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THE ENVIRONMENT AND ITS EFFECT UPON MAN

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THE ENVIRONMENT AND ITS EFFECT UPON MAN

SYMPOSIUM

held at

HARVARD SCHOOL OF PUBLIC HEALTH

August 24–August 29, 1936

as part of

HARVARD UNIVERSITY

TERCENTENARY CELEBRATION

1636–1936



HARVARD SCHOOL OF PUBLIC HEALTH

Boston

1937

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FOREWORD

Man's environment is a subject that has attracted the attention of men from earliest times and interest in it has increased with the growth of society. In its widest sense it is a subject for philosophers and political economists and today it forms the core of all public health study. Its ramifications are wide and a common interest in it brings together, as illustrated in these lectures, such diverse fields as sociology and toxicology.

In an effort to correlate a few of the many aspects of this wide subject, the Harvard School of Public Health invited several experts in various fields to join the members of the Faculty in presenting a symposium on "The Environment and its Effect upon Man" as the School's part in the Harvard Tercentenary celebration.

We wish to express our deep gratitude to our colleagues who prepared these lectures. We are indebted to the *Journal of Industrial Hygiene and Toxicology* for permission to reprint here all the papers except that of Mr. and Mrs. Wells which the *Journal of the American Medical Association* has kindly allowed us to include in this volume.

CECIL KENT DRINKER,
Dean of the School of Public Health.

Boston, January, 1937.

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THE EFFECTS OF SOCIAL ENVIRONMENT*

L. J. Henderson and Elton Mayo

THE human aspect of modern industrial organization attracted no great attention from industrialists until the advent of the European War of 1914; after the outbreak of hostilities the need to accelerate and to maintain production of various necessities quickly provoked a formulation of the problem. Apparently no one had ever sufficiently considered the enormous demand upon industry that would be made by a war-machine organized upon so heroic a scale, for armies counted in millions were a gigantic innovation. Nor had anyone considered the effect of the strenuous and sustained exertion imposed upon those who worked to provide supplies. The authorities in England speedily became aware of a "national lack of knowledge of the primary laws governing human efficiency". In particular, there was "need for scientific study of the hours of work and other conditions of labor likely to produce the maximum output at which the effort of the whole people was aimed". The actual conditions of work set in the munition factories were, in the early days of the struggle, admitted to be progressively detrimental to the worker and consequently unfavorable to that maintenance of output for long periods upon which success in large part depended. Inquiries undertaken by Dr. H. M. Vernon and others appointed by the *British Health of Munition Workers Committee* were effective; the introduction of shorter hours of work, of rest pauses and of other humane innovations resulted in the restoration of morale and the maintenance of production.

The stimulus to inquiry provided by this situation has continued to operate in the years that have elapsed since 1918, and much has been learned of the human factors that are involved in industrial organization for work. Another paper given at this symposium, by Dr. D. B. Dill, will present some of the most recent and interesting findings by physiology in the problem of fatigue. In addition to physiology, psychology has been summoned by industry to aid its determination of appropriate working conditions for the human being in action. In many of these inquiries, and rightly, the worker is considered and studied as an individual. Up to the present there have been few attempts to study the social conditions of work—that is to say, the effect upon morale and production of the situation created by the interrelation of several human beings in an industrial department. This paper is designed to give a brief account of two experiments at the Hawthorne Plant of the Western Electric Company which in a sense stumbled upon this

* From the Fatigue Laboratory and Industrial Research Department, Harvard Business School, Boston.

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problem as an exceedingly important aspect of industrial administration.

Officers of the Western Electric Company were probably moved to begin the researches of 1927 at Hawthorne by two chief influences. The one may be described as a general interest in the problems of the incidence of "fatigue" and "monotony" in factory work. This took its rise, remotely, in the publication by the English Industrial Health Board of its studies of the conditions of work in munitions factories and other industrial plants during and after the War. The other influence may be attributed to the fact that, as good engineers, these same officers were aware that Company policies with respect to human beings were not so securely based as policies with respect to materials and machines. Mechanical processes, the type and quality of materials used, were based upon carefully contrived experiment and knowledge; the human policies of the Company, upon executive conceptions and traditional practices. In determining the human policies, the Company had no satisfactory criterion of the actual value of its methods of dealing with people. A mechanical process as studied in a modern factory will in some way reveal an inefficiency; a traditional method of handling human situations will rarely reveal that it is rooted in mere use and custom rather than knowledge. The hope that an experimental method of assessing the human effect of different working conditions might be discovered must be regarded as counting for something in the development of the experiment. The object was not to increase production but to discover facts. Where production could be accurately observed, records were kept; but this was arranged merely as an essential part of the experimental procedure.

The original "test room" was installed in April, 1927, and continued to operate until 1932, when, for reasons not connected with the experiment, it was abandoned. The principal results here presented have been described by T. N. Whitehead.* The operation selected for study was that of the assembly of telephone relays. Five girl workers were transferred from their usual work surroundings into an experimental room, within which their work was supervised by specially appointed observers. Arrangements were made for the continuous and accurate record of individual output and for other observations that were considered appropriate. It will suffice for our present purpose if we say that the output of the test room workers continued to rise slowly for a period of years. In its upward passage this major gain ignored almost completely experimental changes arbitrarily introduced from time to time by the officers in charge of the experiment, including modification of the hours of work, the introduction of rest periods, etc., except those that modified the social organization of the group.

Thus it became evident that the group was performing two distinguishable, but mutually dependent, functions. On the one hand, the group was performing its technological, or economic, function; on the other hand, the activities of the group were being so modified and controlled as to heighten the social solidarity of the group within itself, and also to stabilize its relations with other groups.

* Social Relationships in the Factory: A Study of an Industrial Group. T. North Whitehead. The Human Factor, *9*, 381 (1935). We have here summarized and paraphrased a large part of this paper.

formed as to the nature of the experiment, and their coöperation was invited. The girls were paid, as before, on the same system of group piece work; but their previous group had contained over a hundred individuals, while in the test room the group, for purposes of payment, consisted of only five members. They were told to work at a comfortable pace, and no emphasis was laid on achieving any given level of output; in fact, they were warned against 'racing' or forced output in any form. Conversation was permitted; on occasion it was general, while at other times it was confined to pairs of neighbors. In addition to these innovations, certain other ex-

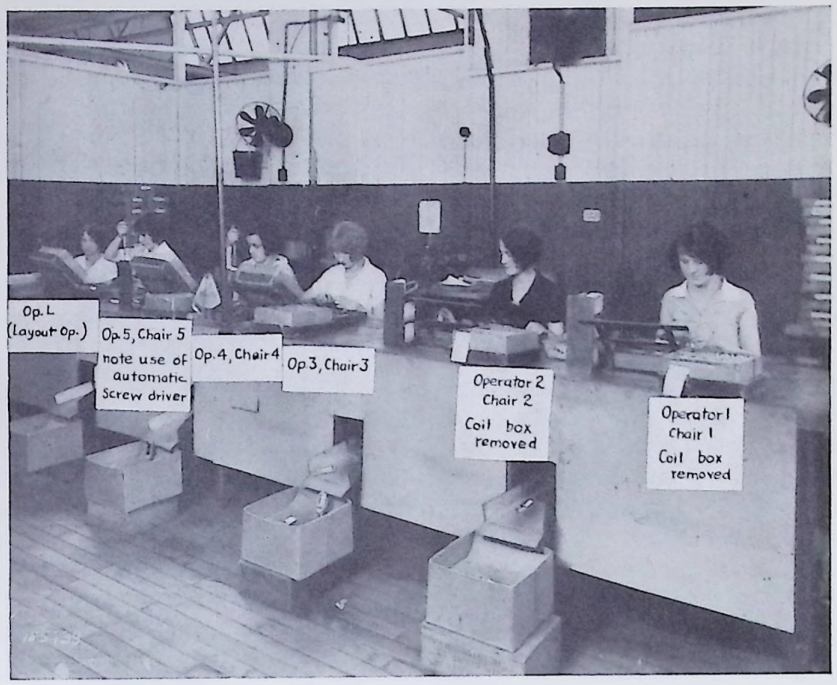


FIG. 1.—Girls at bench assembling relays. (Thanks for reproducing these illustrations is due the editors of Human Factor.)

As time went on, the interplay between the economic and the social functions of industrial groups became the central subject of the Western Electric researches. Although the girls' work itself was not altered, the general conditions in the test room differed in a number of respects from those to which the girls had previously been accustomed. They were in-

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perimental changes were introduced from time to time. The length of the working day was varied, as were also the number of working days in the week, rest pauses were introduced, and so forth.

Figure 1 is a photograph of the girls at work. They are sitting in a row along their work bench, and opposite them are trays containing the necessary parts for assembly. Immediately in front of each girl is a small jig to assist her in building the relays.

Numerous records were kept by the supervisor in charge. Since an automatic instrument recorded, to a fraction of a second, the instant at which each girl completed every assembled relay, we have the minute-to-minute output of each individual over a period of 5 years. Other records relate to quality of output; reasons for temporary stops; the length of time spent in bed every night; periodical medical reports, and so on. Room temperatures and relative humidities were taken hourly and the Chicago Weather Bureau has supplied similar records for outside conditions. In addition to these, a number of other records were kept.

The supervisor and his assistants made extensive daily notes of conversation, and of the relations developing between the workers. The workers were also separately interviewed by an experienced person on a number of occasions in another room. In all, we have volumes of contemporary observations bearing on the characters and dispositions of these girls, their mutual relations, their conversations and attitudes, their home situations, and their leisure hour acquaintances and activities. All this information was collected with the knowledge and consent of the girls themselves; and, as evidence that this consent was real, we may add that two suggested records were vetoed by the girls and so were never kept.

Figure 2 shows the weekly output rates for each of the girls in the test room. Each point, or short horizontal bar, indicates the average number of relays assembled per hour by the worker for the given week.

It will be noticed that girls Nos. 1 and 2 did not enter the test room until the beginning of 1928, when they replaced the original girls 1A and 2A. Similarly, No. 5 left the Company in the middle of 1929, and returned about 10 months later. During this interval her place was taken by No. 5A. In this short account no further mention will be made of Nos. 1A and 2A, but No. 5A entered into the life of the group too vitally to be ignored, and she will be referred to in due course.

All these girls were experts at relay assembly, having already had several years' experience, but it is noticeable from the figure that in every case their output rate increased substantially, the average increase being somewhere in the neighborhood of 30 per cent.

