IN-DEPTH SURVEY REPORT:

THE EFFECT OF WELD PROCESS AND VENTILATION METHOD ON PHYSICAL WORK LOAD, WELD FUME EXPOSURE, AND WELD PERFORMANCE IN A CONFINED-SPACE WELDING TASK

at

Jeffboat Shipyard
American Commercial Barge Lines (ACBL)
Jeffersonville, Indiana

Report Written By
Steven J Wurzelbacher, NIOSH
Stephen D Hudock, NIOSH
Brian D Lowe, NIOSH
Ova E Johnston, NIOSH
Stanley A Shulman, NIOSH

REPORT DATE
November 2000

REPORT NO
EPHB 229-11b

U S DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Division of Physical Sciences and Engineering
Engineering Control Technology Branch
4676 Columbia Parkway - R5
Cincinnati, Ohio 45226

Study Site	Jeffboat Shipyard American Commercial Barge Lines (ACBL) P O Box 610 Jeffersonville, Indiana 47130
SIC Code	3731
Study Dates	April 12-16, 1999
Study Conducted By	Steven J Wurzelbacher, NIOSH Stephen D Hudock, NIOSH Brian D Lowe, NIOSH Ova E Johnston, NIOSH Daniel Almaguer, NIOSH Daniel S Watkins, NIOSH
Employer Representative	Stephen R Morris, Director of Safety (812) 288-1741
Employee Representative	None
Analytical Support	DataChem Laboratories 960 West Levoy Drive Salt Lake City, Utah 84123-2547 (801) 266-7700
Analytical Consultation	Marjorie E Wallace, NIOSH
Manuscript Prepared By	Margaret A Ivory, NIOSH

DISCLAIMER

ABSTRACT

The ergonomic factors affecting safety and performance of shipyard welders, especially those working in confined spaces, have not been adequately studied Such workers typically weld in conditions that provide inadequate ventilation and require static muscular work and awkward, constrained postures Thus, there is a need to establish the effectiveness of engineering interventions, such as static load reduction and alternative ventilation methods, on the basis of reducing musculoskeletal/physiological demand and weld fume exposure among confined-space welders while also enhancing worker performance

To accomplish these aims, this study measured the effect of weld process and ventilation method on the physical work load, weld fume exposure, and weld performance associated with a simulated confined-space welding task Ten male shipyard welders performed eight flat welding tasks [four wire-fed welding tasks (Flux Core Arc Welding or FCAW) and four stick-welding tasks (Shielded Metal Arc Welding or SMAW)] in a functional mock up The mock up was constructed by NIOSH to match the actual dimensions (~2ft by 2ft by 16 ft) of a particular type of barge hull assembly that required inside welding during its manufacture at the participant shipyard For each of the ten welders, two ventilation methods were evaluated in the mock up to determine the resulting weld performance, associated workload, and fume concentrations in the welder's breathing zone, while the eight welding tasks were performed One ventilation method employed a standard air horn that was currently used at the shipyard The other method used a prototype fresh air diffuser designed to improve ventilation Heart rate, ratings of perceived exertion (RPE), electromyographic (EMG) activity from seven upper extremity and torso muscles, discomfort assessment surveys (DAS), total personal particulate concentrations (mg/m^3), and area elemental concentrations (mg/m^3) from air samples were recorded for each task In addition, welding performances in terms of weld quality (as determined visually by an expert welder) and weld efficiency (arc time/total weld time, as determined by videotape analysis) was also evaluated for each task

Overall, statistical results indicated that weld process (wire versus stick welding) had significant effects on subjective physical workload and weld performance Wire welding was associated with significantly higher RPEs (ANOVA, p = 0 0001, estimated difference = 1 06), general DAS outcome (ANOVA, p = 0 0076, estimated difference = 0 42, Friedman Chi Square, p = 3865), and weld efficiency (ANOVA, p=0 0335, estimated difference = 2 19), while stick welding was associated with significantly higher weld quality (ANOVA, p=0 0001, estimated difference = 0 80) These subjective results indicated that exertion was perceived to be "fairly light" during both types of welding, with the 'general state of comfort right now' described as "average" Overall, the low back, knees, and shoulder regions were reported to be the body areas most affected by this welding job In addition, weld process was also found to have a significant effect on objective physical workload, in terms of spectral analyses of the EMG data Specifically, for most muscles tested during left side trials, the percentage of the total signal power in the 10-30 Hz frequency band was found to increase at a significantly (ANOVA, p < 0 05) greater rate for the existing stick electrode welding process than a wire welding process the shipyard has considered adopting Weld process was also found to have a substantial effect on weld fume concentration, as stick welding was associated with greater (ANOVA, p = 0621) personal total

particulate concentrations

Ventilation method was found to have a significant effect on weld fume exposure, such that the standard air horn was associated with lower total particulate concentrations (ANOVA, $p = 0.0184$). In addition, projected minimum TWAs for personal particulate concentrations and area elemental concentrations in many cases exceeded the established ACGIH TLVs, NIOSH RELs and OSHA PELs for stick and wire processes, using both ventilation methods. Thus, it is suggested that additional air sampling be conducted on the actual confined-space welding task that this study modeled, so that alternative ventilation methods can be devised.

In conclusion, this study suggests that engineering interventions for confined-space welders involving weld process and ventilation method changes should be considered carefully, because of the potential significant impact on work load, weld fume exposure, and weld performance. Overall results indicate that a reduction of localized muscle fatigue and weld-fume generation in this specific operation may be realized by a change from the stick-electrode to the wire welding process detailed. However, results also suggest that this change may be associated with higher subjective work loads. Different model welding units, consumables, and operational set-ups may also produce different fatigue states and fume generation rates. Thus, it is suggested that musculoskeletal injury rates and air quality measures be closely monitored before and after any specific process change. Since current ventilation methods appear to be inadequate, it is suggested that additional air sampling be conducted on the actual confined-space welding task that this study modeled. Based on the results of this sampling, which will estimate actual welder exposures, further ventilation control research and alternative PPE options (e.g., full-face air-purifying respirators, positive-pressure supplied-air respirators) may be needed.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

LIST OF ILLUSTRATIONS

INTRODUCTION

Shipyard welders, especially those working in confined spaces, have not been adequately studied as an occupational group in terms of ergonomic factors affecting worker safety and performance Such workers typically weld in conditions that provide inadequate ventilation and that require static muscular work and awkward postures Several studies have indicated that shipyard welders have a high incidence of shoulder pain, and that muscle pain and fatigue are greatest when welding is performed in overhead positions (Torner et al , 1991, Herberts et al , 1981, Herberts et al , 1980) Other research has suggested that these symptoms are due principally to static loading of specific shoulder muscles, such as the supraspinatus and the trapezius (Herberts et al , 1980, Kadefors et al , 1976) These effects have also been found to be reduced by welder experience, welding process, and weld position (Kadefors et al , 1976, Svabova et al , 1989, CTD News, 1997) Specifically, fatigue may differ for stick (shielded metal arc welding, SMAW) and wire-fed (flux core arc welding, FCAW) welding processes (CTD News, 1997) (see Appendix 4 for a detailed task analysis) This fatigue may be reduced in positions where the horizontal distance from the welder's face to the weld arc is minimized and the weld is performed in the flat position while standing or sitting (Svabova et al , 1989)

However, investigators have also suggested that posture affects exposure to weld fumes and that the positions required to minimize exposure are the opposite of those required to reduce static loading and fatigue Specifically, to reduce exposure, the horizontal distance from a welder's face to the weld arc should be maximized while the vertical distance above the arc should be minimized (Farwer, 1982, Grosse-Wordemann and Stracke, 1982, Pomaska, 1982) This is due to the nature of the weld plume, which rises and widens quickly Thus, it appears that welding ergonomics and welding-fume exposure reduction require a compromise in which a combination of static load minimization and fume extraction may offer a solution

Although a large body of evidence suggests that conditions such as static muscle loading and inadequate ventilation represent significant risk factors for musculoskeletal and physiological disorders in many occupations, few studies have investigated the link between these factors and worker performance on specific tasks (NIOSH publication #97-141, 1997) More importantly, even fewer studies have investigated workload and performance as functions of design interventions intended to counteract such risk factors for musculoskeletal and physiological disorders and to increase productivity (Jarvholm et al, 1991, Beauchamp et al, 1997) Thus, the need for such research exists to establish the effectiveness of engineering interventions such as static load reduction and alternative ventilation methods on the basis of not only reducing musculoskeletal, physiological disorders, and weld-fume exposure, but also improving worker performance

OBJECTIVE

The purpose of this study was to determine the possible effectiveness of engineering controls in reducing the rate of musculoskeletal disorders and fume exposure while improving welding performance among confined-space welders at a large shipyard To accomplish these aims, this study evaluated actual welding task performance, workload, and fume exposure under varying conditions of ventilation, posture, and static muscle-loading that might represent those conditions enabled by design interventions and different welding processes By measuring the effects of design interventions and welding processes in a controlled setting, the relationship between worker workload and performance and musculoskeletal risk factors/interventions was then quantitatively as well as qualitatively assessed Based on these findings, recommendations have been made about engineering controls, work practices, weld processes, and training devices (mock-ups) that may make the job of welding in confined spaces at the participant shipyard and other shipyards safer, less-tiring, and more productive

The specific hypothesis of this study was that engineering control interventions and weld process changes (ventilation control and a change from stick to wire welding) would result in a reduction in physical workload as measured in terms of electromyography (EMG), heart rate, and subjective questionnaires of perceived exertion and discomfort assessment It also was hypothesized that these changes would result in a reduction in weld fume exposure as measured in terms of total particulate concentration Finally, it was hypothesized that these interventions would also result in an improvement in weld performance, as measured by weld quality (rated by an expert welder) and weld efficiency (defined as arc time/total weld time)

METHODS AND MATERIALS

SUBJECTS

A controlled comparison study was conducted using 10 male, volunteer, 1st and 2nd class (AWS, 1987) welders performing wire and stick welding tasks under varying conditions of ventilation in a confined-space mock-up All subjects were employees of a large shipyard who were asked to participate through word of mouth and sign up sheets (see attached Form #1, "Call for Volunteers", in Appendix 1) These individuals had achieved certification for at least second class welding (American Welding Society, 1984) with the stick electrode (SMAW) process Each subject had experience, but not necessarily certification, with the wire (FCAW) welding process To be included in the study, each welder had to meet the following requirements (1) have at least 2nd class welding certification, (2) have experience in welding in confined spaces, (3) be free of medical conditions that inhibit welding in confined spaces (such as musculoskeletal disorders, heart conditions, etc) and (4) have received full safety training for stick and wire-fed welding operations These qualifications were determined through subject questionnaires (see Form #2, "Medical/ Eligibility Questionnaire", and Form #3, "Symptom's Survey Checklist" (19) in Appendix 1)

All trials were conducted during the normal working shift of the participant at the shipyard where they were employed Participants had been employed as welders a mean of 29 months (range = 2 5 – 56 months, s d = 17 months) The subjects were all right-handed males, with a mean age of 28 years (range = 19 to 36 years, s d = 6 years) and they worked a mean of 40 5 hours per week (range = 40 – 45, s d = 1 7) Welders were not excluded from participating based on race or ethnic background Additional subject demographics and anthropometric data are provided in Table 1

STUDY DESIGN

A 2X2 factorial design with replicated repeat measures was used for this study In this design each subject had two replicates at each treatment A total of four weld conditions (two ventilation methods by two weld processes), described in the table below, were tested Thus, there were four treatments in each replicate The order of treatments presented to each subject was determined either by Latin Squares design (Cochran and Cox, 1957) - four 4 x 4 squares with two subjects per square- or, for two of the subjects, by randomization in each of the replicates The Latin square design was used in this case to minimize the potential for a presentation order effect on fatigue (see Appendix 2 for further design details and statistical analysis methods) Electromyographic (EMG) data was collected for subjects I through IX only and involved specialized signal processing and statistical treatments, which are discussed in separate EMG sections in this report All other data were collected from subjects I through X However, the data from subject VIII was omitted from statistical analysis because the subject did not complete the wire welding trials A total of 4 weld conditions [2 ventilation by 2 static load (dictated by weld process)], described in the table below, were tested Each condition lasted for approximately 10 minutes or less and was replicated, for a total of 8 trials per subject, conducted successively In addition, 10 minute breaks were taken between each testing condition to address possible fatigue during the course of the study The total testing period lasted 4 hours or less for each subject and 2 subjects were tested each day from 4/12 to 4/16/99

	Static Load (dictated by weld process)	
Ventilation Method	*Stick Welding*	*Wire Welding*
Air- Horn (normal)	1 (NS)	2 (NW)
Vent Tube	3 (VS)	4 (VW)

DESCRIPTION OF VARIABLES

Ventilation Method

Air Horn --

The "air horn" level of the ventilation method variable refers to the breathable air conditions enabled in the confined space using the ventilation method currently employed at the participant shipyard This control consisted of a blower-type air horn that directed a combination of compressed and outside fresh air into the confined space (see Illustrations 1 a, b) This horn was typically positioned at the bottom corner of the entrance to the confined space and is operated from a 0 75 - 1 inch compressed air line with a line pressure of approximately 7 8 atm (115 p s i)

Vent tube --

The "vent tube" level of the ventilation method variable refers to the breathable air conditions enabled in the confined space with the redesigned ventilation tube/vortex This control, which was designed by NIOSH researchers, consisted of a vortex attached to a fresh air supply hose (2 inch by 16 feet) and a mesh diffuser (see Illustrations 2a, b) This device was placed at the back inside of the confined space and directed a combination of compressed and outside fresh air through and out of the confined space Information regarding the development of this device is provided in Appendix 3

Static Load (Dictated by Weld Process)

Stick --

The "stick" level of the static load variable refers to the static-loading condition of the welder's arms that occurred from using the stick-welding (Shielded Metal Arc Welding) process over the trial period (see Illustrations 3a, 4a) This condition did include the rest that was afforded by normal task requirements including changing the weld sticks, body-positioning, striking the arc, and de-slagging (chipping away excess slag from weld with a small hammer) Technical information about the specific stick welding set-up employed in this study is provided in the Methods section Additional general information about stick and wire welding is provided in the task analysis in Appendix 4

Wire --

The "wire" level of the static load variable refers to the static-loading condition of the welder's arms that occurred from using the wire–welding (Flux Core Arc Welding or FCAW) process over the trial period (see Illustrations 3b, 4b) This condition did include the rest that was afforded by normal task requirements including adjusting "stick-out," body-positioning, triggering the arc, and de-slagging (chipping away excess slag from weld with a small hammer) Technical information about the specific wire welding set-up employed in this study is also provided in the Methods section

GENERAL STUDY PROCEDURE AND DESIGN

Mock Up

The mock-up used in this study was constructed to match the actual dimensions (~2 ft by 2 ft by 16 ft) of a particular type of hull assembly-honeycomb that requires inside-welding during its manufacture at the participant shipyard (see Illustrations 5a, 5b) The mock-up itself was set up inside the welder training center on the grounds of the shipyard and included front and rear sections that were designed to be detached and moved The entire front section and the ceiling and upper walls of the rear section of the honeycomb mockup were made of transparent acrylic sheeting (*Acrylite GP* ™) to safely enable actual confined-space welding tasks to be videotaped from a number of views The floor and lower walls of the rear section were constructed of mild steel with removable angle irons between walls and floor These angle irons were held in place by *Destaco* ™ clamps for each trial and aluminum tape was used to seal the gap between the mock-up and the angle iron All welding tasks involved placing two weld beads (~ 3 ft in length) into the corner of two 6 ft angle irons that were placed into openings at the side bottom joints of the rear section of the mock-up

Protocol

Each subject wore the full required personal protective equipment (PPE) necessary for stick welding (Shielded Metal Arc Welding or SMAW) and wire-fed welding (Flux Core Arc Welding or FCAW) in a confined space This includes a welding helmet, insulated overalls, gloves, UV protective face shield, and personal respirator (3M 6300 disposable welding mask) In addition, all welding was conducted in accordance with safe welding guidelines as recommended by the American Welding Society (AWS, 1987) Each subject was asked to rest for one hour before participating in the study During this time, various body dimensions of each subject were measured and the subject's age and weight were determined by self-report (see Form # 5, "Subject Body Dimensions/ Demographics," in Appendix 1)

Each subject was asked to perform eight flat welding tasks (four wire-fed tasks and four stick-welding tasks) in the mock-up which simulated the confined space of a "hull assembly " For each task, the subject was asked to crawl into the mock-up and first "weld" from the rear of the mock-up to the midpoint of the right-side angle iron (approximately 3 ft) At the moment the subject entered the mock-up, air sampling pumps were engaged The "weld" task itself involved placing a weld bead into a pre-formed corner in a detachable angle iron, and did not involve the joining of two separate work surfaces The subject was then instructed to weld the left-side angle iron in the same manner and then de-slag the weld bead on each side Thus, the total weld distance for each task was approximately 6 ft, and typically this required a total weld time of eight to ten minutes with six to seven minutes of this period consisting of arc time Subjects were also instructed to use their dominant hand to guide the welding apparatus during each task and to weld (under these constraints) as they normally would For most subjects, this required that they utilize a kneeling posture similar to the one depicted in Illustrations 6a, b Once the task was completed, the subject was asked to crawl back out of the mock-up At this point, the air sampling pumps were shut down, the subject's heart rate pulse was determined, and the subjective questionnaires were administered The subject was then instructed to sit and rest for approximately ten minutes before the next trial began The entire study of eight trials, including the hour rest break before the study, required four hours or less for each subject All trials were conducted during the normal working shift of the participants, who were paid their normal hourly wage by the shipyard

For the stick welding trials, mild steel stick electrodes were used (16 in, E7024, AWS Class, *Jetweld* brand, AC operated at a current range of 350 to 450 amps) with *Tweco* electrode holders (Model A-38-HD) For the wire-fed welding trials, NR-706 0 78 inch wire (volts 26-28, WFS 300-350, transverse angle 45 degrees, travel angle 10-20 degrees, 1 - 1 5 inch stick out) was used with *Lincoln Magnum* wire weld guns Two 6 ft angle irons were required for each trial To conserve materials, angle irons were re-used every other trial since each separate trial involved welding only half the distance of a particular angle iron To facilitate weld quality determination, each angle iron end was coded using a grease pencil before the start of a particular trial

Additional Experimental Considerations/Limitations

A certain number of experimental design issues must also be mentioned The first deals with the issue of welder experience with the wire-welding process At the time of this study, the participant shipyard was in the midst of a process changeover from stick to wire welding Although all of the subjects were experienced in both stick and wire welding, most were not fully certified wire-welders Thus, subjects may have been generally more experienced in stick welding than wire welding The effects of such a difference cannot be directly quantified The second experimental issue deals with fume exposure levels during all trials involving the normal (blower-type) ventilation method During these trials, a substantial amount of weld fume could not be prevented from being forced out of the gaps surrounding the removable angle irons in the mock-up (see Illustrations 9 a, b) For this reason, fume exposure levels may have been artificially altered during the trials involving the normal ventilation method Finally, the welding tasks performed in this study only closely approximated actual welding This is because the welding tasks evaluated during this study were designed to allow for a period of 6-7 minutes of arc time within an 8-10 minute total weld period Also, the task itself involved placing a weld bead into a pre-formed corner in a detachable angle iron, and did not involve the joining of two work surfaces For these reasons, the studied tasks may not accurately represent other confined-space welding tasks that differ by work practice, technique, or method Thus, all conclusions from this study must consider these specific experimental issues of welder experience, ventilation, and task nature

DESCRIPTION OF MEASUREMENTS/STANDARDS AND STATISTICAL METHODS

Three categories of measures were recorded for each condition, representing physical workload (heart rate, electromyography or EMG, Discomfort Assessment Surveys, and Ratings of Perceived Exertion), weld fume exposure (personal and area, elemental and total particulate), and weld performance (weld quality and weld efficiency) Each condition for every subject was also videotaped to monitor the relationship between welder posture and welding fume exposure and to aid in the assessment of weld performance and workload for each condition For non-EMG data, Analyses of Variance (ANOVAs) were performed to determine significant differences in measures between experimental conditions Data that could be considered to be ordinal in nature were also analyzed using Friedman Chi Squares Pearson Correlation Coefficients were also calculated between all measures and between measures and the demographic/anthropometric data listed in

Table 1 to determine possible co-variates Based on these results, additional ANOVAs were performed on selected measures to examine the effects of correlated variables, such as height, weight, weld class, bi-deltoid breadth, buttock-knee length, and months on the job Of special note, no correlation was found between age and any of the selected measures, and further ANOVAs were not performed on this particular variable Other statistical issues and methods specific to given measures are described below and are further discussed in Appendix 2. Once again, EMG data was collected for subjects I through IX only and involved specialized signal processing and statistical treatments, which are discussed in the following EMG section

Physical Workload

The physical workload for each weld task condition was assessed by manual heart rate monitoring of each subject during task performance, EMG measurements of selected muscle groups, and by subjective workload questionnaires These questionnaires included the Borg Rating of Perceived Exertion (RPE) scale and Bishop and Corlett's Discomfort Assessment Survey (DAS) (see Form #6 and Form #7 in Appendix 1) (Borg, 1970, Corlett et al, 1980) EMG measurements have been used by a number of studies as an indicator of muscle fatigue during welding (Herberts et al, 1980, Kadefors et al, 1976, Jarvholm et al, 1991, Beachamp et al, 1997), and Bishop and Corlett's subjective scale has also been used as a general measure of muscle fatigue (Corlett et al, 1980) Heart rate measures and the Borg scale have also been used by a number of studies to assess physiological workload (Torner et al, 1991, Borg, 1970, Valente and Chiapperini, 1990) Measures of workload for each task were also then compared to standard workload recommendations based on physiological and psychophysical studies

Heart Rate

The subject's resting heart rate (HR) or pulse was manually determined generally during the first hour of rest or at the end of the 10 minute rest period between the first and second trial The subject's heart rate was then also manually determined immediately after the subject had exited the mock-up following each trial Heart rates were then converted into measures of "percent of maximum aerobic capacity," defined as (mean task HR- resting HR)/(maximum heart rate - resting HR)(Astrand and Rodahl, 1977) Maximum heart rate was determined using the following formula [214 - (71 * subject's age in years)] (Cooper et al, 1975)

Electromyography (EMG)

Surface EMG was recorded from seven muscles on the welders' dominant hand (right) side These muscles were the upper trapezius, middle deltoid, anterior deltoid, latissimus dorsi, erector spinae, extensor digitorum communis (digit/wrist extensor), and flexor digitorum superficialis (digit flexor) Disc electrodes were oriented in parallel with the fibers of these muscle groups as per the electrode placement recommendations of Zipp (1982) and Perotto (1996) Minimal preparation of the skin attachment sites were needed with the dry electrode design One subject necessitated some shaving of the trapezius and shoulder region The electrode configurations were bipolar, with preamplification at the recording site The EMG signal was sampled at 992 Hz, notch filtered at 60 Hz, and stored digitally on a computer In post processing, the data was filtered digitally with a 6th order Butterworth bandpass filter (10-350 Hz)

In each welding trial, a 120-second window of data was extracted from the raw, filtered EMG signal from the welding on each side of the honeycomb This 2-minute window was slightly shorter than most subjects' welding times for a single side (which were typically about 2 - 3 min) This 120-s data set was partitioned into five, 24-s windows for which the following procedure was performed The percent of the total signal power spectra falling in the 10-30 Hz frequency band was calculated by Fast Fourier Transform (FFT) and generation of a power spectral density function for each 1-s interval of data (spectogram) using Labview™ (National Instruments, Austin, Texas) The area under each 1-s spectogram function integrated between 10-30 Hz was divided by the total area under the function integrated over 10-350 Hz These 24 percentage values (1 per second, for 24 seconds) were averaged over each of the five, 24-s periods Statistical analyses were performed on the series of five average percentages of the total spectral power in the 10-30 Hz frequency band (henceforth abbreviated as PP_{10-30}) This procedure is illustrated graphically in Figure A2-1 in Appendix 2

The interior of the honeycomb mock-up reached temperatures in excess of 84°F (29° C), with the welders wearing protective long sleeve shirt(s), half-mask respirator, hard hat, and welding visor Not surprisingly, heavy sweating occurred, resulting in several instances of electrode detachment from the welder This was believed to be unavoidable in this environment As a precaution for data integrity, the electrode attachments were inspected visually before and after each trial and detachments were noted Electrode detachments were usually obvious from visual monitoring of the signal in real-time In trials where an electrode detached, data for that particular muscle in that trial were discarded

There were initial concerns about the possibility of interference in the myoelectric potentials from the AC current source of the stick electrode welding process (SMAW) Potential interference was tested by conducting a realistic simulation of a welding trial without actual welding taking place (no current) The myoelectric power in the signal recorded during this "test" trial was compared to that in the regular "live" trial in which actual welding took place This comparison is shown in Figure A2-2 in Appendix 2 The averaged power spectra from the two live trials show no consistent patterns of spectral interference from that of the test trial This was interpreted as evidence for no interference between the welding current and the recording site, pre-amplified myopotentials

Ratings of Perceived Exertion (RPE)

Ratings of Perceived Exertion were determined following each trial using a Borg Rating of Perceived Exertion (RPE) questionnaire (see Form #7 in Appendix 1) After each weld trial, the subject was asked using this questionnaire to describe "how hard they felt that they were working" during the last welding task and to circle the most appropriate phrase or number on the scale The values on this scale have been found to increase rather linearly with workload and have been used as approximations for heart rates For instance, for middle aged people under moderate intensity tasks, the RPE score multiplied by 10 has been found to correspond to measured rates (Borg, 1970) Two separate statistical analyses were applied to the RPE scores For the first, the RPE scores were considered to be continuous rather than discrete variables and an analysis of variance (ANOVA) was then performed on these data (See Appendix 2). For the second, the RPE scores were considered to be ordinal rather than continuous and data were analyzed using a Friedman Chi Square (See Appendix 2)

Discomfort Assessment Survey (DAS)

A Discomfort Assessment Survey was given to each subject following each trial using a modified Bishop and Corlett questionnaire (see Form #6 in Appendix 1) From this questionnaire, three DAS measures were developed DAS-General, DAS-Number, and DAS-Specific

The **DAS-General** measure represented the subject's 'overall discomfort level' as determined by the subject using a 7 point, 10 cm visual analog scale immediately following each weld trial During the actual trials, the scale ranged from a score of "0" extremely uncomfortable to "6" for "extremely comfortable " However, for the purpose of consistent analysis, this scale was converted so that scores increased with discomfort In other words, the DAS-General scale used for analysis ranges from a score of "0" for "extremely comfortable" to "6" for "extremely uncomfortable" The **DAS-Number** measure represented the sum of body areas (out of a potential 15 depicted) that each subject listed as experiencing discomfort immediately following each weld trial or [Σ (body area listed as uncomfortable)] The **DAS-Specific** measure represented the body areas listed as uncomfortable multiplied by a discomfort severity factor of 1-3 and then summed, or [Σ (body area listed as uncomfortable* severity)] Thus, the highest potential DAS-Specific score was 45 (discomfort severity factor of 3 for each of the 15 body areas possible)

To determine DAS-Number and DAS-Specific, the subject was first asked to specify those areas of his body that were most uncomfortable using the diagram on the questionnaire These areas were colored red and were later coded with a severity rating of "3" The participant was then asked to indicate those areas of his body which were the next most uncomfortable These areas were colored yellow and were later coded with a severity rating of "2" Finally, the participant was asked to indicate any other areas that were uncomfortable These areas were colored green and were later coded with a severity rating of "1" During the DAS administration, the participant was not required to list discomfort and was permitted to stop at any level If the participant did not wish to list discomfort at any point (either because he did not feel discomfort or did not wish to report it) , the survey was ended and unlisted body areas were given a severity rating of "0" As with the ratings of perceived exertion, two separate statistical analyses were applied to the discomfort survey data For the first, the discomfort assessment ratings were considered to be continuous rather than discrete variables and an analysis of variance (ANOVA) was then performed on these data (See Appendix 2) For the second, the RPE scores were considered to be discrete rather than continuous and data were analyzed using a Friedman Chi Square (See Appendix 2)

Weld-fume Exposure

The level of weld-fume exposure was determined using personal air sampling (total particulate concentration in mg/m^3) and area sampling (total particulate in mg/m^3 and an ICP elemental scan, in mg/m^3) Levels of oxygen (O_2) were also monitored for select subjects using a direct-reading instrument These measures are described further in the following sections

Personal Air Sampling

The method used to conduct total particulate personal sampling was NMAM-Method 0500, Particulates Not Otherwise Regulated (NMAM, 1994), which is similar to the standard method recommended by the American Weld Society (AWS) to determine fume generation rate (g/min) (AWS F1 2 1999) However, results were reported as (mg/m^3) units to compare to recommended time weighted averages for total weld fume established by the American Conference of Governmental Industrial Hygienists (ACGIH, 1998) Specifically, total particulate sampling was conducted using a PVC filter placed on the lapel of the welder's clothing that was attached to a tube routed to a *Gilian High Volume Air Sampler* operating at 10 l/min (Model # 801012, serial #s 10409, 10410) (see Illustration 7) One personal filter was used for both replications of a particular condition (e g stick with normal ventilation) and total sampling times were recorded and summed for these conditions Field blank samples were also gathered In the event of a filter failure during the first replication, a different filter was used for the second replication In the event of pump failures, sampling time was reduced as determined to be appropriate Failed or corrupted filters were excluded from further analysis Samples were then analyzed for total weight by gravimetric analysis by an independent analytical laboratory (see Appendix 5 for additional information) Raw Concentrations (mg/m^3) for each condition were calculated by dividing the total sample weight by the total volume sampled and by subtracting the nominal concentrations registered by the field blanks Statistical differences in welding fume measures between experimental conditions were then assessed using multi-factor ANOVAs (see Appendix 2) Finally, projected minimum 8-hour time-weighted averages (TWAs) were determined for each condition by the following formula TWA = (weld fume concentration in mg/m^3 by time period in which the concentration was measured)/480 minutes (ACGIH, 1999) These measures represented the minimum 8-hour TWAs because only the weld fume exposure during the testing period (which averaged ~ 20 minutes) was considered These TWAs were then compared to ACGIH TLV/TWAs, and OSHA PELs (ACGIH, 1998, NIOSH publication # 97-140, 1997)

