent to the single-slot and to a 6 in. (152 mm) diameter circular duct. The flow area for the single- and double-slot exhaust configurations was made the same as the 6 in. (152 mm) diameter duct so that the face velocity at the exhaust inlet plane would be the same as that for a 6 in. (152 mm) duct at the same exhaust flow rate.

Two overhead exhaust systems, overhead shelf and slanted overhead, were examined during this study. Fig. 1.8 is a schematic of an overhead exhaust system. The basic dimensions for the overhead and slanted overhead exhaust systems were identical, the only difference being in the location of the exhaust inlet. The overhead exhaust systems were set up by attaching an overhead shelf to the vacuum plenum section.

The exhaust inlet size for both of these systems is shown in Fig. 1.8. When these configurations were tested, panels were installed on either side of the welding work area to duplicate a welding booth arrangement. The side panels helped in controlling the flow of air from a preferred direction.

Fume Simulation Apparatus. A qualitative analysis was made of the characteristics of hot, buoyant plumes containing particulate matter of very small size. From this analysis it was concluded that, relative to the objec-

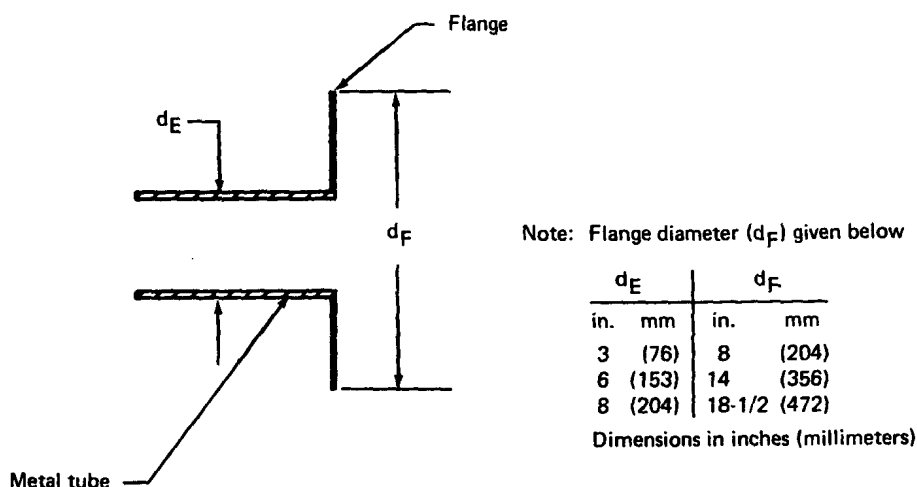


Fig. 1.6—Details of the flanged duct exhaust inlet configurations

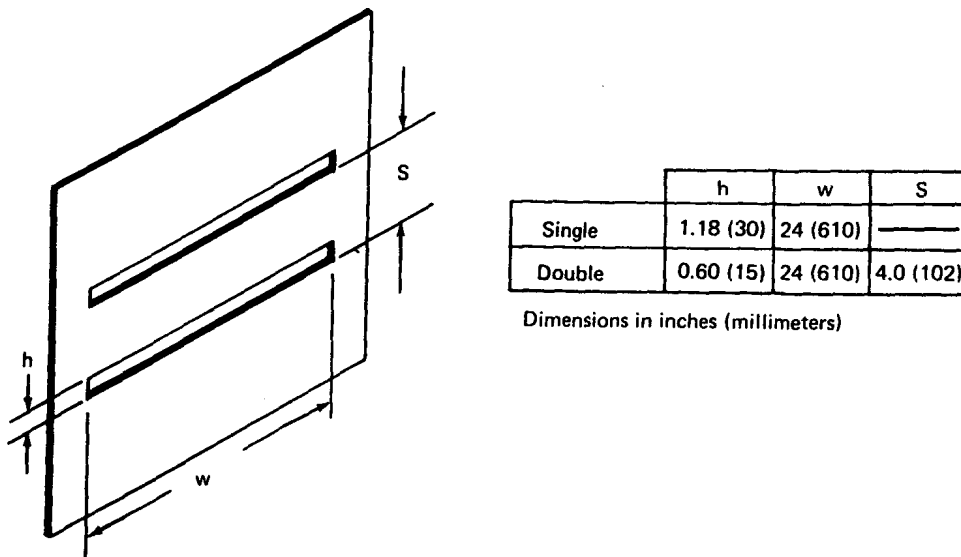


Fig. 1.7—Details of the slotted exhaust inlet configurations (single- and double-slot)

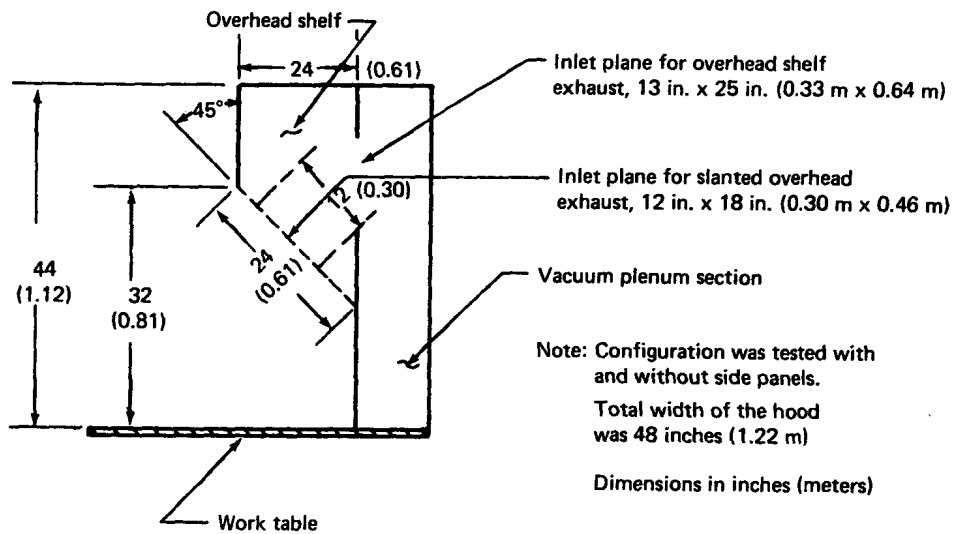


Fig. 1.8—Details of the overhead hood exhaust system

tives of this study, the required simulation of actual welding plumes would exist if the temperatures within the two plumes were equal and the response of the two plumes to a given air current was identical. Equal temperature profiles would result in equal buoyancy and, therefore, equal upward velocities. Identical response to an air current would result when the mass flow rates were equal.

The simulator was a device used to produce plumes representative of a broad range of those generated during actual welding. The reasons for using a simulator instead of actual welding plumes were twofold: it provided a means of obtaining a continuous, long-lasting plume that could be accurately reproduced and quickly changed to simulate different welding operations; and it permitted the use of a tracer gas that could be accurately measured on a real time basis. The underlying consideration was to obtain the maximum possible amount of information and design data within restraints placed on the program.

The apparatus designed, fabricated, and used to duplicate the flow of welding fumes in the vicinity of the welder included a gas heater unit, a gas supply system, and associated monitoring and control systems.

Fig. 1.9 is a schematic of the apparatus used to duplicate the flow of welding fumes. The gas supply system included a two-bottle bank of nitrogen, a two-bottle

bank of carbon monoxide, and associated regulators and valves to control and select the desired gas. Nitrogen was used as an intermediate gas to bring the system up to operating condition and when CO was not being used (periods of time between test runs, etc.). The gas flow rate to the heater was controlled with a needle valve installed in the gas supply lines and was measured using a rotometer.

The gas (CO or N₂) was electrically heated by a heater designed and fabricated at BCL. A schematic of the heater assembly is shown in Fig. 1.10. Gas was introduced into the bottom of the heater and passed over electrically heated elements as it flowed up through the heater. The gas temperature was monitored at the top of the heater in the stagnation chamber using a chromel-alumel thermocouple. The thermocouple output was recorded and monitored on a strip chart recorder. At the heater outlet an orifice plate was used to obtain the desired initial plume size with various orifice plates used to duplicate different welding plumes. The heater shell was insulated to reduce heat losses. The heater operating temperature range was 100° F to 1200° F (38° C to 649° C) and was controlled using a 110 volt (ac) variac controller. **Vacuum Exhaust System.** A system was set up to determine the effectiveness of various local exhaust systems. It included a blower to move the desired amount of air, an orifice plate to measure the amount of air

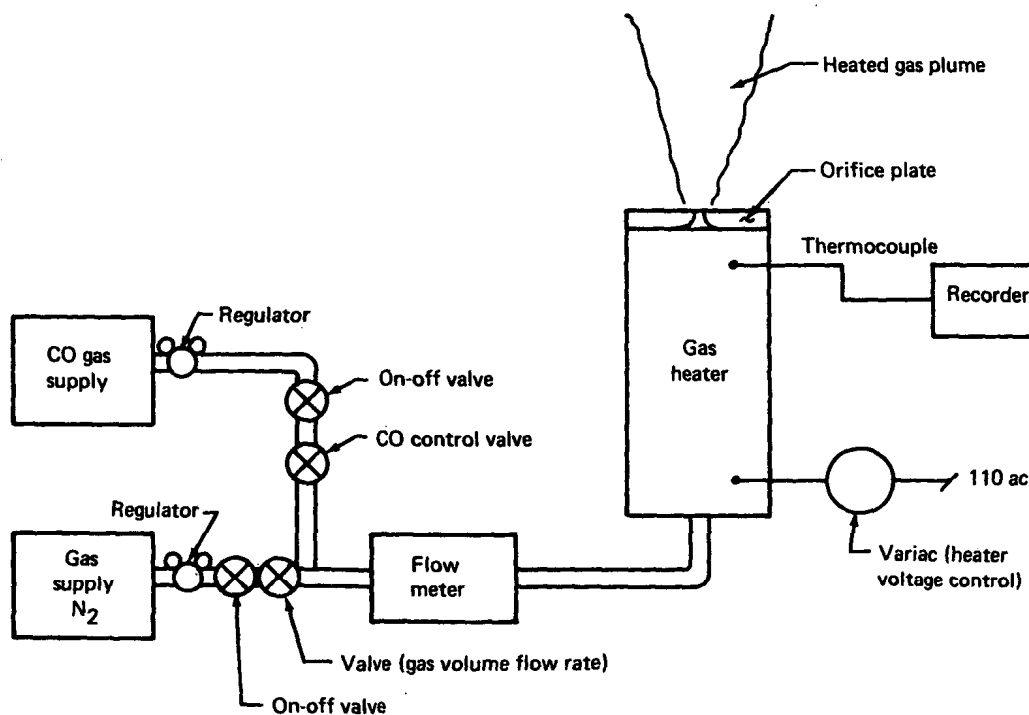


Fig. 1.9—Schematic of fume simulator apparatus

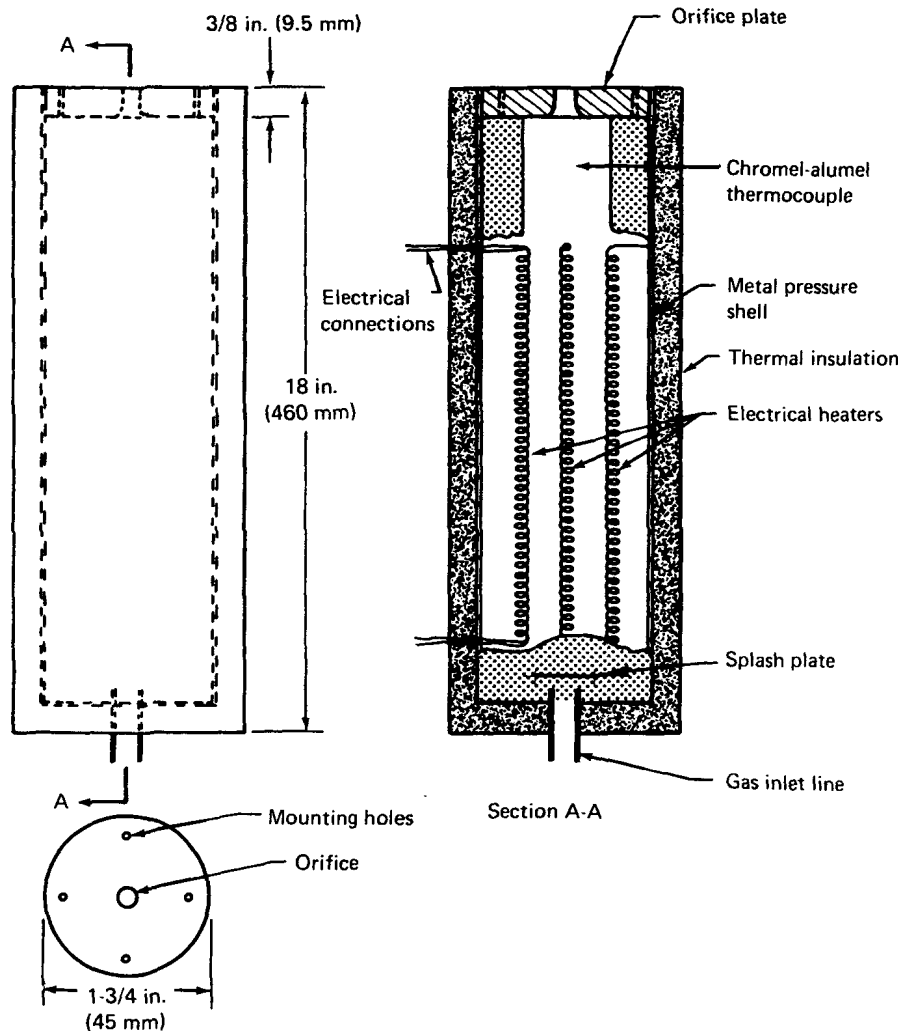


Fig. 1.10—Details of the gas heater

moving through the exhaust system, a CO sampling probe to measure the concentration level of CO in the exhaust duct, and a vacuum plenum to which the various local exhaust systems were connected.

