An Investigation of Potential Health Hazards of Arc Welding Fume Growth with Time

An appreciable portion of welding fume is found to be in the 1 to 7 μm size which is judged to be hazardous to health

BY D. E. CLAPP AND R. J. OWEN

Introduction

The health hazard posed by any airborne particulate is largely determined by the amount of material present in a given volume of air (concentration) and the degree to which the amount is divided (number of particles). Other factors relating to particle deposition and potential injury include the size and shape of the particle, its chemical properties and charge, as well as the physiology and anatomy of the human lung.[1,2] Particle size is perhaps the most important factor, since particles are deposited in the various regions of the human respiratory tract as a function of size as illustrated in Fig. 1.[3] Generally speaking, particles ranging in size from 1 to 7 microns represent the most serious hazard due to retention in the alveolar* region.[4]

The alveolar region is especially sensitive to invasion by inhaled particulates primarily due to the vast surface area in this region. Some experts speculate that, if spread out, the alveolar sacs would cover approximately 70 square meters of surface area.[4] While this region has certain defenses in the form of phagocytes and the cleansing action of its mucous lining, particles are most likely to be retained in this region rather than the upper reaches of the respiratory tract which benefit from a ciliated lining.† Particles retained in the alveolar region, for example, readily enter the lymphatic blood circulatory system through this one-cell thick membrane with potentially serious effects upon the body.[5]

Alveolar—pertaining to alveoli which are air cells of the lungs.

Welding Fume Agglomeration

Welding fume represents an especially hazardous form of airborne particulate due to a propensity for the fume to agglomerate over time. While fume particles are extremely small at time of generation, the agglomeration (growth through particle collision) process can produce a potentially hazardous concentration in a relatively short period after welding has ceased. Fuchs[6] reports that this agglomeration is largely due to thermal effects although hydrodynamic, electrical, and gravitational forces also play a role in the process. Thermal agglomeration is enhanced by the turbulent conditions resulting from heat generated in the welding process. Not only are the fumes themselves hot, but the air in which they are suspended is also hot, thus increasing particle movement and chances for particle collision.

This research was undertaken to investigate the relationship of welding fume size as a function of agglomeration time. Several theoretical studies have been conducted to explain the behavior of particulate agglomeration.[6,7] These studies revealed that particles are believed to agglomerate linearly, but no data regarding the size of the agglomerates have apparently been developed. By sampling fume-contaminated air over a variety of agglomeration times, the fume particle growth can be determined. Since particle deposition in various regions of the lungs is based mainly on size, and the various size-region deposition relationships are known, one may be able to predict the relative hazard of welding fume as a function of time after generation.

The insult to the human body caused by inhalation and deposition of fume particulates will, of course, be largely determined by the metals involved in the welding process. Metal fume fever is a well known condition resulting from inhalation of welding fume and a wide variety of metals appear to cause pulmonary irritation and toxic effects. A study by the American Welding Society[1] and Browning[8] list cadmium, chromium, lead, titanium, magnesium, manganese, mercury, molybdenum, nickel, vanadium, zinc, and fluorides as especially hazardous. A knowledge of welding fume agglomeration behavior over time, coupled with a knowledge of the metals involved in the welding process, should provide a more informed basis for control of exposures to this health hazard.

†*Ciliated—from cilium, "a hairlike process found in many cells that . . . serves . . . as a producer of a current of fluid (as in human nares, trachea and bronchi where ciliated cells . . . assist in the removal of mucus and dust particles)."* (Webster's Third New International Dictionary)