Of great interest are the wave-like irregularities exhibited by each graph. Some of these 'waves' last for months, and others only for a week or two. Moreover, the available output figures show that similar irregularities occurred with durations of as little as a minute or two upwards. At first it was supposed that these variations in working speed might be related to the experimental changes deliberately introduced, or possibly to other changes in physical circumstance, such, for

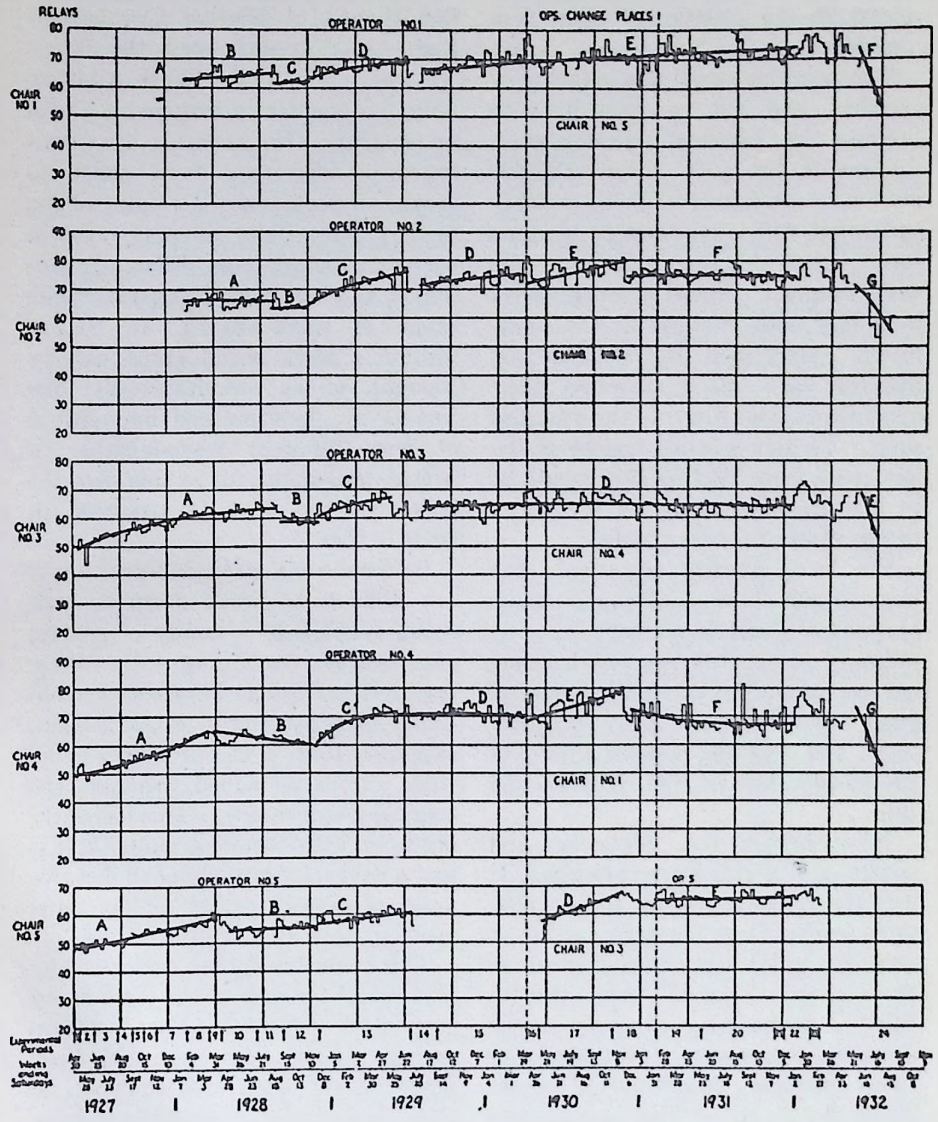


FIG. 2.—Weekly output rates for girls in test room. Each point or short horizontal bar indicates the average number of relays assembled per hour by the worker for the given week.

instance, as temperature, or the worker's own physical state. But a careful analysis of the data forced us to the surprising conclusion that irregularity in speed of work substantially failed to correlate with any changes of physical circumstance. This applied equally whether experimental changes,

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irregular changes of natural circumstances, or those cyclical changes involved in the passage of time were considered.

Since working speed was in fact very variable, and yet so insensitive to changes in physical circumstance, changes in the girls' social relations were next examined as being possibly connected with variations in working speed. And this time positive results were obtained. Speed of work varied markedly with changes in the sentiments entertained by the workers towards each other, towards their supervisors, and towards the group as such. To give a social history of the test room from 1927 to 1932 would be to give an explanation of the major trends shown in these graphs.

We have already remarked that these graphs show an average increase of speed of about 30 per cent. In any ordinary sense they are not learning curves, for the workers all had several years' experience in this particular work, and they had reached a more or less steady state as regards speed and skill.

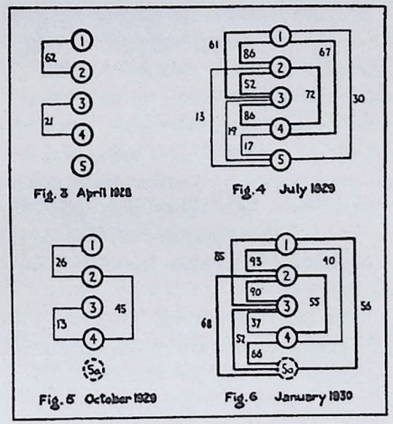
Nevertheless the plateaux and spurts are decidedly suggestive. It was the organization of human relations, rather than the organization of technics, which accompanied spurts in these cases. This illustrates the futility of attending exclusively to the economic motivation of workers, or to their physical conditions of work. These things are of high importance; but no group of workers can be expected to remain satisfied, or to cooperate effectively unless their social organization and sentiments are also protected.

In looking at figure 2 once more, each graph can be imagined as the resultant of a number of wave-like disturbances of differing wave-lengths each superimposed upon the other. An ocean, such as the North Atlantic, only too frequently provides us with an analogy. So often it is simultaneously disturbed from shore to shore by ripples, waves, oceanic rollers, and by tides—four different types of wave-like disturbances, differently produced, and each with its characteristic range of wave-lengths. In similar fashion a work speed graph can be thought of as simultaneously disturbed by superimposed fluctuations of very different wave-lengths, or better, *time-spans*, for in this case the length of the wave is measured in units of time.

By means of a statistical device it is not difficult to break down a work speed graph into a family of curves, each curve containing only those fluctuations lying between certain limits of wave-length, or time-span, and such that, if the ordinates of all these curves be added together, the original graph results. This has nothing to do with harmonic analysis; it is just a device for examining all disturbances of approximately similar time-spans in isolation from the others.

This analysis has been performed by Whitehead for each of the work speed graphs in figure 2. For instance, among others, one curve has been prepared for each girl, showing all those fluctuations of speed whose time-spans lie between 1 and 4 weeks—all other fluctuations have been eliminated from these particular curves. And these 1–4 week time-span curves have been compared with one another to see in what degree the speed fluctuations of one girl correspond with those of another.

The accompanying figures give this information for typical dates throughout the experiment. Figure 3 refers to April, 1928. The five circles represent the five relay assemblers in the order in which they sat, the distinguishing number of each girl being placed within her circle. When the speed fluctuations of two girls show a significant correspondence in the 1–4 weeks time-span, then the pair in question are joined by a line; for example, the pairs 1–2 and 3–4. The figures against the lines indicate the strength of the correspondence stated in percentages, and when this correspondence amounts to 50 per cent or more this is indicated by a thick line. These figures do not refer to correlations (r), but to the squares of correlations (r^2), and are called 'determinations.'



FIGS. 3–6.—Correspondence in output fluctuations.

Determinations have certain theoretical and practical advantages as compared with correlations; but the point to remember is that a determination is always numerically smaller than its corresponding correlation. Thus a correlation of 0.8, or 80 per cent, corresponds to a determination of 0.8^2, or 64 per cent. All the determinations shown in the following figures are positive unless otherwise indicated.

With this preliminary explanation let us examine figure 3. The relay test room had been running for about a year, but Nos. 1 and 2 had been members of the group only for the last 3 months of that time. As the figure shows, these two girls 'determinated' quite strongly. No. 2, of Italian origin, was undoubtedly the leading member of the group. She was the fastest worker, showed the highest score in an intelligence test, and possessed the most forceful character in the room. This girl was ambitious and at times hoped to obtain a secretarial post, but circumstances had prevented this. At the date in question, April, 1928, her mother and sister had recently died, and No. 2 ran her father's house, looked after her younger brothers, and was the principal wage-earner of the family. In the main shop, No. 2 had found little scope for satisfaction, but the test room seemed to offer a greater outlet for her ambitions and energies, and she threw herself into the new situation with vigor. Her friend, No. 1, of Polish origin, possessed a more placid disposition and contentedly followed her strong-minded neighbor. This friendship lasted throughout the 5 years of the experiment.

Workers 3 and 4, both of Polish origin, had been friendly since the

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beginning of the experiment, although they had little in common except their chance propinquity. Neither possessed conspicuous qualities of leadership, though it appears that, in the absence of No. 2, No. 4 might possibly have assumed a dominant position in the group.

Characteristically, No. 5 shows no correspondence in her speed fluctuations with any of the others. A Norwegian by birth, she had lived in the States only a few years and spoke English with difficulty; and this, combined with the fact that she was married, older than the others, and of a phlegmatic disposition, prevented her from ever entering fully into the life of the group.

So figure 3 shows determinations between two pairs of friends, but nothing that could be described as a general state of mutual influence as between the five girls.

Figure 4 illustrates the state of affairs 15 months later, in July, 1929. Here every girl 'determinates' significantly with every other girl, and in many cases the degree of determination is decidedly great. It will be noticed that every determination exceeds 50 per cent, except those involving No. 5 which never exceed 30 per cent.

During the 15 months separating figures 3 and 4 the group had been acquiring common activities, interests and loyalties. To a large extent the group had taken their discipline out of the hands of the supervisor and were performing this function for themselves. To give only one instance: when a girl wished for a half day's leave of absence she had to obtain permission from the supervisor. But a custom had become established by which no girl could ask for such permission unless the group sanctioned it. This leave was seriously debated by the group and not always granted, and we do not think the supervisor ever reversed the decision of the group in this matter. Group solidarity had developed with No. 2 as the unofficial but acknowledged leader; and figure 4 shows the extent to which the girls were influencing each other in respect to speed fluctuations in a particular time-span.

Figure 5 shows an almost complete collapse of group solidarity only 3 months later, in October, 1929. In the interval between figures 4 and 5, No. 5 had left the Company's employment of her own free will, and had been replaced by another relay assembler, No. 5A. This last girl was selected at the request of No. 2, the two having been close friends for some years.

No. 5A was in all respects more congenial to the group than her predecessor; she was of the same age as the others, unmarried, good tempered and coöperative. Nevertheless, No. 5A was unaccustomed to working with her new associates and quite unused to the type of integrated group activity of which she had no previous experience. The result was that, in the 1–4 weeks time-span, she 'determinated' with no one. But, even more significant, others pairs not involving No. 5A also failed to show much mutual influence. Solidarity had fallen all round in consequence of an unassimilated social element, and this in spite of the fact that No. 5A was more popular than her predecessor.

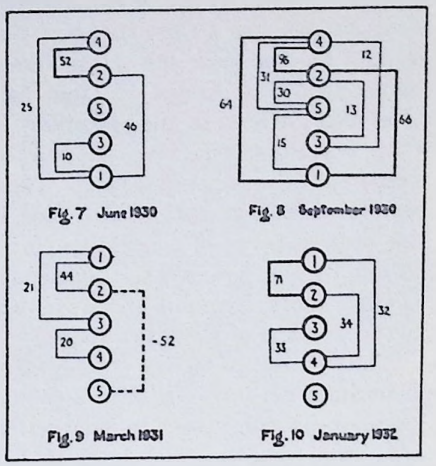
However, this state of affairs did not last long, and 3 months later (figure 6) we find the highest state of integration ever observed in the group in this particular respect. No. 5A had established herself as a participating member of the group and being better adjusted in her surroundings than No. 5, determinations are higher. Every individual determinates with every other; the mean value of all the determinations is 64; and the least is 37, corresponding to a correlation coefficient of 0.6.

Taking figures 4 and 6, the only cases here presented of complete determinations, the mean values of the determinations for neighbors are 66; for two individuals separated by one other, 57; for those separated by two others, 47; for those separated by three others, 43.