Fig. 1.11 shows the arrangement of hardware and instrumentation used in conducting the local exhaust system experiments. The simulator apparatus and local exhaust inlet configurations shown in Fig. 1.9 were discussed in previous sections.

The duct type exhaust inlet configurations were attached to the vacuum plenum with flexible tubing so that the inlet could be positioned at various locations relative to the welding arc, or arc simulator location, or both (noted as welding area in Fig. 1.11). The vacuum exhaust plenum was connected to the blower with 12 in. (0.30 m)

diameter metal ducting. A flow-measuring orifice plate was installed approximately 12 ft (3.66 m) downstream of the vacuum exhaust plenum and 10 ft (3.05 m) upstream of a 90 degree elbow in the ducting to the blower as shown in Fig. 1.11. The CO sampling probe was located 5 ft (1.5 m) downstream of the orifice plate. The blower outlet was exhausted to the atmosphere outside the laboratory.

The orifice plate pressure differential and upstream pressure were measured using inclined and vertical water manometers. CO concentration levels were measured using a Beckman CO Analyzer, Model No. 315B.

The vacuum exhaust plenum was fabricated using a 3/4 in. (19 mm) thick plywood sheet, reinforced with metal angles. The plenum was designed sufficiently

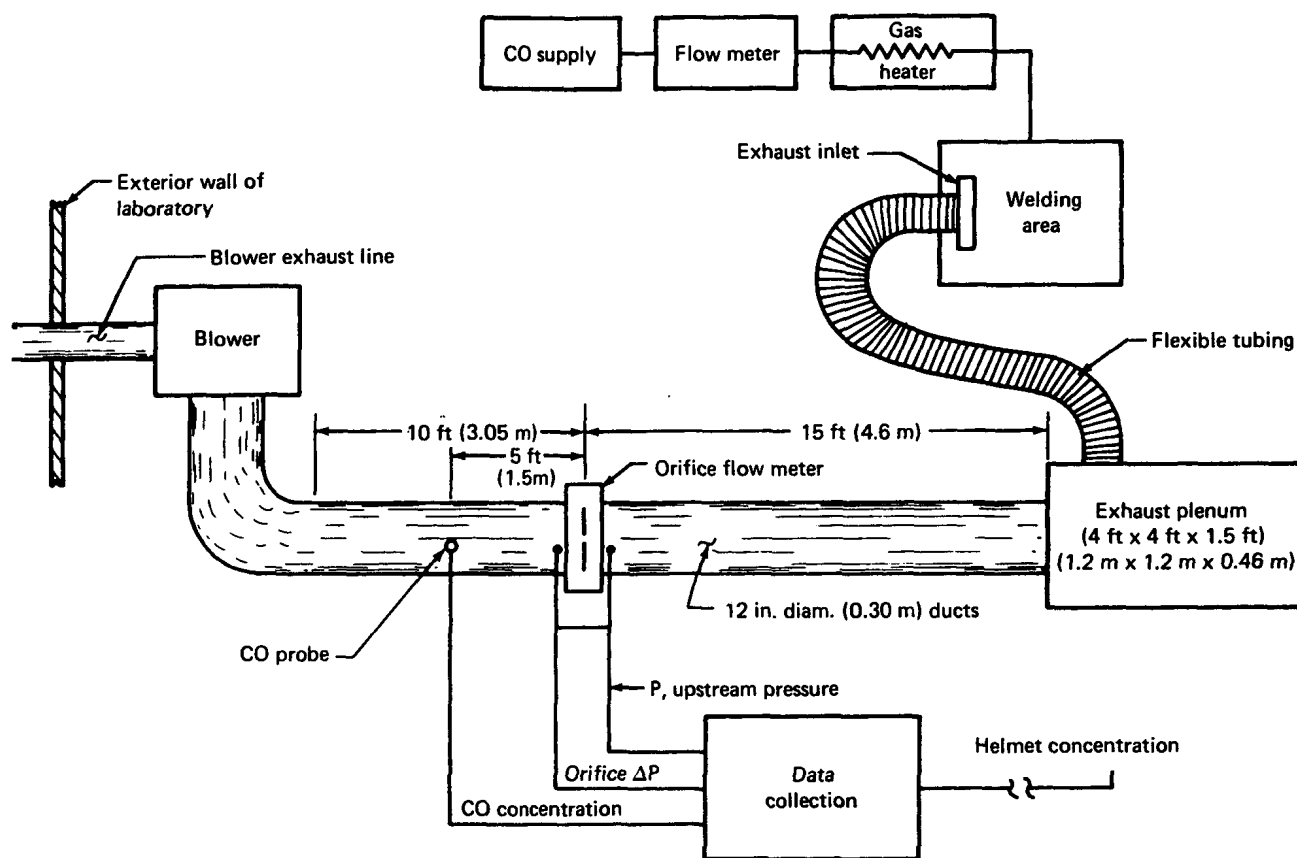


Fig. 1.11—Schematic of test apparatus used in the local exhaust experiments

large (4 x 4 x 1.5 ft [1.2 x 1.2 x 0.46 m]) to reduce non-uniformities in the velocity flow field at the entrance to the slotted and overhead hood configurations.

Instrumentation. All of the instruments used in this study were off-the-shelf items. These included recorders, thermocouples, rotometers, CO analyzer, manometers, and sharp-edge orifices. The instrumentation was checked out after installation to ensure proper operation. Two probes were designed and fabricated at BCL for this study: the CO sampling probe used in the vacuum exhaust duct (12 in. [0.3 m] diameter) to measure CO concentration level, and a multi-sensor thermocouple probe to measure temperatures within the welding plumes and the plumes generated using the simulator.

CO Probe. In order to determine the efficiency of the exhaust devices, it was necessary to measure the CO concentration level in the vacuum exhaust line. Fig. 1.12 is a schematic of the CO probe used to obtain the gas samples. The sampling holes in the probe were sized and located according to conventional practice in order to obtain an equal volume (mass) sample for equal flow

areas in the 12 in. (0.3 m) diameter duct cross section. It was later verified by closing selected sampling holes that the CO concentration within the duct flow cross section was uniform.

Orifice Meter. A standard sharp-edge orifice meter was used to measure the volume flow of gas that passed through the vacuum exhaust system. A 3.6 in. (91.4 mm) and an 8 in. (203 mm) diameter orifice plate were used to cover the range of gas volume flow rates. The calibration curves for both orifices are presented in Fig. 1.13.

Temperature Probe. A temperature probe was used to measure gas temperatures in the plumes generated during arc welding and in the simulator plume. A schematic of the temperature probe is shown in Fig. 1.14. The temperature probe was positioned above the welding and simulator table so that the thermocouple array was in a horizontal plane. An array of eighteen chromel-alumel thermocouples was used to measure plume gas temperature. This large number of thermocouples was needed because of the unsteady flow of the plume. The eighteen thermocouple output signals were recorded simultane-

ously, with a CEC Light Beam Oscillograph, Model No. 5-124. The temperatures at various distances from the arc were easily determined from the oscillograph traces.

Photography. Pictures of the welding plume trajectories were taken as part of the characterization of the fume flow field. The pictures were taken with an Orbit 4 x 5 in. (102 x 127 mm) camera using Polaroid Type S2 film.

Welding Setup. The important aspects in setting up a welding operation in the laboratory are that field opera-

tions are represented as closely as possible and that operational variables can be repeated in a controlled manner.

A welding table having a working area of 24 x 24 in. (0.61 x 0.61 m) at a height of 28 in. (0.71 m) was set up in the laboratory and measurements were made relative to the arc location at the center of the work area. The workpiece was allowed to move opposite the weld direction in a horizontal plane in order to maintain the arc in a constant location for the plume temperature measurements and plume deflection tests.

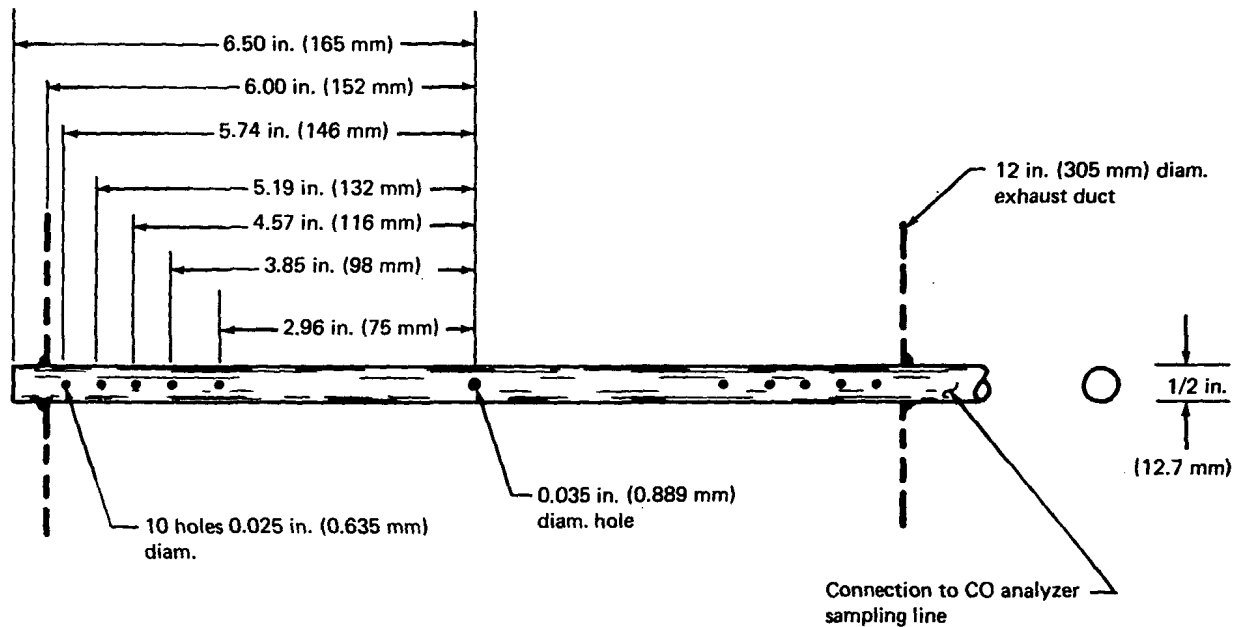


Fig. 1.12—Details of the CO probe.