Area Sampling

The method used to conduct total particulate area sampling was also similar to the standard method recommended by the American Weld Society (AWS) to determine fume generation rate (g/min) (AWS F1 2 1999) In particular, total particulate sampling was conducted using PVC filters operating at sampling rate of 2 l/min using *MSA Personal Sampling Pumps* (*Escort* Model, serial #s 2792, 2772, 2805, 2853, 2778), which were calibrated using a *SKC Ultraflo Calibrator* (Model #709, serial # 010693) These filters were placed at the midpoint of the rear section of the mock-up, approximately 3 in from the side and "ceiling" of the mock-up Subjects I and II were sampled with separate personal filters for both replications of a particular condition (e g stick with normal ventilation) and total sampling times were recorded and summed for these conditions After day 1, area sampling was performed on a per day basis For instance, Subjects III and IV were sampled with the same four filters, one each for all replications (a total of four) of a particular condition Sampling times were then adjusted accordingly and field blank samples were also gathered Differences in welding fume concentrations between conditions were then qualitatively assessed As in the case of personal sampling, in the event of a filter failure during the first replication, a different filter was used for the second replication In the event of pump failures, sampling time was reduced as determined to be appropriate Failed or corrupted filters were excluded from further analysis Samples were then analyzed for total weight by gravimetric analysis by an independent analytical laboratory (see Appendix 5 for additional information) Raw Concentrations (mg/m^3) for each condition were calculated by dividing the total sample weight by the total volume sampled and by subtracting the nominal concentrations registered by the field blanks Finally, projected minimum 8-hour time-weighted averages (TWAs) were determined for each condition by the following formula TWA = (weld fume concentration in mg/m^3 by time period in which the concentration was measured)/480 minutes) (ACGIH, 1999) Again, these measures represented the minimum 8-hour TWAs because only the weld fume exposure during the testing period (which ranged from 33-70 minutes) was considered These TWAs were then compared to ACGIH TLV/TWAs and OSHA PELs (ACGIH, 1998, NIOSH publication # 97-140, 1997)

Metal fume constituents were determined by NIOSH method 7300 which utilizes an ICP (Inductively Coupled Plasma) Elemental Scan and which is also recommended by the AWS for this purpose (NMAM, 1994, ANSI/AWS F1 4-97) Specifically, area air sampling was conducted on the first four subjects only, using MCE filters operating at sampling rate of 2 l/min using *MSA Personal Sampling Pumps* (*Escort Model*, serial #s 2792, 2772, 2805, 2853, 2778), which were calibrated using a *SKC Ultraflo Calibrator* (Model #709, serial # 010693) These filters were also placed at the midpoint of the rear section of the mock-up, approximately 3 in away from the side and "ceiling" of the mock-up Subject I and Subject II each were sampled using two filters, one for each weld process (e g stick and wire) Samples for Subjects III and IV were combined, resulting in two filters, one for each weld process, for both subjects Sampling times were then recorded accordingly and field blank samples were also gathered As in the case of personal sampling, in the event of a filter failure during the first replication, a different filter was used for the second replication In the event of pump failures, sampling time was reduced as determined to be appropriate Failed or corrupted filters were excluded from further analysis Samples were then analyzed for elements using inductively coupled plasma emission (ICP) by an independent analytical laboratory (see Appendix 5 for additional information) Raw Concentrations (mg/m^3) for each condition were calculated by dividing the total sample weight by the total volume sampled and by subtracting the nominal concentrations registered by the field blanks Differences in welding fume composition between wire and stick conditions were then qualitatively assessed Finally, projected minimum 8-hour time-weighted averages (TWAs) were determined for those elements which were indicated by the ICP scan to be substantially present To do so, the following formula was utilized TWA = (weld fume elemental concentration in mg/m^3 by time period in which the concentration was measured)/480 minutes (ACGIH, 1999) These TWAs were then compared to NIOSH RELs and OSHA PELs (NIOSH publication # 97-140)

Oxygen (O_2) levels and mock-up exterior surface temperatures were also monitored for selected subjects using *Biosystems PhD Ultra Gas Detectors* (Model #s 0230102PC, 0230106NC, serial #s 08995, 08986) and a *Tegam Microprocessor Thermometer* (Model #821, Serial # T-183721) As depicted in Illustrations 8 a, b, probes from the gas detectors were inserted at the rear of the mock-up ceiling, while the thermometer wires were inserted into the acrylic sheeting in the middle of the rear section of the mock-up

Weld Performance

Weld performance was assessed with two measures weld quality and weld efficiency To avoid experimental bias, subjects were told that their performance was being evaluated only for the purpose of comparing ventilation methods and weld processes

Weld Quality

Weld quality was determined by expert welders, who were certified as first class welders (AWS, 1987) and employed as welder trainers at the participant shipyard, through a visual, non-destructive examination of the actual weld bead produced during each trial Welds were rated soon after they were completed, thus the experts knew which subjects had performed a given weld Since the weld bead was placed into a pre-formed corner in a detachable angle iron, the standard measure of weld quality, which involves breaking the weld and determining its cross-sectional characteristics, was not possible Instead, the expert welder based their assessment on a five point, equal interval category scale, ranging from "poor" to "excellent" This scale is similar to that used in a past welding study (Beauchamp et al, 1997) Two experts were used, one for the evaluation of the first two subjects and then another expert for the evaluation of all subsequent subjects To account for possible rater differences, the first two subjects were not included in the statistical analysis of the weld quality data As with the ratings of perceived exertion and discomfort surveys, two separate statistical analyses were applied to the weld quality data For the first, the quality ratings were considered to be continuous rather than discrete variables and an analysis of variance (ANOVA) was then performed on these data (See Appendix 2) For the second, the RPE scores were considered to be ordinal rather than continuous and data were analyzed using a Friedman Chi Square (See Appendix 2)

Weld Efficiency

Weld efficiency was determined through videotape analysis by a common industrial weld metric defined as total arc time/total weld time (AWS, 1987) For this purpose, "arc time" was operationally defined to be any continuous time period (greater than 1 second in duration) in which the electric weld arc was present Conversely, a "break" was operationally defined to be any continuous time period (greater than 1 second in duration) in which the electric weld arc was not present A general task analysis was also performed and measures related to weld efficiency, including number/duration of breaks and total weld time, were determined Statistical differences in welding performance measures between experimental conditions were then assessed using multi-factor ANOVAs (see Appendix 2 for further statistical details)

RESULTS

A summary of significant results is provided in Table 17 Note that estimated differences are provided for statistically significant results In general, these estimated differences will differ from the actual difference between the means because the estimate statement averages by giving equal weight to each combination of process and interacting variables

PHYSICAL WORKLOAD

Heart Rate

Raw heart rate results are given in Table 2 and "Percent of Maximum Aerobic Capacity" results are given in Table 3 As indicated, mean heart rates ranged from 108-109 bpm, representing 30 18 - 30 98% of maximum aerobic capacity for all tasks across subjects Overall, a series of ANOVAs indicated that the effects of process, ventilation method, and ventilation method by process on heart rate measures ($p = 7384$, $p = 7229$, $p = 3117$) and percent maximum aerobic capacity measures ($p = 8652$, $p = 8126$, $p = 3036$) were not significant

EMG

Temporal shifts in the percent of the total EMG spectral power in the 10-30 Hz frequency band ($PP_{10\text{-}30}$) were measured by the slope of the linear function regressing $PP_{10\text{-}30}$ against time segment The 24-s time segments extracted from a two-minute welding trial were numbered 1 to 5 An estimate of the linear parameter (i e the slope) relating $PP_{10\text{-}30}$ to the segment number (1 to 5) was obtained by regressing $PP_{10\text{-}30}$ on the time segment number Several measures of change from the first to fifth segment were considered, however, the slope of the regression equation appeared to be the most logical Since the segments are of equal length and there are no breaks between segments, the actual estimator of the slope (using orthogonal polynomials) facilitates an estimate of quadratic and cubic trends over the five segments However, only results using the linear component are presented here As the objective of the study was to examine the welding processes for evidence of an increase in the fatigue measure over time, the estimate of a linear trend was believed to be adequate The slope estimates presented in Figure 5 are in units of fraction increase in $PP_{10\text{-}30}$ per time unit, where the time unit is the length of time between the midpoints of the time segments, or 24 seconds The slope estimates (see Figures 11, a-d) are presented for each of the seven muscles, separately by side (left or right seam), by process (stick welding, wire welding), and by ventilation device (prototype ventilation device, conventional ventilation device) averaged across subjects For some subjects fewer than five segments were available Slope estimates were obtained when at least four segments of data were available Only eight subjects were used, since no EMG data were collected on Subject X, and Subject VIII had little experience with wire welding Consequently his results have been excluded

Statistical models (*Proc Mixed*, SAS Institute, Cary, NC) were generated to evaluate the differences in the slope in PP_{10-30} between levels of the ventilation device and weld process variables, with separate models for the data from the right and left side For each side a model was fit to the slope data, allowing for different means for subject, ventilation device, weld process, and their interactions For the left seam, the average slopes for stick welding compared to wire welding are quite different for anterior deltoid and latissimus dorsi than for the five other muscles Therefore, these two muscles are treated separately from the five other muscles, for which average results are shown in Figures 11a and 11c The design was regarded as a split-plot design (Cochran and Cox, 1957), in which all measurements in the same trial (from the different muscles) were correlated In the statistical models the subjects are treated as fixed effects Hence, the conclusions drawn from the models apply only to the tested welders, rather than to a larger population As an alternative approach, the subjects could have been treated as a random sample (and any conclusions would have applied to the larger population of welders), but this kind of analysis is not presented here

In the bar graphs showing the best fit linear slopes for the left side EMG PP_{10-30} shifts (Figures 11a,c), the confidence limits are identical for all slopes, for all muscles, except for these two muscles For left side welding, with the exception of the anterior deltoid and latissimus dorsi, the muscles' EMG PP_{10-30} values with the stick welding process have substantially larger slope values than those with the wire welding process None of the muscles PP_{10-30} slopes were significantly different from zero with the wire welding process All muscles but the anterior deltoid and latissimus dorsi showed significant positive slopes in PP_{10-30} with the stick welding process, based on two-sided 95% confidence intervals The statistical significance varies with the terms included in the model The value given here is from the model without the order effect within replicate (as specified by the Latin Squares), which is partly confounded with treatment effect, because of the missing values in the design and because for two of the subjects, the treatments were not administered as a Latin Square By omitting the order effect we attribute differences that may be partly due to order entirely to the study variables - process or ventilation This evaluation of process and ventilation effects indicates that, for the average of the five selected muscles, the stick slope exceeds that of the wire by about 0 01, a statistically significant result ($F_{1,32}$=8 35, p=0 007)

The estimated average for the stick welding process with those two muscles excluded is 0 019, which is significantly greater than 0 ($F_{1,32}$ =25, p = 0 0001) On average, for the five muscles showing fatigue, PP_{10-30} would be expected to increase by about 0 076 over the remaining four segments The ventilation variables, both conventional and prototype, averaged over the five muscles, yield estimated slopes of 0.011 (for each ventilation setting, $F_{1,32} > 6.7$, $p < 0.014$). The difference between ventilation treatments is not statistically significant.

For the right seam data, process comparisons associated with erector spinae differed from those associated the other muscles. Also, ventilation comparisons for the anterior deltoid differed from those for the other muscles. Therefore, these two muscles were treated separately from the others, for which average results are shown in Figures 11b and 11d. The statistical models indicated no differences by weld process or ventilation method on the right side. However, the slope estimates for both stick and wire for the five averaged muscles, both equal to 0.006, were individually significant ($F_{1,39} = 4.8$, $p < 0.04$). Also, for the five averaged muscles, the estimated slope for the prototype ventilation, 0.008, is a statistically significant result ($F_{1,39} = 9.99$, $p < 0.004$). Each of the statistically significant results indicates slopes that are different from 0. However, estimated differences between stick and wire, and between conventional ventilation and prototype, tended to be smaller than that for the left seam.

Since all workers were right-handed, the differences between the results for the left side and those for the right side are not surprising. Welding the left side of the honeycomb required the right-handed welders to reach forward and across the body, with the upper arm suspended, creating a greater moment about the dominant side shoulder and the lower back. In addition to the biomechanical disadvantages of right-handers welding on the left side, the left side weld was always made after the right side weld, in immediate succession, thus introducing the potential for fatigue carry-over to influence the fatigue results for the left side. However, this potential for carry-over fatigue was equivalent across all treatment conditions and separate models were generated for the left and right sides. The consistent sequence of right side followed by left side welding adopted in the study favored the preservation of actual work sequence rather than a more rigorous counterbalanced experimental design.

Figure 12 illustrates why the stick process was associated with a greater slope in $PP_{10\text{-}30}$ increase relative to the wire process for the left side. Under both ventilation conditions the stick process produced an average per cent power of less than 18% in the first time segment, but by the fifth segment that value had increased to 22.5%. Conversely, $PP_{10\text{-}30}$ for the wire exhibited a much smaller increase between the first and fifth time segments. (The figure is based only on trials with all five segments of data.)

Anthropometric characteristics (namely height, weight, bideltoid breadth, and chest circumference) of the welders were hypothesized to have an effect on fatigue. Since larger welders are more confined in the honeycomb space it was hypothesized that they would suffer greater localized muscle fatigue. However, no significant correlations between the anthropometric variables and slopes in the $PP_{10\text{-}30}$ vs time segment relationship were observed. Regressing the slope of the $PP_{10\text{-}30}$ vs time segment relationship against the anthropometric measures yielded non-significant regression relationships.

Ratings of Perceived Exertion (RPE)

RPE results are given in Tables 4, A2-1b, and Figure 1 As indicated, the mean score associated with stick welding was 10 92 and the mean score associated with wire welding was 11 82 Both of these scores correspond to a "fairly light" perceived exertion Based on an ANOVA, this process difference was found to be significant (p = 0001), with an estimated difference (stick - wire) of -1 06 However, the effects of ventilation method and ventilation method by process on RPE's were not significant (p = 3458, p = 5064) in terms of an ANOVA Based on a Friedman Chi Square Analysis, which considered the paired differences of average ranks, the process difference was also determined to be significant (p = 0351) (See Table A2-3 in Appendix 2) In addition, RPE's were found to be negatively correlated to the measures of mean subject weld efficiency (r = -0 70) and mean resting heart rate (r = -0 70), and positively correlated to mean subject break time (r = 0 76)

Discomfort Assessment Surveys (DAS)

The DAS-general results provided in Table 5 and Figure 2 indicate that stick welding was associated with a mean General Discomfort Score (DAS-general) of 2 61 whereas wire welding was associated with a mean General Discomfort Score of 2 97 Both of these DAS-General scores characterized the welders' "general state of comfort right now" during each process as "average" Based on an ANOVA, this process difference was found to be significant (p = 0076), with an estimated difference (stick - wire) of -0 37 However, the effects of ventilation method and ventilation method by process on DAS-general were not significant (p = 8538, p = 2423) Based on a Friedman Chi Square Analysis, which considered the differences of average ranks, the process difference was determined to be not significant (p = 3865) (See Table A2-3 in Appendix 2) The DAS-number (number of body areas affected) results are given in Table 6 and Figure 3, and an ANOVA indicated that effects of process, ventilation method and ventilation method * process on this measure were not significant (p = 2655, p = 9242, p = 9242) Also, the effect of process on DAS-number was determined to be not significant in terms of a Friedman Chi Square Analysis (p = 8888) (See Table A2-3 in Appendix 2) The DAS-specific (Specific Discomfort Score) results are provided in Table 7 and Figure 4 An ANOVA indicated that effects of process, ventilation method, and ventilation method * process on DAS-specific also were not significant (p = 1626, p = 8960, p = 6605) The effect of process on DAS-specific was determined to be not significant in terms of a Friedman Chi Square Analysis (p = 6519) (See Table A2-3 in Appendix 2)

In addition, the DAS-number (number of body areas affected) was found to be positively correlated with the subject variables of weld class (r = 0 82) and negatively correlated with subjects' months on the job (r = - 0 69) Based on an additional ANOVA, the effect of weld class was found to be significant (p = 0004), but the effect of subjects' months on the job was found to be not significant (p = 8143) (see Table 2 in Appendix 2) DAS-specific (Specific Discomfort Score) was also found to be positively correlated to the subject variable of weld class (r = 0 85) and an additional ANOVA determined that this effect was significant (p = 0001) (see Table 2 in Appendix 2)

WELD-FUME EXPOSURE

Personal Sampling

Raw total particulate concentrations (mg/m^3) for personal samples are provided in Table 8 and Figure 5 As indicated, the mean concentration was determined to be 211 25 mg/m^3 for stick welding and 149 37 mg/m^3 for wire welding Based on an ANOVA, this process difference was found to be borderline significant (p = 0621) with an estimated difference (stick - wire) of 45 44, after removing the three way interaction term The mean concentration was determined to be 149 90 mg/m^3 for the normal ventilation method and 207 11 mg/m^3 for the prototype method An ANOVA indicated that this ventilation difference was statistically significant (p = 0184) with an estimated difference (normal - prototype) of -59 98, after removing the three way interaction term However, process by ventilation method was found to be not significant (p = 7924) in terms of total particulate concentration Finally, projected minimum 8-hour time-weighted averages (TWAs) are also provided in Table 8 As indicated in Table 8, these averages were found to exceed the ACGIH TLV/TWA of 5 mg/m^3 for three of the four tested conditions normal ventilation with stick welding (mean TWA 6 mg/m^3), prototype ventilation with stick welding (mean TWA 9 mg/m^3), and prototype ventilation with wire welding (mean TWA 5 57 mg/m^3)

Area Sampling

Since area samples were conducted in a manner that was not consistent with the overall study design, statistical analyses were not performed on the area sampling data

However, raw total particulate concentrations (mg/m^3) for area samples are provided in Table 9 for qualitative informational purposes As indicated, the mean concentration was determined to be 456 29 mg/m^3 for stick welding and 445 55 mg/m^3 for wire welding, and 372 96 mg/mg^3 for normal ventilation versus 528 87 mg/mg^3 for the prototype ventilation Projected minimum 8-hour time-weighted averages (TWAs) are also provided in Table 9 As indicated, these averages were found to exceed the ACGIH TLV/TWA of 5 mg/m^3 for all of the tested conditions normal ventilation with stick welding (Mean TWA 24 97 mg/m^3), prototype ventilation with stick welding (Mean TWA 25 80 mg/m^3), prototype ventilation with stick welding (Mean TWA 35 50 mg/m^3), and prototype ventilation with wire welding (Mean TWA 24 71 mg/m^3)

The results of the Elemental Scan (ICP) are provided in Tables 10 a, b for qualitative informational purposes Raw elemental concentrations (mg/m^3) based on area samples are provided in Table 10a Only those elements that were found to be substantially present are indicated in these tables Specifically, for both stick and wire welding this included iron, manganese, lead, and zinc for all subjects sampled In addition, stick welding was associated with substantial concentrations of copper for all subjects sampled, while wire welding was associated with substantial concentrations of aluminum and beryllium for all subjects sampled Finally, projected minimum 8-hour time-weighted averages (TWAs) are provided in Table 10b As indicated, these averages were found to exceed both the specific NIOSH Recommended Exposure Limits (RELs) and OSHA Permissible Exposure Limits (PELs) in the case of stick welding for a number of elements, including copper (mean TWA 0 146 mg/m^3), iron (mean TWA 10 864 mg/m^3), and zinc (mean TWA 14 279 mg/m^3) and the specific NIOSH REL for manganese (mean TWA 1 944 mg/m^3) As well, for wire welding, TWAs were found to exceed both the specific NIOSH REL and OSHA PEL for zinc (mean TWA 0 502 mg/m^3) and the NIOSH RELs for manganese (mean TWA 2 847 mg/m^3) and iron (mean TWA 8 642mg/m^3)

The results of O_2 level monitoring for Subjects I, II, and III are provided in Table 10c Overall, the mean O_2 level for all subjects sampled was 20 81% The lowest level O_2 that was registered was 20 3%, while the highest was 21 1%

WELD PERFORMANCE

Weld Quality

Ratings of weld quality are provided in Table 11 and Figure 6 As indicated, stick welding was found to be associated with a mean weld quality of 4 23 whereas wire welding was determined to be associated with a mean quality of 3 36 Based on an ANOVA, this process difference was found to be significant (p = 0001), with an estimated difference (stick - wire) of 0 80 However, the effects of ventilation method and ventilation method by process on weld quality were not significant (p = 8714, p = 7462) Based on a Friedman Chi Square Analysis, which considered the paired differences of average ranks, the process difference was also determined to be significant (p = 0336) (See Table A2-3 in Appendix 2) In addition, mean weld quality was determined to be negatively correlated with subject variables of height (r = -0 86), weight (r = -0 77), bi-deltoid breadth (r = -0 72), and buttock-knee length (r = -0 69) Based on an additional ANOVA, the effects of subject weight (p = 0001), subject bi-deltoid breadth (p = 0185), and subject buttock-knee length (p = 0240) were determined to be significant (see Table 2 in Appendix 2) However, the effect of subject height was determined to be not significant (p = 3789)

Weld Efficiency

Weld efficiency results are given in Table 12 and Figure 7 As indicated, wire welding was associated with a mean efficiency of 76 69% whereas stick welding was associated with a mean efficiency of 73 31% Based on an ANOVA, this process difference was found to be significant (p = 0335), with an estimated difference (stick - wire) of -2 14 However, the effects of ventilation method alone (p = 0621) and process by ventilation (p = 0713) on weld efficiency were found to be not significant, but quite close In addition, weld efficiency was found to be negatively correlated with the measure of Ratings of Perceived Exertion (RPE), (r = - 0 70) Finally, weld efficiency was also determined to be negatively correlated to the subject variable of buttock-knee length ($r = -0\ 68$) and positively correlated to the subject variable of months on the job ($r = 0\ 70$) The results of an additional ANOVA indicated that the effects of subject buttock-knee length ($p = 0001$) and subject months-on-the-job ($p = 0001$) were significant (see Table 2 in Appendix 2)

As described previously, the weld efficiency measure was based on the ratio of total weld time, which is given in Table 13 and Figure 10, to Total Arc Time, which is provided in Table 14 As indicated, wire welding was associated with a mean total weld time of 401 seconds whereas stick welding was associated with a mean total weld time of 445 seconds Based on an ANOVA, this process difference was found to be significant ($p = 0002$), with an estimated difference (stick - wire) of 39 95 Also as indicated, wire welding was associated with a mean total arc time of 306 seconds whereas stick welding was associated with a mean total arc time of 325 seconds Based on an ANOVA, this process difference was also found to be significant ($p = 0115$), with an estimated difference (stick - wire) of 21 99

The number of breaks (including last de-slagging) was also determined for each condition, and these are provided in Table 15 and Figure 8 Overall, stick welding was associated with 4 44 breaks while wire welding was associated with 6 03 breaks Again, based on an ANOVA, this process difference was found to be significant ($p = 0001$), with an estimated difference (stick - wire) of -1 70 However, the effects of ventilation method and ventilation method by process on the "number of breaks" were not significant ($p = 8889$, $p = 5495$) The mean break time associated with each condition is given in Table 16 and Figure 9 As indicated, break times averaged 26 63 seconds for stick welding and 15 61 seconds for wire welding, and based on an ANOVA, this process difference was found to be significant ($p = 0001$) with an estimated difference (stick - wire) of 10 14 Also as indicated, break times averaged 19 42 seconds for tasks using normal ventilation and 22 94 seconds for tasks using the prototype ventilation method This ventilation effect was also found to be significant ($p = 0018$) Finally, the effect of ventilation method by process on the "mean break time" was not found to be significant ($p = 4743$)

DISCUSSION

To discuss the results of this study, it is important that the nature of the task itself first be understood For this reason, a detailed task analysis of both stick and wire welding is provided in Appendix 4 To reiterate, the specific hypotheses of this study were that weld process changes (from stick to wire welding) and an alternate ventilation control would have the following effects

1 Physical workload would be reduced as measured in terms of electromyography (EMG), heart rate, and subjective questionnaires of perceived exertion and discomfort assessment

2 Weld-fume exposure would be reduced as measured in terms of personal total particulate concentration

3 Weld performance would be improved as measured by weld quality (rated by an expert welder) and weld efficiency (defined as arc time/total weld time)

Although these measures were grouped into similar categories for the sake of simplicity, grouped measures were not necessarily assumed to be correlated For this reason, each measure must be considered singly, as well as in context of the larger category

PHYSICAL WORKLOAD

This study utilized three types of physical workload measures musculoskeletal (e g EMG), physiological (e g heart rate), and psychophysical (e g Discomfort Assessment Surveys, DAS and Ratings of Perceived Exertion, RPE) However, these measures can be further differentiated into two main groups of correlated measures musculoskeletal-psychophysical and cardiovascular-psychophysical This is due to the fact that Discomfort Assessment Surveys (DAS) are typically used to quantify subjective postural/bodily discomfort that may reflect musculoskeletal stress, which in turn may be correlated to objective measures such as EMG Furthermore, Ratings of Perceived Exertion (RPE) are characteristically used to quantify subjective aerobic demand which is often correlated to cardiovascular demand in terms of heart rate For this particular study, this categorization was only partially validated since mean heart rate and RPE were found to be positively correlated ($r = 0\ 68$), but EMG spectral measures and DAS (General, Number, Specific) outcomes were not

Process Effect

Results indicated that the choice of weld process had significant effects on the physical workload associated with the task of confined-space welding Specifically, objective spectral EMG measures suggested that a reduction of localized muscle fatigue in this operation may be realized by a change from the stick-electrode to the wire welding process That is, for most muscles during left side trials, the percent power in the 10-30 Hz frequency band was found to increase at a significantly (ANOVA, $p < 0\ 05$) greater rate for the existing stick electrode welding process than the wire welding process the shipyard has considered adopting On the other hand, wire welding was found to be associated with significantly higher (ANOVA, $p = \ 0001$, estimated difference = 1 06) subjective ratings of perceived exertion (RPE) and significantly higher (ANOVA, $p = 0076$, estimated difference = 0 42) subjective "general discomfort levels" (DAS-general) (see Tables 4, 5, Figures 1,2) Although these subjective and objective workload assessments initially appear to be contradictory, this may not be the case for a number of reasons

First, the process difference for the musculoskeletal-psychophysical measure, DAS-General, was only significant in terms of an ANOVA and was determined to be non significant ($p = \ 3865$) based on a Friedman Chi Square Analysis Once more, heart rate, "specific discomfort score" (DAS-specific), and the "number of body areas affected" (DAS-number) were not significantly affected by weld process Thus, stick welding may have been associated with only one lower subjective measure, RPE, which as a cardiovascular-psychophysical measure was not expected to necessarily correlate with the objective musculoskeletal measure, EMG

Second, all subjective measures are prone to certain response biases such as subject motivation and willingness to complete the required questionnaire This may have been evidenced in terms of the Discomfort Assessment Surveys which resulted in more than 50% zero counts for the discomfort scores for each body area The lack of evidence for correlation between the DAS scores and EMG fatigue measures may have been a result of this insufficient spread in the discomfort score data, since there was such a low percentage of nonzero scores

Third, subjective questionnaires for physical workload also tend to be sensitive to the emotional and mental demands involved in the completion of a task Since welders were better experienced with the stick welding process, they may have had some apprehension about performing the newer wire-welding process, especially in a confined space These "non-physical" demands can often be manifested in actual physical measures (e g elevated heart rate, increased muscle tension) but this is not necessarily the case Thus, the higher RPE's and DAS-General scores for the wire process may have reflected a general attitude towards the wire process that the objective EMG measures did not This would potentially confound the finding that RPE's and DAS-General scores (and thus physical workload) were significantly higher with wire welding

Fourth, the spectral EMG measures may have detected differences in muscle fatigue states produced by the two processes that were below the perceptual threshold for the brief time interval studied When the static exertion times examined in this study (2-3 min of welding followed by a 15 min break) are related to the classic endurance time curves of Rohmert (1960), an exertion level of approximately 25%-35% of maximum voluntary contraction (MVC) is indicated This means that an exertion level of 25-35% MVC can be maintained for 2-3 minutes The static exertions in the welding operation examined in this study were probably much lower than 25% MVC However, measurable changes in a muscle's EMG and in the perception of regional discomfort occur well before the endurance time is reached While the perceived regional discomfort and fatigue appear to have been relatively low in this study, many electromyographic manifestations are of statistical significance - particularly with the stick welding process The small proportion of non-zero discomfort reports might suggest that the electrophysiologic measures of EMG spectral shift are of little practical significance Conversely, these early electrophysiologic indicators may be viewed as precursors to localized muscle fatigue that would be perceived in the form of regional musculoskeletal discomfort over longer periods of welding Anecdotal evidence and informal reports of workers at this shipyard suggest that the latter is the case This study was a realistic *spatial* replication of the welding job insofar as the mock-up was of identical dimensions to the actual work space However, the *temporal* characteristics (work/rest) of the job could not be simulated realistically It is possible that the small, yet statistically significant difference between the two welding processes would increase over longer (more realistic) periods of welding

Despite the relatively high percentage of zero discomfort ratings, both the stick and wire welding processes were associated with an average general discomfort rating (DAS-general) that exceeded 2 6 Hence, both of these scores correspond to a subjective response in which subjects largely rated their "general state of comfort right now" as "average" to "comfortable " The anterior deltoid and latissimus dorsi, showed little differences in fatigue between the weld processes on either side, though there were somewhat different fatigue patterns between the right and left sides Conversely, the middle deltoid showed a dramatic reduction in fatigue with the wire welding process (relative to the stick process) on the left side and no difference on the right side The difference in response between the anterior and middle deltoid is somewhat perplexing given that the welding appeared to involve both abduction (humeral elevation) and flexion of the shoulder

As indicated in the task analysis provided in Appendix 4, stick and wire welding (welding processes) may involve different levels of static shoulder loading On one hand, wire welding may involve less static muscle-loading due to the fact that the wire gun is lighter, less-awkward, and that wire welding requires small gun manipulations for proper welds In fact, the hypothesis that a change from stick to wire welding would reduce physical workload was based largely on these considerations Indeed, the wire-weld gun used in this study weighed 8 lbs (3 6 kg) compared to the stick/electrode holder, which weighed 10 lbs (4 5 kg) However, one case study performed at a large United States shipyard suggested that the wire process may actually involve a greater level of static loading In this case, there was a 45% increase in the ergonomics injury rate during the first ten months after the yard changed a large portion of their welding processes from stick to wire (CTD News 1987) This may have been due to the fact that although the wire process reduced the magnitude of static shoulder loading, it also increased the frequency of this loading since welders were less likely to take sufficient rest breaks Such rest breaks are "built in" to the task of stick welding and some studies have suggested that these breaks significantly reduce the amount of muscle fatigue in other tasks and occupations (Sundelin and Hagberg, 1989, Zwahlen and Adams, 1987) This process difference in break time was also indicated by the present study as stick welding was found to be associated with significantly longer breaks (p = 0001) (see Figure 8) than wire welding Thus, the continuous nature of wire welding could possibly increase the static musculoskeletal loading duration and also increase physiological demand These effects could offset any musculoskeletal advantage that is afforded by the lighter weight of the wire welding gun Hence, although this present study suggests that a reduction of localized muscle fatigue in this operation may be realized by a change from the stick-electrode to the wire welding process, this should be monitored closely to track potential increased injury rates associated with the change