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Sampling Equipment Design

To capture all of the particulates generated in a simulated laboratory

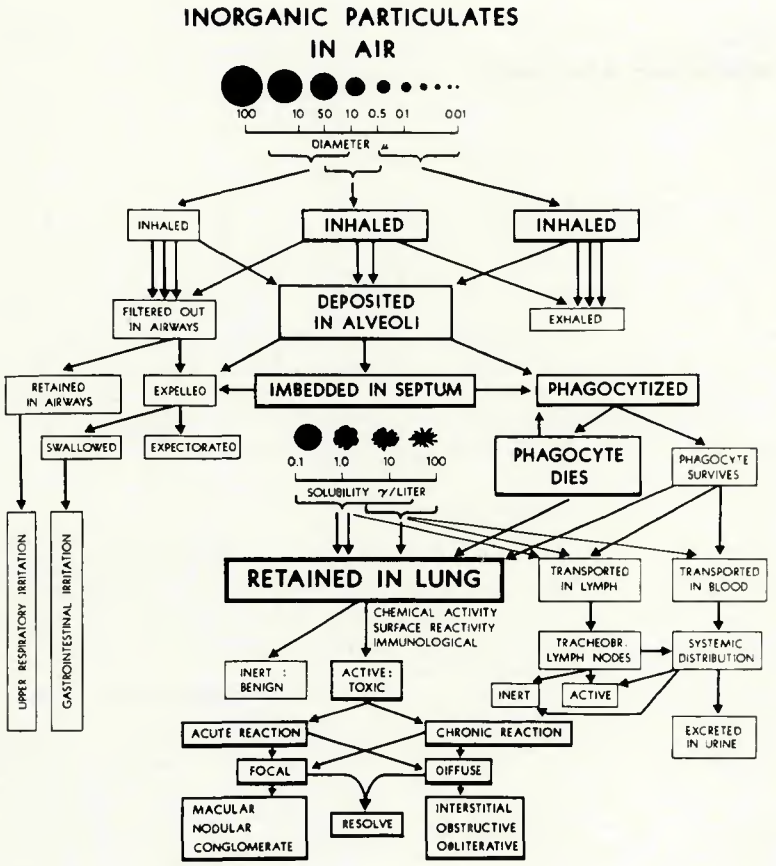

Fig. 1—Particle fate in lung[3]

welding operation, a specialized enclosure was designed and built. For simplicity and ease of construction, a one cubic meter (volume) enclosure was assembled from ½ in. (12.7 mm), A-D grade plywood as shown in Fig. 2.

A collapsible bladder made of 2.5 ml aluminized polyethylene was also constructed to fit within the box to provide a means to conveniently capture and exhaust generated welding fume. A 20 in. (0.51 m) square viewing port was cut into the box with the bladder cut and folded back for a seal at the opening. This opening was covered with a 24 in. (0.61 m) square sheet of ½ in. (12.7 mm) thick plexiglass fitted to overlap the port equally on all edges. The transparent sheet was sealed to the box with rubberized silicone caulking and tightly screwed into place.

As shown in Fig. 2, two holes, approximately 4 in. (102 mm) in diameter, were cut into the viewing port to allow airtight installation of a pair of protective rubber gloves (approximately 12 in. or 0.3 m long). Further, an access opening 8 in. (0.2 m) square, was cut into the upper left quadrant of the viewing port for replacing welding materials in the chamber. A 10 in. (0.25 m) square plexiglass cover plate, with a cork gasket, was used to provide an airtight seal when the plate was secured with wing nuts.

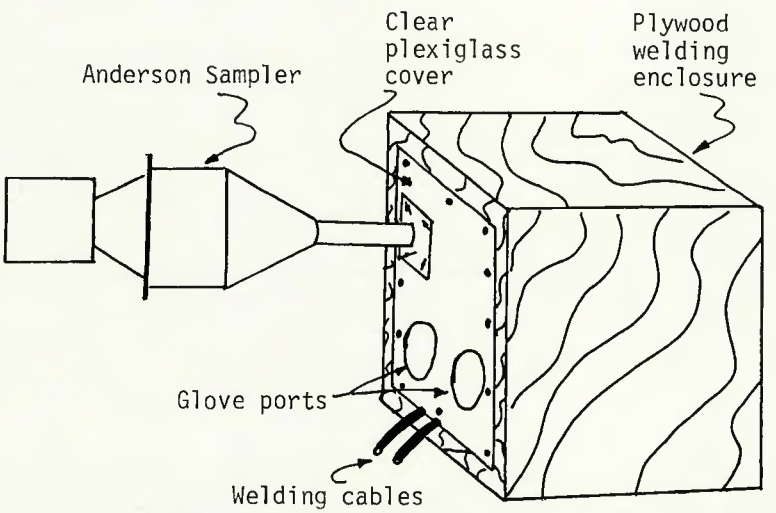

Fig. 2—Sketch of welding enclosure used in investigation

To provide a connection to the sampling equipment, a 2½ in. (63.5 mm) diameter copper pipe, 12 in. (0.3 m) long, was sealed to the cover plate with plasticized putty. This pipe was sized to fit directly into a cone-shaped adapter made from 24 gauge sheet metal which expanded over a length of 18 in. (0.46 m) from the copper pipe to a 12.5 in. (0.32 m) diameter end which fit directly onto the sampler.