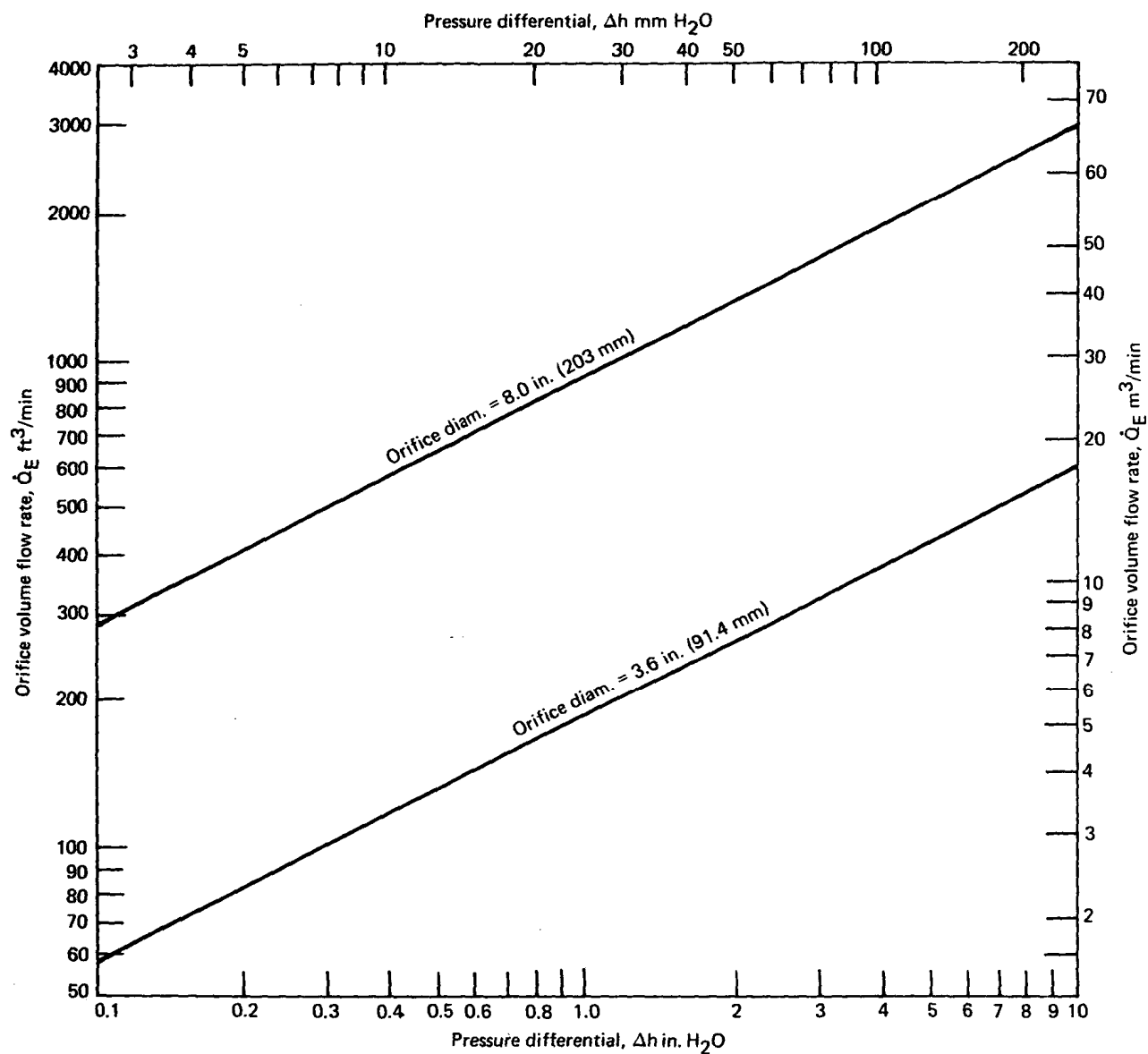


Fig. 1.13—Calibration curves for the 3.6 and 8 in. (91.4 and 203.2 mm) diam. orifice plates

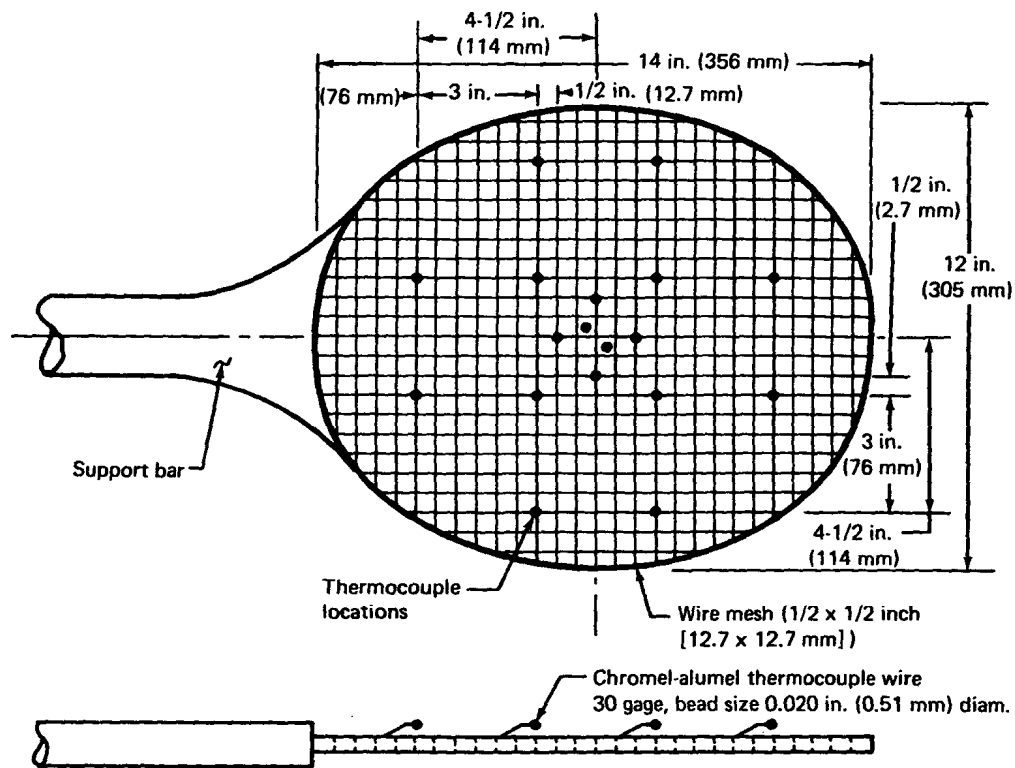


Fig. 1.14—Schematic of the temperature probe

List of Symbols Used in Sections IA, IB, and IC

A_E	= Local exhaust inlet area	$\dot{Q}_s$	= Gas flow rate through heater
C	= Concentration level (Equation 1)	$\dot{Q}_v$	= Ventilation rate (Equation 1)
C_0	= Contamination level in any ventilation air	S	= Slot spacing (Fig. 1.7)
CCO	= Carbon monoxide concentration level (Equation 5)	T_g	= Gas temperature in heater
C^oCO	= Carbon monoxide level without exhaust (Equation 7)	ΔT_f	= Plume temperature, fume
C_s	= Steady-state concentration level (Equation 3)	ΔT_g	= Plume temperature, simulator gas
C_v	= Fume concentration level in welder's breathing zone	ΔT_{g_0}	= Plume temperature above orifice
C_{v_0}	= Fume concentration level in welder's breathing zone for zero ventilation velocity	V_0	= Zero ventilation velocity
d_E	= Local exhaust duct diameter (Fig. 1.6)	V_∞	= Local ventilation velocity
d_F	= Local exhaust flange diameter (Fig. 1.6)	V_R	= Room volume (Equation 1)
d_j	= Orifice diameter	X	= Horizontal distance from arc location
$\bar{D}_p$	= Particle diameter (Equation 4)	X_d	= Plume deflection distance
f	= Fume generation rate	X_E	= Horizontal distance of local exhaust inlet from arc location (Fig. 1.40)
h	= Slot dimension (Fig. 1.7)	Z	= Height above arc location
Δh	= Orifice differential pressure	Z_E	= Vertical distance of local exhaust inlet from arc location
m	= Particle mass concentration (Equation 4)	ϵ_R	= Room contamination factor (Equation 6)
n	= Particle number concentration	ϵ_W	= Welder exposure factor (Equation 7)
ΔP_H	= Differential pressure	η_E	= Exhaust collection efficiency
$\dot{Q}_{AIR}$	= Air volume flow rate (Equation 3)	θ_E	= Angle between exhaust device and welder (Fig. 1.40)
$\dot{Q}_{CO}$	= Carbon monoxide volume flow rate (Equation 5)	θ_v	= Local ventilation direction (Fig. 1.23)
$\dot{Q}_E$	= Local exhaust volume flow rate	ρ_p	= Particle density (Equation 4)

Section IA. General Room Ventilation

Fluid Dynamic Considerations

The fumes and gases generated during welding operations are influenced by the operator and interact with the ambient air currents resulting in a complex flow. The nature of the welding process and the resultant unsteady flow of the fumes and gases further complicate the flow.

In this study, the welding plume is defined as the column of gases and particulate matter resulting from the release of large amounts of energy in a very small volume. The particulate matter of importance in the control of weld fumes consists of those particles whose motion is governed by the hot welding gases and ambient air currents. Typically, the characteristic dimension of these particles (effective diameter) is approximately 1 μm or less.

To aid in understanding the physical processes of importance in the generation and control of weld fumes and gases, it is useful to consider the welding plume in terms of zones. These zones are shown schematically in Fig. 1.15 and are referenced from a horizontal plane through the arc for convenience. Three major zones can be identified: (a) arc zone, (b) welder zone, and (c) free zone. The arc zone is the region where the plume flow is predominantly controlled by the energy release and subsequent heating that occurs from the electric arc. The welder zone is defined as the region in which the presence of the welder influences the plume flow. The free zone is above the welder and is the region in which the plume is influenced solely by room air currents.

The fume and gas flows in the arc zone are strongly influenced by the arc discharge process and the intense arc heating process. The path taken by the plume in this zone is erratic (both vertical and horizontal trajectories) and the fume and gas velocities are relatively high in comparison to the corresponding velocities in the welder and free zones. Control of the fumes and gases in this zone requires external devices that can generate high, induced flow velocities in order to influence the high fume and gas velocities. However, inducing high air currents in the arc zone can have an adverse effect on the quality of the weld.

The characteristic movement of the fumes and gases in the welder zone is upward. The horizontal motion of the plume induced in the arc zone damps out quickly and is essentially zero by the time the gases and fumes reach the welder zone. The plume velocities in the welder zone are relatively low (~ 100 to 500 ft./min [~ 30 to 150 m/min]) and the gases and fumes would rise vertically if they were not influenced by ambient air currents and the presence of the welder. The major characteristic of the plume in the welder zone is that the velocities (gases and fumes) are low; therefore, the path of the plume can be influenced by air currents of small magnitude (natural room air currents can effect the plume trajectory in this

zone). Another important aspect of this zone is that the welder can influence the flow pattern and resulting plume trajectory. Thus, the influence of the welder on the plume must be considered when analyzing the flow characteristics within this zone. This zone can be considered as extending from a few inches from the arc (~ 3.5 inches [~ 80 - 130 mm]) to approximately the elevation of the top of the welder's head. Plume velocities and temperatures decrease in the welder zone as the fumes and gases move upward. It is fairly easy to induce the necessary air currents in this zone to deflect the plume path so that the plume does not engulf the welder's helmet. In the welder zone, the plume must be controlled to protect the welder.

As the welding fumes and gases continue to rise, a well-defined plume is less apparent. In the region above the welder's head, the flow of fumes and gases is predominantly influenced by room air currents. The concentration of fumes and gases will decrease as the fumes and gases mix with the ambient room air. The mixing and diluting process involves many factors associated with the room environment. For example, under circumstances of poor room ventilation, the fumes could collect in the ceiling area. When the welding stops, the fumes would subsequently fall and contaminate the room environment. Also a portion of the fumes would be deposited on surfaces within the room (walls, floors, ceiling, etc.). The long-term room contamination level will depend upon the room ventilation rate, welding process (amount of welding contaminates generated), and the effectiveness of any exhaust system used to collect the welding fumes and gases.

Room Ventilation

The bulk of the fumes generated during welding consists of small particles that remain suspended in the air for a considerable period of time. As a result, their concentration in a closed work area builds up over a period of time, as does the concentration of any gases evolved or used in the welding process. The particles will eventually deposit on the room walls and floor, but the rate at which this occurs is extremely low compared to the rate at which they are generated by welding processes.

Since the particles tend to remain suspended in the air, their concentration can be controlled by general room ventilation. In most cases, general room ventilation is more effective in protecting personnel in the area around the welding operation than it is in protecting the welding operator.

General room ventilation may occur naturally, as when doors and windows are open, or it may require fans and blowers to force and direct the required amount of air through the building or work room. Of course, the effectiveness of general room ventilation is strongly dependent upon the design of the system, be it natural or forced ventilation. The locations at which fresh air is

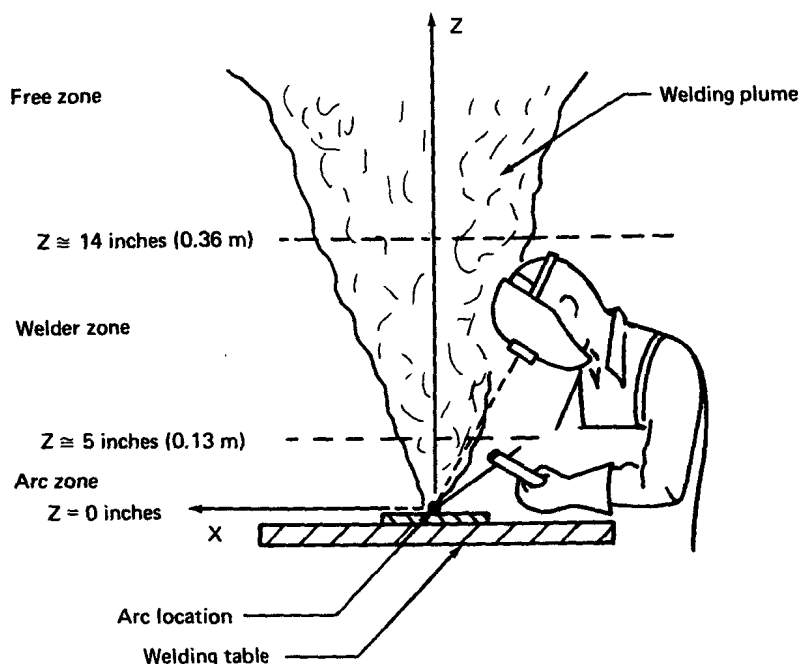


Fig. 1.15—Drawing of welding plume illustrating various zones

introduced and contaminated air is exhausted must be such that the welding fumes and gases are carried away and do not concentrate in dead zones. In some cases, it may be possible to locate the fresh air supply so the incoming air provides the required protection for the welding operator as well as for personnel in the general area.