Figure 7 shows another change by June, 1930, 5 months later. Two events occurred to account for this. In the first place the girls had changed seats, as can be seen from the figure.

This rearrangement was introduced for experimental reasons in April of 1930, and was maintained for 10 months. A change in seating may not seem important to those whose occupation permits them some liberty of bodily action during working hours, but it made a great difference to the relay group. Their work necessitated some degree of visual attention, as well as continuous finger and arm action; it thus determined the position of the body with respect to the workbench. So, of necessity, intimate conversation could only be carried on between neighbors, although general conversation in a raised tone of voice was not uncommon. Thus a change of seating order involved new associates, an entirely different perspective of the whole group and consequently the need for a new orientation.

Shortly after this change No. 5 requested the Company to take her back and to place her again in the test room. The circumstances surrounding this request were pathetic and the request was granted. But the responsible official had not realized the extent to which this action would be resented by the remainder of the group. The fact was that No. 5A was



FIGS. 7–10.—Correspondence in output fluctuations.

decidedly popular and was supporting an invalid father. Her removal from the test room resulted in a small drop in her wages (she was given a somewhat different occupation), and it was supposed to increase her chance of being laid off as a result of the industrial depression, which was then in its early stages. For both these reasons the reinstatement of No. 5 was disliked by the group, and this dislike was transferred to No. 5 herself. In figure 7 No. 5 has no relations with

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anyone, and other determinations are few and relatively weak. However, by September of 1930, three months later, the group began to show signs of reintegration (figure 8). How far this might have gone it is impossible to say, for shortly afterwards the girls were put back into their original order of seating. The result is shown in figure 9. Not only has integration in this respect collapsed, but Nos. 2 and 5 show a marked negative determination (the corresponding correlation equals −0.72). It will be remembered that No. 5A was a close friend of No. 2, and at this time the latter rarely spoke to No. 5 except to snub her. The result is seen in the variations of their working speeds; when one worked faster the other worked slower. Their speeds varied in antiphase. This is the only instance of a negative correlation in the 1–4 weeks' time-span, though more frequent instances are found in some of the other spans.

The occurrence of this one negative determination involving No. 2 should perhaps be considered in connection with the fact that the total of her determinations contributed about 40 per cent more than their proportional share to the total of all the determinations of figures 3–10. In other words, determinations in which No. 2 is involved are approximately twice as great as those in which she is not involved. This presumably is the mark of her leadership, and it is possible that the one negative determination may be partly due to the same influence.

Finally, figure 10 shows the situation about 10 months later, in January, 1932. By this time the depression was at its height, many employees had been laid off and quite evidently the process was bound to continue. For this reason, as well as others, the tone of the relay group had been gradually changing from optimism to resignation. The future was a matter for dread rather than hope and No. 2 in particular was again restless in the feeling that her ambitions were not being realized. The self-discipline of the group showed signs of deteriorating, and the 10 months separating figures 9 and 10 resulted in little growth of solidarity. The group had lost its spring. No. 5 was no longer the object of active resentment, but she was effectively outside the common life and practically never spoke to any of the other girls.

We have briefly compared synchronization of fluctuations, in the 1–4 weeks time-span, with the social sentiments of the workers themselves; and it appears that these two factors tend to vary in close accord with one another. This accord was considerably more detailed than has been explained. Moreover, the story is much the same whatever time-span be considered. For fluctuations have been examined with individual endurances of a minute or two, at one end of the scale, up to those having endurances of nearly 3 months at the other extreme.

In every case, the degree in which the speed fluctuations of two workers correspond relates itself in some fashion to their mutual sentiments; though the type of social sentiment involved does depend somewhat on the length of the time-span chosen.

The second experiment we report has been fully described in a monograph entitled "Management and the Worker" by F. J. Roethlisberger and W. J. Dickson. A study of a bank-wiring room, it constituted the final experimental phase at the end of 5 years' inquiry at the Hawthorne plant. "The method of study was novel in that it utilized two types of investigation simultaneously. One type consisted of an indirect conversational interview, the other of direct observation. The interviewer remained as much as possible an outsider to the group, and the interviews were held by appointment in a private office. The observer was stationed with the group in the rôle of a disinterested spectator. His function was to keep records of performance, and of events and conversations which he considered significant. . . . The attention of both investigators was fixed upon the same group, and the one simply attempted to get information which the other could not get as well, or could not get at all."*

The situation that was revealed in this method of study was very different from that which obtained in the relay assembly test room. Whereas in the test room the collaboration of workers with management was at a high level and the aims of the two groups apparently in perfect accord, the situation in the bank-wiring observation room was quite otherwise. The spontaneous social organization of the latter group seemed to order itself about a certain sentiment of fear or doubt with respect to managerial intention. The group had arrived at a conception of a day's work which was less than the 'bogey' set for the department. This

* Actual Behavior in a Shop. W. J. Dickson. Paper read to Personnel Research Foundation, January 25, 1935.

decision was not the result of careful consideration or logical process; it had 'just happened'. And the output records showed a 'straight-line' production which was closely in accord with the group conception of a day's work. There were a variety of methods by which group discipline was enforced; no individual escaped the group decree. As a result of these practices the departmental efficiency records did not reflect the actual situation. The official incentive plan was not functioning as it was intended. The group had so organized itself—in a purely spontaneous fashion—that the intentions of the engineer organizers were defeated.

To show how completely the informal organization of the group had defeated the official plan, we quote certain findings made by W. J. Dickson, the officer in charge of the investigation. In the original test room experiment, study of the performances of the girl workers after a period of years showed that the comparative achievements of the individuals in respect of output gave a ranking order that coincided very closely with the order assigned by intelligence and vocational tests. Quite a contrary situation revealed itself in the bank-wiring room. The relative rank in output of the various workers was compared with their relative rank in capacity as measured by tests of intelligence and dexterity. "This comparison showed that there was no relation between their ability as measured by these tests and their actual performance. The lowest producer ranked first in intelligence and third in the dexterity tests. The man who scored highest in the dexterity test ranked seventh in

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intelligence and seventh in output. The man who scored lowest in the dexterity test shared first place in intelligence and ranked fifth in output. This then was a situation in which the native capacities of the men were not finding expression in their work. In order to see whether differences in earnings accounted for difference in output, these two factors were then compared. Here again no relation was found. The man who ranked first in earnings ranked fourth in output, and the man who ranked lowest in earnings ranked fifth in output. Two of the men received the same wages, yet one produced an average of 16 per cent more work."* Dickson goes on to point out that careful analysis of all the available data showed that these differences in output related themselves approximately "to the individual's position in the group." That is to say, differences in output related themselves to the social controls established by the informal grouping and not to individual capacity or to economic or logical considerations. Dickson's conclusions, briefly summarized, follow. He expresses a caution that these conclusions apply specifically to the group under observation and are not to be interpreted as generalizations.

1. Output for these operators was a form of social behavior. Their own peculiar concept of or feeling about a day's work was the idea about which the informal grouping was organized. Individual differences of performance were related rather to the individual's position in the group than to his actual capacity.

2. In this situation the supervisory controls established by management had failed. The whole logic of the technical organization was implicated in this failure.

3. The problems encountered were not due to a logical insufficiency in the wage plan. Such plans assume that a worker is primarily moved by economic interest and that he will act logically. The study shows that social considerations outweigh the economic and logical; the workers' actions were based upon non-logic and sentiment—in other words, upon social routine procedures.

4. The study has some interest for vocational work in selection. In the conditions described, scientific selection and placement do not ensure a corresponding efficiency.

5. The conflict of loyalties involved in the dissonance between the official and the actual organization leads to worry and strain, not only for the supervisor but also for the workers. There is reason to believe that the girl workers in the test room, whose work closely reflected their capacities, experienced a feeling of release from this type of strain.

Roethlisberger and Dickson have elsewhere pointed out* that situations such as that described are commonly misinterpreted. It is supposed, for example, that there is a necessary hostility somewhere implicit in the relations between management and the worker, and that restriction of output is consciously contrived. But this type of explanation misses "the essentially non-logical character" of the situation. It is only those who assume

* Op. cit., W. J. Dickson.

* Management and the worker, technical vs. social organization in an industrial plant. Harvard Business School, Bureau of Business Research, Boston, 1934.

that economic interests dominate the individual and that clear logical thinking serves these interests who can argue thus. And it is the assumption, and not the fact, that drives them in this direction. "Logically it could be argued, for example, that it was to the economic interest of each worker to produce as much as he could and to see that every member of his group did the same. But, in actuality, the workers saw to it that no one's output ever exceeded a certain limit. Had they been asked why they limited their output in this way, they would probably have expressed fears of a possible 'rate reduction'. *Yet none of the men in the bank-wiring observation room had ever experienced a reduction of rates. But they acted as though they had.* This behavior was not directly in line with their economic interests, nor was it based on the facts of their own experience with the company."

There are other observations which make the hypothesis of a necessary hostility between management and workers untenable. The Western Electric Company has a long and consistent record of fair dealing with its employees. Both overtly in a very low labor turnover and verbally in the interviewing program, employees have shown a manifest appreciation of the company's attitude. "In the interviews of 1929, when over 40,000 complaints were voiced, there was not a single unfavorable comment expressed about the company in general." It seems to be clear that the hostility hypothesis is an inference from the insufficient assumption of economic interest and logical thinking as fundamentals of human association; it is not an inference from the facts.

"Upon examining more closely the behavior of employees," it became evident that "many of their actions were of the nature of mechanisms to resist too rapid changes in their environment." The opposition to change was not only reflected in all their tactics to keep output constant, but was also implied in all the reasons they gave in justification of their actions. Roethlisberger and Dickson, therefore, conclude that the chief function of the informal groupings which organize themselves on the working line is "resistance to change or any threat of change in their established routines of work or of personal interrelation." This is a very ancient and well-known character of human association.

Scientific management has preferred to work with explanations or hypotheses that are simple and logical. This would be admirable, if one were not guilty of what A. N. Whitehead terms "the fallacy of misplaced concreteness."* But no study of human situations which fails to take account of the non-logical social routines can hope for practical success. Roethlisberger and Dickson give two reasons for the failure of the technical plan in the bank-wiring department. They begin by distinguishing between the technical organization and the informal social organization of the employees. The technical organization is chiefly remarkable "for its logically contrived character" which makes for rapid change. And, just as capacity for change characterizes the technical organization, so resistance to change

* Science and the modern world. A. N. Whitehead. The Macmillan Company, New York, 1926.

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characterizes the informal employee groups. As a result the employee groups feel that they are constantly under fire—in the sense that it is as if the technical experts were constantly battering to pieces any routines of collaboration that the workers develop. This rouses resistance, first, because "the worker is at the bottom level of a highly stratified hierarchy. *He is always in the position of having to accommodate himself to changes which he does not initiate.*" Second, "many of the changes to which he is asked to adjust rob him of the very things that give meaning and significance to his work. His established routines of work, his personal relations with fellow-workers, even the remnants of a cultural tradition of craftsmanship—all these are at the mercy of the technical specialist. He is not allowed either to retain his former traditions and routines or to evolve new ones of any probable duration. Now, the social codes which define a worker's relation to his work and to his fellows are not capable of rapid change. They are developed slowly and over long periods of time. They are not the product of logic, but of actual human association; they are based on deep-rooted human sentiments. Constant interference with such codes is bound to lead to feelings of frustration, to irrational exasperation with technical change in any form." Ultimately, therefore, the disrupted codes revenge themselves by giving rise to informal employee organizations which are opposed to the technical authority.