An Anderson 2000 Sampler, Model 65-000, was used to size the particulates exhausted from the sampling chamber. The particle size cut-off for the four stages of this sampler were 5.5, 2.5, 1.75, and 0.93 μm respectively.[9] A final filter was positioned between the base plate of the sampler and the vacuum source. The filters used in the sampler were of glass fiber material, manufactured by Mead Technical Paper Company, Models 935BJH and 935 BHZ. These non-hydroscopic, binderless glass filters, 14 mm (0.55 in.) thick, were selected to minimize the effects of moisture.

The volume of air flow through the Anderson sampler was controlled from static pressure measurements. According to the manufacturer's instructions, 5.2 in. (132 mm) of water (static pressure) corresponds to the 20 cfm (0.6 m^3/min) flow rate required to maintain the sample size separation described earlier. A Dwyer Instrument Magnehelic vacuum gauge was attached to the sampler by approximately 3 ft (0.9 m) of plastic tube to provide static pressure measurements for flow rate control. The sampler was operated from vacuum provided by a General Metal Works Model 2000, 115 V motor. A Superior Electric Company Powerstat voltage regulator was used to adjust the motor speed and regulate the static pressure required to properly operate the sampler.

All data gathered in this research were gravimetric, and a Mettler H51 AR five-place decimal balance was used to pre-weigh and post-weigh each filter. The weight difference was used in computing the percent of particles passing each stage of the sampler. Before each run, the balance was leveled, secured and zeroed according to the manufacturer's specifications.

To limit the scope of this research, only one type of electrode and base metal were chosen for experimentation. A 5/32 in. (4 mm) diameter E7018

electrode was selected since it is one of the most commonly used electrodes in industry. This electrode is characterized by a smooth, quiet arc, very low spattering and low penetration.[10] The maximum percent composition of metal in this type of electrode is: manganese—1.25%, silicon—0.90%, nickel—0.30%, chromium—0.20%, molybdenum—0.30%, and vanadium—0.80%.

A typical electrode of this type weighs approximately 50 grams. Because E7018 is a low hydrogen electrode, it absorbs moisture quickly. To drive off possible moisture, the electrodes used in this research were placed in a 170 C (338 F) oven for a minimum of 8 hours prior to use. The base metal selected for the experimentation was A131 steel, which is one of the most commonly used low-carbon steels in industry with 0.23% carbon, and 0.90–1.60% manganese.[11]

A Lincoln Electric Company welding machine was used for welding process. This machine, similar to the type found in many industries, was an Idealarc Model 250. For all welding operations, the machine was set at 155 A using DCRP.

Experimental Test Procedures

The goal of this research, as stated earlier, was to investigate the agglomeration of a specific type of welding fume over time. For convenience, a welding time of 30 seconds (s) was chosen. Based upon preliminary testing, this period of welding appeared to generate sufficient fume for sampling purposes. Following a given 30 s welding period, the resulting fume was allowed to agglomerate undisturbed over successively longer periods up to a maximum agglomeration period of four minutes. After allowing the fume to agglomerate in the chamber for the specified period, the Anderson sampler was operated for 60 s to capture a sample of the fume in the chamber for size analysis.

In devising the experimental procedures, six separate tests were conceived as illustrated in Fig. 3. Each test was replicated three times to yield an average value. The same electrode was used for each run of the separate tests so that the chemical composition of the fume for any one test would be identical.

Between each run of each test, the bladder was evacuated by a shop vacuum cleaner twice and refilled with room air. Turn around time between each run was approximately 30 minutes (min) including time required to pre-weigh and post-weigh each filter. During the weighing process, after evacuation, the chamber was allowed to remain quiescent until the next run.