The concentration of fumes and gases that would exist in any closed room can be accurately calculated as a function of time. The governing differential equation for the contamination level in a closed room is given as

$$\text{Equation 1: } V_R \frac{dC}{dt} = -(C - C_0) \dot{Q}_v + f$$

where C is the room contamination level, C_0 is the concentration level in any ventilation air, V_R is the room size, $\dot{Q}_v$ is the ventilation rate, and f is the fume generation rate.

Equation 1 applies, assuming that the contaminant is uniformly spread throughout the room, that there is no loss of fume due to deposition on various surfaces (walls, floors, etc.), and that, if the room is ventilated, the ventilation air is uniformly distributed. If it is assumed that the ventilation air is free of any fume contamination, that is, $C_0 = 0$, Equation 1 can be integrated to obtain the following expression for the room contamination level as a function of time.

$$\text{Equation 2: } C(t) = 3.53 \times 10^4 \frac{f}{\dot{Q}_v} (1 - e^{-\dot{Q}_v/V_R t})$$

with the units for each of the variables being $f \sim \text{g/min}$, $\dot{Q}_v \sim \text{std ft}^3/\text{min}$, $V_R \sim \text{ft}^3$, $t \sim \text{minutes}$, and $C \sim \text{mg/m}^3$

The steady-state or maximum room concentration levels can be determined from Equation 2 by assuming an infinitely large time period.¹ With this assumption, Equation 2 reduces to

$$\text{Equation 3: } C_s = 3.53 \times 10^4 f / \dot{Q}_v$$

Steady-state fume concentration levels (C_s) calculated using Equation 3 are shown in Fig. 1.16 and apply to rooms of all sizes. The concentrations presented in Fig. 1.16 can also be used to estimate room steady-state fume concentration levels if more than one welding operation is in progress. For example: assuming that there are five welding operators each generating fumes at a rate of approximately 0.6 g/min, and that room ventilation rate is 10,000 std ft³/min (283.2 std m³/min)², the room concentration level would be 10 mg/m³ or 5 times the level for a single welding operation. Estimated fume generation rates for various welding processes are presented in

1. The time required to achieve steady-state concentration levels depends upon the room size and ventilation rate.

2. Std ft³/min = standard cubic feet per minute, measured at 0°C and 1 atm. pressure.

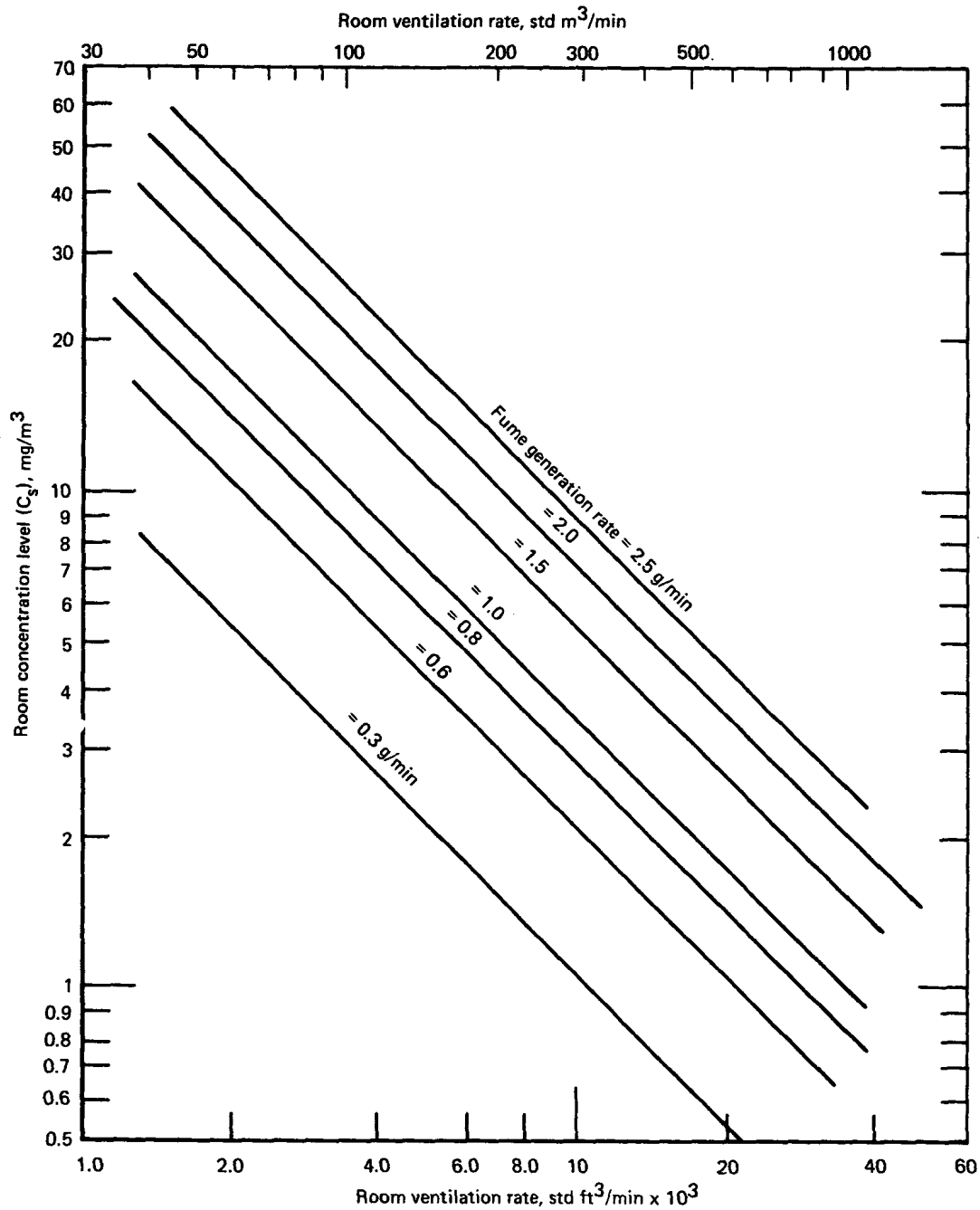


Fig. 1.16—General room ventilation requirements for various welding fume generation rates

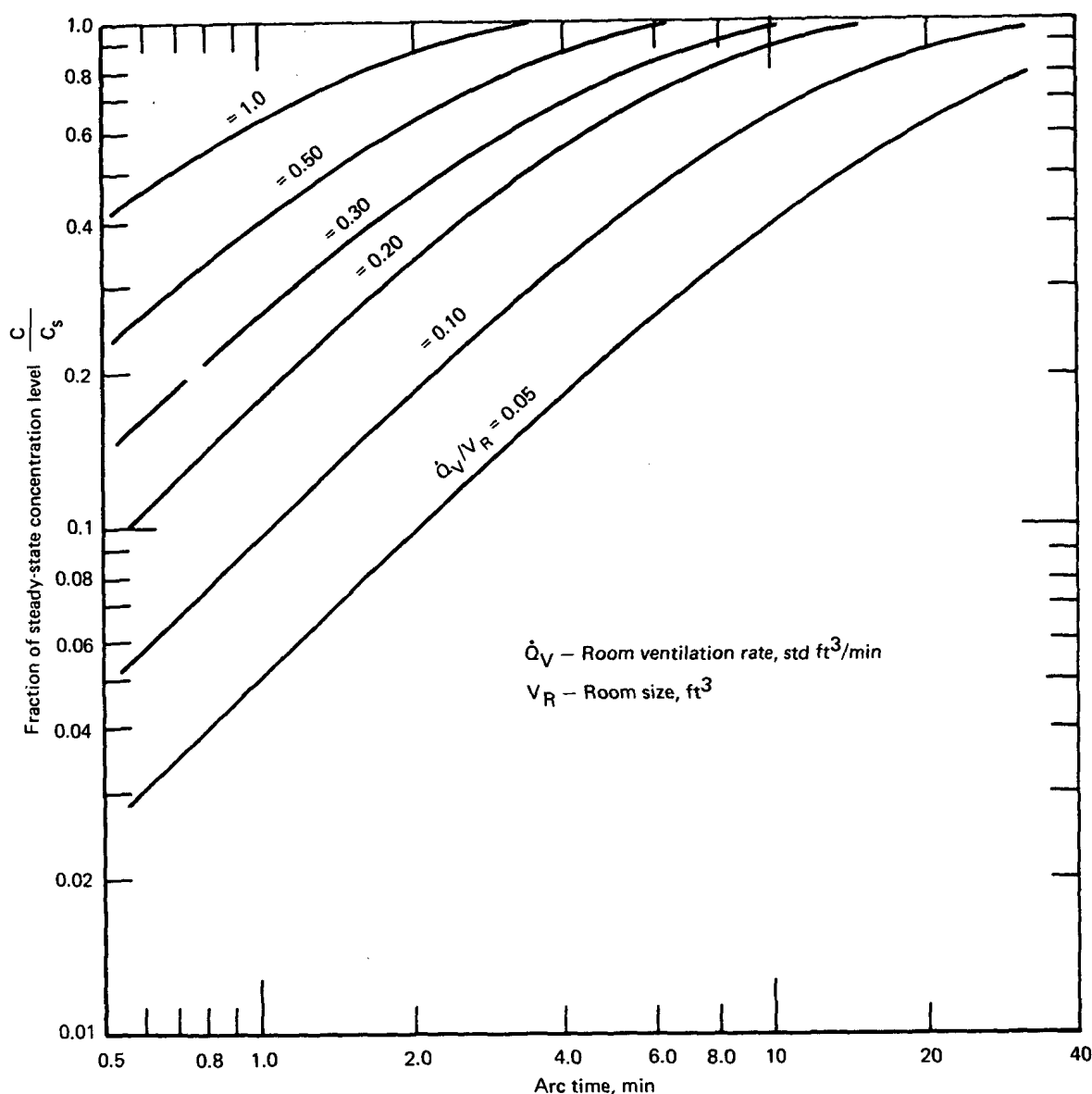


Fig. 1.17—Estimated room concentration level as a function of time for various room sizes and ventilation rates

Part II of this report, and the fume generation rates for a number of the more commonly used processes are given in Appendix A. Fig. 1.16 can also be used to determine steady-state concentration levels for arc times less than 100 percent, which is almost always the case. For arc times less than 100 percent, the time average fume generation rate is used. The time average fume generation rate is obtained by multiplying the fume generation rate, as is shown in Appendix A, by the arc time expressed as a decimal. For example: if, in a one-hour time period, 25 minutes were spent in actual welding, then the arc time would be 25/60 or 0.42.

Using Equation 2, transient concentration levels were determined for time periods less than those required to achieve steady-state levels. Fig. 1.17 shows the room concentration level as a function of time. The concentration level (C), is presented as a fraction of the steady-state value (C_s), and the resulting ratio (C/C_s), is plotted as a function of arc time and $\dot{Q}_V/V_R$ (system time constant). Therefore, in order to estimate room concentration level as a function of time for a particular setup, it is necessary to use both Figs. 1.16 and 1.17.