Ventilation Effect

The effect of ventilation on physical workload was not determined to be significant in terms of any of the non-EMG workload measures employed in this study (DAS-general, DAS-specific, DAS-number, Heart rate, or RPE) However, EMG data (for the left side) did indicate that even though the the ventilation effect was not statistically significant at the 5% level, the prototype did produce estimates for both left and right sides that were statistically distinguishable from 0 ($F_{1,32} > 6\ 7$, $p < 0\ 014$ for the five muscles averaged on the left side and $F_{1,39} = 9\ 99$, $p < 0\ 004$, for the five muscles averaged on the right side) The effect of ventilation on workload was hypothesized because ventilation, if greatly improved, could possibly reduce physical workload especially as measured by cardiovascular-psychophysical terms (heart rate and RPE), which are known to reflect respiration rates and oxygen uptake (Astrand and Rodahl, 1986) On the other hand, a change in workload in terms of musculoskeletal-pyschophysical measures (EMG and

DAS) was not necessarily expected However, such a musculoskeletal effect could have resulted if one of the ventilation methods was physically obtrusive and interfered with the confined-space welding task This certainly was a possibility in the case of the prototype ventilation tube which was placed directly in the immediate working space of the welder, as opposed to the normal ventilation tube which was placed at the entrance to the confined space In fact, several of the subjects complained of this very fact and expressed their displeasure with the prototype ventilation tube The prototype method was also associated with borderline significantly longer total weld times (p = 0727) which may have increased static loading in the muscles studied Thus, the EMG measures appeared to be sensitive to this negative side effect of the prototype ventilation method

Additional Effects

In addition to the main effects of ventilation and weld process, a possible effect of welder experience on physical workload was also indicated by the results Specifically, weld class was found to have a significant effect on both the number of body areas (DAS-number) (p = 0125) and specific discomfort assessment score (DAS-specific) (p = 0001) (see Table 2 in Appendix 2) These findings may indicate a "work-hardening" situation in which inexperienced welders tend to report more bodily discomfort of a greater magnitude more frequently than experienced welders Indeed, past studies have indicated that welder experience has been determined to affect the extent of shoulder muscle fatigue encountered by welders For instance, Kadefors et al 1976, found that "localized muscle fatigue was common in prolonged overhead work in an inexperienced group, whereas experienced welders showed signs of fatigue in the supraspinatus muscle only " This may be due to the effects of adaptation due to specific or general training and skill This is because "inexperienced welders" are typically not allowed to do overhead work until they become certified as 1st Class welders, and thus they do not have specific experience in this task However, general experience may also play a role since "learning a task calling for fine motor capability (such as welding) involves economy of muscle exertion by relaxation of antagonistic muscles with respect to the prime movers active in a voluntary movement" (Kadefors, et al, 1976) This notion is supported by a much more recent study that determined that subjects could "reduce EMG activity voluntarily by 22-47% in the trapezius muscle while keeping different static postures" by using biofeedback techniques (Palmerud et al 1995) Since the task performed in the present study closely approximated a flat weld task, both 1st and 2nd class welders should have had comparable specific experience in this task Hence, it is more likely that any potential difference in physical workload due to welder experience in this study was the result of general work adaptation

General Physical Workload Considerations

In addition to measuring the effect of weld process and ventilation method on physical workload, the overall physical effects of confined-space welding were able to be qualitatively described by this study In general, results indicate that this task is low to moderate in terms of cardiovascular demand and moderate to high in terms of musculoskeletal demand

Cardiovascular Demand

The cardiovascular demand associated with confined-space welding has not been adequately determined The results of one past study on general welders utilizing measures of heart rate, blood pressure, oral temperature and perspiration rate indicated that this demand was not usually excessive, but increased with the temperature of the working environment (Valente and Chiapperini, 1990) Likewise, the outcome of another study utilizing heart rate, respiratory rate, and skin temperature suggested that general welding tasks can require moderate to high cardiovascular output, depending on work factors that increase psychological stress, such as isolation, safety concerns, and repetitiveness (Richter, 1990) Thus, the current literature suggests that the cardiovascular demand associated with welding may vary depending on the specific nature of the welding task, and that a factor such as confinement may increase this demand

The cardiovascular demand for the present study was determined by the cardiovascular-psychophysical measures of heart rate and RPE Overall, stick welding was associated with an average RPE of 10 92 while wire welding was associated with an average RPE of 11 82 Both of these scores correspond to a verbal response in which the "work performed during the last welding task" was characterized as "fairly light" (see Form #7 in Appendix 1) RPE scores have also been used as approximations for heart rate for middle aged people under moderate intensity tasks such that the RPE score multiplied by 10 has been found to correspond to measured rates (Borg, 1970) For this study, this approximation was largely validated since stick welding was associated with an average heart rate of 109 beats per minute (bpm) while wire welding was associated with an average heart rate of 108 bpm As mentioned, RPE scores were also found to be positively correlated to measured heart rates ($r = 0\ 70$) on the basis of individual subject measurements

Cardiovascular demand was also assessed by converting subject heart rates into measures of "percent of maximum aerobic capacity " As mentioned, heart rates were determined by an alternate manual procedure that did not allow the subject's heart rate to be monitored during the actual welding task Therefore, the results may largely reflect the workload associated with climbing out of the confined space mock-up Nonetheless, it is not expected that heart rates during the actual welding tasks were appreciably different from the measured heart rates The "percent of maximum aerobic capacity" parameter, developed by Astrand and Rodahl (1977), and defined to be (mean task HR- resting HR)/(maximum HR - resting HR), approximates the percent of maximum aerobic capacity or VO_2 Max required for a task This percentage is used to determine the extent of physiological fatigue that can be expected from the performance of a particular task and can be compared to a standard guideline, such as the NIOSH lifting equation The 1991 NIOSH lifting equation committee recommended the following limits for aerobic demands posed by different durations of repetitive lifting tasks (1) Repetitive lifting tasks lasting one hour or less should not require workers to exceed 50% of their maximum aerobic capacity value, (2) repetitive lifting tasks lasting 1 to 2 hours should not require workers to exceed 40% of their maximum aerobic capacity, and (3) repetitive lifting tasks lasting 2 hours to 8 hours should not require workers to exceed 33% of their aerobic capacity (NIOSH publication #94-110, 1994) Overall, in the present study, stick welding was associated with an average of 30 89% of subjects' capacities while wire welding was associated with an average of 30 26% of subjects' capacities (see Table 3) Thus, both confined-space welding tasks appear to represent low to moderate physiologically demanding tasks and should be able to be performed repetitively over an eight hour shift without fatigue

These results may be understood if one considers the nature of the confined-space welding task To summarize the task analysis provided in Appendix 4, confined space welding is largely a static rather than dynamic activity Arc time typically represents 40-70% of the total time spent in the task of confined-space welding Other tasks, such as positioning the weld cables and de-slagging (chipping), which are more dynamic in nature, are performed less frequently and still do not involve a great deal of whole body movement However, as stated, the tasks that were studied were approximations of confined-space welding tasks and actual tasks may differ in terms of cardiovascular demand The approximated tasks had arc times in excess of 70% and were probably more static in nature than the actual honeycomb welding tasks modeled As indicated by the aforementioned studies, other important factors to consider are the effects of other environmental stressors such as temperature and humidity The average high ambient temperature for the week in which these trials were conducted was a comfortable 67 degrees F (19 4 degrees C), and a number of subjects remarked that the confined space work becomes much more demanding as temperatures increase Thus, it is suggested that the effect of heat stress on the cardiovascular demand of confined-space welding be further investigated

Musculoskeletal Demand

There are very few ergonomic studies that have been conducted on confined-space welders in shipyards or any other industry However, studies have indicated that general shipyard welders have a high incidence of shoulder pain and clinical signs of musculoskeletal disorders of the upper extremity (Torner et al 1991, Herberts et al 1980, Herberts et al 1981) Other research has suggested that these symptoms are due principally to localized static loading of specific shoulder muscles, such as the supraspinatus and the trapezius, rather than the dynamic physiological requirements of welding work (Herberts et al 1980, Kadefors et al 1976) This may be indicated by findings that the nature of the typical welding musculoskeletal disorder is different from the nature of those found in other occupations that involve predominantly heavy dynamic work For instance, "atrophied shoulder muscles (are) more common among welders than among fisherman, whereas crepitations in the shoulder (tend) to be more common among fishermen" (Torner, et al 1991) Even so, shoulder problems and pain are much more prevalent in welders than other occupations, such as clerks and typists, which do involve a large amount of static work (Torner et al 1991) Thus, the current literature suggests that the principle musculoskeletal demand associated with general welding may be due to an extreme case of static shoulder muscle loading However, until now, this musculoskeletal demand has not been assessed for the specific case of confined-space welding

For the purpose of this study, musculoskeletal demand for confined-space welding was determined by the musculoskeletal-psychophysical measures of EMG and DAS In general, stick welding was found to be associated with an average "general discomfort rating" (DAS-general) of

2 61 while wire welding was associated with an average "general discomfort rating" (DAS-general) of 2 97 (see Table 5) Both of these scores correspond to a verbal response in which subjects largely rated their "general state of comfort right now" as "average " Thus, it appears from an overall self-report that the musculoskeletal demand associated with confined-space welding may be considered to be moderate in extent The nature of this demand can be further revealed through the results of the "Specific discomfort scores" (DAS-specific) given in Tables 6 and 7 and Figures 3 and 4 Overall, these indicate that the lower back was the body area most frequently reported as experiencing some degree of discomfort, followed by the knees, shoulders, and lower legs (see Figure 3) However, when these reports are weighted for the severity of discomfort experienced, knees score the highest followed by the lower back, shoulders, upper and lower arms (see Figure 4) Thus, these results suggest that the principal musculoskeletal demands associated with confined space welding involve the low back and knees in addition to the shoulders This can be explained by considering the constrained working-posture of the welder As mentioned, each subject crawled into the approximately 2ft by 2ft by 16ft confined-space and typically assumed a kneeling posture, such as that depicted in Illustrations 6 a,b Depending on the anthropometry of the welder, this posture involved extreme flexion of the low back and abduction of the shoulder that bears the welding apparatus This type of constrained posture may induce a large degree of contact stress in the knee area and static/awkward loading of the low back and shoulders which may result in a moderate to high musculoskeletal task demand

The results of the EMG spectral measures collected during this study also help to further define the nature of the musculoskeletal demand associated with confined-space welding Chaffin (1973) defined four states of muscle fatigue for which he related perceived muscle symptoms to measurable power spectral density compression State I fatigue, described subjectively as the "realization of 'tightness' or 'slight cramping'," corresponds to a 19% increase in the percentage of signal power in the 4-30 Hz frequency band over its baseline (pre-task) value Little myoelectric power was observed below 10 Hz in the present study, so the difference between the frequency range reported by Chaffin (1973) and that used in the present study is probably negligible PP_{10-30} averaged across all muscles in this study averaged 17 5% and 22 8% for the stick and wire processes respectively in the first 24-s sampling window The values in the fifth sampling window averaged 22 3% and 23%, corresponding to a 27% and 1% increase from the initial baseline values for the stick and wire welding processes, respectively

Figure 13 shows the percentage increases in PP_{10-30} in successive averaging periods over its baseline value for both welding processes and a comparison of these relative increases with Chaffin's (1973) fatigue states The figure shows that the stick welding process was associated with average EMG power spectral density shifts that should correspond to perceivable localized sensations associated with State I and even into the low end of State II ("'cramping' continuous with deep 'hot' pain intermittent") fatigue Conversely, the wire welding process was associated with relative power spectral density shifts consistent with levels below the state in which perceivable fatigue is realized based on Chaffin's fatigue state framework However, the application of Chaffin's fatigue state, power spectral density shift values must be undertaken with caution as they are based on fatigue patterns and spectral compression characteristics of the biceps muscle Other muscle groups may have dissimilar fatigue patterns owing to different fiber type compositions and their corresponding fatiguabilities (Komi and Tesch, 1979) It is also unclear how sensations of "tightness" or "slight cramping" would be manifested in the discomfort assessment survey scaling applied in this study, even if such symptoms did exist

WELD FUME EXPOSURE

Process Effect

Although the results indicated that the process effect on total particulate concentration was not significant (p = 0621), stick welding produced a qualitatively greater mean personal total particulate concentration than wire welding (see Table 8, Figure 5) Assuming that fume leakage during normal ventilation trials remained constant across conditions utilizing the different processes, these results should not be confounded by this issue Thus, the hypothesis that a process change from stick to wire welding would result in reduced weld fume exposure is rejected However, it is important to consider that fume generation rates depend on a number of factors including current and electrode type (Welding Institute of Canada, 1994) Thus, this finding may apply to only the specific operational set-up for welding described in the Methods Section

Ventilation Effect

Due to the issue of fume leakage during normal ventilation trials, comparisons between ventilation methods are problematic Although results indicate that the prototypical ventilation method was associated with a significantly greater mean personal total particulate concentration (p = 0282) (see Table 8, Figure 5), these findings may be skewed Specifically, leakage during only the normal ventilation conditions may have caused the mean personal total particulate concentration for these conditions to be artificially lower than they normally would have been Thus, the difference between the two ventilation methods may not have been significant Nonetheless, even if the effect of fume loss is considered, the hypothesis that the new prototype ventilation method would reduce weld fume exposure in terms of personal total particulate concentration must be rejected

This hypothesis was based on the research described in Appendix 3 There are several possible explanations for the poor performance of the prototype ventilation method The first is that the testing of this device was based on a situation that only approximated weld fume production in a confined-space Specifically, various ventilation methods were evaluated for their efficiency in qualitatively removing a set volume of artificial smoke (as a weld fume substitute) from the "breathing zone" of welder mannequin positioned within the confined-space mock-up Such a situation differed from actual confined-space weld fume production in a number ways One such difference was the fact that the "fume" was not being continuously produced Another difference was that the "fume" removed under lab conditions was relatively static and was not propelled by a thermal updraft During actual welding in the confined space of the mock-up the fume plume rose to the top restriction and vertical movement of the plume was changed into a horizontal movement away from the center of the plume This horizontal movement at the top of the plume combined with the horizontal movement of air provided by the new ventilation device at the base of the plume and set up a re-circulating air mass around the weld

Another possible explanation for the poor performance of the prototype is that the prototype was tested using a 1 inch compressed air line that generated approximately 7 8 atm (115 psi) This compressed air setting was used because it was thought to be similar to the pressure settings using during the actual confined space work at the participant shipyard Under these conditions the vent device achieved a flow rate of 2832-3115 lpm (100-110 CFM) However, during the actual trials the compressed air line that was typically used for confined space ventilation was unavailable Instead, both ventilation devices were operated using a 0 75 in compressed air line from the welding training facility of the participant shipyard Under these conditions, the prototype achieved a flow rate of only 2266 lpm (80 CFM)

Overall Exposure Considerations

Due to limitations such as those described in the previous paragraph, this study was designed to only closely approximate the actual working conditions of a specific confined-space welding task Thus, extrapolations to other actual confined-space welding situations and extrapolations to exposures over eight-hour workdays should be made with caution These limitations notwithstanding, results indicated that weld fume exposures may be excessive during the modeled confined-space stick and wire welding tasks using either the normal ventilation method (blower-type horn) or the prototype method (fresh air diffuser) Although the absolute values of mean personal total particulate concentrations for weld fumes were not hypothesized for this particular study, it should be noted that the mean projected minimum 8-hour TWAs exceeded the ACGIH 8-hour TLV/TWA of 5 mg/m^3 (see Table 8) for three of the four conditions tested As well, the results of the elemental analysis indicated that exposures exceeded a number of specific NIOSH RELs and OSHA PELs for both the stick and wire welding processes (see Table 10b) However, it was determined that the mean oxygen (O_2) level for all subjects sampled was 20 81%, while the lowest level O_2 that was registered was 20 3% This indicates that the oxygen supply within the confined-space was adequate given that the normal concentration of oxygen in ambient air at sea level is 21 1% and that 19 5% is typically used as a low threshold (Beard, 1980)

Although personal particulate samples for each condition were taken over an average period of approximately 20 minutes (2 welding tasks) and sampling times ranged from 33 to 70 minutes for area elemental scans, some extrapolation to an 8-hour workday was possible Projected minimum TWAs for mean personal total particulate concentrations and mean area elemental concentrations were determined by assuming that there was no weld fume exposure for the rest of the workday for the study participants Likewise, the raw elemental concentrations for copper, iron, and zinc all exceeded the specific NIOSH RELs for these elements Since shipyard welders often work in confined-spaces throughout the day, it is likely that actual 8-hour TWAs for particulate exposure are higher However, even if the overall 8-hour TWAs were not exceeded in this case, it is recommended by the ACGIH (American Conference of Governmental Industrial Hygienists) that short-term excursions in worker levels should not exceed 5 times the TLV/TWA (ACGIH, 1999) Before considering PPE protection factors, the raw personal particulate sampling results for this study exceeded the ACGIH TLV/TWA by more than fivefold However, protection factors must be considered and a maximum use concentration for a particular respirator can be estimated by multiplying its protection factor by the short term exposure limit for a particular fume constituent or the overall weld fume concentration Since most welders in confined spaces at the participant shipyard wore half-face air purifying respirators (APR) that are assigned a protection factor (PF) of 10, and the ACGIH short term exposure limit can be estimated to be three times the TWA (i e 3×5 mg/m^3 = 15 mg/m^3), the maximum use concentration for this type of respirator while welding is 150 mg/m^3 Thus, if additional air sampling indicates that this level is exceeded, it is recommended that alternative PPE options, such as a full-face APR's (PF = 50) or positive pressure supplied air respirators (SAR) (PF = 2000 -10000), be considered Thus, it is highly recommended that additional air sampling be conducted on the actual confined-space welding task that this study modeled This will help to determine the actual exposures associated with the task and to aid in the selection of respiratory protection and development of other ventilation methods

WELD PERFORMANCE

As mentioned, the welding tasks performed in this study only closely approximated actual welding Thus, measures of performance on these tasks may not reflect the actual weld performance outcomes to be expected from a weld-process or ventilation change With these limitations in mind, this study employed two distinct categories of weld performance measures weld quality and weld efficiency In general, weld quality can be viewed as a type of "accuracy" variable whereas weld efficiency can be considered a "speed" variable Such speed and accuracy variables are often inversely related in that accuracy decreases with increasing speed

Process Effect

Analyses of variance (ANOVAs) indicate that stick welding was associated with significantly greater weld quality (p = 0001, estimated difference = 0 80) but that wire welding was associated with significantly higher weld efficiency (p = 0335, estimated difference = 2 19) Although these results may seem contradictory, again these performance measures are not necessarily correlated The hypothesis that a change from stick to wire welding would result in improved weld performance was made for two main reasons First of all, it was thought that the awkwardness and weight of the stick apparatus might impede task performance, especially in a confined space Secondly, wire welding involves a continuous feed system that theoretically reduces the delay involved with welding Thus, it was expected that both weld quality and weld efficiency, even if these outcomes are not necessarily correlated, would be increased when the wire weld process was employed Although this was not the case, the finding that stick welding was associated with greater weld quality may be due in part to the possibility that welders were more experienced with this process than wire welding However, it may also be due to some aspect of the stick welding process, unrelated to weight and size, that enables a weld that is better in terms of visual-determined quality

On the other hand, as mentioned, an analysis of variance (ANOVA) also indicated that wire welding was associated with significantly higher weld efficiency This can be understood by considering the findings that although stick welding involved a fewer number of breaks (1 second or greater) ($p = 0001$) (see Table 15, Figure 8), these breaks were significantly longer ($p = 0001$) (see Table 16, Figure 9) than those associated with wire welding In addition, stick welding was associated with a significantly longer total weld time than wire welding ($p = 0001$), averaging 445 seconds (7 24) for the task versus 401 seconds (6 42) for wire welding (see Table 13 and Figure 10) Once more, there are two principle reasons for this increased break time and total weld time with stick welding The first is that a greater amount of de-slagging was performed during welding breaks for the stick process The sub-task of de-slagging, which consists of using a small hammer to chip off the covering or slag of the weld bead, is integral to any welding task and must be considered when assessing measures of weld performance Thus, the time to de-slag was not distinguished from arc-time in calculating total weld time, even though the majority of this de-slagging occurred after the arc-time portion of the welding task had been completed The second reason for the increased total weld time with stick welding was that this process was also associated with a significantly longer arc time than wire welding ($p = 0115$), averaging 325 seconds (5 25) for the task versus 305 seconds (5 05) for wire welding (see Table 14) Thus, it appears that wire welding may be a fundamentally more efficient process than stick welding in terms of both sub-tasks (de-slagging) and primary tasks (arc-time) Nonetheless, due to the fact that stick welding was found to be associated with greater weld quality, the overall hypothesis (that a change in weld process from stick to wire welding will improve weld performance) must still be rejected

Ventilation Effect

Overall, although the results suggest that the method of ventilation did not have a significant effect on weld quality ($p = 1\ 000$) (see Table 11), it may have had a substantial effect on weld efficiency ($p = 0621$) (see Table 12) This is further indicated by the findings that the prototype method was associated with significantly longer break times ($p = 0018$) (see Table 16) and longer total weld times ($p = 0727$) (see Table 13)

This apparent negative efficiency effect of the prototype ventilation method can explained by the fact that the prototype device was not designed to directly improve weld performance Rather, the positive effect of ventilation on performance was hypothesized for many of the same reasons that it was hypothesized that improved ventilation would reduce physical workload That is, if a new ventilation method could reduce contaminants to an extent that the overall physiological workload and irritation level was reduced, it was thought that this would increase the comfort of the welder and potentially enable improved performance On the other hand, a reduction in workload (and increase in bodily comfort) in terms of musculoskeletal/ pyschophysical measures (EMG and DAS) was not necessarily expected

On the contrary, EMG results indicated a slight negative musculoskeletal effect, which may have resulted from the prototype ventilation method being physically obtrusive and interferring with the confined-space welding task However, although the prototype ventilation may indeed have produced a negative efficiency and EMG-determined musculoskeletal effect, it did not appear to be associated with other higher subjective measures of musculoskeletal or cardiovascular demand Rather, it may be that the device was just obtrusive enough to simply slow the overall task of confined-space welding to the point that physical demand was slightly affected while weld quality remained unchanged Such a slow-down may have also been caused by the novelty of the device, since most of the welders who participated had been using the normal ventilation horn for some time

Additional Effects

In addition to the main effects of ventilation method and weld process, a certain number of factors that might effect confined-space welding performance were suggested by the results The first of these involves welder experience, which also was mentioned previously as a possible factor effecting workload Specifically, subjects who had greater experience in terms of months on the job scored significantly higher in weld efficiency measures (p = 0001) and weld efficiency was also correlated to the measure of ratings of perceived exertion (RPE) (r = -0 70) This may indicate that as welders become more skilled, they become more efficient and thus perceive their work as being easier However, it must be noted that a direct correlation between welder experience and RPE scores was not found In addition, weld quality and welder experience were also not found to be correlated Hence, it is unclear whether welder experience had a significant effect on weld performance, at least in terms of the approximated flat weld task that this study examined

Welder anthropometry is the second subject factor that may have had an effect on welding performance in the studied confined-space task This is because results indicate that the subject variables of weight (p = 0001), bi-deltoid breadth (p = 0185), and buttock-knee length (p = 0240) had significant effects on weld quality while the subject variable of buttock-knee length (p = 0001) had a significant effect on weld efficiency Specifically, lighter subjects with smaller anthropometric dimensions performed significantly better on confined-space welding tasks Given the extremely small confines of the mock-up and the typical postures of welders, which are depicted in Illustration 6, this is not surprising The area inside the mock-up where the welder principally worked was approximately 25 inches (63 5 cm) in height and 24 5 inches (62 2 cm) in width In comparison, the mean buttock-knee length (a measure of kneeling height) was 23 8 inches (60 4 cm) while the mean bi-deltoid breadth (a measure of shoulder width) was 21 6 inches (54 9 cm) Thus, larger welders simply may not have had adequate space to perform the complicated manual task of welding

CONCLUSIONS

Due to the described limitations, this study was designed to only closely approximate the actual working conditions of a specific confined-space welding task Thus, extrapolations to other actual confined-space welding situations and extrapolations to exposures over eight-hour workdays should be made with caution With this in mind, statistical results (ANOVA) indicated that weld process had a significant effect on workload, weld fume exposure, and weld performance. Specifically, wire welding was associated with significantly higher Ratings of Perceived Exertion (RPE's) ($p = .0001$), general Discomfort Assessment Survey (DAS) outcome ($p = .0076$), and weld efficiency ($p = .0335$) while stick welding was associated with significantly higher weld quality ($p = .0001$) and localized muscle fatigue [for most muscles the percent power in the 10-30 Hz frequency band was found to increase at a significantly ($p < 0.05$) greater rate for the existing stick electrode welding process]. In addition, the choice of ventilation method was found to have a significant effect on weld fume exposure such that the standard air horn was associated with lower total particulate concentrations ($p = .0282$). However, as discussed, this finding may not be truly significant due to the possibility that fume exposure levels may have been artificially altered during the trials involving the normal ventilation method. Finally, although the oxygen levels associated with the confined-space welding tasks appear to be adequate, projected minimum TWAs for personal particulate concentrations and area elemental concentrations in many cases exceeded the established ACGIH TLV's and NIOSH RELs for the stick and wire processes, using both ventilation methods. Thus, it is suggested that additional air sampling be conducted on the actual confined-space welding task that this study modeled so that alternative ventilation methods can be devised and appropriate respiratory protection can be recommended.

This study suggests that engineering interventions for confined-space welders involving weld process and ventilation method changes should be considered carefully because of the potential significant impact on workload, weld fume exposure, and weld performance. Since the wire welding process may be associated with higher subjective workloads, it is suggested that musculoskeletal injury rates and air quality measures be closely monitored before and after any specific process change. Since the current ventilation method (blower horn) and the prototype ventilation appear to be inadequate, it is suggested that confined-space welders consider PPE options such as supplied air respirators and that further research be applied in the area of ventilation control.