Scientific management has developed a logical flexibility which in itself is admirable. As applied to industrial organization, however, this flexibility perhaps creates more problems than it solves; it is at least true that social sentiments and routines of association find difficulty in adjusting themselves to the rapid 'shift'. But scientific management has never studied the facts of human social organization; it has accepted the nineteenth-century economic dictum that economic interest and logical capacity are the basis of the social order. It would seem possible, therefore, that scientific management has itself done much to provoke that hostility between management and workers which now so inconveniently hampers every development towards 'rationalization'.

There remains comfort, however, to be drawn from the series of experiments at Hawthorne. These experiments—

1. Have called attention to an important group of facts—the facts of spontaneous social organization at the working bench. These facts are of such a nature that they escape the notice of physiological and psychological inquiry.

2. The experiments strongly suggest that the excellent results obtained in the original test room were largely due to the achievement of a comfortable equilibrium between the technical organization, or plant authority, and the spontaneous social organization of the workers themselves. This equilibrium is not generally found in working departments or in other factories.

The facts that we have been considering have revealed and have led us to describe certain characteristics of two social systems, one experimentally (though accidentally) produced, the other a spontaneous

formation whose existence had been ignored. Now there can be little doubt that any group of people who work together sooner or later take on some of the characteristics of such a system, and thereafter so act that their behavior can only be conceived as the resultant of social forces as well as of economic forces and of those psychological forces that are private to the individuals. Social organization is, in fact, a human need; it is, in some measure, necessary and inevitable. Its mere existence disciplines the members and gives rise to sentiments, often very strong sentiments, of loyalty, of personal and group integrity, and not infrequently of pride. No. 2 of the test room, commenting after the event on the decline of output toward the end of the long experiment, at a time when the effects of the depression were at their worst, remarked, "We lost our pride."

Not infrequently the proprieties of the spontaneous social system call for more consideration than the strictly economic interests of the group or the psychological properties of the individual members of the system. This is because the social forces are nearly always strong, and sometimes dominant. Like that of the family, the social organization of any group is *felt* as a real thing, indeed as something far more real than the technical organization of a factory; and spontaneously formed human relations are felt to have a meaning and a value that are lacking in purely hierarchical relations or in those relations that are involved in merely working together in time and place, according to an arbitrarily determined plan.

These statements, assuredly, are platitudes; but they are platitudes that are nearly always forgotten by most men of action in action. Yet, it is urgently necessary that they should be always remembered,—remembered and acted upon. Whenever men work together search should be made to discover and to characterize the social systems that have spontaneously, arisen for these are the worlds in which the individual members feel themselves to be living, just as a mother feels herself to be living not so much in a particular house, in a particular street, in a particular town, as in her family.

If you are talking with, giving orders to, planning for, making use of a man who is living in a world—or *feels* that he is living in a world—of which you are ignorant, whose existence you do not suspect, is it possible that what you say to him, what you command him to do, what you plan for him, what you use him for, will have for him the same meaning that it has for you? Is it not more probable that what seems to you good for him will to him sometimes seem bad, both for himself and for his fragile and insecure social system, which he values and which gives meaning and color to his life? And is there any ground for thinking that what is logical and reasonable to you will be so to him? If you do not know his axioms, it is probable that your axioms will not be his, and, besides, he cannot, in general, be persuaded by reason but only by an appeal to his sentiments. How shall you appeal to sentiments that you do not know?

The stability of the world in which he feels—however non-logically, however irrationally—that he is living—however vague, however unanalyzed

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his feeling—is of first importance to every man. That world is largely made up of his human social relations and of the sentiments that habitually arise in the course of his habitual performance of the routines and rituals of daily life. Change too rapidly imposed from without, for him is evil, because his social system cannot change very rapidly without breaking; it is bound together by sentiments, which change slowly and resist change, because rapid change is destruction of routines and rituals, of habits and of conditioned behavior. Such change is painful even to a dog.

The social environment is what sentiments, routines and rituals make it. From the most perfect family in the world take away the sentiments, the routines and the rituals, and the residue will be unrelated individuals. No doubt the social environment (the various social systems) of a factory is in many ways less important and far less perfect than the social system of a good family. But in several respects it is the same kind of thing and, as experiment shows, it is in several respects so important that it cannot be neglected by anyone who wishes to plan wisely, or even merely to know what he is doing.

The environment is at once physical, chemical, biological, psychological, economic and sociological. As a rule, we all have the strongest feelings about its sociological properties and the least intellectual awareness of them. Often these are the most important properties of the environment. Let us study, weigh, modify and use them.

INDUSTRIAL FATIGUE*

D. B. Dill, A. V. Bock, H. T. Edwards and P. H. Kennedy

I. Introduction

A CURRENT concept regarding the nature of fatigue has been stated by Viteles (1) as follows:

"The word fatigue, as used both popularly and scientifically, refers to three related phenomena:

"1. An overt manifestation in the form of reduced output on the task, known as *work decrement*. 2. A *physiological state* involving changes in organic functions and the production of chemical products of fatigue. 3. A *feeling of fatigue* or tiredness."

The simplicity and coherence of the concept as stated by Viteles give it great pedagogical value but at the expense of truth: the several phenomena involved are not closely related; some of them have little in common. Fatigue, for example, is of great concern to neurologists. Many of their cases are normal in so far as the usual laboratory and clinical manifestations are concerned. Certainly, there is no proof of the production of chemical products of fatigue. These patients, though they may live in idleness, complain of constant fatigue. Gillespie in a study of such cases (2) found no common measure of fatigue which was applicable.

In this paper attention will be directed to various physiological states observed in fatigue. It will be shown that there is no characteristic pattern; the simplest statement that can be made is that the physiologist regards fatigue as a failure to maintain equilibrium or, to use Cannon's terminology, a breakdown of homeostatic forces.

The physiologist does not deny the applicability of the word fatigue to monotonous industrial work although modern usage seems to favor the word boredom. This question has been discussed by Mayo (3) who points out that the words are used interchangeably. At any rate some investigators see in a decreasing output an indication of fatigue (4) while others use the same yardstick for measuring boredom (5). It is safe to deny, however, that boredom describes the breakdown of a finger as it is exercised with an ergograph. The one phenomenon is a problem for the psychologist, the psychiatrist and the sociologist, while the other is one that concerns the physiologist, since it involves well-known physical and chemical changes in muscle. The two phenomena are similar only in superficial respects; fundamentally they are very different.

The fatigue measured by the ergograph has much in common with certain types of breakdown observed

* From the Fatigue Laboratory and the Department of Hygiene, Harvard University, the Massachusetts General Hospital, Boston, and the Youngstown Sheet and Tube Company, Youngstown, Ohio.

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in industrial work. In order to make this clear it is useful to apply the engineer's concept of "factor of safety" to the worker. In a machine or structure the factor of safety is defined as the ratio of the capacity to the greatest expected load. If the ratio is unity, danger of a breakdown is faced since there is no margin for emergencies. Usually a large margin is provided; according to current practice, for example, the factor of safety in bridge design is three or more.

The factor of safety for man may be defined as the ratio of the maximal increment in metabolic rate to the observed increment (6). For most types of routine work in factories, the ratio is three or greater. When such a margin of reserve energy is available tasks are carried out easily and with little awareness of exertion. Fatigue, if it is experienced, cannot be charged to an upset in physiological equilibrium. For the worker in heavy industries and on the farm, for the woodsman, the soldier and the sportsman, the factor of safety may be reduced to a low level and fatigue of the sort produced by work on an ergograph may be experienced.

The term *factor of safety* is applicable both to the body as a whole and to its component parts. In manual labor which brings into action a large proportion of the skeletal muscles the total metabolism of the body is increased several-fold. This places upon the respiratory and circulatory systems heavy demands for maintaining the supply of oxygen and of fuel and for removing end-products of metabolism and dissipating heat. Consequently, many varieties of fatigue and breakdown can be observed in such activity. Skeletal muscles themselves may be incompetent, the heart may fail, or there may be a breakdown of equilibrium in the system as a whole. Specific illustrations will be given later of these situations.

Many industrial jobs place a heavy strain on small units of skeletal muscles, but do not necessarily raise the total metabolism enough to reduce the factor of safety for the heart and lungs to an uncomfortably low level. Fatigue in such a task may be muscular, neuromuscular or of central origin. The cases which are of central origin have been given particular attention by Mayo (3); the others may have a physiological as well as a psychological background.

Since the subject of fatigue has been reviewed during the past year by Simonson (7) few references need be made to the voluminous literature on the subject. Instead, several illustrations will be given from the laboratory and from the field which will picture concretely diverse manifestations of fatigue. Following a classification similar to that of Simonson's these illustrations may be considered in the light of four proposed mechanisms: (a) Accumulation of fatigue substances, (b) Exhaustion of energy reserves, (c) Inadequacy of oxygen supply, and (d) Alteration of physico-chemical state.

II. Accumulation of Fatigue Substances

When the lactic acid theory of muscular contraction was proposed a

substance was at hand which seemed to be the long-sought toxin responsible for fatigue. Its relation to fatigue, however, is more restricted than at first appeared. Fatigue in the intact organism may be experienced without accumulation of lactic acid. Nevertheless, its concentration in the blood remains a useful index to the degree of fatigue in one sort of activity, *viz.*, that in which either the oxygen supply is deficient or the oxidative mechanism of the muscles is not competent to meet the demands placed upon it.

The response of several individuals to a fixed task (8) is shown in fig. 1. Those who were well-trained were able to carry out the task with ease; in the case of the veteran marathon runner, De Mar, there was no accumulation of lactic acid. The magnitude of increase in lactic acid was closely related to the degree of fatigue as indicated by other objective measures, such as the R.Q., and by subjective evidence.

Even though in very strenuous activity lactic acid may be useful in judging fatigue it is not a primary cause of fatigue. If one follows the recovery curves of lactic acid removal and of oxygen uptake, it develops that the oxygen debt* is half paid in the first 6 or 8 minutes of recovery, while

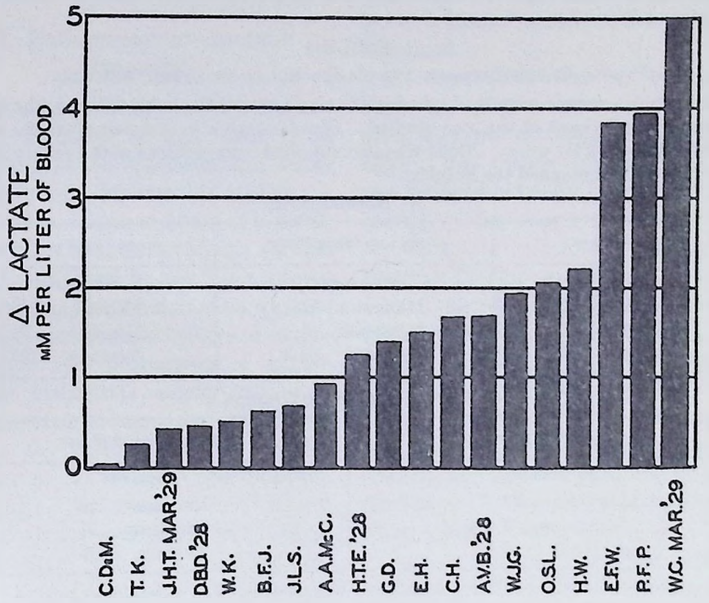


Fig. 1.—The increase in blood lactate in 19 men of varying physical ability. Each man worked at the same rate for 20 minutes. In this work, about 10 times the resting metabolic rate, the quantity of lactic acid produced is closely related to the degree of fatigue.