To illustrate application of Figs. 1.16 and 1.17, the fume concentration in a room was determined assuming

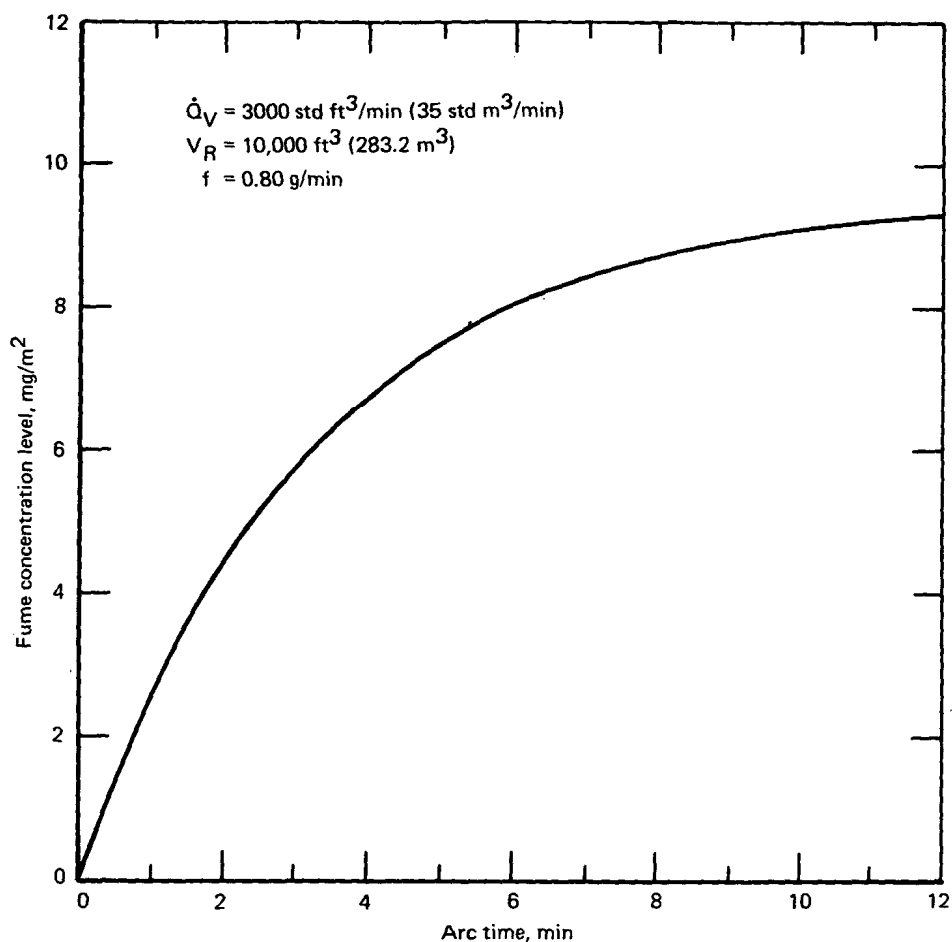


Fig. 1.18—Room concentration level as a function of time for representative room conditions

a room volume of 10,000 ft³ (283 m³), a ventilation rate of 3000 std ft³/min (85 m³/min), and generation of welding fumes at a time average rate of 0.8 g/min. Fig. 1.16 shows that the steady-state concentration level for these conditions would be 9.5 mg/m³. Referring then to Fig. 1.17, it can be seen that for the assumed conditions resulting in a system time constant of 0.3, the room concentration would be one-half of the steady-state value after about 2.5 minutes of continuous welding. Fig. 1.18 shows the room fume concentration level in mg/m³ as a function of time for this example.

cases, does not provide the local control needed to protect the welding operator. Local ventilation is an effective way of providing this protection. For those cases where either room size, arc time, or natural ventilation provides adequate control of general room contamination, only local ventilation would be needed to protect the welder. Since the data needed to design for local ventilation are not available in the literature and cannot be accurately calculated, they were obtained experimentally.

Experiments were performed to determine the effect of the air currents associated with local ventilation on the fume concentration level in the welder's breathing zone. The natural tendency of welding fumes is to rise vertically, due to heating of the air and gases in the immediate vicinity of the electric arc. The welder's head is usually close to or in the plume above the arc; therefore, the welding fumes will flow around the helmet as they move vertically upward, and a portion of the fumes will also penetrate behind the helmet. The amount or concentration of fumes behind the helmet will be a function of

Section IB. Local Ventilation

Data Needed

General room ventilation can effectively control contamination levels within a general area but, in many

the welder's position, the fume generation rate, and the local ventilation rate and direction. In the experimental studies, the reduction in welder exposure levels was determined over a range of air velocities and flow directions.

Calibration of Equipment

Critical Flow Orifice. The critical flow orifice was calibrated with a wet test meter. During orifice calibration, the filter holder, loaded with a filter, was connected ahead of the orifice to duplicate the actual sampling flow condition. The flow rate for the orifice used was 2.7 liters/min when choked flow existed across the orifice. To ensure that the orifice always operated with choked flow and to check for filter clogging during sampling, the pressure drop across the orifice was set and monitored with a pressure gage and installed downstream of the orifice as shown in Fig. 1.2.

Condensation Nuclei Counter. The validity of using the condensation nuclei counter for measuring fume mass concentrations was confirmed as follows. Since the background aerosol concentration ($\sim 40 \mu\text{g}/\text{m}^3$) is negligible compared to the particle concentration caused by welding (typically $\sim 30\,000 \mu\text{g}/\text{m}^3$), the mean particle size should remain the same under various ventilation conditions. For these conditions, the mass concentration can be written as

$$\text{Equation 4: } m = \frac{\pi}{6} n \rho_p \bar{D}_p^3$$

where

m = particle mass concentration, mg/m^3

n = particle number concentration, number/m^3

ρ_p = particle density, $\text{mg}/\mu\text{m}^3$

$\bar{D}_p$ = particle diameter, μm

In Equation 4, it is apparent that the number concentration measured by the particle counter can be directly correlated to the mass concentration. Some measurements were performed to compare the counter output with the actual filter weighing. The comparison, shown in Fig. 1.19, demonstrates that mass measurements obtained using a filter can, indeed, be linearly correlated with the counter output as indicated by Equation 4. Therefore, the real time characteristics of this instrument were used advantageously in the subsequent tests to be described later.

Initially, tests were performed using both the particle counting method and the filter weighing method to measure fume concentration levels. Usually, it was possible to obtain the particle counter data using only one electrode while five electrodes had to be used during the filter weighing measurements to obtain a sufficient sample for weighing. The two measurements were compared and checked for agreement with the calibration curve (shown in Fig. 1.19). The calibration curve was confirmed and subsequent data were taken with the condensation nuclei counter.

Air Current Generator. The ventilation air velocity in the welding zone, 42 in. (1.07 m) from outlet face of the generator, was calibrated in terms of the pressure drop across the packed bed. The calibration curve is shown in Fig. 1.20. This pressure drop was subsequently used to set the air velocity during the experiments.

Experimental Procedure

In conducting the local ventilation experiments, several factors were maintained constant from run to run to eliminate their possible influence on the fume concentration level: (a) welder's posture and head position, (b) initial base metal temperature, and (c) surface contamination. The one important uncontrollable variable was the unsteady flow pattern of natural convection created by the welding arc. This resulted in some variation in the measured values. In order to collect samples as representative and consistent as possible, the following setup and techniques were used.

The welder's head position was controlled by the horizontal bar attached to his helmet (see Fig. 1.5) which assured that his ear was 13 in. (0.33 m) above the arc and 10 in. (0.25 m) away from the arc horizontally. When more than one electrode was needed in order to obtain a measurable fume sample, the base metal was quickly moved after each electrode so the working spot would remain in approximately the same location for each electrode. Therefore, any of the spots coated with slag from the previous electrode were not welded over. All the above procedures were followed because it was found during shakedown tests that the natural fume convection pattern and the ventilation flow pattern can be greatly influenced by these variables.

The experiments were conducted in the following manner: The welder was positioned relative to the direction of the air flow from the generator needed to obtain the desired ventilation flow angle. An arc was struck and power supply adjustments were made to obtain the arc voltage and current specified by the manufacturer for the electrode being used. After the power supply was properly set, welding was started and samples were collected. When more than one electrode was required in order to obtain a measurable sample, fume sampling was performed only during the times when welding was in progress. Therefore, the results apply to 100 percent arc time.

Fume concentration measurements were performed in the welder's breathing zone for a number of ventilation velocity conditions (magnitudes and directions). Fume measurements were also performed under conditions of zero ventilation. The results of the fume measurements follow.

Experimental Results

In order to determine the repeatability of the fume concentration measurements, eight filter measurements

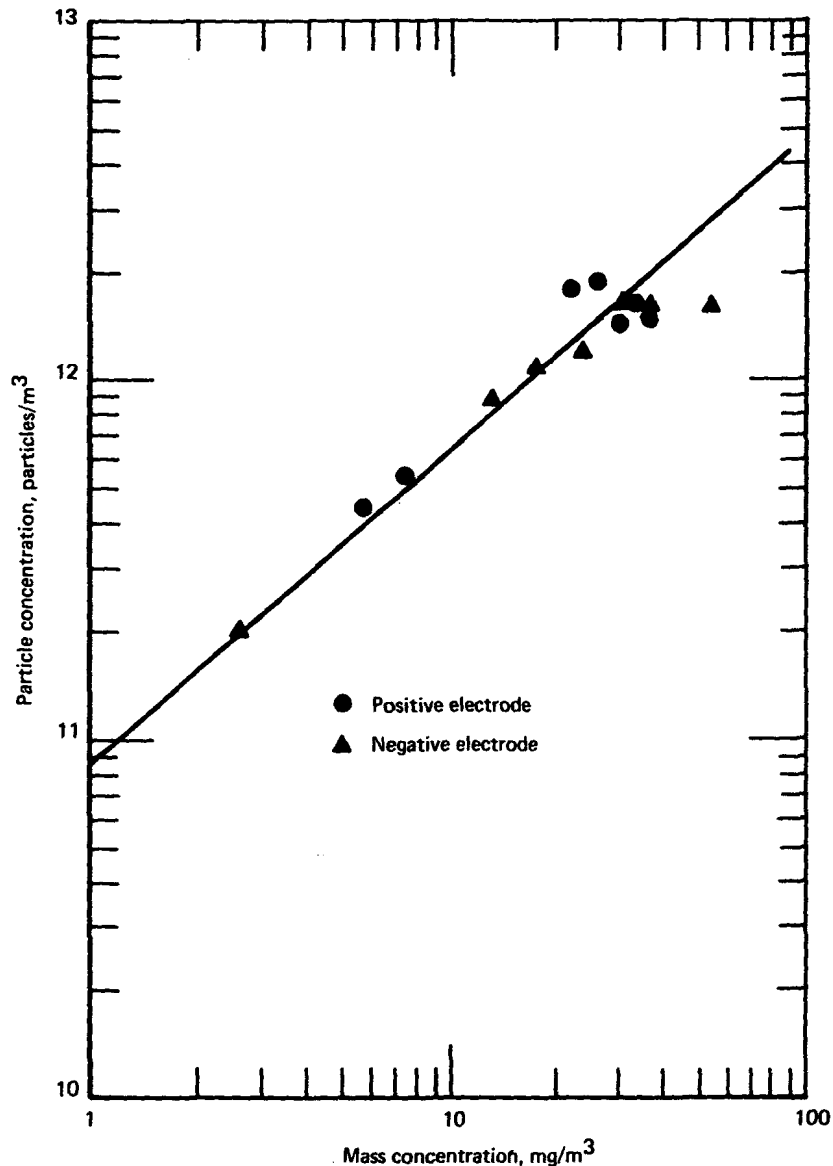


Fig. 1.19—Comparison of condensation nuclei counter and filter weighing results

were made with no ventilation. The results on the tests are shown in Fig. 1.21. The SMAW process was used during this test series using a 5/32 in. (4 mm) diameter E6013 electrode (Code 4). A welding current of 150 A and an arc voltage of 25 V were used for both polarities. The average welding time for each electrode under these conditions was approximately 70 seconds. At least five electrodes were needed to obtain measurable fume mass on the filter. The results shown in Fig. 1.21 indicate that there is a 25 percent scatter in the data.

Fig. 1.22 is a representative recorder trace of the output of the condensation nuclei counter as a function of time. The trace shows that the fume concentration in the welder's breathing zone quickly increases in the first 10 seconds after an arc is struck. The welder's breathing and the intrinsic unsteady flow pattern associated with the welding process cause the fluctuations observed in the counter signal. In reducing the data from the counter output, the area below each curve was integrated to obtain a time average value of fume concentration level.