REFERENCES

American Welding Society [1997] Methods for Analysis of Airborne Particulates Generated by Welding and Allied Processes AWS F1 4-97

American Welding Society [1999] Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission of Welding and Allied Processes AWS F1 2 1999

ACGIH [1999] Threshold Limit Values for Chemical Substances and Physical Agents

Astrand P, Rodahl K [1977] Textbook of Work Physiology McGraw Hill

Beard RR [1981] Inorganic Compounds of Oxygen, Nitrogen, and Carbon Patty's Industrial Hygiene and Toxicology 3rd Ed Volume IIc New York, NY John Wiley

Beauchamp Y, Marchand D, Galopin M, and Goyer N [1997] Impact of the use of welding guns equipped with a fume extraction nozzle on muscular activation, psychophysical perception, and quality of welded joints Advances in Occupational Ergonomics and Safety II Biman Das and Waldemar Karwowski, eds

Borg G [1970] Perceived exertion as an indicator of somatic stress Scand J Rehab Med 2-3 92-98

Cochran WG and Cox GM [1957] Experimental Designs Second Edition, New York, NY JohnWiley

Cooper KH, Prudy JC, White SR, Pollock ML, Linnerud AC [1975] Age-Fitness Adjusted Maximal Heart Rates Institute for Aerobics Research, Dallas, Texas

Connor L, ed [1987] Welding Handbook 8th edition Volume 1 352

Corlett EN, Bishop RP [1976] A Technique for Assessing Postural Discomfort Ergonomics Volume 19, Number 2

CTD News [1997] Training a limbsaver at Newport News

Farwer A [1982] Air pollutants in shielded arc welding, relationship between their formation and the concentration in the breathing zone Schweissen Schneiden 34(2) 97-101

Grosse-wordemann J and Stracke E [1982] Relationships between exposure to fumes when welding and welding position is dictated by design considerations Schweissen Schneiden 34(2) 109-112

Hales TR, Bertsche PK [1992] American Association of Occupational Health Nursing Journal 40(3) 118-128

Herberts P, Kadefors R, Broman H [1980] Arm positioning in manual tasks an electromyographic study of localized muscle fatigue Ergonomics 23(7) 655-65

Herberts P, Kadedors R, Andersson G [1981] Shoulder pain in industry an epidemiological study on welders Acta Orthop Scan 52(3) 299-306

Jarvholm U, Palmerud G, Kadefors R, Herberts, P [1991] The effect of arm support on suprapinatus muscle load during simulated assembly sork and welding Ergonomics 34(1) 57- 66

Kadefors R, Petersen I, Herberts P [1976] Muscular reaction to welding work an electromyographic investigation Ergonomics 19 543-548

NIOSH [1994] Particulates not otherwise regulated, total Method 0500 In Casinell ME, O'Connor PF, eds NIOSH manual of analytical methods 4th ed Cincinnati, OH U S Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No 94-113

NIOSH[1994] Elements by ICP Method 7300 In Cassinelli ME, O'Connor PF eds NIOSH manual of analytical methods 4th ed Cincinnati, OH U S Department of Health and human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No 94-113

NIOSH [1994] Applications Manual for the Revised NIOSH Lifting Equation U S Department of Health and human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No 94-110

NIOSH [1997] Pocket guide to chemical hazards U S Department of Health and human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No 97-140

NIOSH [1997] Musculoskeletal disorders and workplace factors a critical review of epidemiologic evidence for work-related MSD's of the neck, upper extremity, and low back U S Department of Health and human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No 97-141

Palmerud G, Kadefors R, Sporrong H, Jarvholm U, Herberts P, Hogfors C, Peterson B [1995] Voluntary redistribution of muscle activity in human shoulder muscles Ergonomics *38*(4) 806-15

Pomaska H [1982] The effects of welding conditions on the air polluting substances during shielded arc welding Scheissen Schneiden *34*(2) 102-107

Richter, KH [1990] On the physical strain on arc welding operators depending on work order Schweisstechnik *40*(7) 309-314

Soderberg GL, Cook TM [1984] Electromyography in biomechanics Physical Therapy *64* 1813-1820

Svabova K, Vuk Z, Malek B [1989] Work Position in manual arc welding—reducing the strain on welders Welding in the World *27*, 21-13

Torner M, Zetterberg C, Anden U, Hanson T, Lindell V [1991] Workload and musculoskeletal problems a comparison between welders and office clerks Ergonomics *34*(9) 1179 -1196

Valente T and Chiapperini D [1990] Evaluation of bodily stress in welding by means of physiological and thermal measurements Riv Ital Saldatura *42*(2) 135-138

Viitasalo JHT, Komi PV [1975] Signal characteristics of EMG with special reference to reproducibility of measurements Acta Physiol Scand *93* 531-539

Welding Handbook [1987] Connor L, ed 8th edition Volume 1 352

Zwahlen HT, Adams CC [1987] A quantitative work-rest model for VDT work In Asfour SS, ed Trends in Ergonomics/Human Factors IV Amsterdam Elsevier Science Publishers

TABLES

*Note that Subject VIII was dropped from all statistical analyses

Table 1: Selected Anthropometric and Demographic Subject Data

	Subjects										
	I	II	III	IV	V	VI	VII	IX	X	Mean	SD
Age (yrs)	27	35	31	36	28	30	19	29	21	28 4	5 7
Weight (kg)	104 5	81 4	70 1	63 3	106 3	97 3	106 3	86 0	63 4	86 5	39 8
Height (m)	1 778	1 753	1 753	1 727	1 803	1 829	1 791	1 753	1 727	1 768	0 035
Gender	m	m	m	m	m	m	m	m	m	---	---
Resting Heart Rate (beats per minute, bpm)	68	88	52	68	84	72	78	66	66	71	11
Maximum Heart Rate [214-(.71*subject's age in years)]	195	189	192	188	194	193	201	193	199	194	4
Functional Reach (m)	0 838	0 838	0 826	0 749	0 813	0 826	0 787	0 813	0 749	0 804	0 035
Bideltoid Breadth (m)	0 597	0 521	0 495	0 495	0 610	0 572	0 546	0 559	0 546	0 549	0 041
Buttock-knee Length (m)	0 597	0 572	0 572	0 572	0 648	0 622	0 635	0 597	0 622	0 604	0 029
Chest Circumference (m)	1 118	1 118	0 940	0 927	1 219	1 181	1 156	1 067	1 079	1 089	0 100
Welding Class	1	2	1	2	2	1	2	1	1	---	---
Months on the Job	44	19	56	36	11	36	2 5	24	33	29 1	16 7
Hours Per Week Worked	40	45	40	40	40	40	40	40	40	40 5	1 7
Lost Work Days Last Year	0	0	0	0	4	7	0	0	0	1 2	2 5
Light Duty Days Last Year	0	0	0	0	0	2	0	0	0	22	67
Musculo-skeletal Pain Present?	Yes	Yes	No	No	Yes	Yes	No	No	No	---	---

Table 2: Heart Rate Results (beats per minute, BPM)

	Replication	Condition NS (normal ventilation with stick welding)	NW (normal ventilation with wire welding)	VS (prototype ventilation with stick welding)	VW (prototype ventilation with wire welding)
Subject I	1	n/a	82	92	104
	2	100	88	92	72
Subject II	1	92	120	132	136
	2	112	134	108	108
Subject III	1	84	92	102	90
	2	108	102	96	102
Subject IV	1	104	102	108	96
	2	104	108	102	108
Subject V	1	126	119	120	126
	2	126	120	126	n/a
Subject VI	1	126	108	114	102
	2	96	108	102	114
Subject VII	1	126	120	126	102
	2	120	126	120	120
Subject IX	1	108	102	96	96
	2	102	108	108	102
Subject X	1	108	114	114	120
	2	114	120	114	108
Mean		109 18	109 61	109 56	106 23
SD		12 69	13 56	12 09	14 68

Variable Levels	Variable Type	Mean	SD
Stick Welding	Process	109 37	12 26
Wire Welding	Process	107 97	14 01
Normal Ventilation	Ventilation	109 4	12 95
Prototype Ventilation	Ventilation	107 94	13 31

Anova Results (See Appendix 2)	
Process	p = 7384
Ventilation	p = 7229
Process * Ventilation	p = 3117

Table 3: Percent Maximum Aerobic Capacity [(mean task HR- resting HR)/ (maximum HR- resting HR)], where Maximum HR = [214-(.71*subject's age in years)]

	Replication	**Condition NS** *(normal ventilation with stick welding)*	**Condition NW** *(normal ventilation with wire welding)*	**Condition VS** *(prototype ventilation with stick welding)*	**Condition VW** *(prototype ventilation with wire welding)*
Subject I	*1*	n/a	11 02	18 90	28 35
	2	25 20	15 75	18 90	3 15
Subject II	*1*	3 96	31 68	43 56	47 52
	2	23 76	45 54	19 80	19 80
Subject III	*1*	22 86	28 57	35 71	27 14
	2	40 00	35 71	31 43	35 71
Subject IV	*1*	30 00	28 33	33 33	23 33
	2	30 00	33 33	28 33	33 33
Subject V	*1*	38 18	31 82	32 73	38 18
	2	38 18	32 73	38 18	n/a
Subject VI	*1*	44 63	29 75	34 71	24 79
	2	19 84	29 75	24 79	34 71
Subject VII	*1*	39 02	34 15	39 02	19 51
	2	34 15	39 02	34 15	34 15
Subject IX	*1*	33 07	28 35	23 62	23 62
	2	28 35	33 07	33 07	28 35
Subject X	*1*	31 58	36 09	36 09	40 60
	2	36 09	40 60	36 09	31 58
Mean		30 52	31 40	31 25	29 05
SD		9 64	8 01	7 28	10 05

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	30 89	8 39
Wire Welding	Process	30 26	9 01
Normal Ventilation	Ventilation	30 98	8 72
Prototype Ventilation	Ventilation	30 18	8 68

Anova Results (See Appendix 2)	
Process	p = 8652
Ventilation	p = 8126
Process * Ventilation	p = 3036

Table 4: Ratings of Perceived Exertion (RPE) Results (Berg Scale; 1970)

	Replication	Condition NS *(normal ventilation with stick welding)*	NW *(normal ventilation with wire welding)*	VS *(prototype ventilation with stick welding)*	VW *(prototype ventilation with wire welding)*
Subject I	*1* *2*	9 11	11 n/a	9 9	11 9
Subject II	*1* *2*	13 13	13 13	13 13	13 13
Subject III	*1* *2*	9 9	11 11	11 11	11 11
Subject IV	*1* *2*	9 9	9 9	9 9	9 9
Subject V	*1* *2*	11 13	13 15	13 15	15 n/a
Subject VI	*1* *2*	8 9	9 9	8 10	8 10
Subject VII	*1* *2*	11 11	13 13	11 11	13 13
Subject IX	*1* *2*	11 11	13 11	9 11	13 11
Subject X	*1* *2*	11 15	15 15	13 15	15 15
Mean		10 72	11 94	11 11	11 71
SD		1 87	2 13	2 14	2 26

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	10 92	1 99
Wire Welding	Process	11 82	2 17
Normal Ventilation	Ventilation	11 31	2 07
Prototype Ventilation	Ventilation	11 40	2 19

Anova Results (See Appendix 2)		**Friedman Chi Square Results (See Appendix 2)**	
Process	p = 0001	Overall Significance	p = 0351
Ventilation	p = 3458	(See Table A2-3 in Appendix 2 for Paired Differences of Average Ranks)	
Process * Ventilation	p = 5064		

Table 5: General Discomfort Score (DAS-general) Results (Bishop and Corlett, 1975)

	Replication	**Condition NS** *(normal ventilation with stick welding)*	**Condition NW** *(normal ventilation with wire welding)*	**Condition VS** *(prototype ventilation with stick welding)*	**Condition VW** *(prototype ventilation with wire welding)*
Subject I	*1* *2*	3 3	3 2	3 2	3 2
Subject II	*1* *2*	3 3	4 3	3 3	3 3
Subject III	*1* *2*	2 2	5 4	4 3	2 3
Subject IV	*1* *2*	2 2	2 2	2 2	2 2
Subject V	*1* *2*	3 4	4 5	4 5	5 n/a
Subject VI	*1* *2*	3 3	3 3	2 3	2 3
Subject VII	*1* *2*	3 2	3 3	2 2	2 3
Subject IX	*1* *2*	2 1	3 3	2 2	4 3
Subject X	*1* *2*	1 3	1 3	2 3	3 3
Mean		2.5	3.11	2.72	2.82
SD		0.79	1.02	0.89	0.81

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	2.61	0.84
Wire Welding	Process	2.97	0.92
Normal Ventilation	Ventilation	2.81	0.95
Prototype Ventilation	Ventilation	2.77	0.84

Anova Results (See Appendix 2)		**Friedman Chi Square Results (See Appendix 2)**	
Process	p = .0076	Overall Significance (See Table A2-3 in Appendix 2 for Paired Differences of Average Ranks)	p = .3865
Ventilation	p = .8538		
Process * Ventilation	p = .2423		

Table 6: Number of Body Areas Affected (DAS-number) Results
(Bishop and Corlett, 1975)

	Replication	**NS** *(normal ventilation with stick welding)*	**NW** *(normal ventilation with wire welding)*	**VS** *(prototype ventilation with stick welding)*	**VW** *(prototype ventilation with wire welding)*
Subject I	*1*	3	3	3	3
	2	3	3	3	3
Subject II	*1*	4	4	3	4
	2	4	4	4	4
Subject III	*1*	2	0	2	2
	2	0	2	0	0
Subject IV	*1*	4	4	4	4
	2	5	5	5	4
Subject V	*1*	1	1	2	5
	2	6	4	7	n/a
Subject VI	*1*	1	0	0	1
	2	0	0	0	0
Subject VII	*1*	6	6	6	6
	2	6	5	6	6
Subject IX	*1*	0	4	0	4
	2	0	6	4	3
Subject X	*1*	4	5	0	0
	2	0	0	0	0
Mean		2 72	3 11	2 72	2 88
SD		2 27	2 11	2 37	2 06

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	2 72	2 29
Wire Welding	Process	3	2 06
Normal Ventilation	Ventilation	2 92	2 17
Prototype Ventilation	Ventilation	2 8	2 19

Anova Results (See Appendix 2)		**Friedman Chi Square Results (See Appendix 2)**	
Process	p = 2655	Overall Significance (See Table A2-3 in Appendix 2 for Paired Differences of Average Ranks)	p = 8888
Ventilation	p = 9242		
Process * Ventilation	p = 9242		

Table 7: Specific Discomfort Score (DAS-specific) Results (Bishop and Corlett, 1975)

	Replication	**Condition NS** *(normal ventilation with stick welding)*	**Condition NW** *(normal ventilation with wire welding)*	**Condition VS** *(prototype ventilation with stick welding)*	**Condition VW** *(prototype ventilation with wire welding)*
Subject I	*1*	6	6	6	6
	2	6	6	6	6
Subject II	*1*	9	9	8	8
	2	9	9	9	9
Subject III	*1*	5	0	2	3
	2	0	4	0	0
Subject IV	*1*	11	11	11	10
	2	14	14	13	11
Subject V	*1*	2	2	4	12
	2	14	10	16	n/a
Subject VI	*1*	1	0	0	1
	2	0	0	0	0
Subject VII	*1*	6	8	6	12
	2	6	8	12	6
Subject IX	*1*	0	8	0	8
	2	0	12	8	6
Subject X	*1*	10	14	0	0
	2	0	0	0	0
Mean		5 5	6 72	5 61	5 76
SD		4 88	4 79	5 20	4 38

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	5 56	4 47
Wire Welding	Process	6 26	4 55
Normal Ventilation	Ventilation	6 11	4 80
Prototype Ventilation	Ventilation	5 69	4 75

Anova Results (See Appendix 2)		**Friedman Chi Square Results (See Appendix 2)**	
Process	p = 1626	Overall Significance (See Table A2-3 in Appendix 2 for Paired Differences of Average Ranks)	p = 6519
Ventilation	p = 8960		
Process * Ventilation	p = 6605		

Table 8: Personal Sample Total Particulate Results: Raw Concentrations (mg/m³) and Projected Minimum 8-hour TWA (mg/m³)

	NS (*normal ventilation with stick welding*)		NW (*normal ventilation with wire welding*)		VS (*prototype ventilation with stick welding*)		VW (*prototype ventilation with wire welding*)	
Subjects *Sampled over both* ***Rep-lications***	**Raw Measured mg/m³**	***Projected Minimum 8-Hour TWA****	**Raw Measured mg/m³**	***Projected Minimum 8-Hour TWA****	**Raw Measured mg/m³**	***Projected Minimum 8-Hour TWA****	**Raw Measured mg/m³**	***Projected Minimum 8-Hour TWA****
I	148 88	*4 96*	46 69	*1 26*	254 59	*9 02*	102 56	*3 85*
II	189 50	*7 90*	89 78	*3 37*	173 25	*7 22*	62 00	*1 16*
III	200 47	*7 10*	128 69	*4 29*	186 06	*6 59*	119 02	*4 24*
IV	n/a	*n/a*	149 47	*5 29*	356 00	*13 35*	212 81	*7 09*
V	66 22	*2 48*	85 06	*3 19*	235 90	*9 83*	290 31	*7 86*
VI	154 57	*4 51*	353 80	*3 69*	281 07	*8 78*	n/a	*n/a*
VII	n/a	*n/a*	115 00	*4 79*	187 19	*8 19*	148 29	*6 49*
IX	301 35	*10 67*	162 67	*5 08*	352 67	*11 02*	192 29	*6 78*
X	105 00	*4 38*	101 25	*3 38*	187 28	*7 02*	178 84	*7 08*
*ACGIH TWA/TLV *for welding fumes as Total Particulate Not Otherwise Classified* 5 mg/m³ OSHA PEL *for overall welding fume* none								
Mean	166 57	*6 00*	136 93	*3 82*	246 00	*9 00*	163 37	*5 37*
SD	75 45	*2 74*	88 55	*1 24*	71 31	*2 16*	71 45	*2 28*

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick	Process	211 25	81 52
Wire	Process	149 37	79 62
Normal	Ventilation	149 90	81 79
Prototy	Ventilation	207 11	81 14

Anova Results (See Appendix 2)		**(Three way interaction removed)**
Process	p = 0749	p = 0621
Ventilation	p = 0282	p = 0184
Process * Ventilation	p = 7924	-------

Table 9: Area Sample Total Particulate Results: Raw Concentrations (mg/m^3) and Projected Minimum 8-Hour Time-Weighted Averages (TWAs)

		NS *(normal ventilation with stick welding)*		NW *(normal ventilation with wire welding)*		VS *(prototype ventilation with stick welding)*		VW *(prototype ventilation with wire welding)*	
Subjects *Sampled over Replications Indicated*		**Raw Measured mg/m^3**	***Projected Minimum 8-hour *TWA***	**Raw Measured mg/m^3**	***Projected Minimum 8-hour *TWA***	**Raw Measured mg/m^3**	***Projected Minimum 8-hour *TWA***	**Raw Measured mg/m^3**	***Projected Minimum 8-hour *TWA***
I	*1 2*	283 75	*9 46*	115 77	*3 13*	527 06	*18 67*	556 84	*22 04*
II	*1 2*	412 75	*17 19*	359 17	*13 47*	506 00	*21 08*	405 29	*14 35*
III **IV**	*1 2* *1 2*	375 14	*27 35*	370 61	*25 47*	451 14	*32 90*	314 24	*21 60*
V **VI**	*1,2* *1 2*	164 53	*10 97*	343 00	*21 44*	451 14	*45 29*	314 24	*31 42*
VII **VIII**	*1 2* *1,2*	239 88	*21 49*	273 50	*11 40*	467 98	*45 82*	543 06	*35 07*
IX **X**	*1 2* *1 2*	645 68	*63 33*	891 74	*79 88*	762 12	*49 22*	570 14	*23 76*
Mean		353 62	*24 97*	392 30	*25 80*	558 95	*35 50*	488 79	*24 71*
SD		169 02	*19 93*	262 31	*27 63*	119 56	*13 33*	113 25	*7 45*

***ACGIH TWA/ TLV** *for welding fumes as Total Particulate Not Otherwise Classified* **5 mg/m^3**
OSHA PEL *for overall welding fume* **none**

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	456 29	176 01
Wire Welding	Process	445 55	200 49
Normal Ventilation	Ventilation	372 96	211 35
Prototype Ventilation	Ventilation	528 87	115 38

Table 10a: Elemental Scan (ICP) Results: *Raw Concentrations* (mg/m³)

	Analyte Concentration (mg/m³)							
	Aluminum	Beryllium	Copper	Iron	Lithium	Manganese	Lead	Zinc Oxide
NIOSH REL (mg/m³)*	5	0 0005	0 1	5	0 025	1	0 100	5
OSHA PEL (mg/m³)*	none	0 002	0 1	10	0 025	5	0 050	5
Subject	***Process***							
	Stick (SMAW)							
Subject I			0 288	112 091	0 061	19 695	0 364	143 92
Subject II			0 263	111 170		20 00	0 363	145 301
Subject III			0 271	107 129		19 286	0 343	142 851
Mean			**0 274**	**110 13**		**19 660**	**0 357**	**144 024**
SD			**0 013**	**2 639**		**358**	**0 012**	**1 228**
	Wire (FCAW)							
Subject I	15 625	0 003		92 156	15 468	28 123	0 422	101 543
Subject II	22 857	0 003		99 909	20 000	35 712	0 343	124 988
Subject III	16 667	0 002		90 894	16 667	29 545	0 364	113 63
Mean	**18 383**	**0 0027**		**94 320**	**17 378**	**31 127**	**0 376**	**113 387**
SD	**3 909**	**0 0005**		**4 881**	**2 348**	**4 034**	**0 041**	**11 724**

mg/m³ = milligrams of contaminant per cubic meter of air

*The NIOSH and OSHA standards pertain to specific compounds/forms of the listed element

Aluminum– Aluminum welding fumes
Beryllium– Beryllium and Beryllium compounds
Copper– Copper fume
Iron– Iron oxide fume
Lithium– Lithium hydride
Manganese– Manganese fume
Lead– NIOSH metallic lead, lead oxides and lead salts OSHA metallic all inorganic lead compounds and a class of organic compounds called soaps
Zinc– Zinc oxide this requires a conversion (*1 25) of the original data based on a ratio of atomic weights

Table 10b: Elemental Scan (ICP) Results:
Projected Minimum 8-hour Time Weighted Averages (TWAs)

	Analyte Concentration (mg/m³)							
	Aluminum	Beryllium	Copper	Iron	Lithium	Manganese	Lead	Zinc
NIOSH REL (mg/m³)*	5	0.0005	0.1	5	0.025	1	0.100	5
OSHA PEL (mg/m³)*	none	0.002	0.1	10	0.025	5	0.050	5
Subject/ Process								
Stick (SMAW)								
Subject I			0.020	7.706	0.004	1.354	0.025	9.895
Subject II			0.022	9.264		1.666	0.030	12.109
Subjects III			0.396	15.623		2.812	0.050	20.832
Mean			**0.146**	**10.864**	**0.004**	**1.944**	**0.035**	**14.279**
SD			**0.217**	**4.194**	**----**	**0.768**	**0.013**	**5.783**
Wire (FCAW)								
Subject I	1.042	0.0002		6.144	1.031	1.875	0.028	6.769
Subject II	1.667	0.0002		7.285	1.458	2.604	0.025	9.114
Subjects III	2.292	0.0003		12.498	2.292	4.062	0.050	15.624
Mean	**1.667**	**0.0002**		**8.642**	**1.594**	**2.847**	**0.034**	**10.502**
SD	**0.625**	**5.77 E 05**		**3.387**	**0.641**	**1.114**	**0.0137**	**4.587**

mg/m³ = milligrams of contaminant per cubic meter of air

*The NIOSH and OSHA standards pertain to specific compounds/forms of the listed element Aluminum– Aluminum welding fumes Beryllium– Beryllium and Beryllium compound, Copper – Copper fume Iron– Iron oxide fume Lithium– Lithium hydride Manganese– Manganese fume Lead– NIOSH metallic lead lead oxides and lead salts OSHA metallic all inorganic lead compounds and organic soap compounds Zinc - Zinc oxide this requires a conversion (*1.25) of the original data based on a ratio of atomic weights

Table 10c: Weld Fume Exposure Results: Oxygen (O_2) Levels

	O_2 Percentage	O_2 Percentage	O_2 Percentage (Mean)
Subject I	21.0	20.5	20.8
Subject II	21.1	20.3	20.7
Subject III	21.1	20.5	20.9

Table 11: Weld Quality Results (expert visual rating on scale 1 - 6)

	Replication	Condition NS *(normal ventilation with stick welding)*	NW *(normal ventilation with wire welding)*	VS *(prototype ventilation with stick welding)*	VW *(prototype ventilation with wire welding)*
Subject I	*1*	4 5*	3*	3 5*	4*
	2	4*	4*	3 5*	3 5*
Subject II	*1*	4 5*	5*	5*	5*
	2	4*	4 5*	3 5*	4 5*
Subject III	*1*	4	4	4	3 5
	2	4 5	3 5	4	4
Subject IV	*1*	4 5	4	4 5	3
	2	5	4 5	5	3 5
Subject V	*1*	4	3	4	3
	2	2 5	2	3	4
Subject VI	*1*	4 5	1 5	4 5	3
	2	5	3	3 5	2
Subject VII	*1*	4 5	1 5	5	1 5
	2	5	4	4 5	3 5
Subject IX	*1*	4	4	4 5	3 5
	2	3	3	4	4 5
Subject X	*1*	4	4 5	4 5	4 5
	2	4	4 5	5	3 5
*Subjects I and II were eliminated from the analysis for quality because they were rated by a different welding expert					
Mean		4 18	3 36	4 29	3 36
SD		0 72	1 06	0 58	0 84

Variable Levels	Variable Type	Mean	SD
Stick Welding	Process	4 23	0 64
Wire Welding	Process	3 36	0 94
Normal Ventilation	Ventilation	3 77	0 96
Prototype Ventilation	Ventilation	3 82	0 85

Anova Results (See Appendix 2)		Friedman Chi Square Results (See Appendix 2)	
Process	p = 0001	Overall Significance	p = 0336
Ventilation	p = 8714	(See Table A2-3 in Appendix 2 for Paired Differences of Average Ranks)	
Process * Ventilation	p = 7462		

Table 12: Weld Efficiency [(arc time/total weld time)*100] Results

	Replication	Condition NS *(normal ventilation with stick welding)*	Condition NW *(normal ventilation with wire welding)*	Condition VS *(prototype ventilation with stick welding)*	Condition VW *(prototype ventilation with wire welding)*
Subject I	*1* *2*	70 21 (%) 76 03	71 55 78 51	71 62 72 38	76 16 77 97
Subject II	*1* *2*	74 6 67 37	81 42 79 63	75 44 72 63	69 44 76 65
Subject III	*1* *2*	80 64 85 29	79 76 83 18	73 16 84 1	81 68 82 72
Subject IV	*1* *2*	74 88 78 77	82 04 84 22	77 56 77 63	78 15 87 66
Subject V	*1* *2*	50 77 64 81	72 55 62 53	56 06 59 01	54 78 n/a
Subject VI	*1* *2*	79 79	86 09 87 03	78 03 80 12	81 63 86 27
Subject VII	*1* *2*	69 55 77 17	63 83 74 55	73 73 68 49	59 03 70 46
Subject IX	*1* *2*	78 56 77 25	82 17 79 41	75 28 78 87	76 92 70 29
Subject X	*1* *2*	65 68 68 44	78 2 78 76	74 27 72 84	74 94 74 08
Mean		73 22	78 08	73 40	75 22
SD		7 98	6 82	6 82	8 66

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	73 31	7 32
Wire Welding	Process	76 69	7 78
Normal Ventilation	Ventilation	75 65	7 71
Prototype Ventilation	Ventilation	74 29	7 71

Anova Results (See Appendix 2)	
Process	p = 0335
Ventilation	p = 0621
Process * Ventilation	p = 0713

Table 13: Total Weld Time Results (seconds)

	Replication	**Condition NS** *(normal ventilation with stick welding)*	**Condition NW** *(normal ventilation with wire welding)*	**Condition VS** *(prototype ventilation with stick welding)*	**Condition VW** *(prototype ventilation with wire welding)*
Subject I	*1* *2*	480 (sec) 413	239 377	458 449	432 413
Subject II	*1* *2*	441 429	409 432	456 464	396 394
Subject III	*1* *2*	521 401	336 422	375 371	461 381
Subject IV	*1* *2*	430 405	373 397	450 447	412 381
Subject V	*1* *2*	522 395	419 379	503 444	513 n/a
Subject VI	*1* *2*	381 357	302 251	396 332	332 255
Subject VII	*1* *2*	555 473	495 444	491 511	576 518
Subject IX	*1* *2*	443 400	387 374	441 407	416 414
Subject X	*1* *2*	507 526	399 419	478 475	427 463
Mean		448 83	380 78	441 56	422 59
SD		58 10	64 62	48 10	73 15

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	445 19	52 69
Wire Welding	Process	401 09	71 12
Normal Ventilation	Ventilation	414 81	69 71
Prototype Ventilation	Ventilation	432 34	61 38

Anova Results (See Appendix 2)	
Process	p = 0002
Ventilation	p = 0727
Process * Ventilation	p = 0115

Table 14: Total Arc Time Results (seconds)

	Replication	Condition NS *(normal ventilation with stick welding)*	Condition NW *(normal ventilation with wire welding)*	Condition VS *(prototype ventilation with stick welding)*	Condition VW *(prototype ventilation with wire welding)*
Subject I	*1* *2*	337 (sec) 314	171 296	328 325	329 322
Subject II	*1* *2*	329 289	333 344	344 337	275 302
Subject III	*1* *2*	435 342	268 351	284 312	382 327
Subject IV	*1* *2*	322 319	306 342	349 347	342 334
Subject V	*1* *2*	265 256	304 237	282 262	281 n/a
Subject VI	*1* *2*	301 282	260 222	309 266	271 220
Subject VII	*1* *2*	386 365	316 331	362 350	340 365
Subject IX	*1* *2*	348 309	318 297	332 321	320 291
Subject X	*1* *2*	333 360	312 330	355 346	320 343
Mean		327 33	296 56	322 83	315 53
SD		43 45	47 99	30 96	39 04

Variable Levels	Variable Type	Mean	SD
Stick Welding	Process	325 08	37 25
Wire Welding	Process	305 77	44 29
Normal Ventilation	Ventilation	311 94	47 74
Prototype Ventilation	Ventilation	319 29	34 79

Anova Results (See Appendix 2)	
Process	p = 0115
Ventilation	p = 5571
Process * Ventilation	p = 1958

Table 15: Number of Breaks (including last de-slagging)

		Condition			
	Replication	**NS** *(normal ventilation with stick welding)*	**NW** *(normal ventilation with wire welding)*	**VS** *(prototype ventilation with stick welding)*	**VW** *(prototype ventilation with wire welding)*
Subject I	*1* *2*	4 5	4 6	4 5	9 4
Subject II	*1* *2*	4 4	8 5	4 4	5 6
Subject III	*1* *2*	6 4	7 7	5 5	7 7
Subject IV	*1* *2*	4 4	7 5	4 4	4 3
Subject V	*1* *2*	4 4	3 6	5 4	8 n/a
Subject VI	*1* *2*	5 5	6 4	5 4	5 5
Subject VII	*1* *2*	6 4	10 6	4 5	6 8
Subject IX	*1* *2*	4 5	6 7	4 4	8 10
Subject X	*1* *2*	5 5	4 5	4 4	5 5
Mean		4 56	5 89	4 33	6 18
SD		0 70	1 68	0 49	1 94

Variable Levels	**Variable Type**	**Mean**	**SD**
Stick Welding	Process	4 44	0 61
Wire Welding	Process	6 03	1 79
Normal	Ventilation	5 22	1 44
Prototype	Ventilation	5 23	1 66

Anova Results **(See Appendix 2)**	
Process	p = 0001
Ventilation	p = 8889
Process * Ventilation	p = 5495

Table 16: Mean Break Time (including last de-slagging) Results (seconds)

		Conditions			
	Replication	**NS** *(normal ventilation with stick welding)*	**NW** *(normal ventilation with wire welding)*	**VS** *(prototype ventilation with stick welding)*	**VW** *(prototype ventilation with wire welding)*
Subject I	*1* *2*	35 75 (sec) 19 80	17 00 13 50	32 50 24 80	12 78 15 25
Subject II	*1* *2*	28 00 35 00	9 50 17 60	33 75 31 75	24 20 15 33
Subject III	*1* *2*	14 33 14 75	9 71 10 14	18 20 11 80	11 29 6 75
Subject IV	*1* *2*	27 00 21 50	9 57 11 00	27 75 25 00	17 25 16 33
Subject V	*1* *2*	x64 25 34 75	x38 33 23 67	44 20 45 00	29 00 n/a
Subject VI	*1* *2*	16 00 15 00	7 00 7 75	19 75 16 50	12 20 7 00
Subject VII	*1* *2*	28 17 27 00	17 90 18 83	32 25 32 20	39 33 19 13
Subject IX	*1* *2*	23 75 18 20	11 50 11 00	27 25 21 50	12 00 12 30
Subject X	*1* *2*	34 80 31 20	21 75 17 80	30 75 32 25	21 40 24 00
		x not included >3 SD	x not included >3 SD		
Mean		25 00	13 84	28 18	17 38
SD		7 74	5 08	8 75	8 28

Variable Levels	Variable Type	Mean	SD
Stick Welding	Process	26 63	8 31
Wire Welding	Process	15 61	7 00
Normal	Ventilation	19 42	8 59
Prototype	Ventilation	22 94	10 02

Anova Results (See Appendix 2)	
Process	p = 0001
Ventilation	p = 0018
Process * Ventilation	p = 4743