* The reader unfamiliar with the concept "oxygen debt" is referred to the papers of A. V. Hill. His book, "Living Machinery" (9) contains a clear statement of the elementary facts.

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the lactic acid concentration in whole blood may have just attained its maximal value by this stage of recovery (10) and the capacity for anaerobic work may be almost completely restored. Interesting proof of this fact was obtained at an indoor trackmeet in Boston this past winter. Eulace Peacock won two successive heats and the final of the 50-meter dash with intervening rest periods of only 6 or 8 minutes. His time in the semi-final tied the meet record although he must have had a high lactic acid value when he began the second and the third races. Six minutes after the last race a blood sample was obtained and his lactic acid was found to be 88 mg. per cent or 1,000 per cent of the normal rest value. Yet he did not appear tired at this time and so far as could be judged he could have run again.

The level of activity in the experiments referred to in fig. 1 was about 10 times the resting rate. If the level is less than six times the resting rate, as in most industrial jobs, there will be little or no increase in lactic acid concentration in the blood. Our evidence on this subject was accumulated on workmen at Boulder Dam and on steel men at Youngstown, Ohio. The latter group was doing particularly heavy work; some of them worked at tasks too heavy to carry on continuously and as shown in table 1, had high pulse rates and yet had normal blood lactic acid.

Lactic acid is not the only substance proposed as the toxin of fatigue. Recent studies suggesting that ammonia may be concerned have been reviewed by Simonson (7). Ammonia is liberated in muscular contraction and is

TABLE 1

PULSE, BLOOD LACTATE AND BLOOD SUGAR IN STEEL WORKERS

Several pulse counts were made during the day's work; the value given is the highest observed count in each of the men studied. Blood samples were drawn from the normal men immediately after work. Blood was also obtained from patients with heat cramps but not until they had reached the hospital.

A. Normal Men

PULSE IN 12 MEN	BLOOD LACTATE IN 10 MEN	BLOOD SUGAR IN 66 MEN
	mg. per cent	*mg. per cent*
Maximum, 160	Maximum, 13.1	Maximum, 142*
Minimum, 132	Minimum, 8.4	Minimum, 81
Average, 143	Average, 10.3	Average, 103

B. Men with Heat Cramps

BLOOD LACTATE IN 6 MEN	BLOOD SUGAR IN 32 MEN
mg. per cent	*mg. per cent*
Maximum, 24.3	Maximum, 165
Minimum, 9.0	Minimum, 91
Average, 13.4	Average, 116

* One observation is omitted. A value of 303 was found in a man who proved to be a diabetic.

known to be toxic in low concentration. Further evidence is required to establish its rôle, if it has one, in fatigue. Toxins derived from traumatized muscles have been held to be the cause of shock (11), but the existence of such toxins has not been proved. Such substances as histamine have not been shown to have direct relation to fatigue.

III. Exhaustion of Energy Reserves

This subject does not require extended discussion because there is no evidence that the well-nourished workman seriously depletes his energy reserves in the course of the day's work. On the contrary, our evidence on this subject, obtained in the Youngstown steel mills, indicated that steel workers maintain an adequate reserve of carbohydrate. The proportion of carbohydrate utilized is usually estimated by collecting expired air and determining the ratio of carbon dioxide production to oxygen consumption, i.e., the R.Q. One cannot collect expired air for evaluating the R.Q. of steel workers without interfering with the rhythm of their job. It is possible, however, to obtain two other useful indices of fuel reserves. We know that in heavy work the preferred fuel is carbohydrate (12). If work is continued for a long time in the laboratory without food, the diminishing reserve of carbohydrate is associated with a falling R.Q., a reduction in efficiency, a decreasing blood sugar concentration and the appearance of acetone in the urine (13). In no case in the steel mills either in normal workmen or in those suffering from the effects of heat was a strikingly low blood sugar observed (see table I) nor was acetone found in the urine. On this evidence we are content to conclude that even in heavy industrial work fuel depletion and, in particular, carbohydrate depletion are not important causes of fatigue. While the reserves of energy undergo rhythmic variations throughout the ordinary day's work the amplitude of oscillation is but a small fraction of the potential amplitude.

A reservation should be made, however. Men who come to work after a period of unemployment may have a low reserve of energy as well as a reduced capacity for transforming energy. They may require some days or weeks to reach an equilibrium between income and outgo. For example, records of the Civilian Conservation Corps show gains in weight of from 8 to 10 lbs. in newly enrolled men in many camps. Anyone who undertakes a task taxing his capacity and for which he is unfitted or untrained may find that glucose or other readily available fuel is of real value when taken between meals.

Our conclusion that the average workman suffers little handicap from fuel depletion during his day's work leaves unexplained the copyrighted results of Laird (14). He reports that fatigue in students doing tapping tests is favorably modified by the ingestion of certain sugars, maltose being peculiarly effective.

We do not dispute the claim that the introduction of rest pauses in which food is supplied may influence work output favorably, as has been shown recently by Haggard and Greenberg (15). In an excellent discussion of industrial fatigue they recognize

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the dependence of productivity in a factory on the social situation; they also believe it depends on frequency of meals. Although their provision of two free meals was associated with an increase in output, the social situation did not remain constant in the meanwhile. Perhaps the observed increase in production was a token of the workers' appreciation of the consideration shown for their welfare. The pleasure and interest in two free meals may have been more important than the altered energy reserves.

The thesis of Haggard and Greenberg that mechanical efficiency shows large variations with meals and that meals should be frequent is interesting but requires substantiation. It is difficult to believe that mechanical efficiency on a bicycle ergometer can increase from 20 to 28 per cent after meals. This is at variance with the observations of other students of the physiology of muscular exercise. It is only necessary to refer to Lusk (16). Immediately after a fasting dog ingests 70 to 100 gm. of glucose "*mechanical work may be accomplished at the expense of 5 per cent less energy than when glucose is not taken.*" This corresponds to an increase of 1 per cent in efficiency rather than of 8 per cent.

IV. Inadequacy of Oxygen Supply

The capacity for transporting oxygen, as suggested in Section II, is adequate in the healthy man engaged in any ordinary activity. In the individual with cardiac defect or in high altitudes it may become a limiting factor in muscular activity and an important cause of fatigue. In South America, for example, there are hundreds of thousands of people living above an altitude of 2 miles in whom the mechanism for oxygen transport is constantly under greater stress than at sea level. Studies made in Chile during 1935 (17) indicate that the problems of activity at high altitude are of particular concern to the newcomer; after some months or years acclimatization is so complete that life in moderate comfort is possible as high as 3 miles. The period of transition has long been recognized by these people as a severe ordeal. Monge (18) has found that in the Incan period two armies were maintained at high altitudes. These were used alternately in maritime conquests. Each 2 months they exchanged stations and in this way may have developed a capacity for rapid adaptation. Monge believes that the experiences of the Bolivians in the Chaco, where suffering from heat was extreme and deaths from pulmonary disease were numerous, substantiate the wisdom of the Incas.

Some animals suffer more in high altitude than man. Cats are especially sensitive while two members of the camel family, the llama and the vicuña are by nature well-endowed for life in high altitude (19). The former is used for heavy work up to 17,500 feet.

With the growth of air transport, fatigue in the aviator is a problem which is concerning an increasing number of people. This subject has been discussed by Bauer (20), Grow (21) and Bassett (22). Grow advances the hypothesis that "fatigue is due to the excessive generation of nerve impulses and originates in the nervous tissues of the body." He has observed that after a short flight in bad weather over bad terrain a great sense of fatigue and exhaustion, out of all proportion to the duration of the flight, is felt upon landing. "The constant bombardment of the brain by fear stimuli has induced an outpouring of nerve energy producing fatigue and with a resultant muscular tenseness."

has under way experiments which, it is hoped, will provide more valid tests than those now in use (24).

The question frequently is raised by engineers as to what altitude should be considered maximal for safe and comfortable flight. This cannot be answered categorically since passengers may have cardiac or pulmonary defects which render them hyper-

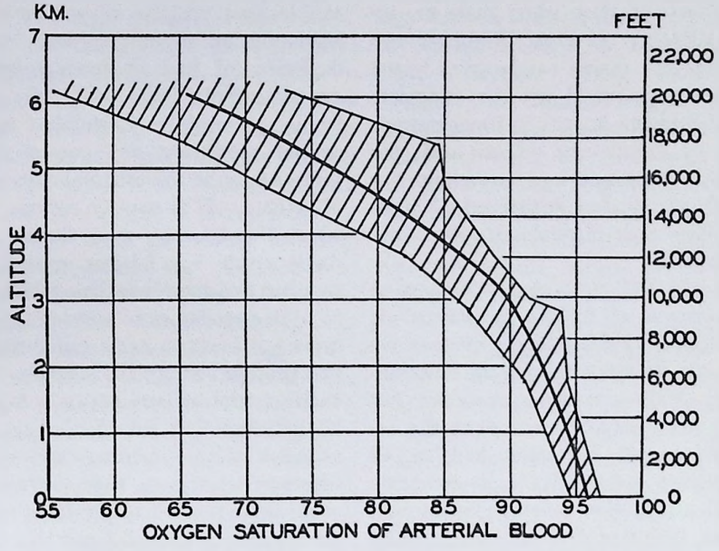


FIG. 2.—The range in saturation of arterial blood in relation to altitude. From 4 to 17 men were studied at each station. The results at 5,750 feet are from Stammers (25). All the other values are from our own observations either in Leadville or in Chile. These results correspond to partial or complete acclimatization; the saturation may be lower in the rapid transition characteristic of airplane flights. In two flights we have found saturations of 77 per cent at 13,000 feet and 68 per cent at 16,000 feet.

Some of the earliest tests for aviators were developed by Schneider (23). In spite of the considerable advance made in testing candidates for the Air Corps, only one-half of those who pass the first test are able to qualify as pilots. The recently established laboratory of the Army Air Corps at Dayton, under Armstrong's direction, esthetic to low oxygen. If one neglects factors other than partial pressure of oxygen, it may be concluded that 10,000 feet is the critical altitude below which the oxygen saturation of blood is influenced only moderately by altitude and above which the effect is large. This conclusion is based upon direct examination of arterial blood

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at various altitudes up to 20,000 feet and including a few observations made in a plane. Fig. 2 has been prepared to illustrate these findings. The many factors other than low oxygen such as noise, air pressure changes and emotional stimuli are operative at all altitudes but cannot be considered simply as additive. That is, a given emotional stimulus may produce a different response when superimposed on anoxemia than when there are no complicating factors. Probably no satisfactory answer can be given to the question proposed by the engineers until subjects known to have respiratory or circulatory defects and who may or may not be emotionally unstable are studied during actual flight by clinicians, physiologists and psychologists.

Bauer (20) quotes an interesting illustration of fatigue in war pilots which falls in the category of excessive burdens on small units of the musculature. "The aviator . . . must turn not only his head but his eyes to the extreme angle. He must look in all directions constantly." To illustrate how much the aviator twists and turns, it is reported that a number of cases were noted during the war of a considerable hypertrophy of the neck muscles due to constant use.