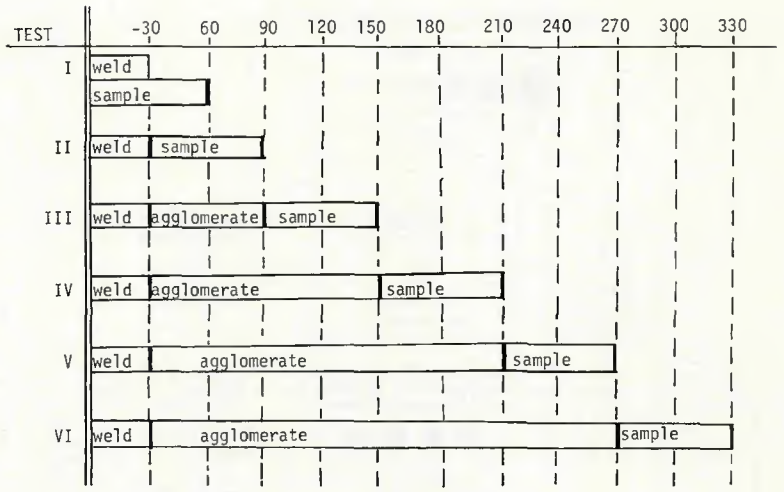

Fig. 3—Experimental test procedure

As shown in Fig. 3, agglomeration periods in intervals of 1 min were established from 30 s during welding to 4 min after welding ceased. The 4 min maximum period was considered adequate to demonstrate the agglomeration phenomenon and was chosen to help limit this research. In sampling for 60 s, at 20 cfm (0.6 m^3/min), approximately 58% of the suspended aerosol was captured. This volume was deemed to be a representative sample of fume present in the chamber.

The formulation of these proposed test procedures led to a number of questions regarding the expected influence of certain parameters on the experimental results. These questions dealt with four specific areas as follows:

1. The influence of shorter or longer welding periods in lieu of the 30 s chosen for this research.
2. The effects of agglomeration periods far longer than the four minute maximum allowed for the experimental runs.
3. The relative amount of welding materials which was actually vaporized into fume vs. losses due to spattering and adherence to the walls of the sampling chamber.
4. The efficiency of two chamber evacuations to remove remaining aerosol in the chamber after an experimental run to prevent possible interferences with subsequent tests.

As a result of these questions, a set of four "verification" tests was devised. Further detail on the procedures employed in conducting these tests, along with the resulting data, is given in the following section.

Results of Verification Tests

During all testing, the room temperature (regulated by the building air conditioning system) remained at a constant 75 F (23.9 C). The barometric pressure during the test sessions ranged from 29.60 to 29.91 in. (751.8 to 759.7 mm) of mercury. Each of the questions posed earlier was addressed in a test and, for convenience, these tests have been labelled alphabetically.

Test A—Influence of Welding Time on Particle Size Distribution

The theory of aerosol behavior suggests that the amount of aerosol present will affect the agglomeration of the particles due to the presence of more material for collision.[7] There is no theory, however, regarding the particle size distribution resulting from welding periods of varied times. Here, then, selected welding periods will be evaluated relative to their influence on fume size distribution.

Since variations in welding times alone were of interest, an attempt was made to maintain the aerosol generated as a constant on all runs. For convenience, 0.2 g of aerosol was chosen as the weight to be maintained while varying welding times. Thus, in the results shown in Table 1, the

Table 1—Results of Varying Welding Time on Fume Size Distribution

Stage	Size, μm	Weld 10 s, sample 60 s[a]	Weld 30 s, sample 30 s[a]	Weld 60 s, sample 10 s[a]
1	5.5	97.80	97.49	97.19
2	2.5	94.35	93.89	93.13
3	1.75	89.04	87.98	85.68
4	0.93	74.76	69.52	66.63

[a] Percent passing.

Table 2—Results of Extended Agglomeration Time on Fume Size Distribution

Stage	Size, μm	Agglomeration period 1 min[a]	5 min[a]	20 min[a]
1	5.5	97.19	97.05	97.40
2	2.5	94.39	92.44	91.60
3	1.75	88.53	84.55	80.98
4	0.93	71.48	62.52	54.89

[a]Percent passing.

Table 3—Results of Investigation of Amount of Welding Materials Vaporized as Fume

Agglomeration period	Weight loss in welding materials, grams	Amount of aerosol captured, grams	Percent of aerosol captured
1	2.84	0.21068	7.41
5	2.41	0.21567	8.94
10	2.07	0.14017	6.77
20	2.03	0.15410	7.59

chamber was sampled for 60 s for the welding time of 10 s to accumulate approximately 0.2 g of particulate. When welding was extended to 60 s, sampling was reduced to 10 s. The 30 s welding operation was followed by 30 s of sampling corresponding to the proposed experimental procedure.