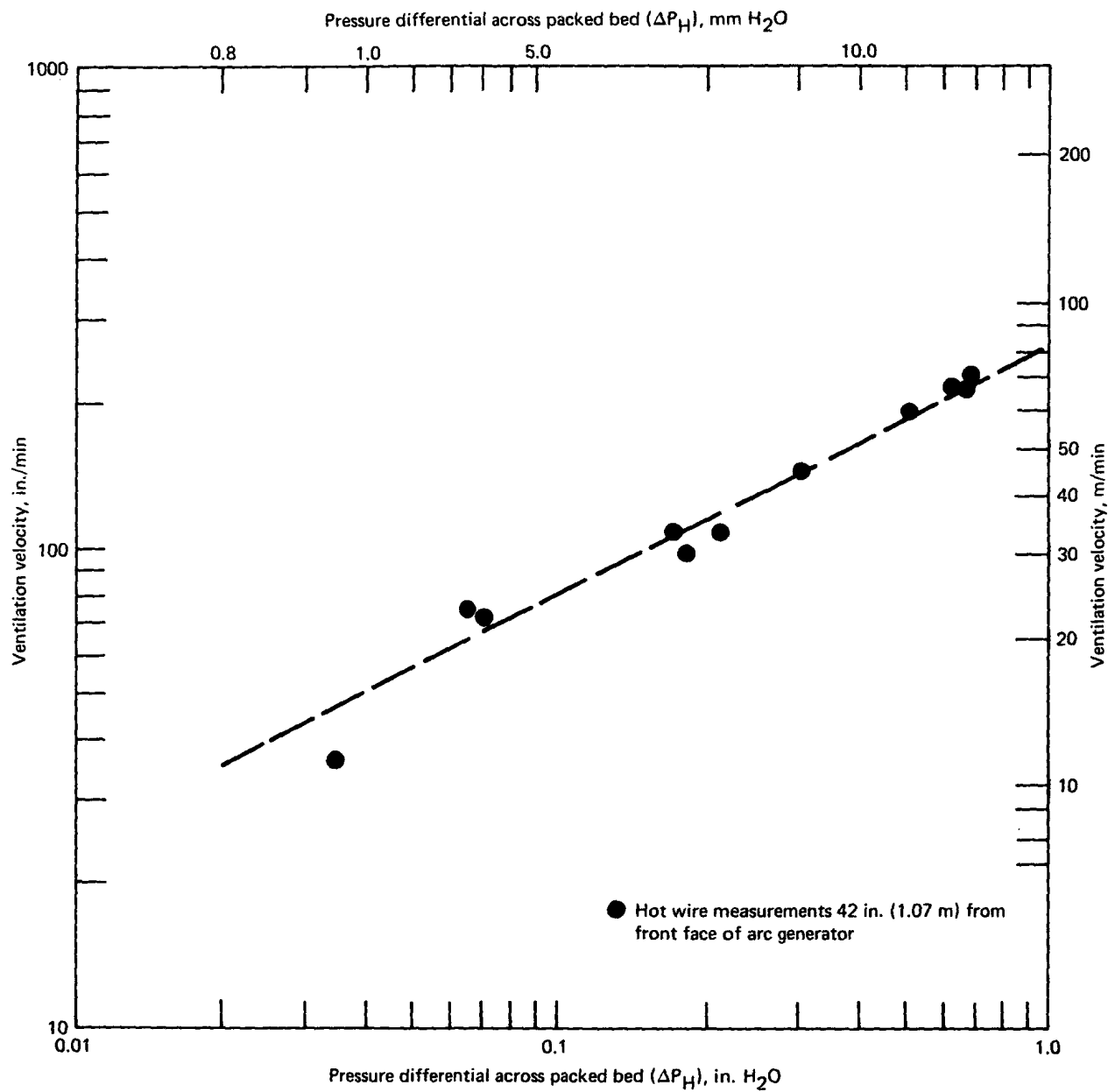


Fig. 1.20—Calibration data for the air current generator

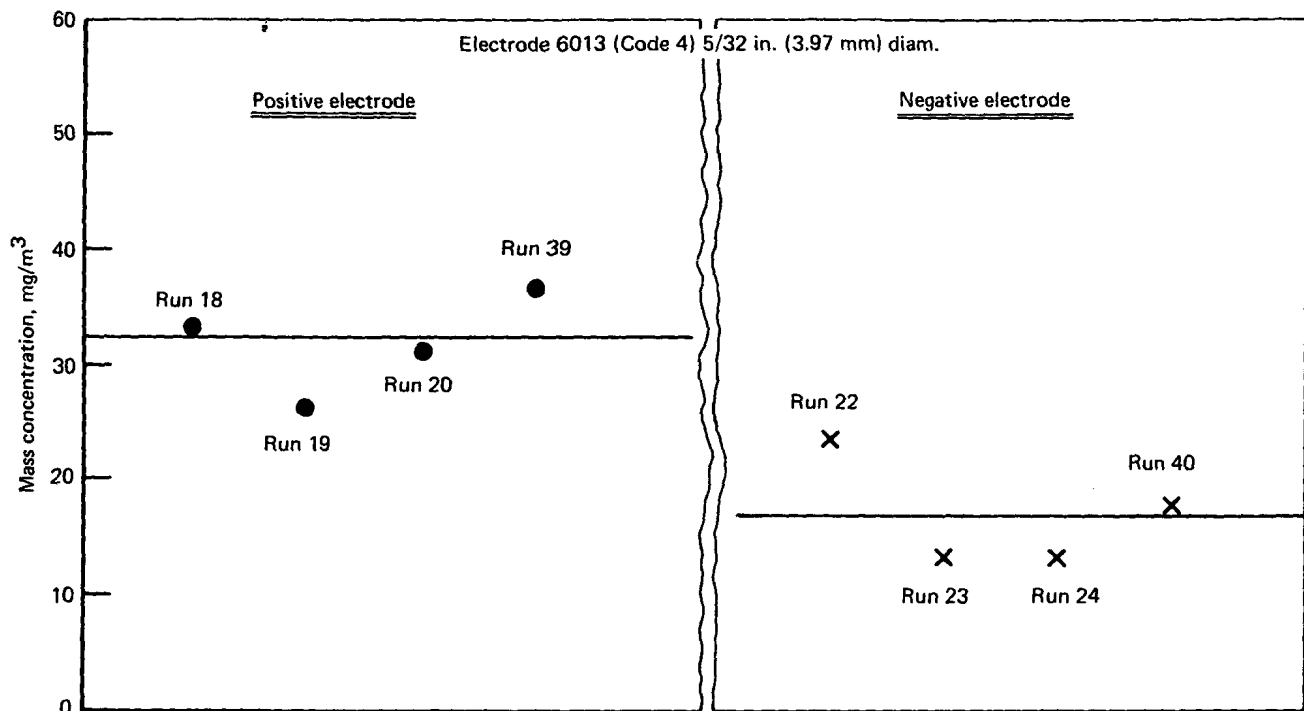


Fig. 1.21—Results of fume concentration repeatability tests

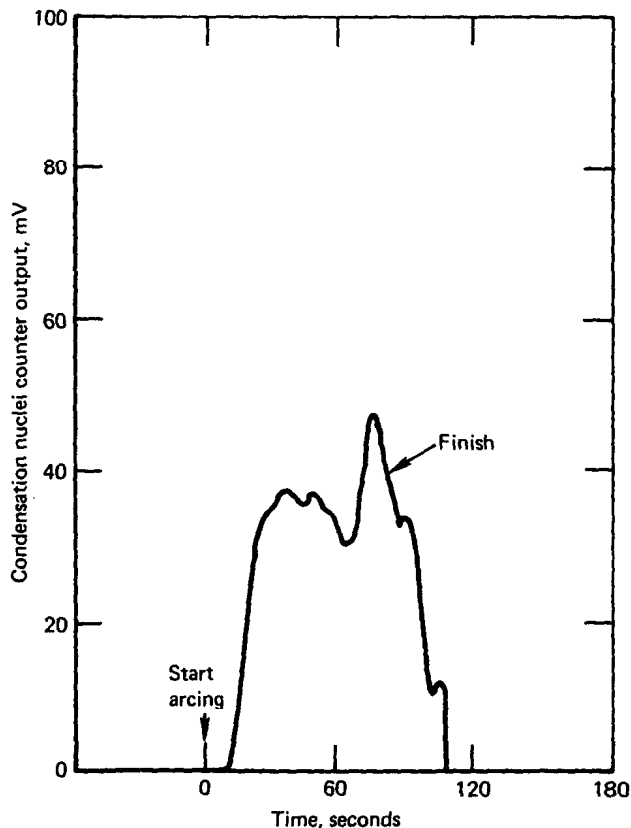


Fig. 1.22—Representative strip chart recording of the condensation nuclei counter output signal

The reduction in fume concentration level in the welder's breathing zone is presented as a function of ventilation conditions (air speed and direction) in Figs. 1.23, 1.24, and 1.25. The fume concentration level is expressed as a percentage ratio of the fume concentration level obtained with ventilation air to that measured for zero ventilation velocity. The results from the experiments conducted with the air flow from the welder's left, $\theta_v = 90^\circ$, are shown plotted in Fig. 1.23 for ventilation velocities from zero to 100 ft/min (0-30 m/min). The fume concentration level drops quite rapidly from the level at zero ventilation to approximately 10 percent at about 80 ft/min (24.4 m/min). It can be assumed that the fume concentration level will decrease even further as the ventilation velocity is increased. The fume concentration level for electrode negative polarity is approximately 50 percent of the electrode positive polarity level at zero ventilation velocity. The fume concentration level for zero ventilation (C_{v_0}) was 37 mg/m³ when operating with electrode positive polarity.

The fume concentration measurements performed with the air current generator behind the welder ($\theta_v = 0^\circ$) and in front of the welder ($\theta_v = 180^\circ$) are presented in Fig. 1.24. The results for $\theta_v = 0^\circ$ (ventilation from behind the welder) show that there is an increase of approximately 20 percent in the fume concentration level as the ventilation velocity is increased from zero to 40 ft/min (12.2 m/min). From 40 ft/min (12.2 m/min) to 200 ft/min (61.0 m/min), the fume concentration level decreases linearly by approximately 80 percent and 60 percent for the elec-

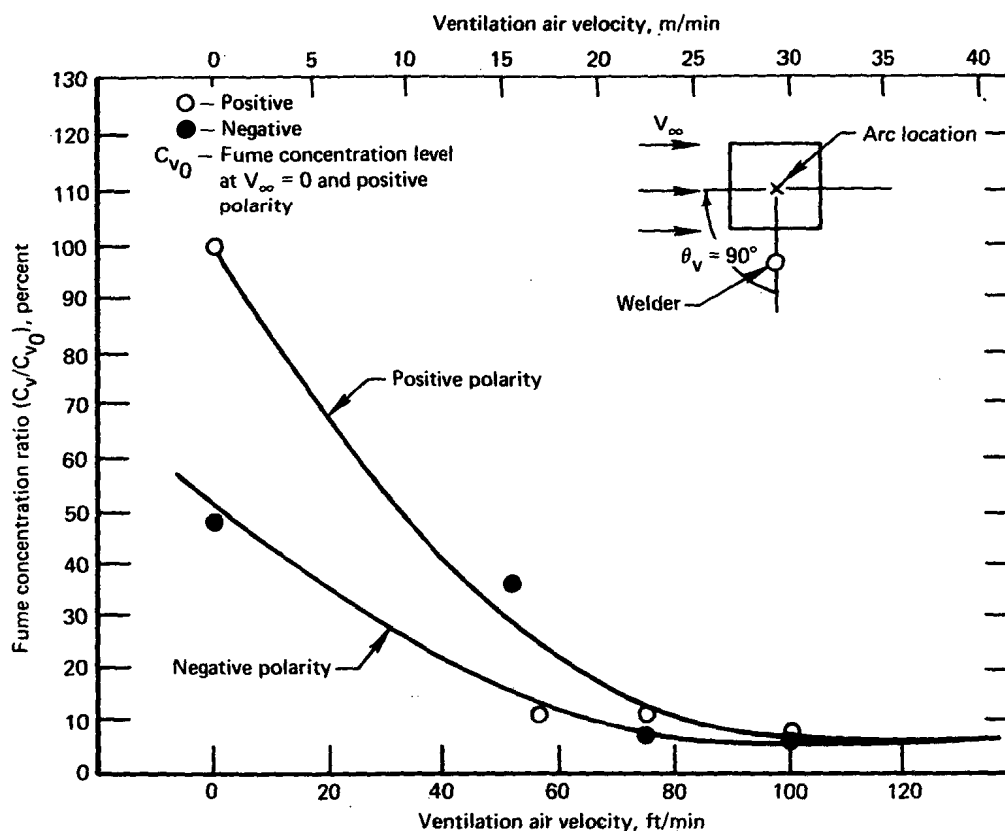


Fig. 1.23—Fume concentration level in the welder breathing zone as a function of ventilation velocity for $\Theta_v = 0$ and 90°

trode positive and negative configurations, respectively. The results obtained for $\theta_v = 180^\circ$ (ventilation from in front of the welder) as a function of ventilation velocity showed an increase in fume concentration level of 20 to 30 percent. The fume concentration level does not decrease as the ventilation rate is increased.

The data for ventilation from directions of $\theta_v = 45^\circ$ and 225° are presented in Fig. 1.25. It is evident from the data plotted in Fig. 1.25 that the fume concentration level is not reduced appreciably (20 percent) until the ventilation rate is increased above 110 ft/min (33.5 m/min).

In order to highlight the dependence of the fume con-

centration level on the direction of the ventilating air flow, the data at a velocity of 50 ft/min (15.2 m/min) are shown as a function of ventilation direction (θ_v) in Fig. 1.26. It can be observed that the fume concentration is strongly dependent upon the flow direction. A cross draft ($\theta_v = 90^\circ$) is found to be the most effective in moving fumes from the welder's breathing zone. If this direction is not possible for a particular working condition, an angle of 45° (or 315°) between the welder and the flowing air position is the next best configuration.

Fig. 1.27 is a similar plot for a higher ventilation rate, and, generally, the same conclusions concerning the direction of air flow can be made.