Anyone who has attempted a new task is familiar with the experience that muscles called into strenuous activity are sore and stiff for some days. Eventually this fatigue wears off and the task which once was difficult becomes easy. The mechanism of this adaptation is not entirely clear although hypertrophy of the muscle such as that referred to by Bauer may be one characteristic feature. It is possible that fatigue in local units of the musculature, which may occur with an adequate oxygen saturation of the blood, is due to an incapacity of muscle cells to transform energy at the necessary rate. This incapacity disappears with training.

V. Alteration of the Physico-Chemical State

The attempt to relate fatigue to simple and specific causes such as accumulation of fatigue substances, depletion of fuel or inadequacy of oxygen supply have been only partially successful. Certainly under special conditions any one of these factors may be the predominant cause of fatigue. It is equally certain that when the average man finishes his day's work his fatigue cannot be ascribed to a specific fatigue substance, to hypoglycemia or to anoxemia. We must fall back on some other sort of explanation than the simple and therefore the preferred type. A similar situation has led physiologists to abandon the elementary and easily remembered theory that carbon dioxide alone controls respiration. This theory soon developed flaws, so a more high-sounding theory of pH control was advanced. We now must accept the less concrete theory proposed by Henderson (26) that a large number of interrelated factors are concerned in the control of respiration. Under some conditions one factor may be predominant, under different conditions others come forward.

The effects of high environmental temperature may be cited to illustrate the dependence of well-being on maintenance of homeostasis. Breakdown may occur in the normal workman

without signs of fuel depletion, oxygen deficiency or lactic acid accumulation. Our studies at Youngstown covered three groups of workmen: (a) normal men who were able to carry on their work in the mills without breakdown; (b) workmen sent to the hospital with heat cramps; and (c) workmen sent to the hospital with heat prostration. All of these, even the normal men, experienced a considerable disturbance in equilibrium during the day's work.

The strikingly large water exchange in healthy workmen in hot weather is illustrated in table 2. The average man has a water intake of more than 5 liters during 8 hours of work. During the same period only 7 per cent of this quantity of water is excreted by the kidneys. With this large exchange one can assume that the water of foods and metabolism is roughly equal to that excreted by the lungs plus that of insensible perspiration. What we have called "extrarenal water loss" amounts to about 6 liters in the average man and can be considered approximately equal to the volume of sweat. Since sweat contains from 0.05 to 0.5 per cent salt, it follows that the salt loss in sweat may range from 3 to 30 gm. per day in these men. The usual intake with food is from 10 to 20 gm. It is easy to see, therefore, that in the exceptional case one may have a man with sweat of high salinity working at a hot job which results in the production of 8 or 9 liters of sweat. Such a combination is apt to lead to salt depletion and heat cramps.

While there were not many men in our groups who put out urine of a low salt content one must bear in mind that the one sample covers the entire 8 hours of work. During the work period the salt level in the blood may be at the normal level early in the day, but unless salt is supplied may drop to a low level by the end of the day. For this reason it seems particularly important to provide salt throughout the period of work rather than to depend on getting enough with meals.

Most of these men were receiving salt during these experiments. Even so, there was an average weight loss of 1.2 kg. during work and as great a loss as 4.1 kg. Many men lost no weight or even gained weight. A loss in weight is due almost entirely to an excess of water excretion over water intake. Ingested water cannot be retained unless there are solutes present in the body to bring the blood solution to the normal salinity. In these workmen the substance almost wholly responsible for maintaining water balance is sodium chloride.

The cases with heat cramps were those who underwent an upset in equilibrium which differed quantitatively but not qualitatively from that experienced by their fellows. Hospital studies of workmen suffering from cramps revealed a very considerable depletion of salt with the blood plasma concentration of both sodium and chloride below the threshold level of the kidney.

They presented the following picture: (1) dehydration, (2) lowered concentration of sodium and chloride ions in blood plasma, (3) little or no sodium or chloride in urine, (4) increased serum protein concentration, (5) increased red cell count, and (6) normal osmotic pressure. The injection of physiological salt solution left their osmotic pressure unchanged,

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TABLE 2

Body weight and water exchange in normal steel workers

(The temperatures given are from the U. S. Weather Bureau records in Youngstown)

U.S.W.B. maximum temperature	Name	Age	Job	Body weight			Work period: 8 hours				Estimated extra-renal water loss	Recovery period: 16 hours		
				0 hour	8 hours	24 hours	Water intake	Volume of urine	Specific gravity of urine	Chloride in urine		Volume of urine	Specific gravity of urine	Chloride in urine
°F.		years		kg.	kg.	kg.	liters	liters		gm.	liters	liters		gm.
89	Wegeli	48	Sheet Shearman	70.4	69.5	71.0	4.08	0.46	1.032	2.52	4.52	0.94	1.032	4,89
89	Holesky	25	Opener	80.6	79.5	79.7	2.09	0.32	1.033	3.93	2.87	0.64	1.034	5.25
89	Yellock	36	Shearman	69.3	67.8	70.2	4.37	0.48	1.027	6.67	5.39	0.35	1.034	2.94
86	Enbanks	48	Blast Furnace	63.9	63.4	65.1	3.23	0.54	1.019	4.36	3.19	1.15	1.018	4.91
86	Curry	52	Blast Furnace	86.3	84.9	87.6	4.19	0.33	1.024	4.55	5.26	1.47	1.011	7.06
86	Desptovich	40	Crane Operator	61.4	60.6	62.6	2.09	0.58	1.027	8.7	2.31	0.66	1.030	8.18
86	Sbrkoff	48	Blast Furnace	49.4	48.6	50.0	1.57	0.27	1.029	4.26	2.10	0.50	1.030	7.27
79	Gallagher	35	Doubler	63.4	61.5	62.6	7.30	0.20	1.036	1.56	9.00	0.97	1.020	3.42
79	F. Parks	45	Heater	92.8	89.9	91.0	7.40	0.19	1.032	1.87	10.11	0.38	1.032	0.67
79	Van Meter	45	Roller	87.7	84.4	86.6	6.50	0.17	1.034	0.67	9.63	0.44	1.039	1.48
79	H. Parks	22	Heater	59.5	58.2	60.3	4.75	0.23	1.032	2.00	5.82	0.44	1.038	2.92
79	Grura	41	Rougher	81.6	77.5	81.3	5.60	0.14	1.035	1.17	9.56	0.56	1.036	4.38
79	Hefferman	33	Heater	68.6	69.8	69.6	11.40	1.07	1.006	1.47	9.17	1.05	1.010	3.00
79	Stevens	36	Heater	68.0	65.5	67.2	5.90	0.21	1.028	2.06	8.19	0.86	1.030	2.78
73	Whan	44	Heater	81.5	80.2	81.8	3.68	0.48	1.030	2.10	4.50	1.41	1.018	10.10
73	McLaughlin	49	Roller	74.5	71.9	74.0	4.40	0.41	1.026	5.29	6.59	1.12	1.024	10.12
73	Wojnick	38	Matcher	76.8	75.9	77.1	7.20	0.17	1.027	1.85	7.93	2.06	1.008	8.44
73	Kinsey	34	Rougher	64.6	62.8	64.2	7.80	0.42	1.022	4.89	9.18	0.52	1.032	5.80
80	Bond	33	Open Hearth	63.5	62.2	63.5	4.56	0.23	1.034	2.65	5.63	0.47	1.035	3.93
80	Sullivan	34	Open Hearth	77.6	77.1	78.1	2.66	0.37	1.032	5.82	2.79	0.30	1.037	2.93
80	Martinko	29	Open Hearth	69.4	69.0	69.8	4.94	0.54	1.028	6.07	4.80	1.13	1.021	5.97
80	McPhillip	34	Open Hearth	77.6	77.6	77.6	3.61	0.17	1.031	1.57	3.44	0.58	1.028	4.40
80	Hensel	47	Open Hearth	67.6	66.7	67.6	4.94	0.90	1.018	10.64	4.94	1.49	1.027	6.38
86	Gessler	46	Roller	69.4	67.5	69.2	3.90	0.12	1.035	0.74	5.68	0.52	1.036	1.92
86	Austin	52	Roller	62.2	60.3	61.9	6.98	0.27	1.022	1.37	8.61	1.35	1.018	4.97
86	Katz	47	Heater	85.9	83.6	86.2	6.22	0.45	1.028	7.96	8.07	1.34	1.028	1.48
86	Crum	36	Heater	100.0	98.8	99.6	7.79	0.64	1.028	12.50	8.35	1.47	1.032	1.30
86	Maxwell	48	Matcher	64.2	63.3	64.6	6.57	0.21	1.028	2.95	7.26	1.06	1.022	9.83
90	Smith	43	Heater	93.4	92.1	93.7	6.77	0.15	1.035	1.33	7.92	0.75	1.030	2.18
90	Radnly	45	Rougher	76.0	74.4	76.2	5.13	0.15	1.034	1.85	6.58	0.87	1.034	6.62
90	Aned	25	Heater	93.2	92.6	93.7	8.61	0.08	1.030	0.82	9.13	0.68	1.034	3.70
90	Sager	46	Roller	75.5	74.4	76.0	6.15	0.20	1.034	1.40	7.05	0.85	1.032	4.51
90	Holland	38	Roller	65.8	65.8	66.0	8.71	0.47	1.027	4.70	8.24	1.30	1.025	7.18
83	Pantot	57	Rolling Mills	63.5	64.4	63.5	3.57	0.20	1.028	1.64	2.47	0.92	1.012	1.34
83	Eadie	45	Rolling Mills	64.3	63.9	64.3	4.62	0.16	1.034	2.08	4.88	0.49	1.036	8.10
85	Davis	45	Bessemer	77.3	76.6	77.1	2.94	0.27	1.026	2.65	3.37	1.17	1.010	2.33
85	Simone	49	Bessemer	71.7	69.4	71.2	2.52	0.31	1.028	4.49	4.51	0.63	1.036	3.29
85	Englehardt	55	Bessemer	86.6	84.9	87.0	5.04	0.22	1.034	2.60	6.52	0.60	1.030	1.17
85	Delvic	41	Bessemer	83.0	83.4	83.0	5.87	0.27	1.026	1.59	5.20	1.12	1.016	6.80
85	Papowich	58	Bessemer	76.4	76.6	77.1	5.04	0.60	1.036	1.80	4.24	1.04	1.034	5.84
85	Cenci	30	Bessemer	78.9	77.1	79.6	3.36	0.28	1.028	3.73	4.88	0.80	1.012	5.66
Mean.....		41.5		74.2	73.0	74.4	5.22	0.34	1.029	3.48	6.09	0.878	1.027	4.77

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altered the other conditions towards normal, and simultaneously brought complete relief.

As an outcome of these experiments one of the authors (P. H. K.) provided early in 1935 for the addition of 0.1 per cent salt to drinking water used in the Campbell Sheet Mill, a unit of the Youngstown Sheet and Tube Company. A lot of persistent talking was necessary at the beginning to quiet the objections of the men to the salt in the water. During the winter the concentration was reduced to 0.04 per cent. In February it was increased to 0.07 per cent and in the middle of March, to 0.10 per cent. At the present time (the middle of June) the only complaints come from the Brier Hill Open Hearth men who have urged the management to introduce salt in their water such as is done in the Campbell plant.

The concentration of salt which is tolerable depends on the temperature of the water. The steel world for many years has believed that water under 50°F. was harmful. Our experiments at Youngstown revealed no support for this idea and the present practice is to cool the salted water to 46°F. Experience proves that this colder water was very pleasing to the men and at the same time makes detection of the salt by taste impossible. The concentration at times has gone as high as 0.14 per cent without a single complaint. Experiments indicate, however, that 0.2 per cent is objectionable.