The data in Table 1 are a conversion of the raw gravimetric data to a more convenient format typical of aerosol studies. The values shown are the percent passing each sampler stage. As an example, the raw data for column 1 in Table 1 were 2.64, 4.13, 6.37, 17.11, and 89.58 mg for each of the four sizing stages and the final filter, respectively. These individual weights were summed to cumulative totals for each stage as 2.64, 6.77, 13.44, 30.25, and 119.83 mg; then converted to percentage values yielding 2.20, 5.65, 10.96, 25.24, and 100%. Finally, these percentage values were each substracted from 100% to obtain the percent passing each stage as displayed in Table 1. Similar calculations were performed for all tabulated percent passing data displayed throughout this paper.

In considering the effects of varied welding periods, it is apparent that the longer (60 s) welding time produced a greater accumulation of particulate on stages 3 and 4, indicating an expected growth in fume particulate sizes. This growth is probably due to increased thermal activity from extended welding as well as increased elapsed time before sampling. These results, however, did not vary from expectations significantly to suggest a variation in the 30 s welding period proposed for the experimental runs.

Test B—Effects of Extended Agglomeration Times on Particle Size Distribution

Based on preliminary testing and information developed from the literature review concerning particle agglomeration, it was expected that the effect on particle size distribution due to longer agglomeration times would vary substantially. In this test, the welding time was held constant at 30 s and a size distribution was obtained after 1, 5 and 20 min of agglomeration using a 30 s sampling period.

By examining Table 2, the variation in fume agglomeration over extended time may be readily seen. The data are an average of two runs of the test at each time period; they show a pronounced increase in the quantity of particles above 0.93 μm (fewer particles passing this stage). Similarly, growth is evident at stages 2 and 3. Thus, the fume is agglomerating rapidly with most growth in the smallest sizes.

These results agree with expectations and underscore the increased health hazard posed by aged fume, since the agglomeration process continues for a considerable time after welding has ceased and larger fractions of the fume grow to sizes retained in the lung. In the experimental tests discussed later, a maximum agglomeration period of 4 min was maintained to standardize the tests within a reasonable span of time for experimentation.

Test C—Amount of Aerosol Vaporized Into Fume

In structuring the experimental procedures for this research, it was of interest to determine the amount of welding materials actually vaporized into fume and captured by the sampler during a given welding and sampling period. Furthermore, it was of interest to investigate this parameter over various agglomeration times. For these purposes, a series of runs were conducted by first welding for 30 s and sampling for 30 s following agglomeration times of 1, 5, 10, and 20 min. In these tests, only the final filter was used since total sample weight (not size distribution) was desired. The results of these tests are summarized in Table 3.

From Table 3, it may be seen that approximately 7.67% of aerosol was captured, on the average, over agglomeration periods of 1, 5, 10, and 20 min, respectively. These values, of course, are influenced by the selection of a 30 s sampling time which was chosen as a reasonable period considering other aspects of the validation test.

It was of interest that the relative percentage of aerosol captured remained relatively constant over the varied lengths of agglomeration time. Although a 30 s sampling time appeared adequate for this research, a 60 s sampling time was adopted for the actual experimental runs to ensure an even larger sample of the fume concentrations generated.

Test D—Efficiency of Two Evacuations Following an Experimental Run

This test was devised to evaluate the amount of aerosol remaining in the chamber after a typical run as well as the adequacy of two complete evacuations in removing remaining aerosol at the end of a test run. This test began with a 30 s welding period, 1 min of agglomeration, and a 30 s sampling period.

The chamber clearing was started as soon as the sampler was removed. In this process, the bladder was emptied as much as possible, refilled with room air, then re-evacuated and again refilled. Following evacuation, the bladder was allowed to remain undisturbed for 30 min, which corresponds to the total elapsed time for turn

Table 4—Results of Testing Chamber Evacuation Method

Run	Weight loss in welding materials, grams	Amount of aerosol captured, grams 1 min	30 min
1	2.84	0.21068	0.00080
2	2.11	0.14838	0.00075
3	2.17	0.15661	0.00063

Table 5—Results of Experimental Tests

Stage	Size, μm	Agglomeration time: 0 s, test 1[a]	0 s, test 2[a]	60 s, test 3[a]	120 s, test 4[a]	180 s, test 5[a]	240 s, test 6[a]
1	5.50	96.21	97.85	97.08	97.91	97.55	97.51
2	2.50	92.96	95.41	94.94	95.27	93.72	93.83
3	1.75	86.17	92.27	91.82	91.97	87.85	87.74
4	0.93	70.79	84.98	83.78	84.68	72.28	70.90

[a] Percent passing.

around between experimental runs. After the 30 min waiting period, the chamber was again sampled for 30 s using only the final filter in the sampler.