Table 17: Summary of Significant Results

	Statistical Results (See Appendix 2)		
Measures	**Process** [stick (S) versus wire (W)]		**Ventilation Method** [air horn (N) versus fresh air diffuser (V)]
Physical Workload			
Ratings of Perceived Exertion (RPE)	ANOVA $W > S$, $p = 0001$	Friedman Chi Square $W > S$, $p = 0351$	----
General Discomfort Assessment Survey (DAS-General)	ANOVA $W > S$, $p = 0076$	Friedman Chi Square (Not significant) $W > S$, $p = 3865$	----
EMG Percentage of the total signal power in the 10-30 Hz frequency band	ANOVA $S > W$ $p < 05$ (For most muscles the percent power in this frequency band was found to increase at a significantly ($p < 0.05$) greater rate for the stick electrode welding process than the wire welding process)		----
Weld Fume Exposure			
Personal Particulate Concentration (mg/m³)	---		ANOVA $V > N$, $p = 0282$

Table 17: Summary of Significant Results

Measures **Weld Performance**	**Process** [stick (S) versus wire (W)]		**Ventilation Method** [air horn (N) versus fresh air diffuser (V)]
Weld Quality (Subjects I and II eliminated)	ANOVA S > W, p = 0001	Friedman Chi Square S > W, p = 0336	----
Weld Efficiency	ANOVA W > S, p = 0335		----
Total Arc Time	ANOVA S > W, p = 0115		----
Number of Breaks (including last de-slagging)	ANOVA W > S, p = 0001		----
Mean Break Time (including last de-slagging)	ANOVA S > W, p = 0001		----

FIGURES

Figure 1 Ratings of Perceived Exertion (RPE) Results

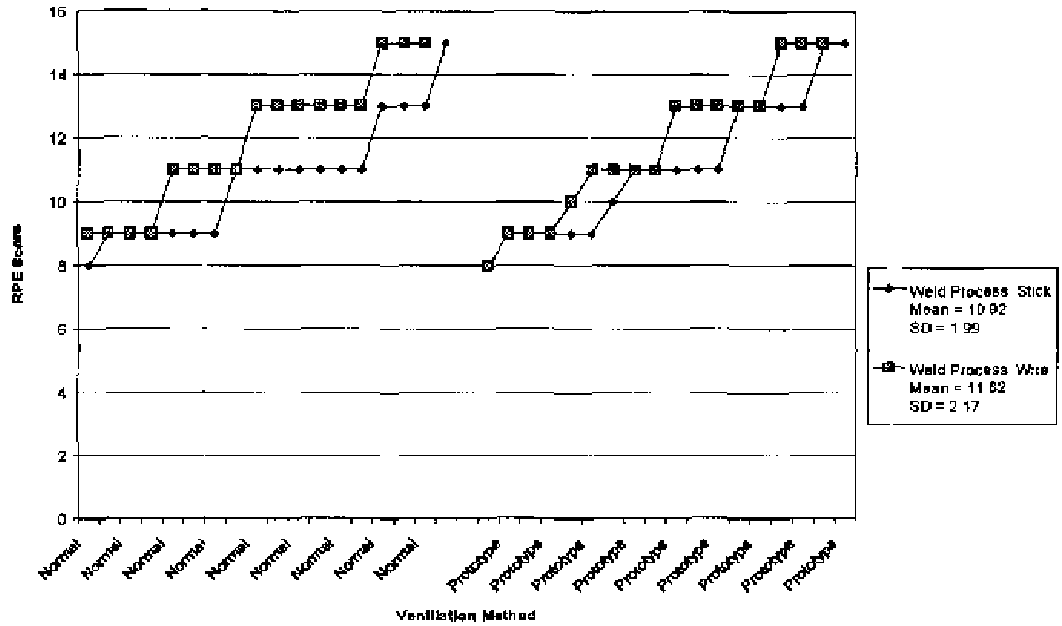


Figure 2 DAS-General (General Discomfort Score) Results

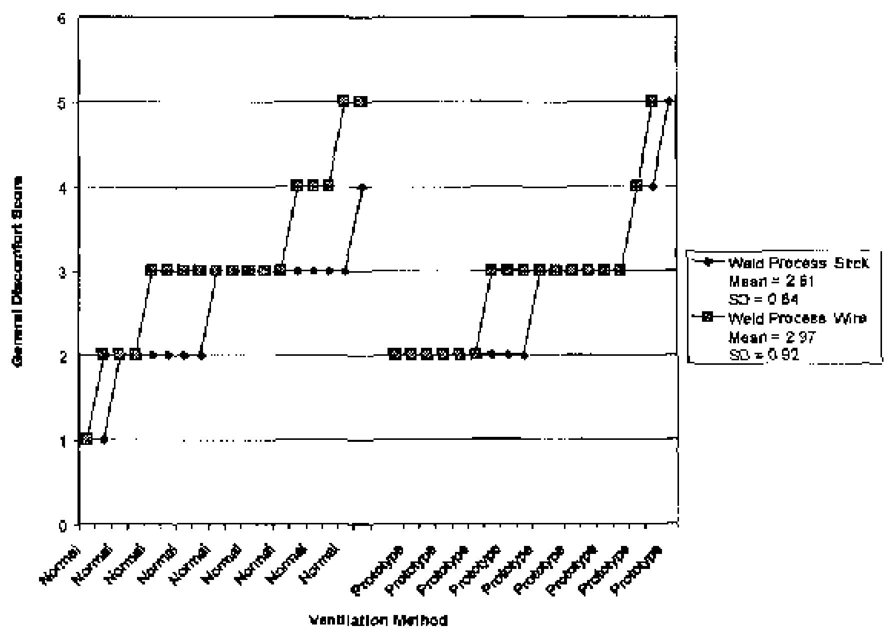


Figure 3 DAS-Number- Number of Discomfort Reports Across Subjects by Body Area and Experimental Condition

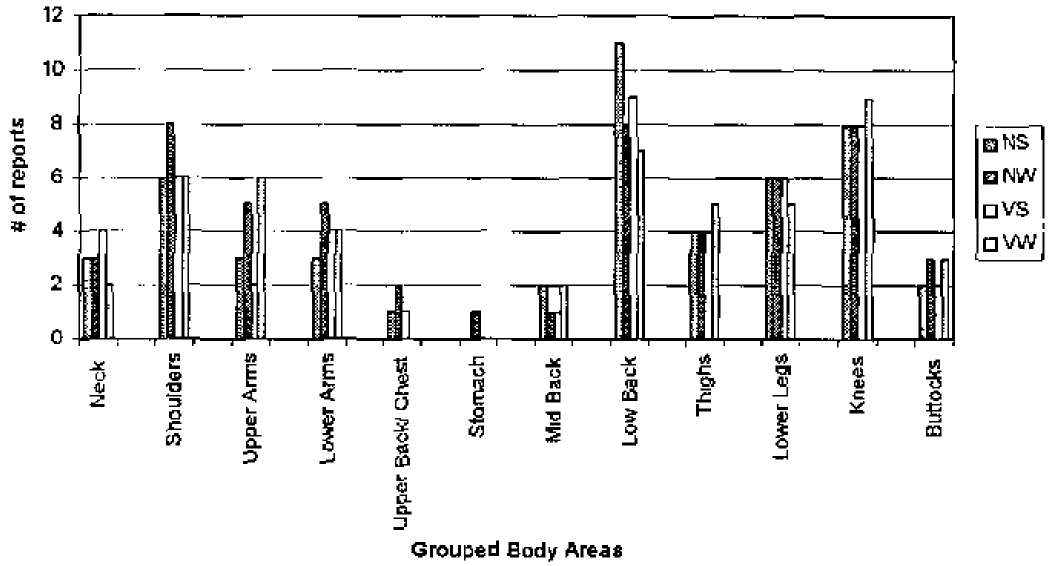


Figure 4 DAS-Specific (# of reports * severity) Across Subjects by Body Area and Experimental Condition

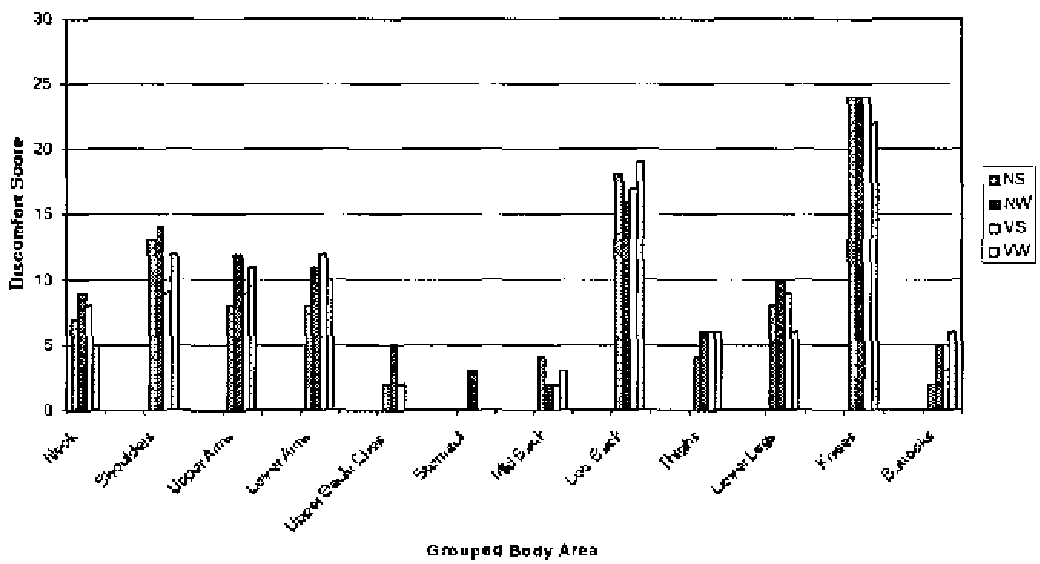
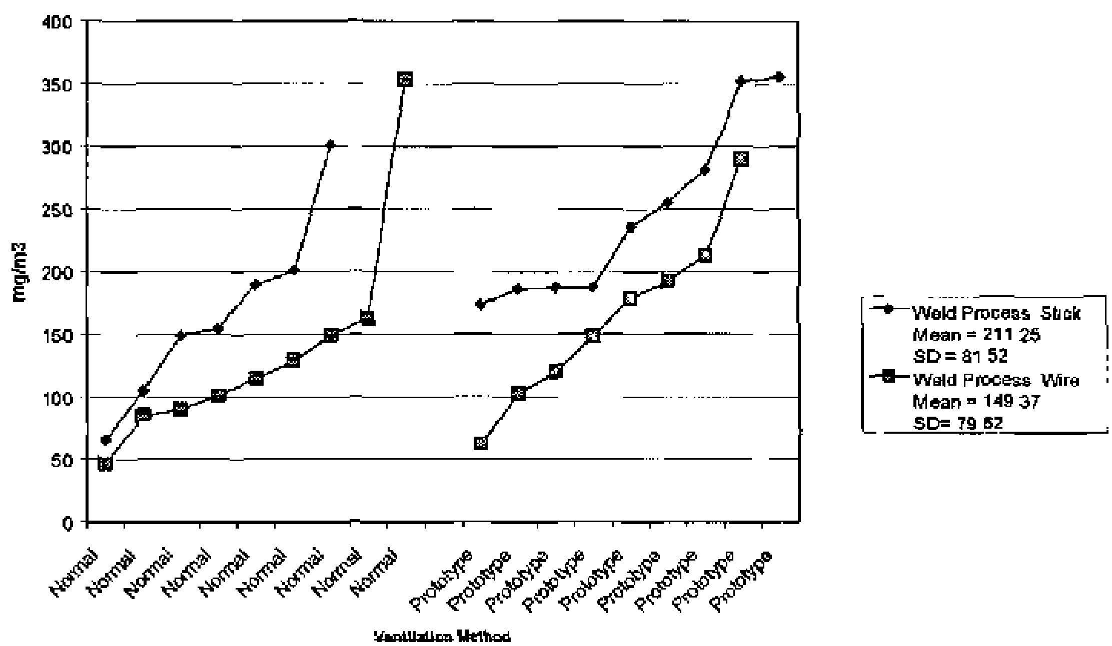


Figure 5: Total Personal Particulate Concentration (mg/m3)



Prototype Mean = 207 11, SD = 81 14
Normal Mean = 149 90 SD = 81 79

Figure 6 Weld Quality Results

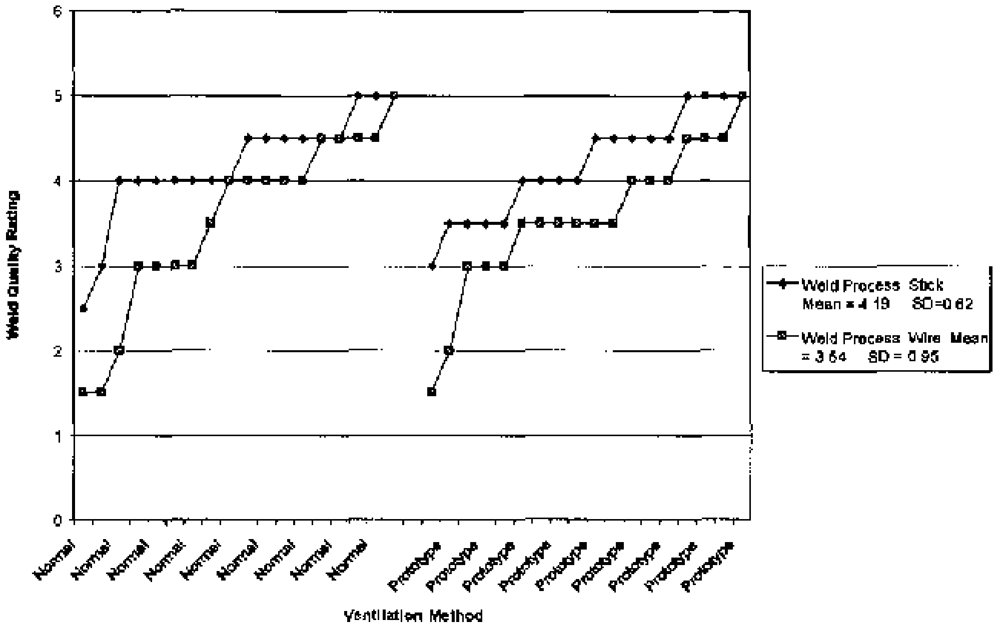


Figure 7 Weld Efficiency [(arc time/ total weld time)*100] Results

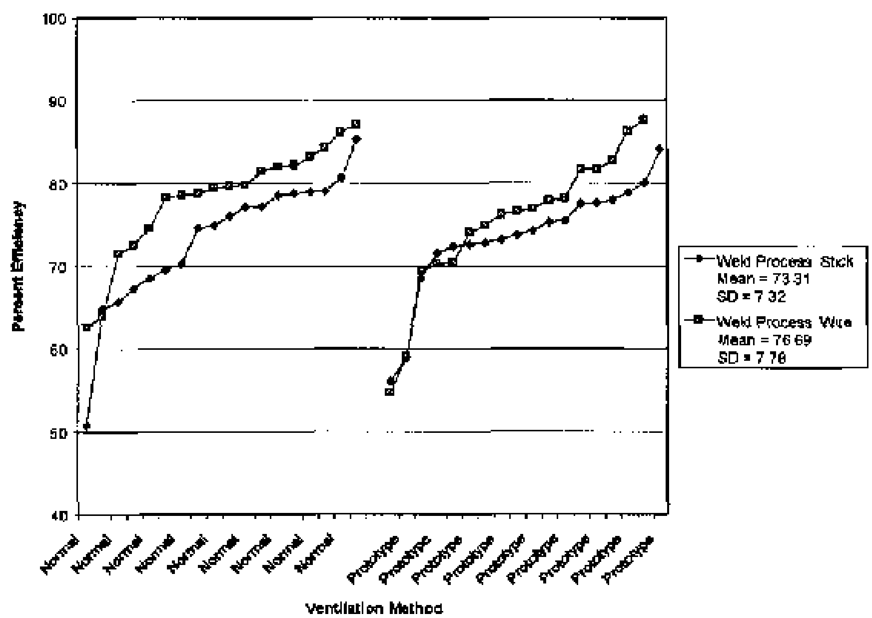


Figure 8 Number of Breaks

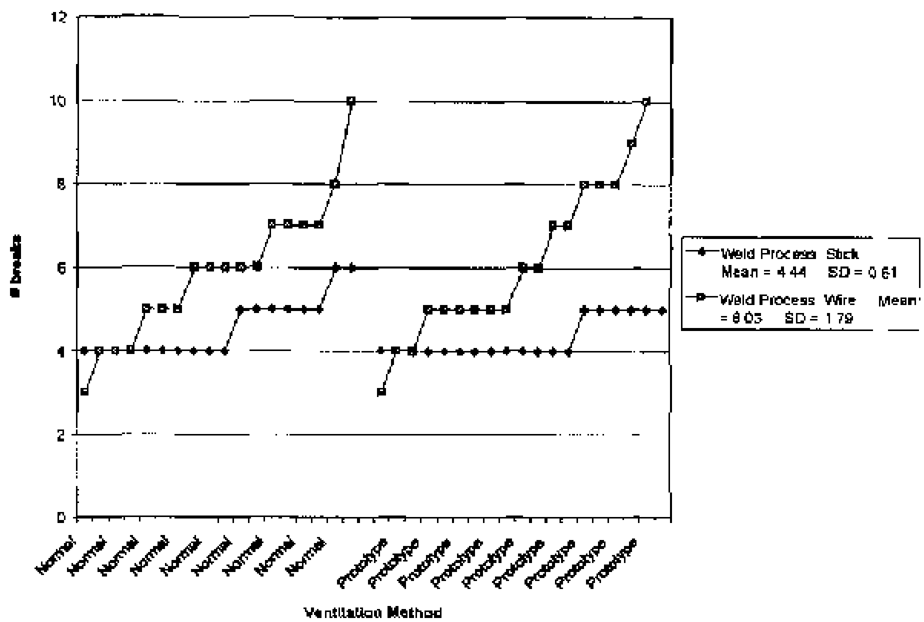


Figure 9 Mean Break Time

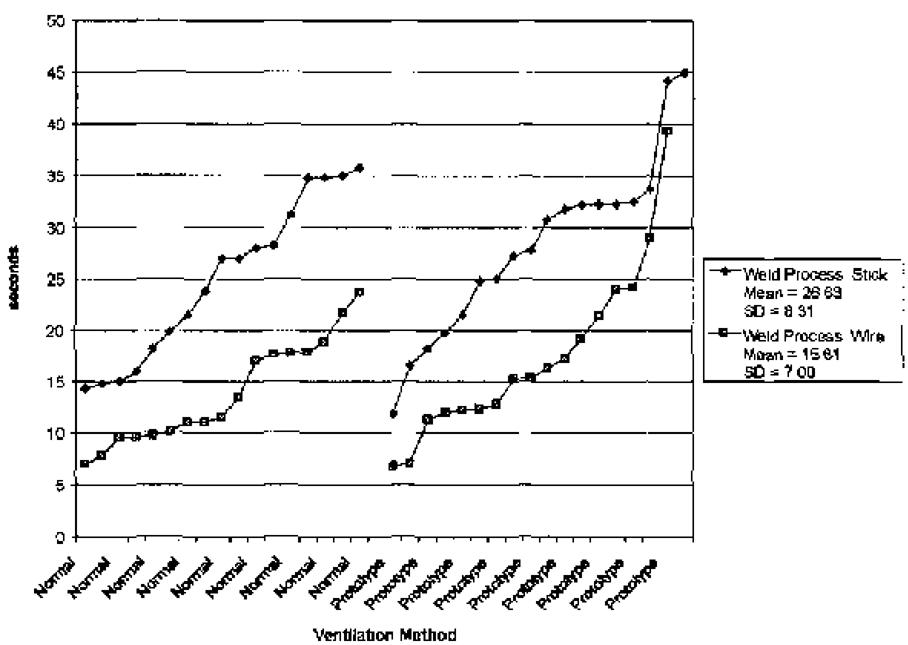


Figure 10 Total Weld Time

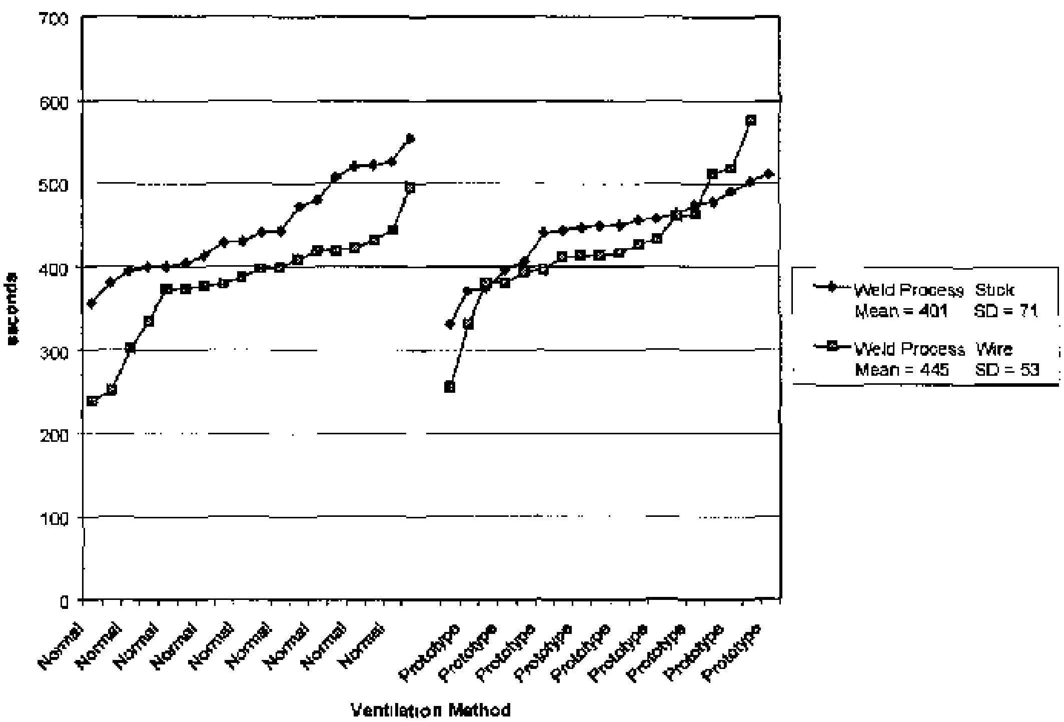
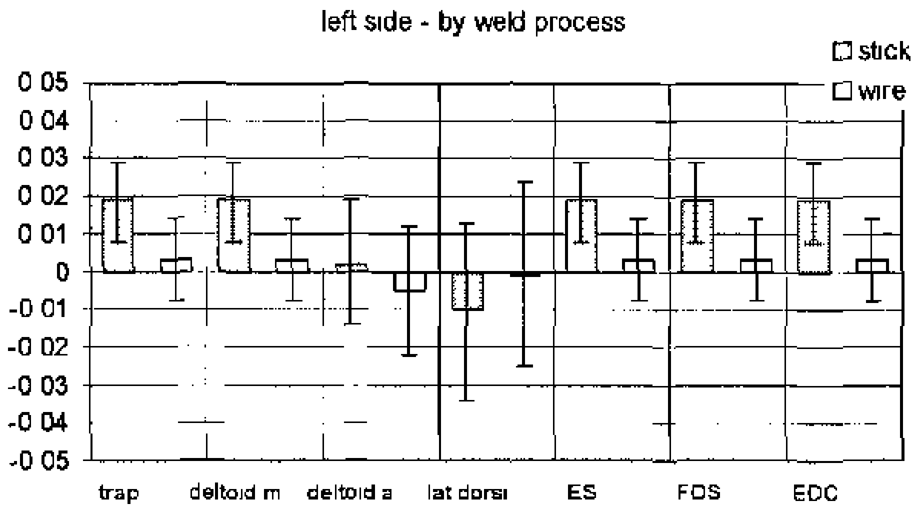
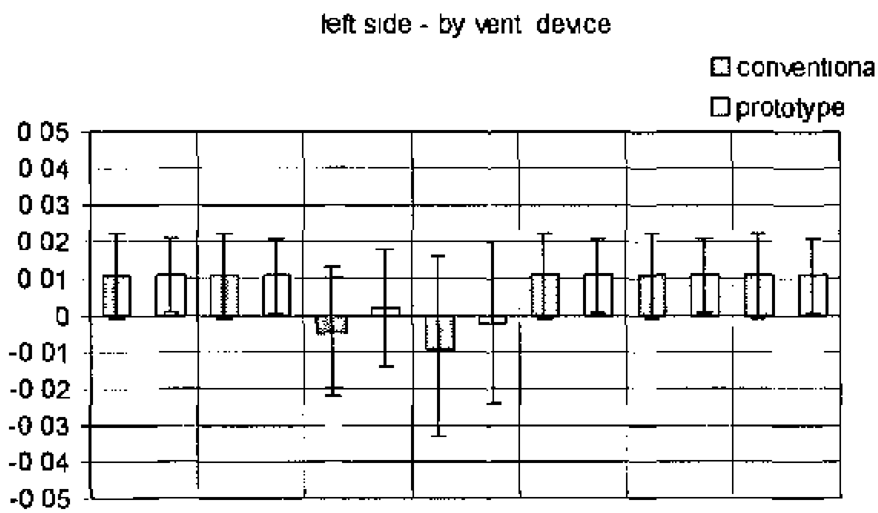


Figure 11 a, c: Slopes of the resulting linear equation when regressing percent of total EMG power in the 10-30 Hz frequency band against time averaging window (a) left side by weld process (c) left side by ventilation device

(a)

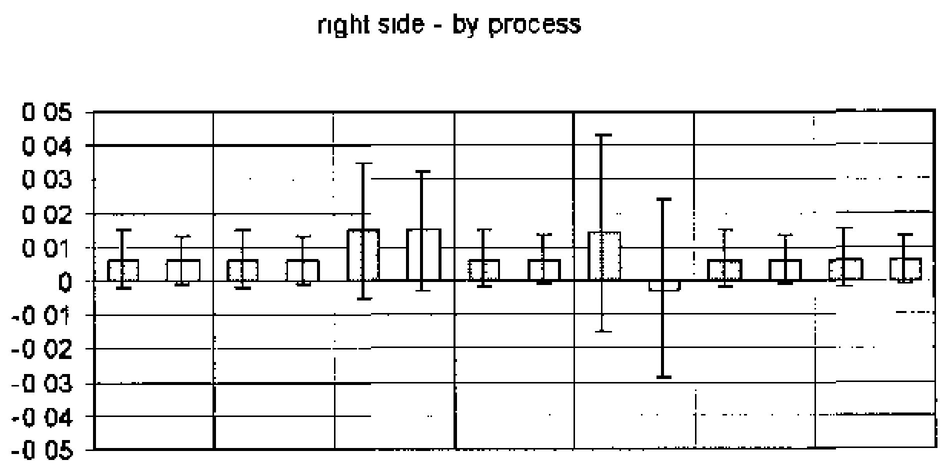


(c)



Figures 11 b, d: Slopes of the resulting linear equation when regressing percent of total EMG power in the 10-30 Hz frequency band against time averaging window.
(b) right side by weld device, (d) right side by ventilation method

(b)



(d)

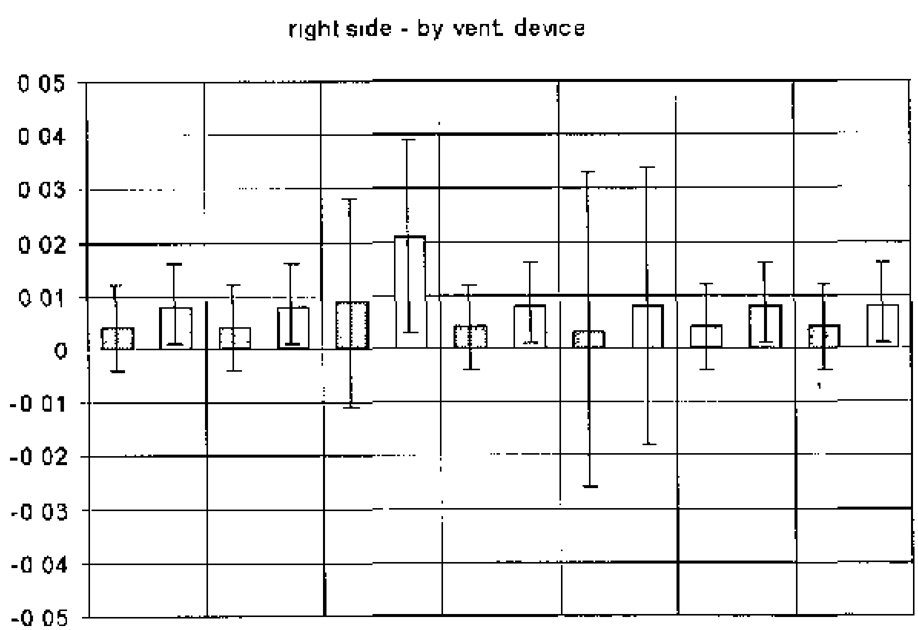


Figure 12: Percentages of the total signal power in the 10-30 Hz frequency band ($PP_{10\text{-}30}$) averaged across all subjects and muscles. The averages are shown by time sequence number for the welding processes and ventilation devices.