The results during the summer of 1935 were very favorable. The Campbell Sheet Mill was the only hot mill that was supplied with salted water all season. This Department worked almost constantly in the worst hot wave and it was never necessary to slow the mill down as is often the case in hot weather. There was not a single exhaustion or cramp case in the mill all summer.

This year (1936), with a considerable number of new men on the job there have been among 12,000 workmen 22 heat cases, 11 with cramps and 11 with exhaustion.* All but three of these were diagnosed by first aid men or nurses. Only one case was hospitalized over night; he had taken Epsom salts the previous night and had had diarrhea through the next working day. The other 21 cases were treated with a level teaspoon of salt every half-hour for three doses with all the water desired between doses. These men returned to work the following day and there was no recurrence of symptoms. Eighteen of these men were doing hot work either after a lay-off or after a transfer from a cold job. Special attention is now being paid to provide new men on hot work with additional salt for a few days. Salt dispensers are located near hot jobs and foremen instruct new workers in their use.

The importance of acclimatization to high temperature is related to the fact that the salt concentration in sweat is high for the first few days. It may decrease more than 50 per cent during the period of adaptation (27). Accordingly the salt requirement for the new man is twice as great as for the seasoned worker, other things being equal. However, even after

* In the early days of the industry it was not unusual to have this number of men sent home in one or two days. As recently as June, 1933, 12 cases were put to bed in one day.

adaptation Dill, Jones, Edwards and Oberg (28) have shown that the individual variation in salt concentration in sweat remains large. This probably explains why some men are more susceptible to heat cramps than others.

The slowness with which sound practices become established is illustrated by the history of the provision of salt for men doing hard work in a high temperature. Talbott's review of heat cramps (29) shows that the efficacy of salt has been known in some circles for a great many years. Glover, for example, has been using it in Cleveland steel mills since 1927 (30). Yet when we visited Boulder City in 1932 the chief advice being given to workmen was, "The doctor says 'Drink plenty of water!'" And 2 years later the medical officer for one large steel company advised treating cases of heat cramps with glucose injection only.

Failure to reestablish equilibrium during rest and sleep means that fatigue becomes cumulative. It was possible to ascribe some cases of cramps or prostration observed during 1934 at Youngstown to overtime work or to overindulgence in liquor. In the one condition there is excessive upset in equilibrium during work and at the same time a shortened period for recuperation. In the other case liquor may reduce the food and salt intake, thus interfering with recovery processes. Vomiting is especially serious since it opens a new channel for loss of sodium and chloride ions.

Early experiences at Boulder Dam prove the ability of man to undergo extremely rigorous conditions during work, provided rest and sleep are adequate. The first summer of construction was unusually hot,—shade temperatures at the dam site reaching 128°F. on two occasions. Sometimes the temperature remained above 100° until after midnight. In the dormitories near the dam site sleep was difficult and sweating almost continuous. There were 15 deaths from heat and an undetermined number of non-fatal cases of cramps and exhaustion.

Our studies were carried out during the next summer. All workmen were then housed on the plateau at Boulder City. Here the temperature was lower, dormitories were air-conditioned and normal sleep was possible even in the daytime. The few heat cases brought to the well-equipped hospital at Boulder City responded readily to treatment; there was not a single death from heat. While many factors were responsible for the improved record during the second summer, the difference in the environmental conditions during the 16 hour period of recovery was certainly of major importance.

There is no fully satisfactory explanation for the severe cramps experienced by steelworkers, stokers, railway firemen, etc. Water intoxication is not responsible, as Haldane believed (31), since the osmotic pressure remains normal and the cure consists in administering isotonic salt solution. While there is a major change in concentration of protein and of the sodium and chloride ions in blood plasma and probably in tissue fluids, it is not possible to assign the increased irritability to any one of these factors alone. Probably prolonged or severe muscular activity is an essential feature, for men doing hard work are the

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characteristic victims. It is a reasonable hypothesis that the severity of cramps depends both on intensity of work and degree of salt loss. The cramps experienced by football players may well lie in the same category as heat cramps. Their salt loss is less, but the intensity of exertion is greater. Experiments initiated by Dr. T. K. Richards and continued by Dr. Augustus Thorndyke (of the Harvard Department of Hygiene) on the effects of extra salt on the incidence of cramps in football players has been favorable. The players are advised to use salt liberally with meals, and bouillon is provided during intermission in play. No case of severe cramps has been observed in Harvard football players Eho have followed this regime.

The reduction in incidence and severity of heat exhaustion cases because of salt ingestion is more difficult to understand than the effect of salt on heat cramps. Cases of exhaustion are not characterized by excessive salt depletion. This subject merits further study since this form of breakdown is common in many sections of North America.

Closely linked to the problem of maintaining equilibrium are the regulating and coördinating mechanisms. This complicated subject deserves careful study in relation to fatigue, but cannot be dealt with in detail here. Reference may be made to Cannon's work on this subject (32, 33) and to Peters' studies of the exchange of fluids in man (34). Mention should also be made of the rôle of the adrenal cortex; the facts that muscular weakness is a characteristic feature of Addison's disease, in which the adrenals are diseased, and that the hormone is intimately concerned with maintenance of sodium and chloride levels seem quite significant (35). The concentration of these two ions must be accurately regulated for well-being.

Summary

Illustrations are given of fatigue in which (a) the accumulation of lactic acid is a notable feature; (b) the exhaustion of energy reserves makes the use of glucose or other readily available fuel advisable; (c) the inadequacy of oxygen supply contributes to breakdown, and (d) alteration in physico-chemical state is observed. These various mechanisms are not mutually independent and there appears to be little prospect of developing a simple and adequate hypothesis regarding the origin and nature of fatigue.

The water and salt exchange in a group of steel workers is presented as an illustration of fatigue in which disturbance of physico-chemical equilibrium is an outstanding feature. It is shown that work under very rigorous conditions can be carried on provided the diet is suitable and the period of rest and sleep is adequate. In such activity the danger of breakdown is reduced by supplying cold drinking water containing 0.1 per cent salt.

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AIR BORNE INFECTION*

H. D. Chope and W. G. Smillie

THE science of bacteriology rests upon the initial experiments of Pasteur relating to air borne infections. He showed conclusively by his classical experiments that sterile flasks of broth were infected by living micro-organisms when exposed to the air.

It was soon shown that micro-organisms produced diseased conditions in man, particularly if the skin or mucous membrane was broken. It was quite logical to maintain the assumption that some micro-organisms, perhaps all of them, were potentially harmful. It was assumed also that air was the chief source, or at least one of the important sources of human infection.

Thus the early work of Pasteur firmly fixed the idea in the scientific minds of the day that human disease was air borne. This conclusion was a natural and easy transition from Pettenkofer's theory that disease was due to certain poisons which were generated in a polluted soil and that these deadly emanations were transmitted through the air to human beings, thus producing cholera, typhoid fever, smallpox and other conditions. To make the transition from Pettenkofer to Pasteur's theory, it was only necessary to substitute micro-organisms for the word poisons.

Pettenkofer's hypothesis was not an original one. The conception that disease might be transmitted from person to person through the medium of the air dates back to antiquity.

Historical Development

Four hundred years before Christ, Hippocrates wrote in his book "On Winds" (1) "According to all appearances the cause of disease should be found in the air, when it enters the body in excess or in insufficient quantity or too much at a time or *when tainted by morbid miasmas.*"

Up to the time of Hippocrates, evil spirits, displeased gods, or other supernatural forces were held responsible for disease and pain; the priest or witch doctor was the physician; and theology, philosophy and medicine were one and the same science.

Since these early times air always has been assigned an important part as the cause of disease. Hippocrates described four elements which controlled disease, fire, air, water and earth. Galen, 600 years later, taught the same doctrine.

Air was also thought by civilizations other than the Greek and Roman to be a disease bearer. Rhazes, the famous Arabian physician, in his classical work (2) in which he clearly

* From the Department of Public Health Administration, Harvard School of Public Health, Boston.

distinguishes measles from smallpox makes the following statement: "As for old men, smallpox seldom happens to them except in pestilential, putrid and malignant constitutions of air in which this disease is chiefly prevalent." Another Arabian physician, Ibu al Khatib, advised (3): "A disinfection of the circumambient air by good clean smells, and the avoidance of the places where one may expect corruption from those sick and dead of the disease, their clothes, vessels and utensils, avoidance of entry into an infected house or of approach to the neighborhood of the sick."

During the middle ages the teachings of Galen prevailed, and the scientific world was principally occupied with philosophical debates. Not until the writings of Fracastorius (4) who described and named the Great Pox in his poem "Syphilis sive Morbus Gallicus" do we find further contribution to ideas of air and disease. He divided contagious diseases into three categories: (a) Those that infect only by contact, (b) those that infect by contact and by fomites, and (c) those that infect not only by direct contact or through the agency of a residuary center or focus of infection, but also those that are capable of spreading their infective elements over wide areas. He also anticipated the germ theory by nearly 400 years when he elucidated his belief that contagious diseases were caused by "seminaria contagionum" or seeds of contagion, which were capable of reproduction and probably carried in the air.

It is at about this time that we find two great influences affecting scientific thought. First, the fetters of ancient tradition were being thrown off and the experimental method was being recognized. Harvey discovered the circulation of the blood. Many other great names of that period have been carried down to posterity because of their careful experimental observations —Malphigi, Fallopius, Eustachius, Pacchioni, Wharton and many others.

The second great influence upon scientific advancement was the development of the microscope. The first microscopist was Athanasius, who in 1658 published his "Scrutinum Pestis" which put forth the ideas of "contagia animata"—or animals of contagion. This was a step ahead of Fracastorius's theory of seeds of contagion.

Leeuwenhoek (5) (1632–1732) spent his life developing the microscope and making microscopic observations. He constructed some 375 microscopes and was the first to describe bacteria. He discovered these micro-organisms when he looked at material that he had scraped from his teeth.

The discovery by Leeuwenhoek of animalculae poured oil on the fire of controversy over spontaneous generation. The proponents of the theory, which had prevailed since the earliest records of scientific history, were finding trouble in proving that frogs sprang from mud and that mice were generated by cheese and rags. But when Leeuwenhoek showed the presence of microscopic organisms in water that had been exposed to the air, the scientists of the day who believed in spontaneous generation seized this new evidence and began a controversy that lasted nearly a hundred years as to the origin of these animalculae.

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In 1668 Redi, by using the experimental method, proved that maggots were not spontaneously generated in meat. But Leeuwenhoek's microscope brought into view a world of life formed of individuals so small that "the easy passage from atoms to organisms" was suggested.

In 1777 Spallanzani published his experiments in answer to Needham and Buffon, postulating organic molecules. The work was so precise and the conclusions so clearly drawn that spontaneous generation was dealt a serious blow. He definitely showed that organic matter in the form of living germs was present in the air. These results were substantiated later by the work of Schwann and Schulze (6).

Just as the theory of spontaneous generation seemed doomed to die, the director of the Museum of Natural History at Rouen, F. A. Pouchet, opened up the whole question again. He had a good name as a scientist and his attack on the opponents of spontaneous generation was so vehement that it stirred up considerable comment. In fact, this controversy was sufficient to attract the interest of Pasteur (7) who set out, against the advice of Dumas, to settle the question of spontaneous generation once and for all. Pasteur had already studied fermentation and was well prepared to put this new proposition to the critical analysis of his scientific mind. In his paper on "The Organized Corpuscles existing in the Atmosphere", which was published in 1862, he reported his historical experiments. He collected floating particles and studied them under the microscope. He repeated the experiments of Spallanzani, Schwann, Schultze and others, and showed the fallacy of Pouchet's arguments. He carried flasks to Mer de Glace and exposed them to the glacial air; after this exposure, only one flask in twenty showed growth. Flasks treated in the same way in the lowlands showed growth in twenty of twenty.