Three runs of this test were conducted with the results shown in Table 4. Clearly, two chamber evacuations were very satisfactory in eliminating the possibility of interferences between subsequent runs.

Results of Experimental Tests

As discussed earlier, the experimental runs were devoted to studying the behavior of welding fume growth as a function of time. For these tests, the welding time and sampling time were held constant at 30 and 60 s, respectively. The verification tests were intended to study certain variations in these parameters, as discussed in the previous section.

The six tests presented here represent an attempt to study fume growth by increasing increments of agglomeration time followed by an analysis of the fume particle size distribution. The first two tests were intended to allow essentially no agglomeration, with sampling in test 1 started simultaneously with the start of welding. In test 2, sampling was started immediately after the termination of welding. In the remaining four tests, agglomeration was allowed to increase in increments of 60 s beginning with a 60 s agglomeration period in test 3. The layout of the scheme of the six tests was shown earlier in Fig. 3.

Each of the six tests was replicated three times. The weights of fume were determined for each sampler stage and converted into the percent passing each stage (as described earlier in the discussion of verification tests). The results of these tests are shown in Table 5.

It is clear from examining the data in Table 5 that the fume is growing appreciably as increased time for agglomeration is permitted. This growth, however, appears to occur as a step increase which may be observed between tests 4 and 5 (120 to 180 s after welding). In test 4, 84.86% passes stage 4 while in test 5 only 72.28% passes this stage. This growth is further seen at stage 4 in test 6 with only 70.90% passing, indicating that 29.10% of the fume is larger than .93 μm, and thus a larger fraction of the fume represents a hazard to the unprotected welder.

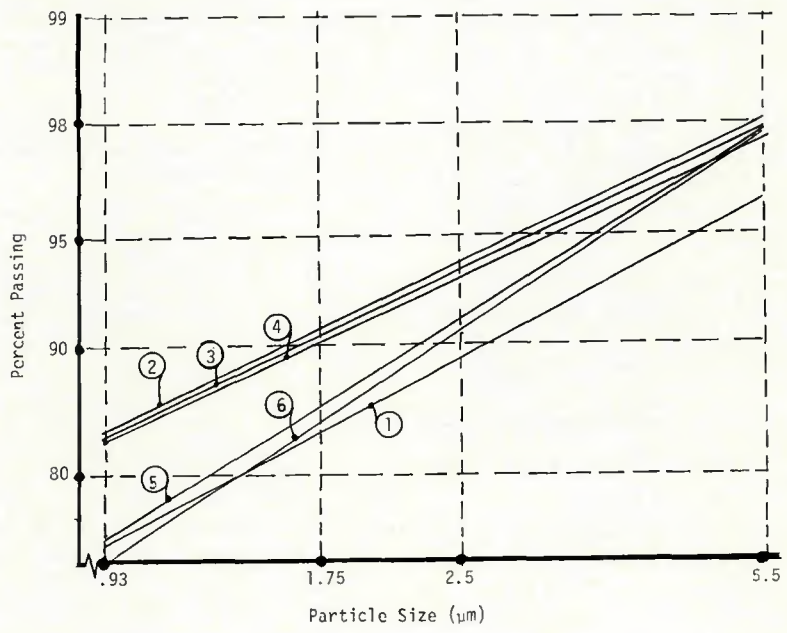

Fig. 4—Comparison of experimental tests

These results are further evidenced if the data from Table 5 are plotted as shown in Fig. 4. In that log-probability plot, a distinction is clearly apparent at the 0.93 μm level between tests 5 and 6 and tests 2, 3, and 4. Test 1 is anomalous in that results for that test do not follow this pattern due probably to artificially induced agglomeration caused by heat and flow in the sampling train. It will be recalled that in test 1, sampling was started during welding when the fume was considerably hotter and more turbulent while the sampler was operated.