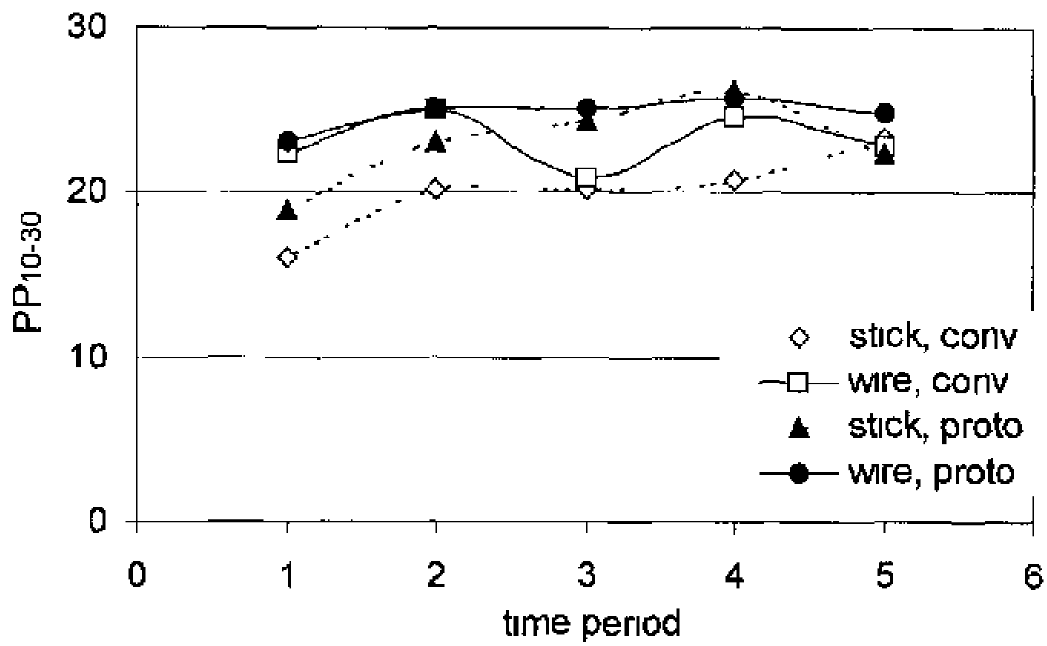
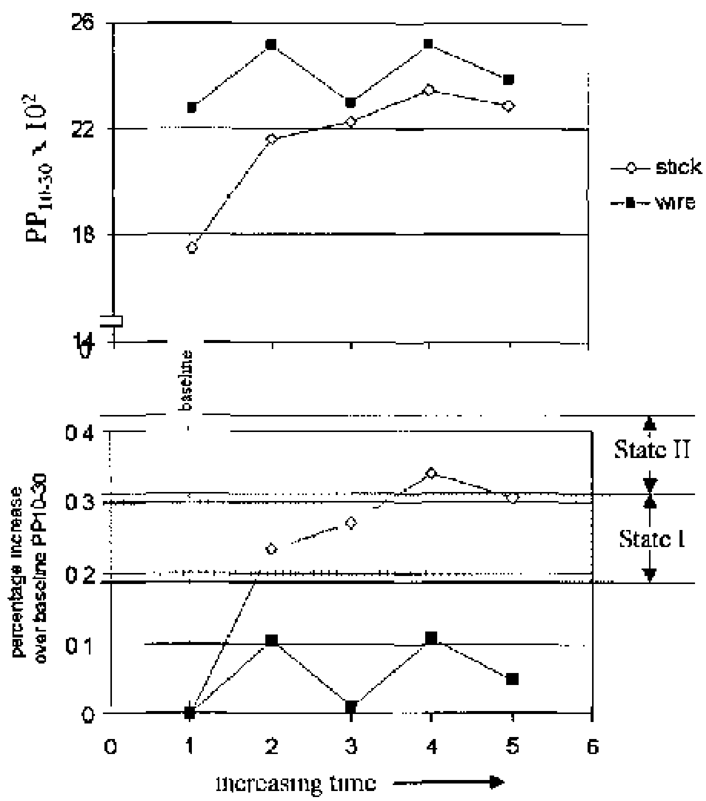


Figure 13 (Top) PP_{10-30} averages for stick and wire welding processes as a function of time segment (Bottom) Increases in the PP_{10-30} measure relative to its baseline value (time segment 1) The fatigue States I and II correspond to the shifts in power spectral density described by Chaffin (1973) The stick welding process PP_{10-30} values shifted upward by a percentage large enough to be described by Chaffin's fatigue states as State I and lower State II fatigue levels. The wire welding process PP_{10-30} values did not increase (relative to baseline) enough to reach State I levels



ILLUSTRATIONS

Illustration 1 a, b : Normal Ventilation– Blower-type horn

1a

1b

Illustration 2: Prototype Ventilation Device: Fresh Air Diffuser

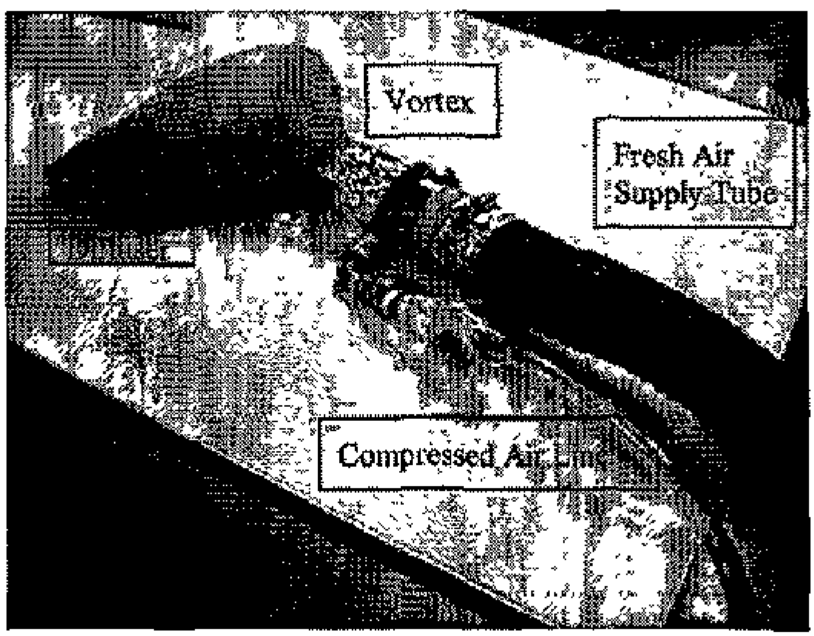
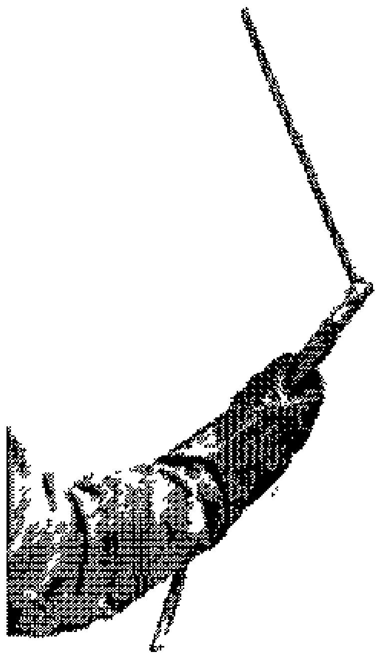
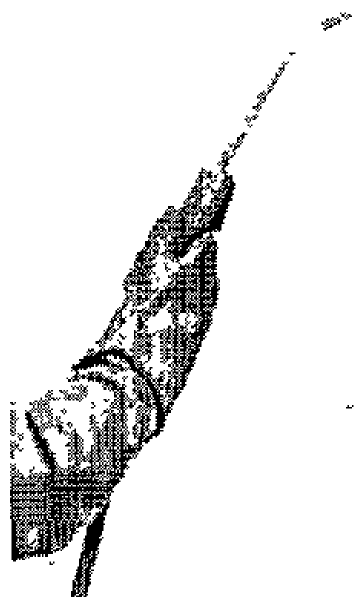


Illustration 3: Stick and Wire Welding Comparison

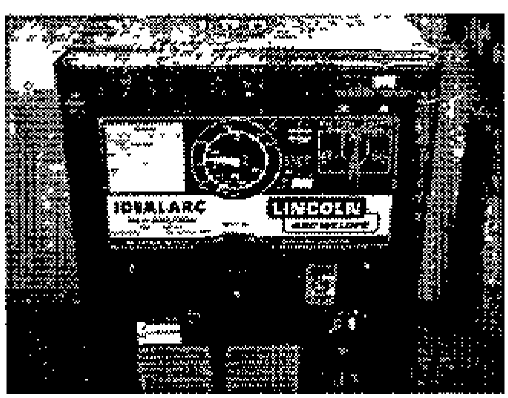


3a Stick Welding (SMAW)

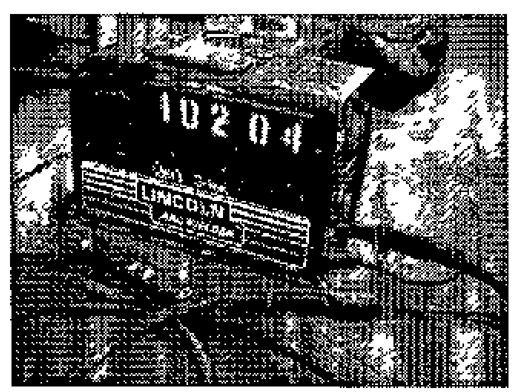


3b Wire Welding (FCAW)

Illustrations 4 a,b: Stick and Wire Comparison, Continued

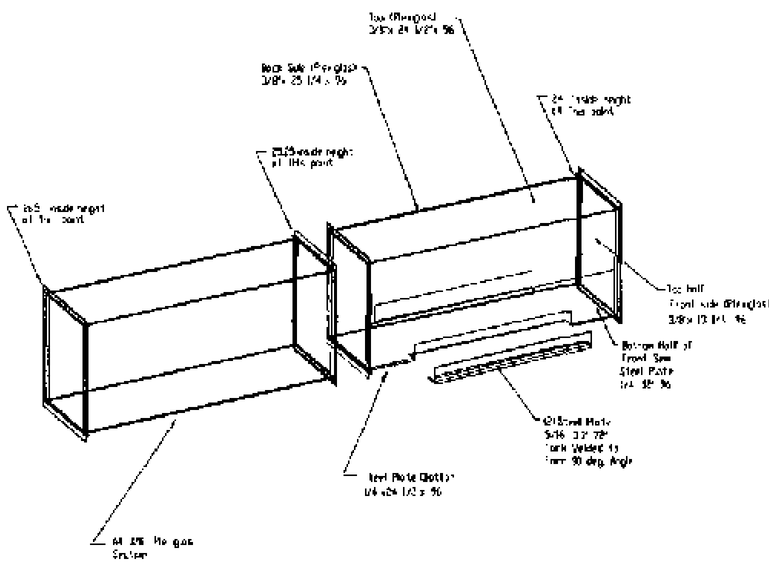


4a Stick welding unit



4b Wire welding unit

Illustration 5: Welding Mock-up Specifications



Mockup

Confined Spaces Welding Test

Illustration 6. Typical Confined-Space Welding Posture

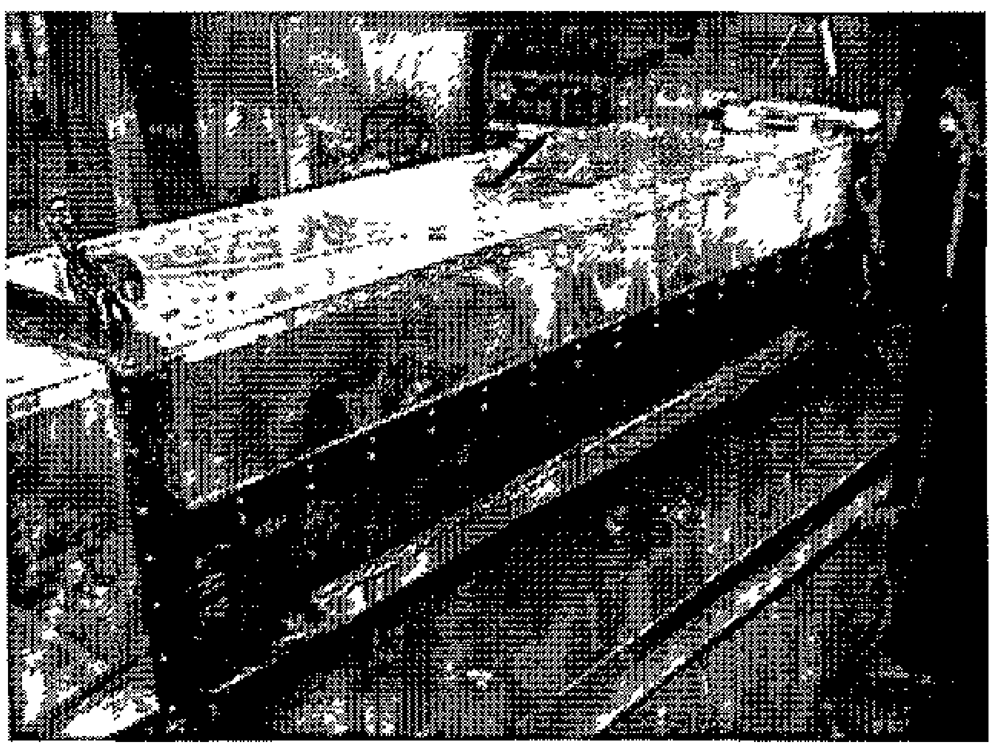
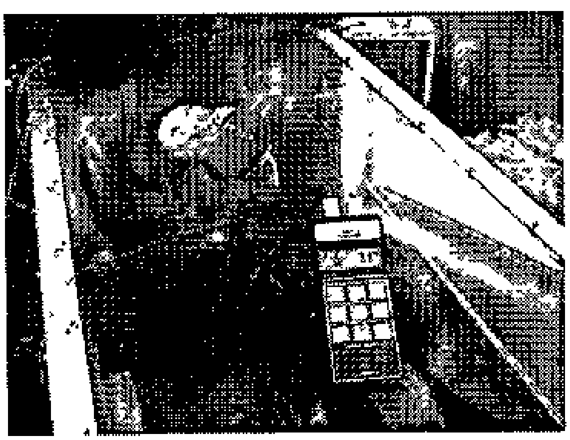
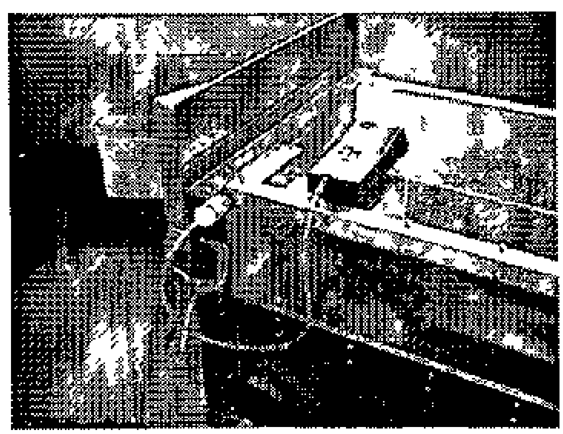


Illustration 7: Experimental Set-up

Illustration 8a: Temperature Sensor
Illustration 8b: Oxygen Sensor



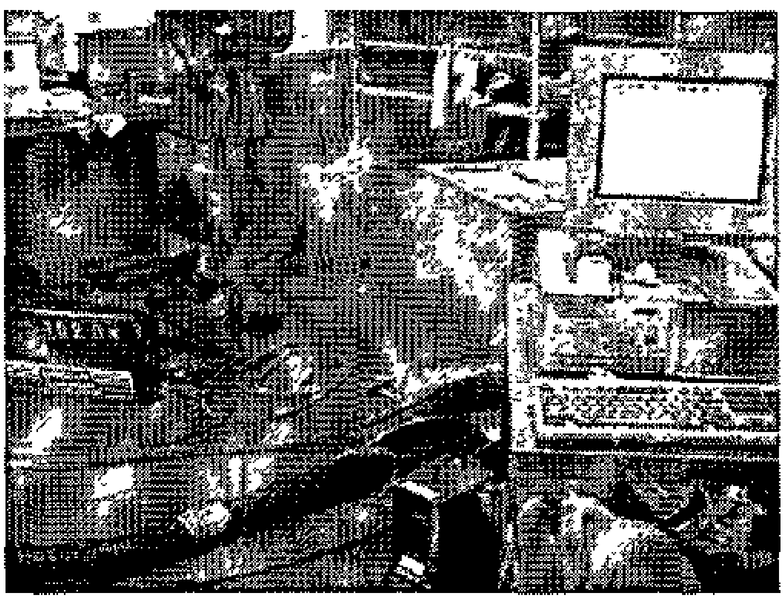
8a



8b

Illustrations 9 a, b: Ventilation Experimental Issues

9 a Welding Fumes Being Forced Out of Back End of Confined-Space Mock -Up When Using the Normal Ventilation Horn



9 b Welding Fumes Being Expelled From Entrance of Confined Space Mock-up Using the New Ventilation Tube

APPENDIX 1: PARTICIPANT FORMS

Form #1: CALL FOR VOLUNTEERS

NEEDED VOLUNTEERS FOR A WELDING STUDY

WHAT: NIOSH (National Institute for Occupational Safety and Health, a United States government research agency) and *participant shipyard* are sponsoring a study to determine the effectiveness of engineering controls in reducing muscle and joint disorders and improving welding performance in the "honeycombs"

WHY: **BENEFITS:** The personal benefits of participating in this study include a greater awareness of the possible ways to make the job of welding in confined spaces safer, less-tiring, and more productive The participants will also benefit from knowing that they are part of a study that aims to improve the work conditions of their fellow welders

RISKS: You should not experience any discomfort or injury beyond what is normally experienced in stick-welding in "honeycombs" on a daily basis at the shipyard Such welding work does involve the potential risk for muscle/ joint fatigue and injury, electrical shock, eye damage due to utraviolet light exposure, fume inhalation, and skin burns from the stick-welding unit and excess slag

WHO: To be eligible, participants must

1 Be a 2[nd] Class Welder
2 Have experience in the welding in confined spaces
3 Be free of medical conditions that inhibit welding in confined-spaces (such as musculoskeletal disorders or heart conditions)
4 Have received full safety training for stick and wire-fed welding operations

WHERE: The study will take place in a mock-up in the shipyard welding school and **will last 4 hours total** (8 trials, 10 minutes each) for each participant **All trials will be conducted within the participants normal working shift.**

WHEN: **April 8 -20**

* **All volunteers will receive their normal hourly wage (paid by the *participant shipyard*) for their participation in this study.**

*****Questions/ Comments? Contact Steve Hudock, Ph.D , Senior Safety Engineer (NIOSH) at (513) 841 -4385***

FORM # 2: MEDICAL/ ELIGIBILITY FORM

Providing information for this form is strictly voluntary. It will be used only to determine eligibility for the NIOSH welding study based on your medical condition and welding experience. All information is confidential and will only be available to NIOSH investigators.

1 Do you have 2nd Class welding certification? ____________

2 Do you have experience in welding in confined spaces? ________

3 Have you received full safety training on stick-welding operation, including safe work practices and the use of personal protective equipment? ____________

4 Do you currently have a muscle or joint problem that would prevent you from performing stick welding in a confined space? If yes, please explain

____

5 Do you currently have a breathing or heart condition that would prevent you from performing stick welding in a confined space? If yes, please explain ____

SUBJECT #

FORM #3A: INFORMED CONSENT (NIOSH)

NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH (NIOSH)
CENTERS FOR DISEASE CONTROL
U.S. PUBLIC HEALTH SERVICE
U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

You have been asked to participate in a NIOSH research study. We explain here the nature of your participation, describe your rights, and specify how NIOSH will treat your records

---

I. DESCRIPTION

1. **Title: Engineering Côntrols for Welders in Confined Spaces**

2. **Sponsor and/or Project Officer: Stephen D. Hudock, Senior Safety Engineer, DPSE**

3. **Purpose and Benefits: The purpose of this study is to determine the effectiveness of ergonomic/ ventilation controls and different welding processes in reducing muscle and joint disorders and weld-fume exposure while improving welding performance. The usefulness of the measures and procedures to perform such evaluations will also be investigated. The personal benefits of participating in this study include a greater awareness of the possible ways to make the job of welding in confined spaces safer, less-tiring, and more productive. The participants will also benefit from knowing that they are part of a study that aims to improve the work conditions of their fellow welders.**

I. CONDITIONS OF THE STUDY

1. **You will be asked to flat weld in a confined-space mock-up under four different work conditions and each of these conditions will be repeated for a total of eight weld trials. These conditions include: 1) Stick welding using a blower-type air horn as ventilation 2) Wire welding using a blower-type air horn as 3) Stick welding using a new ventilation device , 4) Wire welding using a new ventilation device. The mock-up itself is made of Plexiglas ™ (Acrylite ™) and steel and is 2 ft by 2ft by 16 ft, and will be set-up inside the welder training center at the (participant shipyard).**

During each weld trial, you will be asked to crawl into the mock-up and weld 2 flat fillet joints (6 ft in length each), located on the left and right sides of the mock-up. The entire weld trial should last around 10 minutes and you should use up 2-4 weld sticks (for the trials that require stick welding). Between each trial, you will be given a ten minute rest break and will be asked to fill out two brief surveys which describe the way certain muscles and body areas feel and describe how hard you feel you are working. (See Form #6, "Bishop and Corlett Discomfort Assessment Survey" and Form # 7,"Borg Scale of Perceived Exertion") The entire study of 8 trials (including the hour rest break before the study) should require no more than 4 hours of your time away from your normal job. All trials will be conducted during your normal working shift.

During each weld task, your heart rate and the shoulder muscle activity will be recorded using painless methods. The muscle activity from four of your shoulder muscle groups will be collected through electromyographic (EMG) receivers with adhesive pads attached to the skin surface. Your shoulder area will first be cleaned with pads soaked with rubbing alcohol and may be slightly roughened. Your shoulder area may also be shaved if your hair keeps the pads from staying in place on your skin. This cleaning, roughening, and shaving is necessary to provide the best possible electrical readout.

The adhesive EMG pads will then be applied to the skin surface on four of your shoulder muscle areas. Your heart rate will also be recorded with another small receiver by an adhesive pad that will be attached to your chest. All of these receivers will be attached to your skin and then covered with your normal clothing and protective welding coveralls. Cables from these EMG and Heart Rate receivers will be gathered at your back and will connect into a small, lightweight belt-pack, worn under your clothing and protective gear.

A personal air sampling filter will also be attached on the lapel of your weld suit and a small tube from this filter will be gathered towards your back underneath your clothing. A single fiber optic cable from the belt-pack will then be combined with this air sampling tube and routed out of your clothing and protective gear at waist level, just above your hips. This will make sure that you are still fully protected by your personal protective equipment and clothing. A NIOSH researcher will also guide this combined cable away from you as you enter and leave the mock-up and position yourself during each welding trial. With your permission, you will also be videotaped as you perform each task. (See Form #8, "General Photo Release", to grant this permission)

Before welding is begun, you will be asked to perform a maximum voluntary contraction (MVC) test which is commonly used in EMG studies. During this test, you will be asked to crawl into the mock-up and to assume a certain posture (such as laying on your side). You will then be asked to put your arm in a sling that is attached to the floor of the mock-up and to raise your arm in steady manner until you are raising it as hard as you can for 20 seconds. You will be asked to rest for 2 minutes and then you will be asked to repeat the test. The total time for both of these tests will be less than 5 minutes. These MVC tests should only be performed once at the beginning of the trials, but may have to be repeated if the EMG pads fall off of your skin during the trials.

You will be given a medical/ eligibility questionnaire before you are allowed to take part in this study to make sure that you are certified for confined-space welding and that you are free from medical conditions that would prevent you from safely participating. (See Form # 2, "Medical / Eligibility' Questionnaire") Before participating, you will also be asked to complete a form that asks how certain areas of your body have felt in the past after welding. (See Form #4, "Symptoms Survey Checklist")

During periods of welding, you will be required to wear the full Personal Protective Equipment (PPE) necessary for stick welding inside the honeycombs at the (participant shipyard). This includes insulated overalls, gloves, welding helmet, UV protective face shield, and personal breathing mask (3M 8812 disposable welding mask). Also, all welding will be done in a safe manner in accordance with safe welding guidelines as recommended by the American Welding Society.

You will be asked to rest for 1 hour before participating in the study. During this time, a number of your body dimensions will be measured with a tape measure, including the length of your upper and lower legs, chest circumference, shoulder width, arm length, and your overall height. Your age and weight will also be asked and determined at this time. (See Form #5, "Subject Body Dimensions")

2. You should not experience any discomfort or injury beyond what is normally experienced in stick-welding in "honeycombs" on a daily basis at the (participant shipyard). Such welding work does involve the potential risk for muscle/ joint fatigue and injury, electrical shock, eye damage due to utraviolet light exposure, fume inhalation, and skin burns from the stick-welding unit and excess slag.

   You may experience slight discomfort during the EMG measurement procedure. This procedure includes the cleaning of your shoulder area with rubbing alcohol, which may cause a slight burning sensation on your skin which may involve a slight roughening of your skin with a paper towel. It also may involve the shaving of certain areas of the shoulder and chest if your body hair in this area prevents the EMG and Heart Rate pads from being attached to your skin. Also, you may experience slight discomfort when the adhesive EMG and Heart Rate pads are removed from your skin

Welding in the mock-up may also involve additional risks since you will be not be able to move as freely as normal since you will be attached to the EMG and heart rate receivers and fiber optic/ air sampling cables. A NIOSH researcher will guide these cables to keep them out of your way so you can get in and out of the mock-up almost as normally as you would get in and out of the honeycomb sections at the (participant shipyard)..

Welding in the mock-up may also involve additional risks of injury due to the fact that the mock-up is made of acrylic sheets (Acrylite GP ™, like Plexiglas ™) and steel. The mock-up has been designed to safely enable actual confined-space welding tasks to be videotaped from a number of views. To insulate against the heat of the welding arc and excess slag during the welding procedure, the area where these tasks will be performed has been constructed of 3/16 in steel plate (the rear bottom surface and half of the rear side surfaces). Actual weld beads will be deposited into removable "angle irons". Other areas of the mock-up have been constructed out of 3/8 inch Acrylite ™ sheets to allow videotaping. Although Acrylite ™ can burn, it has an allowable continuous service temperature of 180 to 200 degrees F. It is unlikely that the Acrylite ™ portions of the mock-up will be subjected to heat of this level or that slag will contact the Plexiglas in a way that could produce a fire. However, the surface temperature of the mock-up will be checked constantly throughout the trials. In the event that the surface temperature reaches 120 degrees, the trial will be stopped and you will be asked to exit the mock-up Fire extinguishers will be readily available and first responders will be on hand to deal with potential fires or medical emergencies. The mock-up itself has also been approved for use in this study by the Fire Prevention Bureau of the (participant shipyard district). Standard (participant shipyard) safety procedures will be followed in any emergency.

If you have any reaction to the tests/ procedures your should contact Dr. Stephen D. Hudock, Senior Safety Engineer, at (513) 841-4385

3. The procedures (actual welding task performed in a mock-up) and measures suggested (heart rate monitoring, EMG monitoring, subjective questionnaires) are the safest and most appropriate measures available for workload and performance assessment. Other measures exist , such as fine wire EMG's , but they are inappropriate because these wires would have to

be inserted into your skin.

4. Injury from this project is unlikely. But if it results, medical care is not provided other than emergency treatment. If you are injured through the negligence of a NIOSH employee you may be able to obtain compensation under Federal Law. If you want to file a claim against the Federal government your contact point is: Public Health Service Claims Office: (301) 443-1904. If you are injured through the negligence of a NIOSH contractor, your claim would be against the contractor, not the federal government. If an injury should occur to you as the result of your participation, you also should contact: Dr. Stephen D. Hudock, Senior Safety Engineer, at (513) 841-4385

1. If you have any questions about this research or your rights as a member of this study, contact: Dr. Stephen D. Hudock, Senior Safety Engineer, at (513) 841-4385 or Dr. Michael J. Colligan, Psychologist, at (513) 533-8222.

2. Your participation is voluntary and you may withdraw your consent and your participation in this study at any time without penalty or loss of benefits to which you are otherwise entitled.

   You will not be compensated by NIOSH for your participation but you will be paid by Jeffboat for your study participation during your regular shift.

3. NIOSH will provide you and your doctor (if you wish) with all findings from your medical tests (and any other examinations) in written form delivered via the U.S. Postal service. We will do this when the study is finished, or sooner, if appropriate.

I. USE OF INFORMATION

The National Institute for Occupational Safety and Health (NIOSH) of the Centers for Disease Control (CDC), an agency of the Department of Health and Human Services, is authorized to collect this information, including your social security number (if applicable), under provisions of the Public Service Act, Section 301 (42 U.S. C. 241); Occupational Safety and Health Act, Section 20 (29 U.S.C. 699); and Federal Mine and Safety and Health Act of 1977, Section 501 (30 U.S.C. 95). The information you supply is voluntary and there is no penalty for not providing it. The data will be used to evaluate illnesses and deaths resulting from diseases related to shipyard welding, to determine their causes and to prevent them in the future. Data will become part of CDC Privacy Act system and may be disclosed to appropriate State or local health departments to track occupational musculoskeletal/

physiological disorders. An accounting of the disclosures that have been made by NIOSH will be made available to you upon request. Except for these and other permissible disclosures expressly authorized by the Privacy Act, or in limited circumstances when required by the Freedom of Information Act, no other disclosure may be made without your written consent.

II. SIGNATURES

I have read this consent form and I agree to participate in this study.

PARTICIPANT____________________________(Signature)
Age__________

(and guardian, if required)______________________________
Date__________

I, the NIOSH representative, have accurately described this study to the participant.

REPRESENTATIVE________________________(Signature)
Date__________

FORM #3B: INFORMED CONSENT (UNIVERSITY OF CINCINNATI)

UNIVERSITY OF CINCINNATI

Consent to Participate in a Research Study

Title of Study:
Engineering Controls for Welders in Confined Spaces

Investigator Information:

Principal Investigator: Steve Wurzelbacher
Telephone number: (513) 841 -4407

Amit Bhattacharya, Ph.D.
Scott Clark, Ph.D.
Steve Hudock, Ph.D.(NIOSH)
Stan Shulman, Ph.D. (NIOSH)
Faculty Supervisors/Co-investigators

Introduction

Before agreeing to participate in this study, it is important that the following explanation of the proposed procedures to be read and understood. It describes the purpose, procedures, benefits, risks, discomforts and precautions of the study. It also describes alternative procedures available and the right to withdraw from the study at any time. It is important to understand that no guarantee or assurance can be made as to the results. It is also understood that refusal to participate in this study will not influence standard treatment for the subject.

I ______________________________ have been asked to participate in the research study under the direction of Steve Wurzelbacher. Other professional persons who work with him as study staff may assist or act for him.

I will be one of approximately nine subjects to participate in this trial.

Purpose

The purpose of this research study is to determine the effectiveness of engineering controls (weld process change and ventilation controls) in reducing muscle and joint disorders, reducing weld fume exposure, and improving welding performance. The usefulness of the measures and procedures to perform such evaluations will also be investigated.

1

Duration

My participation in this study will last for approximately four hours.

Procedures:

I have been told that during the course of this study, the following will occur:

I will be given a medical/ eligibility questionnaire before I am allowed to take part in this study to make sure that I am certified for confined space welding and that I am free from medical conditions that would prevent me from safely participating. During periods of welding, I will be required to wear the full Personal Protective Equipment (PPE) necessary for stick welding inside confined spaces at the (participant shipyard). This includes insulated overalls, gloves, UV protective face shield, and a personal breathing mask (3M 8812 disposable welding mask). Also, all welding will be done in a safe manner in accordance with safe welding guidelines as recommended by the American Welding Society.