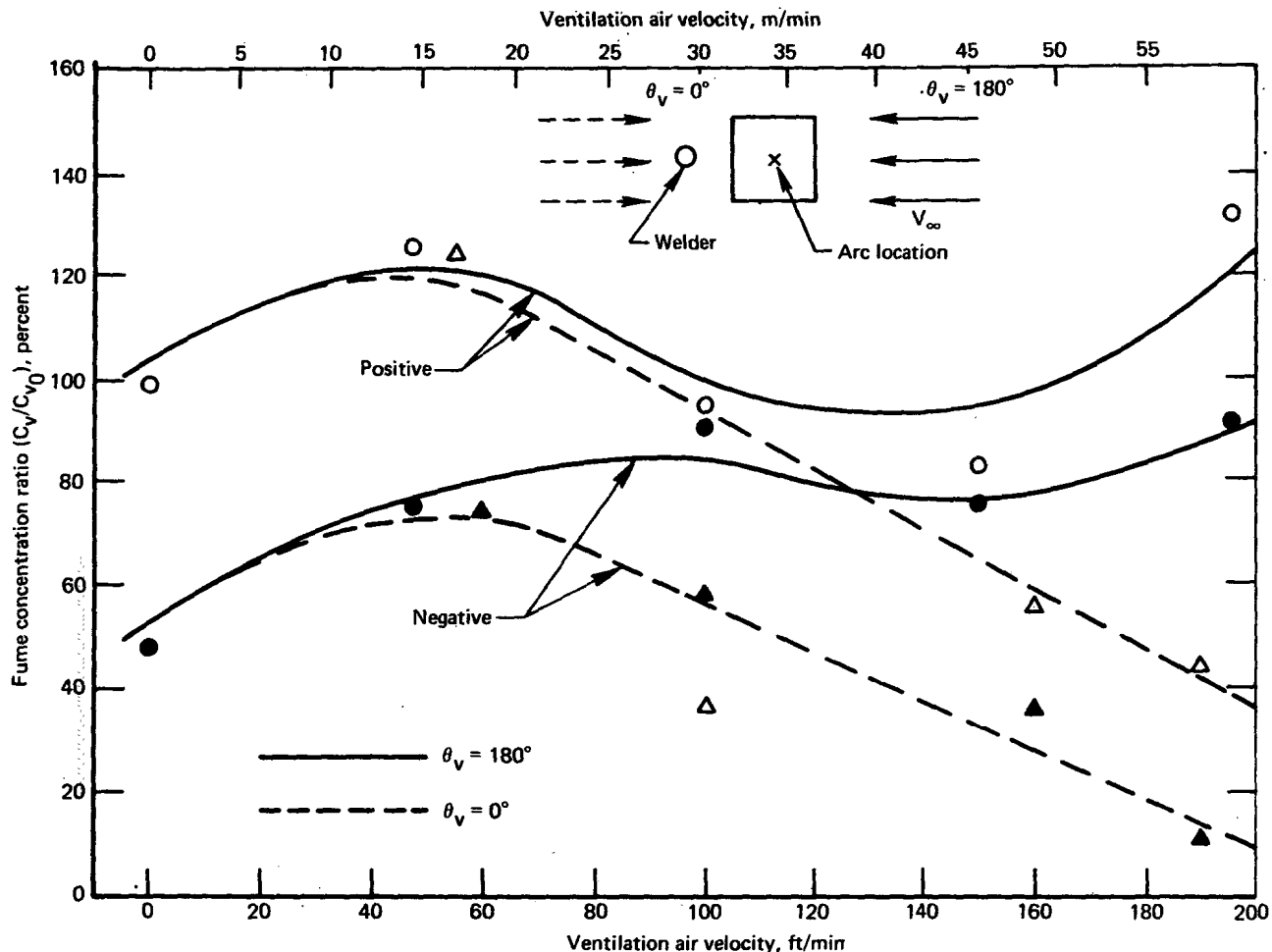


Fig. 1.24 – Fume concentration as a function of ventilation air velocity for $\Theta_v = 0$ and 180°

Section IC. Local Exhaust Studies

The results presented in Section IB, Local Ventilation, showed how local air currents can be used to control fume concentration in the welder's breathing zone. It is evident that the environment in which welding is performed will rise in fume concentration unless general ventilation is employed. In the local exhaust experiments discussed in this section, the performances of various exhaust inlet designs are evaluated based on their effec-

tiveness in collecting and reducing the welder's exposure to the fumes. The experimental variables were collector configuration, collector location, and exhaust flow rate.

Prior to the local exhaust experiments, two other experimental test series were carried out: (1) characterization of welding plumes for various welding processes, and (b) determination of the simulator operating conditions required to duplicate actual welding plumes.

Details of the test apparatus used, the test procedures followed, and the results obtained are presented in this section.

Calibration of Equipment

The CO probe and sampling train were checked out by introducing a metered amount of CO into the vacuum supply system and varying the air volume flow rate through the vacuum system. The CO concentration measured at the probe location should have been equal to

$$\text{Equation 5: } C_{CO} = \frac{\dot{Q}_{CO}}{\dot{Q}_{CO} + \dot{Q}_{AIR}}$$

where C_{CO} is the CO concentration level and $\dot{Q}_{CO}$ and $\dot{Q}_{AIR}$ are the volume flow of carbon monoxide and air, respectively, if the probes were collecting a sample

having an average concentration.

Figure 1.28 shows the CO concentration levels based on Equation 5, the known amount of CO introduced, and the measured CO concentrations. Agreement between the predicted and actual values is excellent, indicating that samples representative of the average concentrations were being obtained. A Beckman CO Analyzer, Model No. 315B, was used to measure the CO concentration level. This instrument was calibrated using factory calibration gases that contain precisely measured percentages of CO. Calibration curves for this instrument are given in Fig. 1.29.

Figure 1.13 shows the calibration curves for the orifice plates.

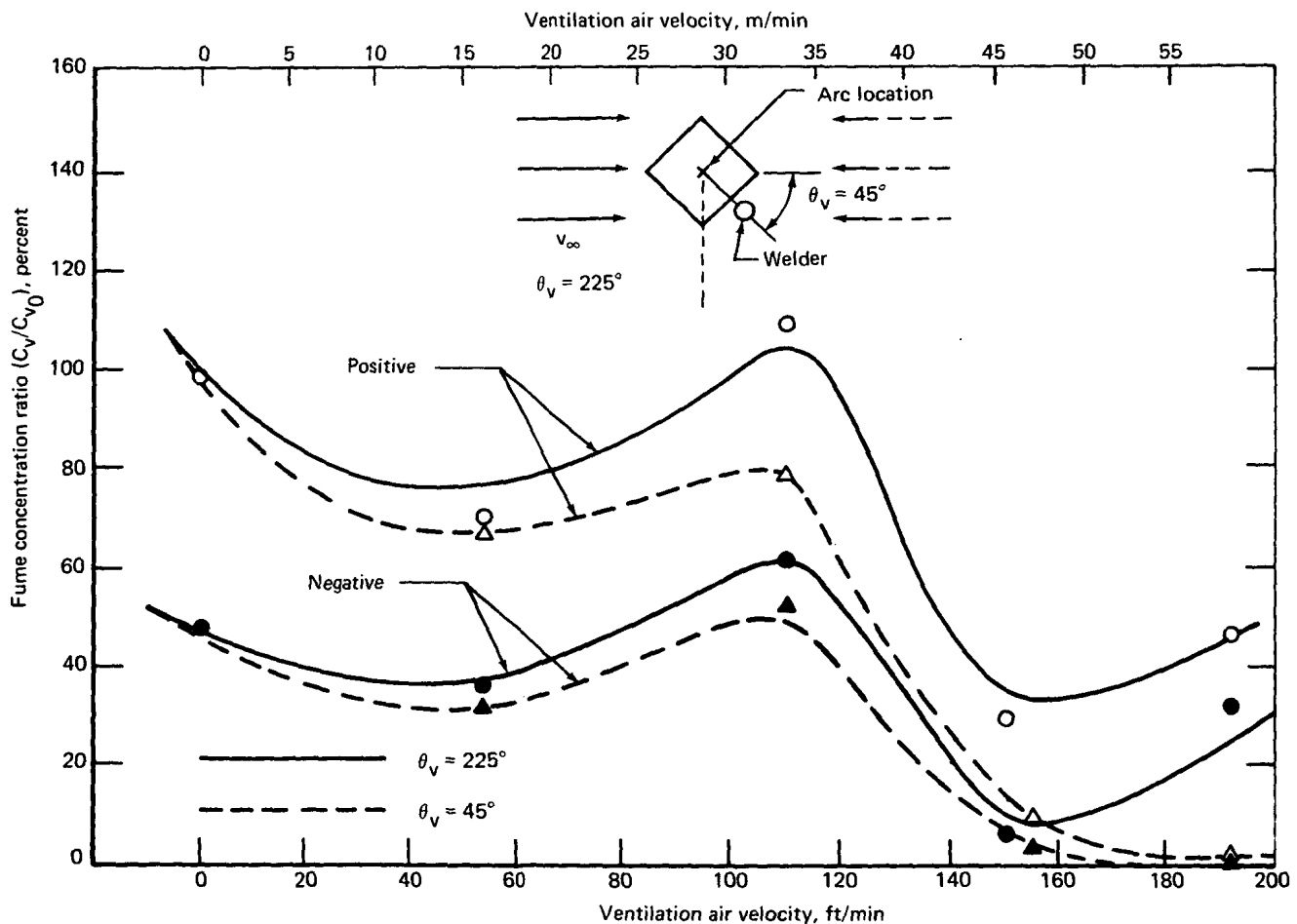


Fig. 1.25—Fume concentration as a function of ventilation air velocity for $\Theta_v = 45^\circ$ and 225°

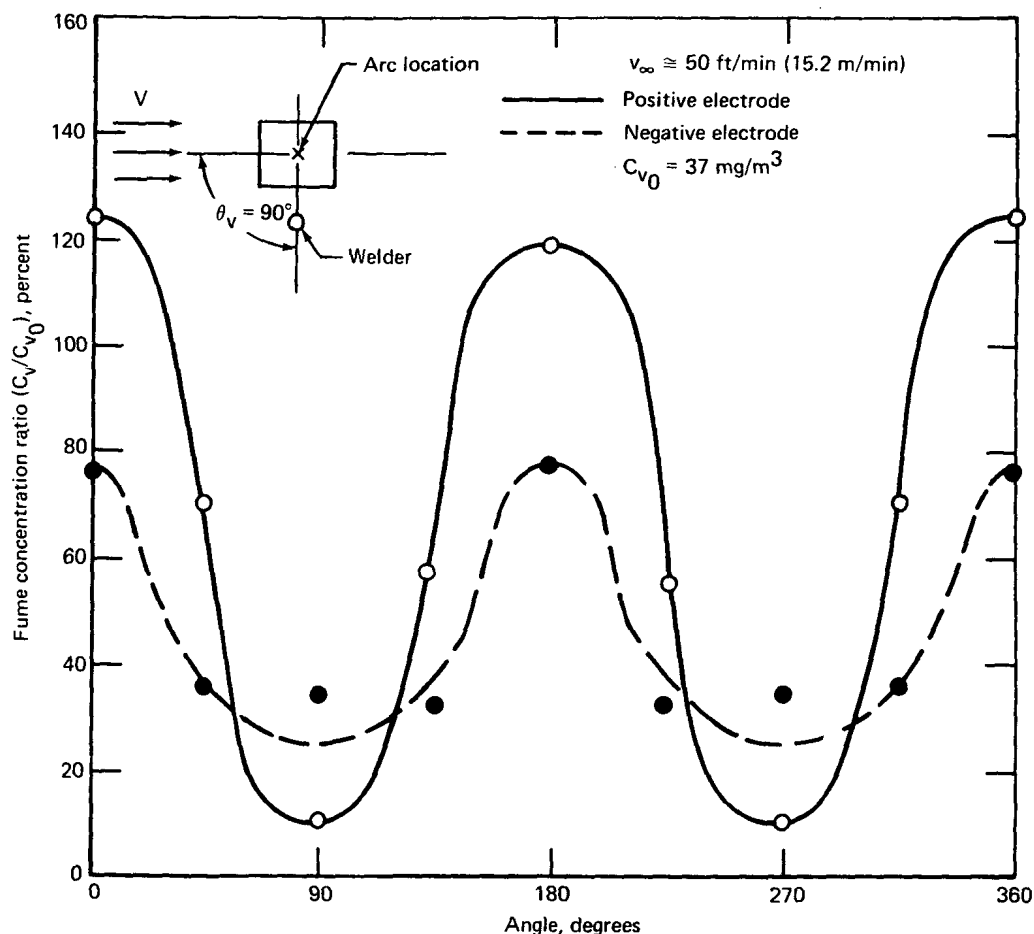


Fig. 1.26—Fume concentration as a function of ventilation direction (θ_v) at a ventilation velocity of 50 ft/min (15.2 m/min)

Experimental Procedure

Three types of experiments were conducted as part of the local exhaust studies: (a) welding fume characterization experiments, (b) simulator characterization experiments, and (c) local exhaust system experiments. The first set of experiments was conducted in order to obtain baseline data on the welding plume temperature and deflection characteristics. The second set of experiments was conducted to establish the simulator operating conditions required to duplicate fume flow conditions measured in the first set of experiments. The third set of experiments was conducted to evaluate the performance of various inlet exhaust configurations. The procedures followed in performing these experiments are described below.

Fume Characterization. There are many welding processes in use throughout the welding community. Associated with these many processes is an even larger number of techniques that are used in welding operations. The test matrix of welding processes selected in this study as a test base included those processes most commonly used by the welding community that generate welding fumes at rates covering the spectrum associated with most welding processes.