Another aspect of interest is the apparent lack of change at the 5.5 μm level among all tests (again with the exception of test 1). This result suggests that very little growth occurs in fume particles larger than 5.5 μm. Approximately 3% of the fume remains above this size throughout the series of tests 2 through 6. This result agrees with particle agglomeration theory which suggests that larger particles are most affected by gravity and settle more rapidly while sub-micron size particles generally remain suspended and collide with similar particles constituting the agglomeration process.[7]

The results summarized in Table 5 and Fig. 4 give little information on growth in the sub-micron range (below 0.93 μm). Growth is assumed in this range, at possibly the greatest rate, but particle sizes greater than 1 micron were of particular interest in this research. Again, particles in the range of 1-7 microns appear to pose the greatest threat to the human respiratory system. In these results, it is clear that sub-micron particles rapidly grow into the hazardous range while the distribution of these particles does not change appreciably above 5.5 μm.

Conclusion

The research described in this paper was undertaken to investigate the health hazard of fume agglomeration in the arc welding process. It is well known by health professionals that local ventilation and personal protection equipment are essential to protect the welder's respiratory system. The results of this investigation readily show that an appreciable fraction of welding fume is in the hazardous size range of 1-7 μm. Furthermore, within a relatively short time interval after welding, the fume particles below 1 μm begin to grow into this size range.

The data gathered in this research suggest that approximately 2 min after welding ceases (agglomeration period of test 4), the fume begins to experience a significant growth in the smaller ranges. Thus, the welder is

exposed to a health hazard during and immediately after welding, but this hazard becomes more pronounced as the fume ages. Verification test B, discussed earlier, supports the assumption that this growth process continues well beyond the 4 min of agglomeration allowed in these tests.

These results should be considered in light of the limited scope of this investigation. Here, only one type of base metal and electrode was used and the welding period was limited to 30 seconds, although longer periods were investigated in the verification tests. All of the tests conducted in this research were influenced by difficulties in attempting to weld for precisely 30 s. Similarly, some difficulty was encountered in precisely controlling the equipment in the sampling train on each of the separate runs of each test.

Despite the limitations and possible inaccuracies of this research, the vital need to protect the welder's respiratory system is clearly demonstrated. No person who welds, even with relatively harmless materials, should allow himself to inhale the fumes resulting from that process both during welding and following the process. This need may not seem apparent to the welder, since a large fraction of the fume may be invisible; furthermore, welding is frequently done in widespread, temporary locations. Despite these facts, the health hazards of these fumes are significant and more pronounced when more hazardous (e.g., chromium) fumes are generated. Welders, and management responsible for welding personnel, have an important responsibility to control welding fume and avoid inadvertent threats to health.

References

1. *The Welding Environment,* American Welding Society, Miami (1973).
2. Casarett, L. J., and Doull, J., *Toxicology—The Basic Science of Poisons,* MacMillan, New York (1975).
3. Howe, H. F., "The Pneumoconicses, Diagnosis, Evaluation, and Management," *Arch. of Envir. Health,* 7:130 (1963).
4. *The Industrial Environment—Its Evaluation and Control,* National Institute of Occupational Safety and Health, Cincinnati (1973), p. 139.
5. Guyton, T., *Textbook of Medical Physiology,* 2nd Ed., Wiley & Son, New York (1968), p. 474.
6. Fuchs, N. A., *The Mechanics of Aerosols,* MacMillan, New York (1964), p. 187.
7. Davies, C. N., Ed., *Aerosol Science,* Academic Press, London, 1966.
8. Browning, E., *Toxicity of Industrial Metals,* Butterworths, London (1961), p. 296.
9. *Operating Instructions,* Anderson 2000, Inc., P. O. Box 20769, 2000 Sullivan Road, Atlanta, Georgia 30320.
10. *Specifications for Mild Steel Covered Arc Welding Electrodes* (A5.1-69), American Welding Society, Miami (1969).
11. Parker, E., *Materials Data Book,* McGraw-Hill Book Company, New York (1967), p. 10.
12. Owen, R. J., "Determination of Welding Fume Size with Time Using E7018 Electrodes and A131B Base Metal," Unpublished master's thesis, Texas A&M University (1976).