I will be asked to rest for 1 hour before participating in the study. During this time, a number of my body dimensions will be measured with a tape measure, including the length of my upper and lower legs, chest circumference, shoulder width, arm length, and my overall height My age and weight will also be determined at this time.

I will be asked to flat weld in a honeycomb mock-up under four different work conditions and each of these conditions will be repeated for a total of eight weld trials. These conditions include: 1) normal stick welding (same as current job conditions in the honeycomb), 2) stick welding using a new ventilation tube, 3) normal wire welding (same as current job conditions in the honeycomb), 4) wire welding using a new ventilation tube. The mock-up will be full size (2 ft by 2ft by 16 ft), made of Plexiglas and steel, and will be set-up inside the welder training center at the (participant shipyard).

During each weld task, my heart rate and the shoulder muscle activity will be recorded using painless methods. The muscle activity from four of my shoulder muscle groups will be collected through Electromyographic (EMG) receivers with adhesive pads attached to the skin surface. My shoulder area will first be cleaned with pads soaked with rubbing alcohol and may be slightly roughened. The hair on my shoulder area may also be shaved. This cleaning, roughening, and shaving is necessary to provide the best possible electrical readout. The adhesive EMG pads will then be applied to my skin surface in the proximity of four shoulder muscle areas. My heart rate will be collected by another small receiver attached to my chest. I will also be videotaped during each task.

I will be asked to rest for 1 hour before participating in the study. During this time, a number of my body dimensions will be measured with a tape measure, including the length of my upper and lower legs, chest circumference, shoulder width, arm length, and my overall height My age and weight will also be asked and determined at this time.

Before welding is begun, I will be asked to perform a maximum voluntary contraction (MVC) test which is commonly used in EMG studies. During this test, I will be asked to crawl into the mock-up and to assume a certain posture (such as laying on my side). I will then be asked to put my arm in a sling that is attached to the floor of the mock-up and to raise my arm in steady manner until I am raising it as hard as I can for 20 seconds. I will be asked to rest for 2 minutes and then I will be asked to repeat the test. The total time for both of these tests will be less than 5 minutes. These MVC tests should only be performed once, before welding begins and not during the rest of the trials. This test may have to be repeated if the EMG receivers fall off my skin.

After the MVC testing period, I will be asked to perform 8 flat welding tasks [4 wire-fed tasks (Flux Core Arc Welding or FCAW) and 4 stick-welding tasks (Shielded Metal Arc Welding or SMAW)] in a mock-up simulating the confined space of a "hull assembly". For the stick welding trials, mild steel electrodes (sticks) will be used [16 in, E7024--- AWS Class, Jetweld brand, AC operated at a current range of 350 –450 amps]. For the wire-fed welding trials, NR-706 5/64" wire will be used [Volts: 26-28, WFS: 300-350, Transverse Angle: 45 degrees, Travel Angle: 10-20 degrees, 1"-1 ½" stick out. Each trial should last about 10 minutes. Between each trial, I will be given a ten minute rest break and will be asked to fill out two brief surveys which describe the way certain muscles and body areas of mine feel and describe how hard that I feel I am working. The entire study of 8 trials (including the hour rest break before the study) should require no more than 4 hours of your time away from my normal job.

Exclusion

I should not participate in this study if any of the following apply to me:

1 I have not received 2nd class welding certification
2 I do not have experience in the welding in confined spaces
3 I am not free of medical conditions that inhibit welding in confined-spaces (such as muscle and joint disorders, heart conditions, difficulty in breathing etc...)
4 I have not received full safety training for stick –welding operations.
5 I am not 19 years of age or older.

Risks/Discomforts

I have been told that the study described above may involve the following risks and/or discomforts and safeguards and/or precautions to avoid them:

"The subject should not experience any discomfort or injury beyond what is normally experienced in stick-welding in confined spaces on a daily basis at the (participant shipyard). Such welding work does involve the potential risk for musculoskeletal fatigue and injury, electrical shock, eye damage due to utraviolet light exposure, fume inhalation, and skin burns from the stick-welding unit and excess slag."

"The procedures (actual welding task performed in a mock-up) and measures suggested (heart rate monitoring, EMG monitoring, subjective questionnaires) have been used by previous welding studies because they are the safest and most appropriate measures available for workload and performance assessment. The subjects may experience slight discomfort during the EMG measurement procedure. This procedure includes the cleaning of the shoulder area with isopropyl alcohol, which may cause a sensation of slight burning of the skin in some individuals and possible slight abrasion with a rough paper towel. Also, some individuals may experience slight discomfort when the adhesive EMG pads are removed from the shoulder area."

"To reduce the potential for the injuries associated with SMAW (stick-welding), all subjects have been properly trained in the safe use of SMAW (stick) welding units and the safety precautions (including personal protective equipment) outlined in the Methods section will be required."

"In addition, each subject's heart rate and perceived exertion will be monitored continuously throughout each trial, and the trial will be terminated if the subject's discomfort becomes excessive or if the subject's heart rate reaches 75% of their predicted maximum heart rate [214- (.71*subject's age in years)]. "

There also may be risks and/or discomforts which are not yet known.

Pregnancy

If I am a woman of childbearing potential, I will not participate in this research study unless I have a negative pregnancy test and, with the investigator's knowledge and approval, I am employing a form of birth control approved by the resident physician. I agree to inform the investigator's immediately if: 1) I have any reason to suspect pregnancy; 2) I find that circumstances have changed and that there is now a risk of becoming pregnant; or 3) I have stopped using the approved form of birth control.

Benefits

I have been told that I will receive no direct benefit from my participation in this study, but my participation may help health and safety professionals determine possible ways to make the job of welding in confined spaces at the participant shipyard, and possibly other shipyards, safer, less-tiring, and more productive.

Alternatives

Alternative procedures exist but are inappropriate because of questionable validity, as in the case of "simulated welding tasks in a mock-up or in a production situation" or because they would unduly interrupt production at the participant shipyard and would lack controllability as in the case of "actual welding in a production situation". Other workload measures exist , such as fine wire EMG's , but they are inappropriate due to invasiveness.

New Findings

I have been told that I will receive any new information during the course of the study concerning significant findings that may affect my willingness to continue my participation.

Confidentiality

Every effort will be made to maintain confidentiality of my study records. Agents of the United States Food and Drug Administration (FDA), National Institute for Occupational Safety and Health (NIOSH), and the University of Cincinnati will be allowed to inspect my medical and research records related to this study. The data from the study may be published; however, I will not be identified by name. My identity will remain confidential unless disclosure is required by law.

Financial Costs to Subject

Funds are not available to cover the costs of any ongoing medical care and I remain responsible for the cost of non-research related care. Tests, procedures or other costs incurred solely for purposes of research will not be my financial responsibility. If I have questions about my medical bill relative to research participation, I may contact Steve Wurzelbacher (513- 841-4407) or Steve Hudock, Ph.D. (513-841- 4385).

Compensation in Case of Injury

The University of Cincinnati Medical Center follows a policy of making all decisions concerning compensation and medical treatment for injuries occurring during or caused by participation in biomedical or behavioral research on an individual basis. If I believe I have been injured as result of research, I will contact Steve Wurzelbacher at (513) 841-4407 or Harry Rudney at (513) 558-7348. I understand that by signing this informed consent statement I am not waiving the right to seek any legal options to which I am entitled.

Payments to Participants

I have been told that I will receive my normal hourly wage (paid by the participant shipyard) for my participation in this study.

Right to Refuse or Withdraw

I understand that my participation is voluntary and I may refuse to participate, or may discontinue my participation at any time, without penalty or loss of benefits to which I am otherwise entitled. I also understand that the investigator has the right to withdraw me from the study at any time. I understand that my withdrawal from the study may for reasons related solely to me (e.g. not following study-related directions form the investigator; a serious adverse reaction) or because the entire study has been terminated.

Offer to Answer Questions

This study has been explained to my satisfaction by ______________________________
and my questions were answered. If I have any other questions about this study, I may call Steve Wurzelbacher at (513) 841-4407. If I have any questions about my rights as a research subject, I may call Harry Rudney at (513) 558-7348. If a research related injury occurs, I will call (513) Harry Rudney at 558-7348.

Participation in Another Study

If I am participating in another study, I will have indicated this as follows:

© YES. If yes, please provide the Principal Investigator's name and title of study.
Principal Investigator's name: ______________________________
Title of study: ____

© NO.

I have read the information provided above. I voluntarily agree to participate in this study. After it is signed, I will receive a copy of this consent form.

Subject Signature
Date

Legal Representative Parent
Date

Signature of Investigator
Date

Witness Signature
Date

© **Check box if verbal assent is obtained by investigator.**

FORM # 4: SYMPTOM SURVEY CHECKLIST

Symptoms Survey: Ergonomics Program

Date __/__/__/

____

Plant **Dept # Job #** **Job Name**

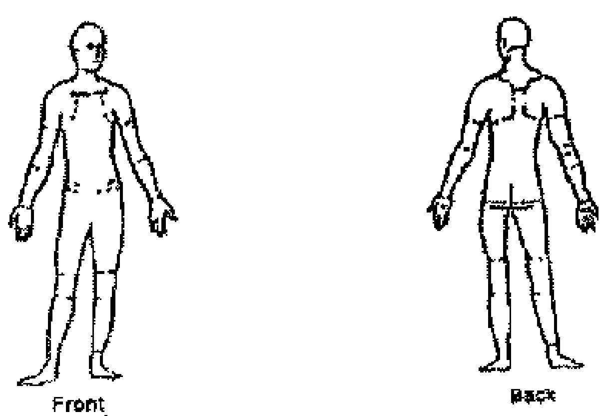
Other jobs you have done in the last year (for more than 2 weeks)

____	______	______	________	___months___weeks
Plant	**Dept #**	**Job #**	**Job Name**	**Time on THIS job**
____	______	______	________	___months___
weeks **Plant**	**Dept #**	**Job #**	**Job Name**	**Time on THIS job**

Have you had any pain or discomfort during the last year?

__Yes __No (if NO, stop here)

If YES, carefully shade in the area of the drawing which bothers you the MOST



(Continued)

(Complete a separate page for each area that bothers you)

Check Area __Neck________Shoulder __Elbow/Forearm______Hand/ Wrist___Fingers

__Upper Back___Low Back_____Thigh/ Knee__________Low Leg______Ankle/ Foot

1 Please put a check by the word(s) that best describe your problem

__Aching __Numbness (asleep) __Tingling

__Burning __Pain __Weakness

__Cramping __Swelling __Other

__Loss of Color __Stiffness

2 When did you first notice the problem? _____(Month) _____ (Year)

3 How long does each episode last? (Mark an X along the line)

________/________/________/________/________

1 hour 1 day 1 week 1 month 6 months

4 How many separate episodes have you had in the last year?____________________________

5 What do you think caused the problem?____

____

____

______

6 Have you had this problem in the last 7 days? __Yes __ No

7 How would you rate this problem (mark an X on line)
NOW

____

None Unbearable

When it was the WORST

____

None Unbearable

8 Have you had medical treatment for this problem? __Yes __No

8a If NO, why not?____

______8b If YES, where did you receive treatment?________________________________

____________1 Company Medical ______Times in past year ___
2 Personal Doctor ______Times in past year ___
3 Other ______Times in past year ___

8c If YES, did the treatment help? ___Yes ___No

9 How much time have you lost in the last year because of this problem?_______Days

10 How many days in the last year were you on restricted or light duty because of this problem?
_______Days

11 Please comment on what you think would improve your symptoms

____
____
____
____
____

Developed by Thomas R Hales of the National Institute for Occupational Safety and Health, and Patricia K Bertsche, of the Occupational Safety and Health Administration

FORM # 5: SUBJECT BODY DIMENSIONS/ DEMOGRAPHICS

SUBJECT # __________

AGE __________

SEX __________

WEIGHT __________

HEIGHT __________

FUNCTIONAL REACH __________

BIDELTOID BREADTH __________

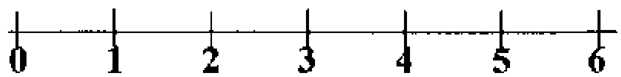
BUTTOCK-KNEE LENGTH __________

CHEST CIRCUMFERENCE __________

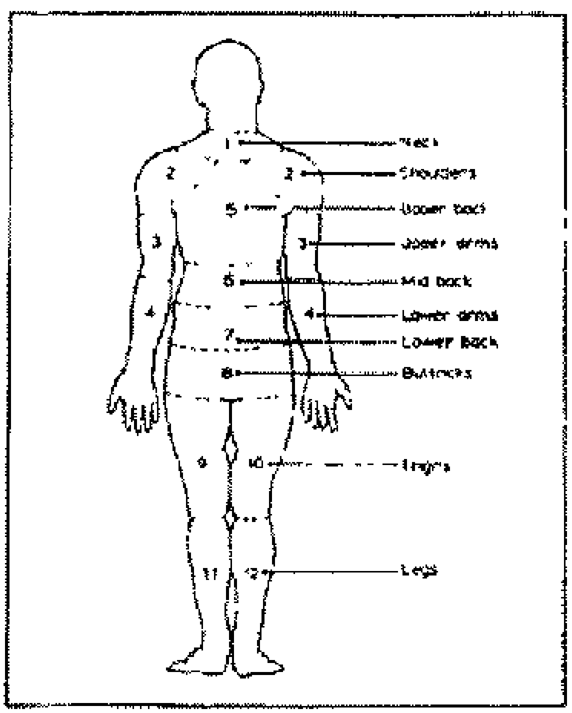
FORM # 6: BISHOP AND CORLETT DISCOMFORT ASSESSMENT SURVEY

A) How would you rate you general state of comfort right now? Circle the number next to the most appropriate answer.

0 Extremely comfortable
1 Very comfortable
2 Comfortable
3 Average
4 Uncomfortable
5 Very uncomfortable
6 Extremely uncomfortable



B) Mark the area(s) of your body that feel most uncomfortable. (The subject will be asked to do this for the next most uncomfortable and so on until all body areas are ranked).



Form # 7: BORG SCALE OF PERCEIVED EXERTION (RATINGS OF PERCEIVED EXERTION, RPE)

How would you describe the work performed during the last welding task? Circle the number that best fits this level of work.

6	
7	**Very, very light**
8	
9	**Very light**
10	
11	**Fairly light**
12	
13	**Somewhat hard**
14	
15	**Hard**
16	
17	**Very hard**
18	
19	**Very, very hard**
20	

Subject # ______

Trial # ______

Form # 8: GENERAL PHOTO RELEASE

A. I agree to allow the National Institute for Occupational Safety and Health (NIOSH) to photograph/ videotape me and use my photograph/ videotaped image.

I hereby agree to allow my photographic image/ videotaped image to be used (without my name, both singly and in conjunction with other persons or objects) by the National Institute for Occupational Safety and Health of the U.S. Department of Health and Human Services.

B. NIOSH will use my photograph/ videotaped image in a publication that other persons are free to copy. I understand that this publication will be printed without copyright protection and may be distributed free or sold.

C. No one will ever pay me for the use of this photograph/ videotaped image. I understand that for the use of my photographic image/ videotaped image, I will receive no financial compensation or payment of any kind from the United States Government or from any agency of the Government or from any person making a copy of the government publication now or at any time in the future.

____

Name

____

Signature

____

Address

____

Telephone

APPENDIX 2: STUDY DESIGN/ STATISTICAL ANALYSIS

As mentioned, a 2X2 factorial design with replicated repeat measures was used for this study The order of treatments presented to each subject was determined either by repeated Latin squares or by randomization (2 subjects only) Specifically, for Subjects I and II, V and VI, VII and VIII, and IX and X, treatments were ordered according to four separate 4X4 Latin Squares while the treatments for Subjects III and IV were ordered randomly Due to experimental issues, Subject VIII was dropped from further analysis and the resulting groups to be analyzed included three complete Latin Squares, one incomplete Latin square, and two randomly ordered subjects EMG data was collected for subjects I through IX only and involved specialized signal processing and statistical treatments, which are discussed in EMG portions of the Methods and Results sections of this report

The Latin square design was used in this case to address the possible order effect of fatigue In the statistical analysis of this kind of design, the effect of treatment sequence can be removed, if it is found to be insignificant Thus, as the first step in analyzing the results of this study, ANOVAs were performed on the six subjects ordered by complete Latin squares to determine if the effect of order was significant Based on the results provided in **Table A2-1a**, it was determined that the effect of order was generally not significant ANOVAs were then performed on the three remaining subjects which included Subjects III and IV, whose treatments had been randomly ordered, and Subject VII, who represented an incomplete Latin square The results of these ANOVAs, which did not consider order effects, are also given in **Table A2-1a** After using an F-test to check for homogeneity of variance, the results of these first two analyses (based on six and three subjects, respectively) were then combined to produce an estimated difference and a standard error with specified degrees of freedom These estimates were then compared to estimates produced when all nine subjects were analyzed by another series of ANOVAs which did not consider the effect of order Based on this comparison, which is provided in **Table A2-1b**, the analysis using the full nine subjects was determined to be statistically valid and was thus used for the overall report Additional ANOVAs were then performed to determine the effect of subject covariates that had been suggested by post-hoc correlation analyses, and the results of these analyses are provided in **Table A2- 2** Finally, data that could be considered to be discrete in nature were also analyzed using Friedman Chi Squares, and the results of these analyses are provided in **Table A2- 3.**

Table A2-1a: Comparison of Statistical Analyses

Measure		Analysis of Subjects Ordered by Complete Latin Squares (Subjects I, II, V, VI, IX, X) p-values	Analysis of Subjects with Randomly-Ordered Treatments, and an Incomplete Latin Square (Subjects III, IV, VII) p-values	Analysis of Combined Subjects (cited in report) p-values
Heart Rate	*Subject*	0013	0549	0001
	Process (stick versus wire)	8454	2430	7384
	Ventilation (normal versus prototype)	9309	3133	7229
	*Process * Ventilation*	6448	1859	3117
	Treatment Order	8989	---	---
Percent of Maximum Aerobic Capacity	*Subject*	1119	4169	0916
	Process	7493	2246	8652
	Ventilation	8347	2853	8126
	*Process * Ventilation*	5990	1714	3036
	Treatment Order	9353	---	---
RPE	*Subject*	0001	0001	0001
	Process	0011	0001	0001
	Ventilation	4110	2707	3458
	*Process * Ventilation*	8125	2707	5064
	Treatment Order	0072	---	---

Table A2-1a: Comparison of Statistical Analyses				
Measure		**Analysis of Subjects Ordered by Complete Latin Squares (Subjects I, II, V, VI, IX, X)** **p-values**	**Analysis of Subjects with Randomly-Ordered Treatments, and an Incomplete Latin Square (Subjects III, IV, VII)** **p-values**	**Analysis of Combined Subjects (cited in report)** **p-values**
DAS-General	***Subject***	0006	0081	0001
	Process	0315	1806	0076
	Ventilation	3864	3300	8538
	Process* Ventilation	9365	1806	2423
	Treatment Order	1894	---	---
DAS-Number	***Subject***	0012	0001	0001
	Process	178	6011	2655
	Ventilation	9765	1	9242
	Process* Ventilation	9765	1	9242
	Treatment Order	8821	---	---
DAS-Specific	***Subject***	0007	0001	0001
	Process	1924	7564	1626
	Ventilation	8750	6647	8960
	Process* Ventilation	8750	5748	6605
	Treatment Order	8361	---	---
Personal Particulate	***Subject***	3047	---	0257
	Process	--	---	0749
	Ventilation	3422		0282

Table A2-1a: Comparison of Statistical Analyses

Measure		Analysis of Subjects Ordered by Complete Latin Squares (Subjects I, II, V, VI, IX, X) p-values	Analysis of Subjects with Randomly-Ordered Treatments, and an Incomplete Latin Square (Subjects III, IV, VII) p-values	Analysis of Combined Subjects (cited in report) p-values
	Process* Ventilation	--		7924
	Treatment Order	5571	----	---
Weld Quality*	***Subject***	2556	3065	3689
	Process	0102	0001	0001
	Ventilation	2168	4049	8714
* does not include subjects 1 and 2	***Process* Ventilation***	8872	5490	7462
	Treatment Order	1339	—	---
Weld Efficiency	***Subject***	0001	5439	0001
	Process	0010	5902	0335
	Ventilation	1751	2411	0621
	Process* Ventilation	0214	9813	0713
	Treatment Order	4425	----	---
Arc-time	***Subject***	2273	8024	6421
	Process	0048	3216	0115
	Ventilation	2394	9136	5571
	Process* Ventilation	8126	1318	1958
	Treatment Order	3881	—	---

Table A2-1a: Comparison of Statistical Analyses				
Measure		Analysis of Subjects Ordered by Complete Latin Squares (Subjects I, II, V, VI, IX, X) p-values	Analysis of Subjects with Randomly-Ordered Treatments, and an Incomplete Latin Square (Subjects III, IV, VII) p-values	Analysis of Combined Subjects (cited in report) p-values
Number of Breaks	***Subject***	2975	0238	0607
	Process	0026	0026	0001
	Ventilation	3914	2303	8889
	Process* Ventilation	1550	4369	5495
	Treatment Order	4314	—	---
Mean Break Time	***Subject***	0001	0080	0001
	Process	0001	0032	0001
	Ventilation	0642	0302	0018
	Process* Ventilation	9448	3515	4743
	Treatment Order	0464	—	---
Total Weld Time	***Subject***	0001	8834	0001
	Process	0001	4736	0002
	Ventilation	0939	4371	0727
	Process* Ventilation	1060	0865	0115
	Treatment Order	5258	—	---

Table A2- 1b: Justification for Combining Subjects

		Combined Estimates from Complete Latin Squares, Incomplete Latin Square and Randomized Trials			Estimates Based on Combined Subjects		
Measure	*Comparison Type*	**Student's T Estimated Difference**	**Standard Error of Estimated Difference**	**Degrees of Freedom, dF**	**Student's T Estimated Difference**	**Standard Error of Estimated Difference**	**Degrees of Freedom, dF**
RPE	***Process*** *(stick versus wire)*	1 06	16	28	1 06	215	37
DAS-General	***Process***	-0 37	17	29	42	15	38
Weld Quality	***Process***	0 80	15	30	80	157	39
Weld Efficiency	***Process***	2 19	98	29	-2 14	97	38
	Ventilation *(normal versus prototype)*	1 77	98	29	1 87	97	38
Arctime	***Process***	20 84	8 75	29	21 99	8 28	38
Number of Breaks	***Process***	1 67	34	29	1 70	34	38
Mean Break Time	***Process***	10 15	1 09	27	10 14	1 00	36
	Ventilation	3 32	1 09	27	3 45	1 02	36
Total Weld Time	***Process***	39 08	10 90	29	39 95	9 69	38
	Ventilation	18 13	10 90	29	17 90	9 69	38

Table A2- 2: Additional ANOVA's: Between Subject Variance Analysis									
	Condition Variables			*Subject Variables*					
Measure	Process p value	Venti-lation p value	Process * Venti-lation p value	Height p value	Weight p value	Bi-Deltoid Breadth p value	Buttock -Knee Length p value	Months on Job p value	Weld Class p value
DAS Number	1979	8811	8763	—	—	—	—	8143	0004
DAS-Specific	2085	7602	7508	—	—	—	—	—	0001
Weld Quality	0091	3003	4594	3789	0001	0185	0240	—	—
Weld Efficiency	0001	1267	0070	—	—	—	0001	0001	—

Table A2-3: Friedman Chi Square Analysis							
Measure	*Overall Significance*	*Paired Differences of Average Ranks* *NS = normal ventilation with stick welding* *NW = normal ventilation with wire welding* *VS = prototype ventilation with stick welding* *VW = prototype ventilation with wire welding*					
		NS-NW	**VS-VW**	**NS-VW**	**NW-VS**	**NS - VS**	**NW-VW**
Weld Quality	p = 0336	1 14	1 57	0 92	-1 78*	-0 64	-0 21
Ratings of Perceived Exertion (RPE)	p = 0351	-1 44+	-1 00	-1 44+	1 00	-0 44	0
DAS-General	p = 3865	-0 89	-0 56	-0 61	0 83	-0 06	0 28
DAS-Number	p = 8888	0 11	-0 44	-0 06	0 28	0 39	-0 17
DAS-Specific	p = 6519	-0 11	-0 44	0 17	0 72	0 61	0 28

+ significant at 10% level
*** significant at 15% level**

Figure A2-1: Procedure for deriving the average percent of the total EMG signal power in the 10-30 Hz frequency band ($PP_{10\text{-}30}$)

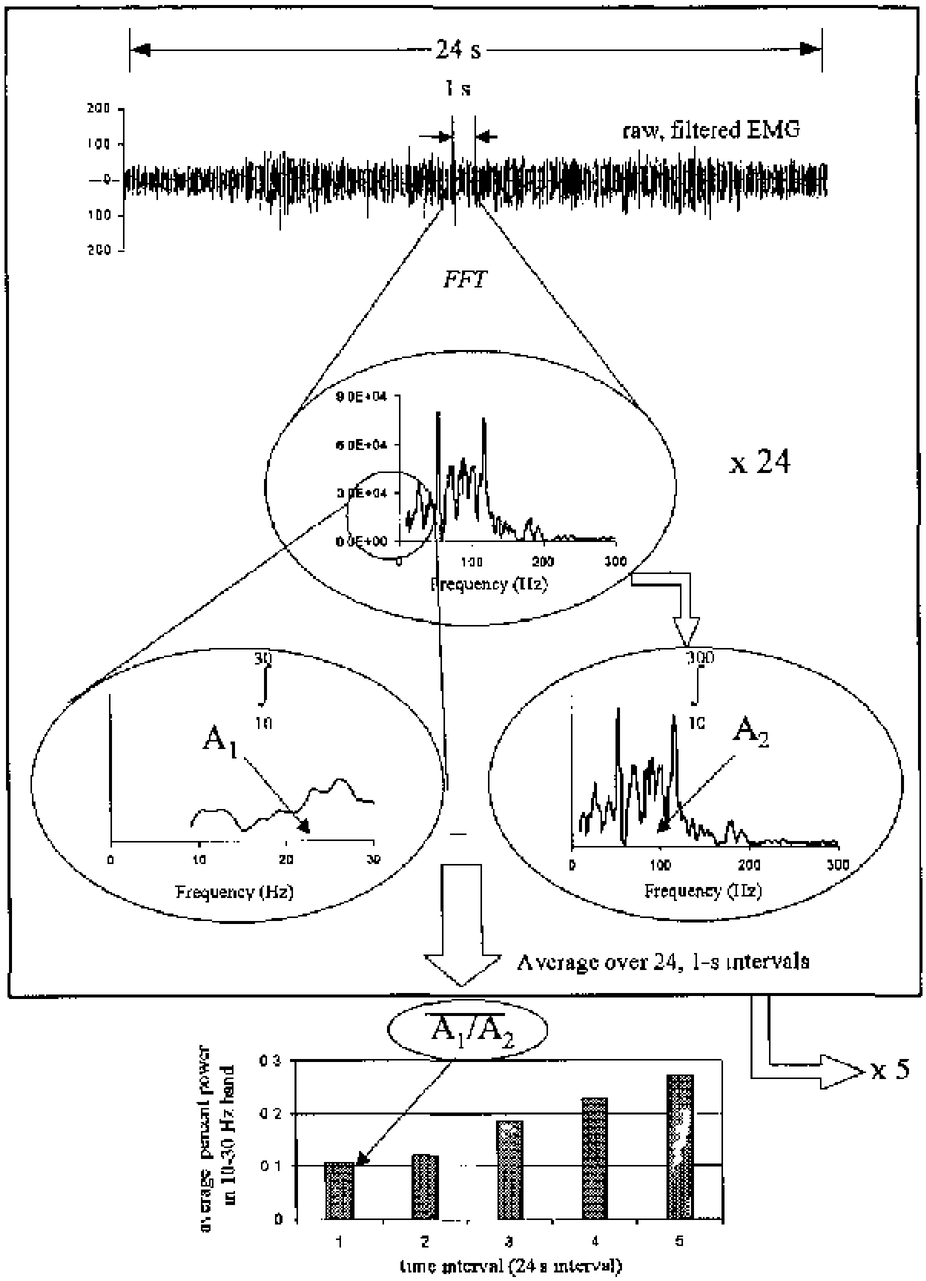
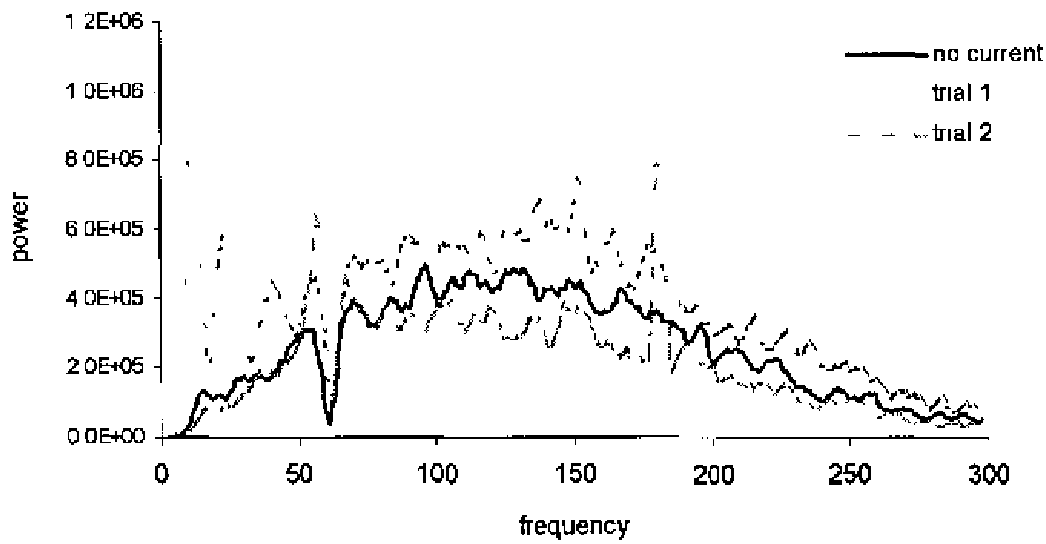


Figure A2-2: EMG AC Interference Test

Graphical results for a test of possible interference between welding current and myopotentials. Two experimental trials under identical conditions are shown with a third trial conducted under these conditions but with no welding current. There are no clear interference patterns evident in the spectral density function (Spectral density functions are averaged over each one-second intervals in the trial) The notch at 60 Hz is due to notch filtering of the EMG signal at this frequency Median frequencies of the averaged spectra are 127 Hz for trial 1, 126 Hz for trial 2, and 132 Hz for the no current trial These results were interpreted as evidence for negligible interference from the welding process.