Table 1.1 is a list of the welding processes that were used to characterize the thermodynamic and fluid dynamic behavior of welding plumes. The welding was conducted using the electrode manufacturers' recommended values of arc voltage and current. The test matrix includes shielded arc welding, flux cored arc welding (automatic), and gas metal arc welding (auto-

Table 1.1
Welding test matrix

Electrode type	Code no.	Electrode diam.		Arc current, A	Arc voltage, V	Welding speed		Wire feed rate		Shielding gas	Shielding gas flow rate		Electrode stickout	
		in.	mm			in./min	m/min	in./min	m/min		ft ³ /h	m ³ /h	in.	mm
Shielded metal arc welding														
E6010	1	5/32	3.97	150	26	9	0.23	---	---	---	---	---	---	
E7018	10	5/32	3.97	170	23	9	0.23	---	---	---	---	---	---	
E7024	7	5/32	3.97	210	40	8	0.20	---	---	---	---	---	---	
E316-16	25	5/32	3.97	150	27	8	0.20	---	---	---	---	---	---	
E7018	10	3/32	2.38	65	21	6	0.15	---	---	---	---	---	---	
E7018	10	3/16	4.76	220	22	9	0.23	---	---	---	---	---	---	
Flux cored arc welding (automatic)														
E70T	40	3/32	2.38	480	30	16	0.41	205-210	5.21-5.33	CO ₂	45-50	1.27-1.42	1-1/2	38.1
E70T-4	56	3/32	2.38	390	30	16	0.41	290-300	7.37-7.62	---	---	---	2-3/4	69.9
Gas metal arc welding (automatic)														
E70S-3	57	0.045	1.14	285	35	16	0.41	430	10.92	AR-20 ₂	45-50	1.27-1.42	1.0	25.4
ER5356	60	0.045	1.14	165	23	16	0.41	360	9.14	AR	45-50	1.27-1.42	3/4	19.1

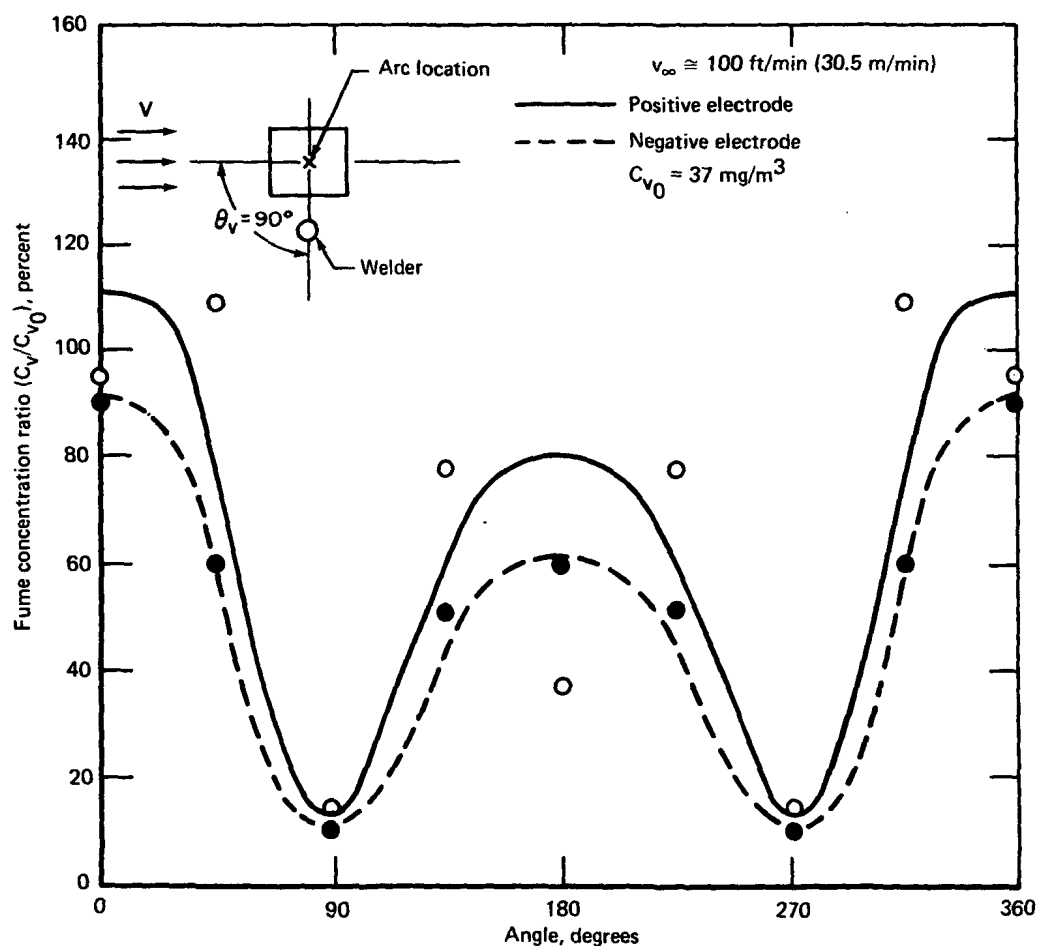


Fig. 1.27—Fume concentration as a function of ventilation direction (θ_v) at a ventilation velocity of 100 ft/min (30.5 m/min)

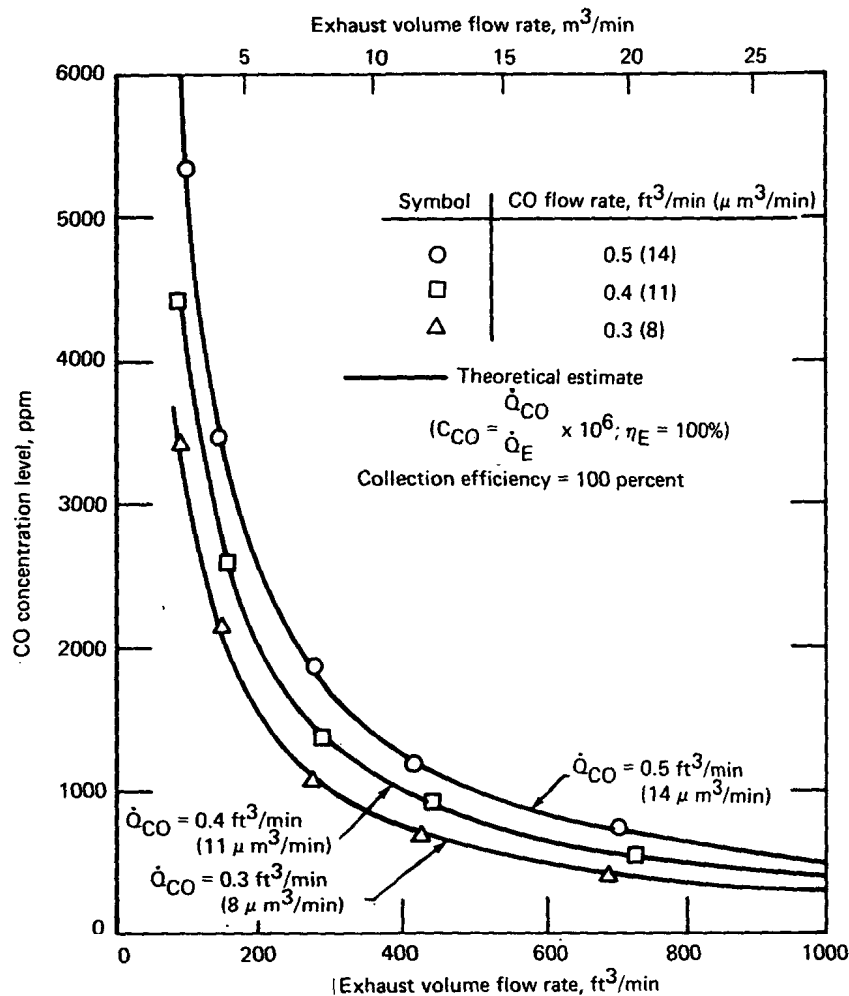


Fig. 1.28—CO probe calibration data

matic). Ten different electrodes were examined. The “code number” designations shown in the test matrix correspond to different electrode manufacturers.

Accepted criteria for establishing the similarity of plumes (such as a weld plume) require an equivalence between buoyancy forces (which are thermally induced) and momentum forces. In these tests, the buoyancy forces of the weld plume were matched with the simulator by ensuring similar plume temperature distributions with respect to height above the arc. The momentum forces of the weld plume were matched with the simulator by ensuring similar plume deflection in a given air current.

Accordingly, two properties of the plumes were measured during the characterization experiments: temperature profile and flow path in a known crosswind. Each welding process was performed alternately by using one of the six pieces of 1/2 in. (12.7 mm) thick mild steel plates. This maintained the plate temperature at a relatively constant level. Positioning the welder out of the fume flow during these experiments provided the desired unobstructed flow field that facilitated characterization of the plume temperature and deflection. It should be noted that the welder was included in the experiments to evaluate the effectiveness of the various local exhaust devices.

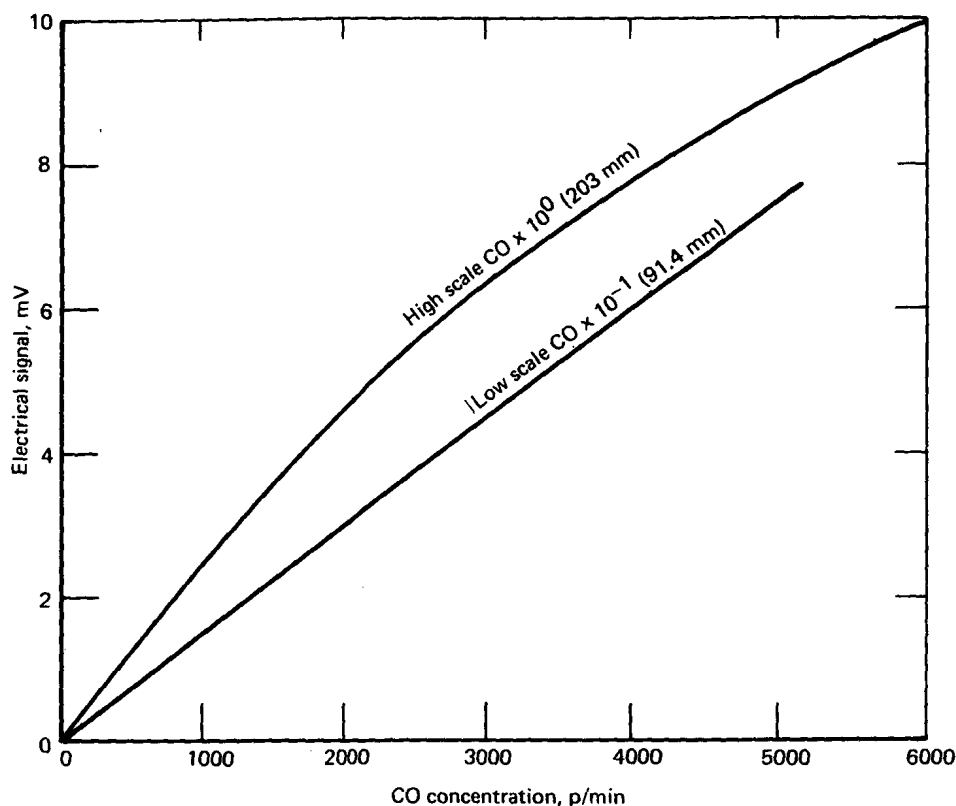


Fig. 1.29—Calibration curves for the Beckman CO analyzer

Temperature measurements were obtained using the temperature probe at various heights above the arc between 5 and 15 in. (130 and 380 mm). The maximum temperature at each elevation was determined from the oscillograph recordings of the temperature probe thermocouples. After the temperature data were obtained for a given welding process, pictures of the plume were taken to define the fume flow path (trajectory). The hot fumes and gases resulting from welding have a natural tendency to rise because of the upward buoyancy force resulting from a difference in density between the hot welding gases and the air. If no external forces acted on the rising fumes and gases, they could continue to rise in a vertical direction with little or no sideward motion until the plume was cooled by mixing with the surrounding air. The air current generator discussed previously was used to generate a controlled, uniform air flow. An air current of 80 ft/min (24.4 m/min) was used for these tests. This air speed was found to deflect the plume out of the region of the welder's helmet in the local ventila-

tion experiments and to provide sufficient plume deflections for accurate measurement. Photographs of the plumes generated from each of the welding processes were obtained and analyzed to determine the plume deflection at a height 25 in. (635 mm) above the arc. Figure 1.30 is a representative plume photograph.

Simulator. Simulator-generated plumes were studied for a wide range of simulator operation conditions. These studies showed that the simulator could be used to produce plumes that duplicated those of hot gases and fumes generated during various welding processes.

The simulator-generated plume experiments were conducted in the following manner: A desired gas flow to the heater was set, and the heater gas temperature was allowed to reach a steady-state value. Plume temperatures were measured at various heights above the heater outlet orifice. These measurements were performed using the same instrumentation (temperature probe and recorder) and procedure discussed in "Fume Characterization." After the temperature data were obtained, a