APPENDIX 3: PRELIMINARY VENTILATION STUDY

The fresh air diffusion ventilation system (prototype vent tube) that was assessed during the overall study was developed to improve the efficiency of removing weld fumes from confined-space weld areas Current methods employed in the participant shipyard included the use of an air horn and an air ring to direct compressed air into the confined space to remove weld fumes by turbulent air flow **(See Illustrations A3-1a, 1b and Illustrations A3-2a, 2b)** Such methods may not be effective for particularly long and narrow confined- spaces, such the honeycombs modeled by this study This may be due to a number of factors First, the device may not be able to create a sufficient amount of turbulence far inside the space due to the fact that the velocity of an air device is approximately only 10% of its face velocity at a distance equal to 30 diameters away from the pressure jet opening Secondly, air movement in such a confined-space may be impeded by the welder's own body Finally, the air at the area of the weld arc is heated, creating a vertical rising plume of weld fumes with unknown velocity Since the welding is performed in a confined space (closed on five sides), the fume plume rises to the top restriction and the vertical movement of the plume is changed into a horizontal movement away from the center of the plume This horizontal movement at the top of the plume combined with the horizontal movement of air at the base of the plume sets up a recirculating air mass around the weld (Johnston, 1999) Thus, for these reasons, it was hypothesized that a more effective ventilation method would involve the introduction of a sufficient volume and velocity of air into the area in front of the welder (at the back of the confined space) to overcome the horizontal back flow from the weld plume and to remove the fume by a directional, diffused flow

Two alternative methods were then devised to accomplish these aims The first involved an air ring covered with a diffusing material and placed at the back of the confined space The second alternative method consisted of a vortex attached to a fresh air supply hose (05m * 5m) and a mesh diffuser **(See Illustrations A3-3a, 3b).** This device was also placed at the back inside of the confined space and directed a combination of compressed and outside fresh air through and out of the confined space

The standard and alternative ventilation methods were then evaluated for their efficacy in qualitatively removing a set volume of artificial smoke (as a weld fume substitute) from the 'breathing zone' of welder mannequin positioned within the confined-space mock-up To do so, factorial comparisons were arranged to evaluate the methods for various combinations of ventilation device positions (e g horn blowing in at 30 degrees from bottom), mannequin posture (e g kneeling versus lying), and mannequin position (e g front, middle, back of mock-up) Overall, the qualitative results of these trials indicated that the alternative methods were more effective than the standard methods in terms of 'mean time to breathing zone smoke clearance' **(See Figure A3-1a)** and the posture of the mannequin was also found to have a substantial effect on fume clearance **(See Figure A3-1b).** In addition, the following observations were made about each main method

Air Horn

The air horn when tested in an open environment produced an output of 34-40klpm (1200 to 1400 cfm), using 2 8 klpm (100cfm) compressed air at 6 atm (90 psi) When the air horn was used in the area in front of the welder, a highly turbulent area of re-circulation approximately 2 5 m long was established and the net effect was only 2 8 klpm (100 cfm) of air moving from the weld chamber open end (equal to the amount of compressed air used)

Air Ring

Results from the air ring were similar to that of the air horn

Air Ring With Diffuser

Results from using the air ring inside of a diffuser bag showed improved smoke removal from the weld area This is a result of eliminating turbulent re-circulation The net flow rate of fresh air was still 2 8 klpm (100 cfm) or equivalent to compressed air flow

Vortex air mover inside diffuser bag with fresh air tube

Results indicated that this method was the most effective for clearing smoke from in front of welder because it eliminated turbulence and the recycling of the weld fumes within the confined weld space even with a net flow rate of 3 1 klpm (110 cfm) Air velocities achieved (12 7 cm/s) are considered low Higher flow rates can be achieved by using diffuser materials with higher permeability rates, and higher static pressure in the supply lines However addition of the fresh air tube did not significantly increase the net air flow from the space open end This is possible due the restrictive nature of the diffuser bag Permeability of material used to make the diffuser bag is estimated to be in the range of 10 to 15 % open area Future use of diffuser bags should be limited to materials of known permeability Metallic Meshes and screens are commercially available with open area ranging from ten to 80 %

Thus, based on the results of this preliminary ventilation study, it was decided that the prototype vortex vent tube showed promise as an alternative ventilation device for confined-space welding The effectiveness of this alternative device was then compared in the overall study to the standard air horn, which was the most common ventilation method utilized for confined-space welding tasks at the participant shipyard

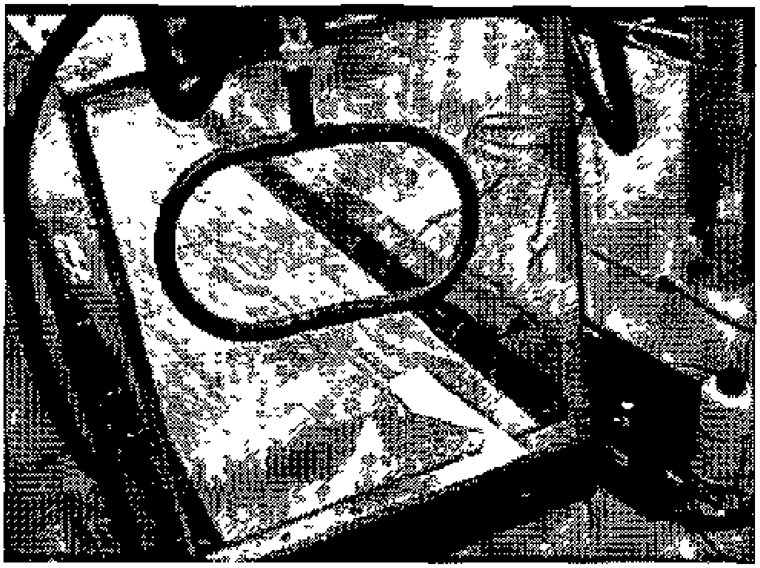


Illustration A3-1a. Air ring ventilation device (not assessed during overall study)

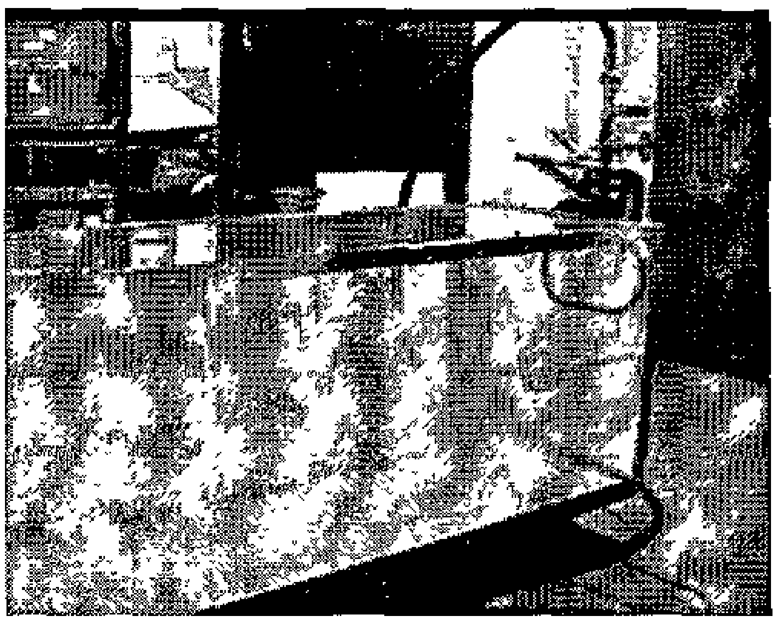


Illustration A3-1b. Air ring being tested during preliminary study

Illustration A3-2a Air horn ventilation device, eventually assessed during overall study

Illustration A3-2b Air horn being qualitatively tested during preliminary study

Illustration A3-3a: Prototype Alternative Ventilation Device

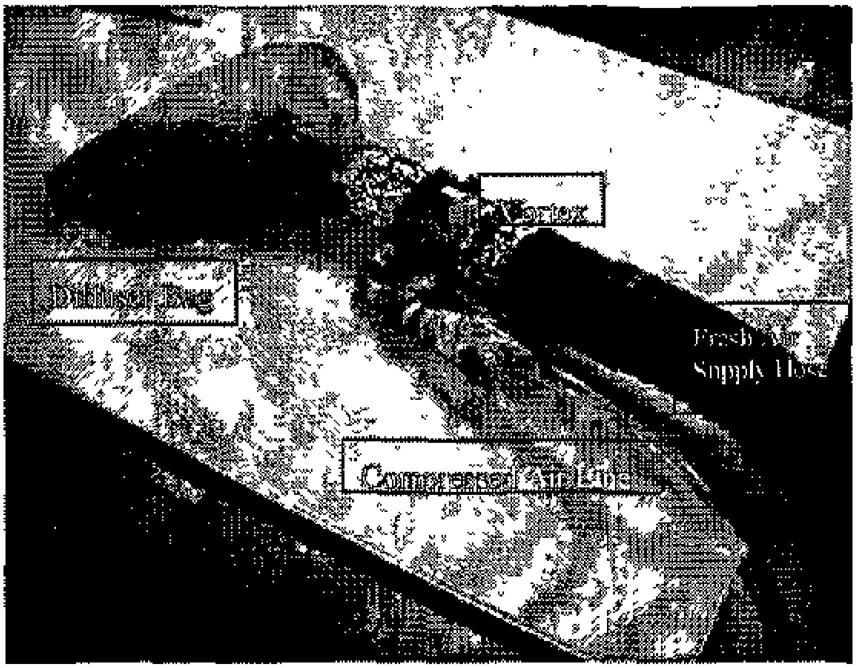


Illustration A3-3b: Placement of device within mock-up

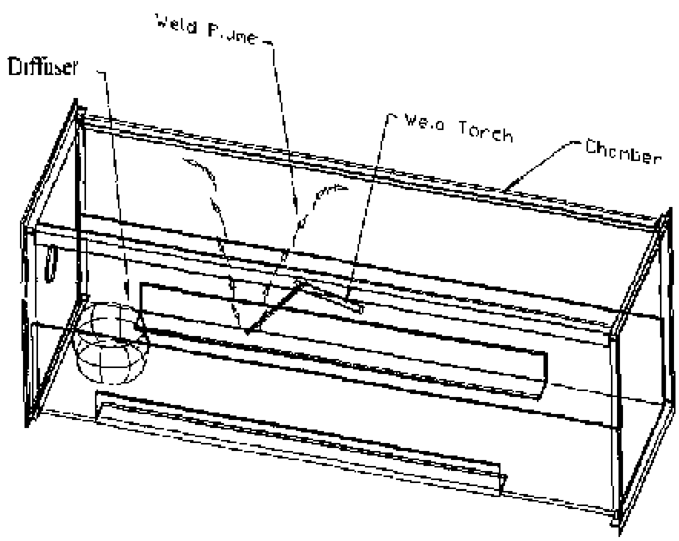


Figure A3-1a: Preliminary Ventilation Test Results; Effect of Vent Device, Vent Position

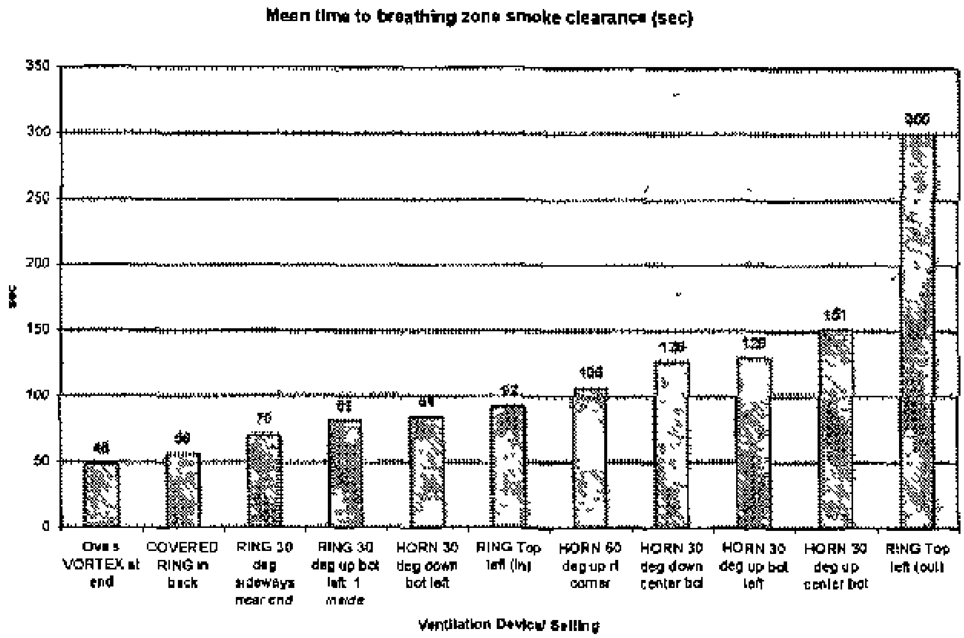
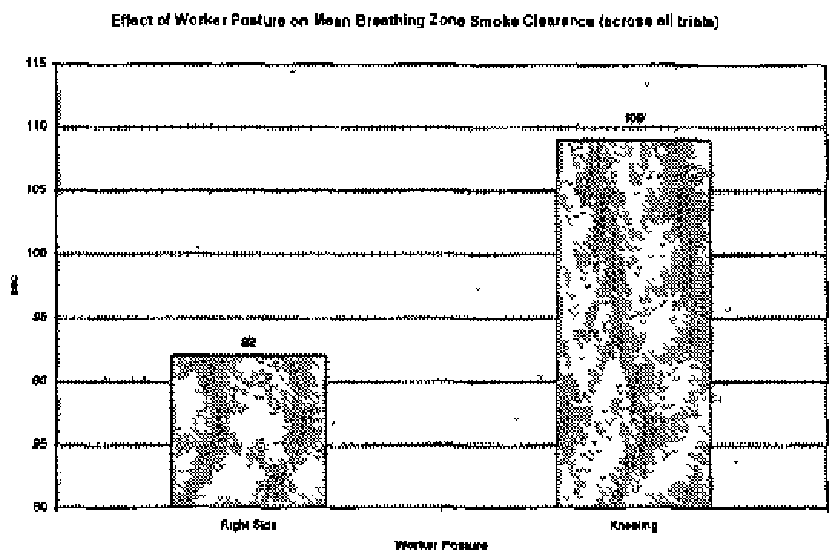


Figure A3-1b: Preliminary Test Results; Effect of Worker Posture



APPENDIX 4: CONFINED-SPACE WELDING TASK ANALYSIS

In order to understand the problems associated with confined space welding, the task itself must first be analyzed To this end, two main confined-space welding processes that are used in ship construction and general industry will first be described These include **stick** (otherwise known as SMAW- Shielded Metal Arc Welding) and **wire** (otherwise known as GMAW- Gas Metal Arc Welding or FCAW- Flux-Cored Arc Welding) Although both of these welding processes utilize an electric arc to join metals together at a temperature around 10,000 degrees F, each requires different techniques and equipment

Stick Welding

Stick welding is a manual process that involves the skilled use of a flux-covered metal electrode held at the welding surface with an electrode holder The generalized stick welding task in a confined space can be broken down into the following elements

1) Select the proper amperage for the stick based on the application on scrap pieces
2) Enter confined space
3) Position body (whole body and posture) and supplies (e g electrode holder and cables, sticks, chipper, wire brush, flashlight, cloth, and PPE—helmet, UV visor, gloves, half-mask respirator) for the weld
4) Attach the stick electrode to the holder
5) Wipe surface to be welded with cloth
6) Flip helmet visor up to sight the seam section to be welded (usually with a flashlight in dark or confined spaces)
7) Flip visor down and strike the electrode tip lightly on work surface to establish arc (BEGIN ARC TIME)
8) Hold the electrode over the weld surface and guide the weld deposition at the proper electrode angles, arc length, and travel speed to establish a quality weld (END ARC TIME)
9) Replace weld stick when consumed
10) De-slag the weld with a chipper, wire brush

The welder first selects the amperage for the stick to ensure that the electrode will melt properly This is done by performing test welds on scrap pieces and checking the weld quality Burn-through holes are visual cues that the amperage is too high, while little joint depth is a cue that the amperage is too low This step is performed usually only once for each new weld application and is not part of a welder's typical daily tasks

Thus, the task normally begins when the welder positions their body and their tools inside the confined space to reach the area to be welded This requires dynamic strength to pull the weld cables, which generally weigh a pound per foot and to carry a box of welding rods (10 to 50 lbs) into the space, while in a constrained posture The welder then positions their body to be able to effectively wield the electrode holder over the seam to be welded Typical postures employed depend on the extent of confinement as determined by the physical dimensions of the space and the anthropometry of the individual welder and often include lying on the stomach, lying on the side, or kneeling

Once in position, the welder then begins the actual stick welding task by striking the electrode tip lightly on the work surface Throughout the period in which the electric arc is established, known as "ARC TIME", the welder is required to support the weld stick and holder in a steady manner at specified electrode angles (work angle and travel angle) to the surface while in a prone position Once more, the load is also supported while simultaneously lowering the stick as it is consumed in order to maintain a constant arc length (distance from electrode tip to weld surface) This requires the "elevation of the shoulder combined with flexion and abduction of the shoulder joint up to a range of 100 degrees" (Kadeforas et al, 1976) and static contraction of several shoulder muscles, including the trapezius, deltoidus, supraspinatus, and the rhomboidus, and back muscles The weight of the holder/electrode and cable depends on the size of the stick In shipyard construction, the stick is usually 16 * 25 inches long (2 lbs) and the total assembly weighs approximately 10 lbs before the stick is consumed Thus, the static load supported by the welders is low to moderate in magnitude, however, it must be maintained with precision for extended periods over the course of an eight hour shift

The optimal electrode angles required for the task depend on the type of joint being made, e g t-weld, butt-weld For instance, for a t-joint the work angle (angle between the vertical piece and the electrode) should be 45 degrees while the travel angle (angle between the electrode and the normal to direction of travel) should be 15 degrees The proper arc length must also be maintained to ensure weld quality This is typically requires the welder to keep the electrode tip away from the weld surface a distance approximately equal to the diameter of the stick electrode, which can range from 1/8 to ½ inches All of these angles must be maintained in addition to guiding the weld electrode along a specified weld travel path and maintaining a proper travel speed while assuming the weight of the electrode assembly

Thus, upon analysis, stick welding is a physically demanding and complex task, requiring not only dynamic and static strength but also skilled hand-eye coordination Electrode angles and arc length are generally determined using the visual, auditory and haptic senses The most important visual cue for weld performance that the welder uses is the appearance of the weld shape itself A quality weld will appear uniform and slightly convex Wide welds are a visual cue to the welder that their travel speed may be too slow (the weld is piling up) and/or that the arc length is too long Thin welds, conversely, are an indication of possible fast travel and/or short arc length The differentiation between speed and arc length as the cause of the poor weld shape is largely determined by auditory cues, other visual clues, and certain haptic clues For instance, an arc length that is too long will produce a 'coarse, uneven cracking sound' while a short arc will produce a 'soft buzzing noise'(Connor, 1987) Once more, short arcs can be indicated when the electrode tip attaches to the weld surface or 'feels' drawn to the surface

Wire Welding

"Wire welding is a semi-automatic process in which a continuous wire electrode is automatically fed through a welding gun" (Connor, 1987) The generalized task of wire welding can be broken down into the following elements

1) Select the proper wire feed speed (amperage) and voltage for the application on scrap pieces
2) Enter confined space
3) Position body (whole body and posture) and supplies (e g weld gun and cables, chipper, wire brush, flashlight, cloth, and PPE- helmet, UV visor, gloves, half-mask respirator) for the weld
4) Wipe the surface to be welded with a cloth
5) Flip helmet visor up to sight the seam section to be welded (usually with a flashlight in dark or confined spaces)
6) Flip visor down and establish the arc by holding the gun near the workpiece and depressing the trigger (BEGIN ARC TIME)
7) Hold the gun over the weld surface and guide the weld deposition at the proper electrode angles, gun manipulations, electrode 'stick out', and travel speed to establish a quality weld (END ARC TIME)
8) *De-slag the weld with a chipper, wire brush (*not required with GMAW)

The first step in wire welding involves selecting the proper wire feed speed and voltage for the application on scrap pieces As in the case of stick welding, this requires that the weld quality of test seams be rated, and this step typically is not repeated in a welder's work day for the same weld job To actually begin the weld task, the welder must position themselves in the confined space in a manner similar to that described for stick welding However, with wire welding, the welder is generally less burdened than in the case of stick welding because the weld gun is lighter (2-6 lbs) and less awkward then the stick/ holder assembly Furthermore, once in position, the welder simply has sight the seam and to position the gun close to the weld surface and pull the trigger (no contact is required) to initiate the electric arc

After the arc has been established (ARC TIME), the welder is required to support the weld gun at specified electrode angles (work angle and travel angle) to the surface, in a manner similar to that described for stick welding Again, as with stick welding, all of these angles and gun manipulations must be maintained in wire welding in addition to guiding the wire electrode along a specified weld travel path and maintaining a proper travel speed However, unlike the case in stick welding, the welder does not have to continuously adjust the arc length because the wire is being automatically fed as it is consumed Rather, in wire welding the welder must check the amount of electrode stick-out and manipulate the weld gun to create certain patterns in the weld as it is being deposited

"Electrode stick-out is the length of un-melted wire coming out of the contact tip of the welding gun" (Connor, 1987) and it effects the amperage drawn by the wire as well as the weld quality Stick-out is a direct result of the wire feed speed and is not frequently adjusted during the actual weld task, but can be fine tuned if needed Special gun manipulations dependent on the type of joint welded are also required in wire welding to produce quality weld joints For instance, in the case of t-joints, the wire tip should be moved in a series of ovals as the weld seam is deposited while in the case of butt-joints the wire tip should be moved in a 'zig-zag' pattern Thus, on one hand, wire welding may seem to require less static loading than stick welding due to the reduced weight of the gun and because of the need to produce these slight movements However, on the other hand, wire welding may require more static loading because it is more continuous than stick welding This is due to the fact that it does not have the 'built in breaks' that the change of weld stick affords welders engaged in stick welding

Thus, although wire welding does not require the degree of skill that stick welding does, wire welding is still a physically demanding and complex task in its own right However, as in the case of stick welding, there are a number of visual, auditory, and haptic cues for weld performance that are available to the welder For instance, a fast travel speed will produce a thin bead and will be accompanied by "popping sounds as the wire comes into contact with the cold metal just ahead of the weld puddle" In addition, auditory cues can also indicate the need to alter 'stick-out' as a good wire speed should sound like 'bacon frying'

APPENDIX 5: ADDITIONAL AIR SAMPLING ANALYSIS INFORMATION

DATA CHEM LABORATORIES INC
A SORENSON COMPANY

May 10, 1999

RE Seq 9181-CB
Gravimetric

ANALYTICAL REPORT

SUBMITTED TO	Steve Wurzelbacker
SUBMITTED BY	Robert L Quigley
REFERENCE DATA	
Analysis of	Total Weight
Project I D No	ECTB-99-8490
Sample Type	PVC Filter
Samples 71	Analyses 71
DataChem Laboratory Nos	99N04144 through 99N04214

The above numbered samples were analyzed for total weight by gravimetric analysis following the NMAM-Method 0500 (4th ED) with the following modifications 1) The filters and backup pads are stored in an environmentally controlled room (21± 3 C and 50 ± 5% R H) and are subjected to the room conditions for at least two hours for stabilization prior to tare and gross weighing and 2) Two weighings of the tare weight and the gross weight are performed The averages of the weighings are used for the total weight analysis

The total weight of each sample was determined by weighing the sample plus the filter on an electrobalance and subtracting the previously determined tare weight of the filter Sample values less than LOD are reported as not detected (ND) Total weight values less than the LOD will be included in the report in the sample comments section and are for informational purposes only

The reported values have not been field blank corrected

The instrumental precision of the microbalance is 0 001 mg The method allowable difference between two weighings of a filter is 0 01 mg Due to variable factors such as overloading, hygroscopicity of sample, and the physical integrity of the filter itself, the actual precision can be considerably poorer and occasional slight net negative weights may be expected Studies on the physical integrity of various PVC filters have shown that the weight of the filter may vary by 0 02 mg Because of this factor, the LOD for this report is 0 02 mg

All of the samples in this set except 99N04148, 99N04149, 99N04161, 99N04165, 99N04166, 99N04179, 99N04189, and 99N04202 had sample weight values that exceeded the method recommended maximum sample weight of 2mg

Results are tabulated on the following page(s)

Jeffery S. Ward for RLQ
Robert L Quigley
Analyst

Jeffery S. Ward
Jeffery S Ward

CINCINNATI LABORATORY
4388 Glendale Milford Road
Cincinnati Ohio 45242 3706
513-733-5336 FAX 513-733-5347

NOVATO OFFICE
11 Santa Yorma Court
Novato California 94945
415 897 9471 FAX 415-893 9469

CORPORATE OFFICE
SALT LAKE CITY LABORATORY
960 West LeVoy Drive
Salt Lake City Utah 84123-2547
801 266-7700 FAX 801 268-9992

BALTIMORE OFFICE
10 Juliet Lane #203
Baltimore Maryland 21236-1220
410-529 3675 FAX 410 529 5354

RICHLAND OFFICE
913 Wellsian Way
Richland Washington 99352-4116
509 943 5856 FAX 509 943 5654

DATA CHEM LABORATORIES INC

A SORENSON COMPANY

May 10, 1999

RE: Seq. 9181-CA
ICP

ANALYTICAL REPORT

SUBMITTED TO: Steve Wurzelbacker

SUBMITTED BY: Michelle Paradise

REFERENCE DATA:

Analysis of:	Metals
Project I.D. No.:	ECTB-99-8490
Sample Type:	Filter
Sample(s): 9	Analyses 243
DataChem Laboratory No.:	99N04135 through 99N04143

The above samples were prepared and analyzed according to NIOSH Method 7300 (NMAM fourth edition, 8/15/94) modified for microwave digestion. Samples were microwave digested with 10 ml of 1 1(v/v) nitric acid. After digestion, samples were diluted to 25 ml with ASTM Type II water.

The samples were analyzed using a Thermo Jarrell Ash ICAP 61-E inductively coupled plasma emission spectrometer controlled by ThermoSpec software. The instrument and operating conditions were as follows.

RF Generator:	2.5 KVA Crystal controlled, operating at 27.12 MHz with automatic power control and automatic tuning.
Nebulizer:	Cross-flow pneumatic, sample supplied by a peristaltic pump.
Torch:	Quartz.
Spectrometer:	0.75 meter polychromator with 39 channels.
Optics:	0.75 meter Rowland Circle, Pashen-Runge mount, 1510 or 2400 grooves/mm ruled grating at 500 nm
Argon Plasma Gas Flow Rate:	High flow.
Plasma Observation Height:	13 mm above load coil.
Nebulizer Gas Flow Rate	0.65 L/minute, mass controlled

CORPORATE OFFICE

CINCINNATI LABORATORY
4388 Glendale-Milford Road
Cincinnati Ohio 45242-3706
513-733-5336 FAX 513-733-5347

NOVATO OFFICE
11 Santa Yorma Court
Novato California 94945
415 897-9471 FAX 415-893-9469

SALT LAKE CITY LABORATORY
960 West LeVoy Drive
Salt Lake City Utah 84123-2547
801 266-7700 FAX 801 268-9992

BALTIMORE OFFICE
10 Juliet Lane #203
Baltimore Maryland 21236-1220
410-529-5675 FAX 410-529-5355

RICHLAND OFFICE
313 Wellsian Way
Richland Washington 99352-4116
509 943-5858 FAX 509 943-5654

Radio Frequency Power:	1150 watts.
Number of Exposures:	3 exposures.
Integration Time:	5 seconds.

The results have not been field blank corrected.

The limits of detection and limits of quantitation are as follows:

ANALYTE	LOD ug/filter	LOQ ug/filter
Aluminum	1.	4.
Arsenic	3.	8.
Beryllium	0.01	0.04
Calcium	3.	8.
Cadmium	0.08	0.3
Cobalt	0.2	0.8
Chromium	0.5	2.
Copper	0.08	0.3
Iron	0.8	3.
Lithium	0.03	0.08
Magnesium	0.5	2.
Manganese	0.01	0.04
Molybdenum	0.3	1.
Nickel	0.6	2.
Lead	0.5	2.
Phosphorous	2.	4.
Platinum	3.	8.
Selenium	2.	4.
Silver	0.08	0.3
Sodium	2.	7.
Tellurium	0.8	3.
Thallium	3.	8.
Titanium	0.2	0.4
Vanadium	0.08	0.3
Yttrium	0.02	0.04
Zinc	0.5	2.
Zirconium	0.08	0.3

Results between the LOD and LOQ are semi-quantitative.

Samples 99N04135 and 99N04139 were diluted due to high concentrations of Fe, Mn, & Zn. Samples 99N04136 and 99N04142 were diluted due to high concentrations of Fe, Li, Mn, & Zn and interferences with Ag, V, & Y. Sample 99N04140 was diluted due to high concentrations of Fe, Li, Mn, & Zn and interferences with Ag & V. Sample 99N04141 was diluted due to high concentrations of Fe, Mn, Na, & Zn and interferences with Te. These samples were diluted and reported as follows:

99N04135 - 10x(Fe & Mn), 20x(Zn).
99N04136 - 10x(Fe, Li, Mn, Ag, V, & Y), 20x(Zn).
99N04139 - 10x(Fe & Mn), 20x(Zn).
99N04140 - 10x(Fe, Li, Mn, Ag, & V), 20x(Zn).
99N04141 - 10x(Mn, Na, & Te), 50x(Fe & Zn).
99N04142 - 10x(Fe, Li, Mn, Ag, & Y), 20x(V), 50x(Zn).

The LODs and LOQs have been multiplied accordingly on the analytical report. The LODs and LOQs have been raised for Co, Mo, and Ni due to instrument instability for these analytes.

The results are tabulated on the following page(s).

Michelle Paradise

Jeffery S Ward
Section Manager
Inorganic Chemistry
Spectroscopy Section