Lister (8), being convinced by Pasteur's experiments and drawing inspiration from them, developed antiseptic surgery. As disease particles were born in the air and as the selfsame particles were found in pus from wounds, it seemed logical to believe that the pus or putrefaction was produced by organisms in the air that fell into the wound. He devised an elaborate operating room technic which provided for saturation of the air about the zone of the operating field with a finely divided carbolized vapor. Lister met with great opposition from his colleagues, not on the grounds that infection was or was not air borne, but rather because his fellow surgeons did not believe that septic conditions were due to living, growing micro-organisms.

Lister also thought that these pathogenic bacteria came from putrefaction of the dead, and he was horrified to find that men who had died with cholera had been buried in crypts near the hospital. He believed that the emanations from these bodies were responsible for the spread of infection through the air to the wards that were adjacent to the burying place.

Lister himself was one of the first to discover that air infection did not play an important part in surgical infections and abandoned the use of the carbolized spray in his operating room.

Following the discoveries of Pasteur

that bacteria actually lived in the air and also that bacteria caused disease, many scientists jumped to the conclusion that all living bacteria might be harmful to mankind and that all might be air borne. What reasoning could be more logical than the hypothesis that all or most all diseases were spread through the medium of the air? The epidemiological evidence in malaria and yellow fever, for example, could admit of no other tenable conclusion. They must be air borne. It required nearly 50 years to break down this theory and prove that these diseases were not borne through the air directly, but were transmitted from person to person through the bite of an infected mosquito that used the air as its medium.

Air borne infections were shown to be quite a common occurrence in other fields. It was easy to demonstrate that cheeses, wines, milk, meats, meat products and the like were infected by bacteria that travelled through the air. It had long been suspected that many plant diseases were transmitted through air borne channels and in no other manner.

Was it not more than probable that animal and human diseases were transmitted through this same vehicle?

Thus an elaborate system was developed for sterilization of the environment of an individual who had suffered from infectious diseases. Various gaseous disinfectants were employed. Formaldehyde fumigation became the standard technic. The purpose of gaseous fumigation was not solely to disinfect the linen and bedding of the patient, but rather to kill any organisms that might remain in the atmosphere after the patient had died or after he had been discharged from isolation.

Many instances were reported of infections, particularly smallpox, malaria and yellow fever, that had been carried long distances through the air. The conception of the rôle of the "carrier" in the spread of infection had not been developed; "spontaneous generation" of disease processes was untenable; therefore the only possible source of numerous outbreaks of infections must be a transmission of the living agent through the medium of the air.

As our knowledge of modes of infection increased, however, the former long list of air borne diseases decreased correspondingly.

The Gastro-intestinal Infections

Snow's studies of the "Broad Street Pump" epidemic of cholera in London and Budd's classical studies of the rôle of water in transmission of typhoid fever gave strong epidemiological proof that the most important vehicle of infection in this group of diseases is polluted water. This work was done long before the specific infectious agents of these conditions were discovered. To this early work was added the transmission factor of contaminated food as a source of gastro-intestinal infection. Much later, the importance of the carrier as a source of food and water contamination was determined. All subsequent evidence has substantiated the early theories that this great group of contagious diseases is not transmitted through the medium of the air. All our accumulated bacteriological and epidemiological evidence proves conclusively that food and drink are the chief

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sources of the gastro-intestinal infections.

Insect Borne Diseases

The conception of Theobald Smith that insects might serve as intermediate hosts in transmission of infection opened an entirely new field in epidemiology. Diseases, the transmission of which could not possibly be explained on any other basis than through the medium of the air, now were clearly explainable on other grounds. Malaria had been the best example of a typical air borne infection, and now it was shown to be transmitted by anopheles mosquitoes. The early records of the U. S. Marine Hospital Service are full of accounts of heroic efforts by the staff officers to check yellow fever through measures intended to sterilize the infected air. It was a severe blow to the theory of air borne infection when scientific workers discovered that yellow fever could be transmitted only through the bite of Aedes Egypti mosquitoes. One by one, many of the diseases of man, of animals, and of plants as well, that formerly were considered as typical air borne infections were discovered to be transmitted through the medium of insects, or some other intermediate host.

Diseases Spread through the Discharges from the Respiratory Tract

A large number of important infectious diseases are included in this category. All the common communicable diseases of childhood, such as measles, scarlet fever, diphtheria, etc., as well as influenza, pneumonia, tuberculosis, cerebro-spinal meningitis, poliomyelitis, the most common of all human infections—the "common cold", and a host of other diseases are spread through the discharges from the nose and throat of mankind. It is quite clear that, in a limited sense at least, these infections are always air borne. The only question is the length of the radius that these infections will spread through the air from the infected host. For many years it was believed that the infection radius was extensive and elaborate isolation and quarantine regulations were formulated to prevent the spread of infection from the patient to others through the air. Contagious hospitals were far removed from general hospitals, in fact, from all human habitation, because of the supposed danger of air borne infection.

Charles V. Chapin, from his long experience in the care of contagious disease, became convinced that close personal contact was the most important factor in transmission of respiratory diseases and was able to show that the infectious agents of many of the most contagious diseases do not spread more than a few feet from the host, if proper aseptic technic is followed.

In 1912 Chapin made a thorough review of the literature up to that time (some 208 articles) (10) and came to the following conclusions:

1. The theory of the aerial transmission of disease was developed as the most reasonable way of explaining the phenomena of infection.
2. Contact infection with carriers and missed cases affords a better explanation of the phenomena.
3. The best medical thought has been steadily restricting the supposed sphere of aerial transmission.
4. Only a few authorities now assert that disease is carried by the atmosphere outside of dwellings, and this assertion is made only in regard to smallpox.
5. Bacteriology teaches that former ideas in regard to the manner in which diseases may be air borne are entirely erroneous; that most diseases are not likely to be dust borne and they are spray borne only for 2 or 3 feet, a phenomenon which, after all, resembles contact infection more than it does aerial infection as ordinarily understood.
6. Surgeons at first developed aseptic surgery on the theory that air infection was of the highest importance. They have gradually learned to pay less attention to it, until at present some of the best surgeons consider it a negligible factor.
7. Animal experimentation indicates that tuberculosis and anthrax may be air borne and that plague and some other diseases are not.
8. There is no good clinical evidence that the common diseases are air borne. There is considerable clinical evidence that scarlet fever, diphtheria, smallpox, measles, whooping cough, typhoid fever and plague are not easily transmissable through the air.

In the main, Chapin's conclusions have stood the test of time. Subsequent epidemiological evidence has emphasized the fact that personal contact is an essential factor in the transmission of most of the infections that are spread through discharges of the nose and throat.

How important then is the air as a vehicle in transmission of these contact infections? Since Chapin's studies, most authorities have agreed that the radius of infection from the host is dependent only upon (a) the distance that droplets of moisture from coughing and sneezing will spread, and (b) the length of time that the infectious agent will live in the droplet after it has been expelled from the human host. Since droplets fall amost immediately to the earth, the air itself would play little or no part in transmission of infection.

There can be little question but that Chapin was correct in his conclusions that close personal contact is a very important factor in transmission of the respiratory group of infections. Is it the only factor? It is almost impossible to rule out direct contact of a susceptible individual with an infected person, since it is so difficult to prove that contact has not occurred.

The whole question was reopened following an epidemic of psittacosis (11) in the National Institute of Health in Washington. These epidemiological studies indicated strongly that the infection in this instance was air borne. Careful studies excluded other modes of transfer. If this disease, due to a filterable virus, could be transmitted through the air as a medium, is it not possible that the virus of the common cold, the virus of influenza, of small pox and measles, of encephalitis and other conditions could be transmitted also through the same medium? Laidlaw's studies with distemper of dogs (12) indicate at least the possibility that this infection might be transmitted through the air for some distance.

Is it not worth while to reopen this subject, if suitable methods of study

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can be devised to yield satisfactory results? A better understanding of the epidemiology of the common cold would warrant such an effort. We have comparatively little exact knowledge of the bacteriology of the air, even though bacteriology as a science is based on Pasteur's original studies of the presence of micro-organisms in the air. It is true that epidemiological evidence has been accumulated which clearly shows that most of the infections that were once considered as air borne are undoubtedly transmitted through other vehicles. But it would be a great mistake to conclude without further evidence that air plays no part as a vehicle of transmission of communicable diseases.

Methods for Determination of Bacteria in the Air

Early Methods of Enumerating Bacteria with Fluid Media

1. Pasteur (13) in a work already quoted tried to obtain a quantitative estimate of bacteria in the air by a method somewhat similar to the present day methods used for estimating *B. coli* in water or in shellfish. He exposed a number of flasks to different atmospheres and then sealed them. The flasks were incubated and the contaminated ones were counted.

2. Tyndall (14), before the discovery of solid media by Koch, set up a method of estimating bacteria in air. He prepared a table with 100 apertures in it. Into each of these he placed a tube of nutrient media. Then he exposed the board to the air that was to be studied and counted the tubes that were contaminated.

3. Miquel (15) was the first to apply the filtration principle to air. He filtered air through glass wool. This glass wool was then washed with a definite quantity of sterile water. Small aliquot parts of this water were then added to many tubes of broth. The amount inoculated into the tubes was supposed to be so small that only a part of the tubes became infected. Miquel contended that the organisms were distributed at such wide intervals that not every part of the wash water contained an organism. Therefore, the tubes that did show growth must have received only one organism.

Methods of Enumerating Bacteria through Utilization of Solid Media

1. In 1881 Koch (16) published his plate method of obtaining pure cultures. In the experiments of Pasteur and others, broth had been exposed to the air as a qualitative test for the presence of bacteria. With the advent of the solid culture media, it became possible to make a quantitative estimate by exposing a plate of solid media to the air for a definite length of time and then counting the colonies that developed on the plate after it had been inoculated.

2. In an effort to make the method more quantitative and determine the number of bacteria per liter of air, Hesse (17) in 1883 devised the Hesse tube. This was a glass tube 70 cm. long and .75 cm. in diameter which had previously been coated with nutrient agar on the inside. A known volume of air was then slowly drawn through the tube and the colonies counted.

3. Frankland (18) in 1886 worked with the Hesse method, but decided that it was not accurate, as the direction of the wind played a large rôle in introducing organisms. He found that outside determinations were higher than indoor determinations, irrespective of aspiration; so he devised a method based on Miquel's glass wool filtration, but using solid media. Some of the glass wool plugs were coated with sugar and others were not. After aspiration of a definite volume of air the plugs were placed in sterile water (5, 10 or 20 cc.) and thoroughly shaken until broken up. Measured quantities of this water were then mixed with agar and plated, and after the plates were incubated, the colonies were counted.

4. In 1888 Petri (19) described his method which was also based on the principle of filtration. He filtered the air through a tube containing sand which would pass a 100 mesh sieve. The tube was 9 cm. long and 1.6 cm. in diameter. A definite volume of air was filtered. The sand was then mixed with normal saline solution and aliquot parts of the solution were plated. In 1896 Ficker (20) modified this method by substituting ground glass for the sand. Sedgwick (21) suggested in 1888 that sugar be substituted for the sand and described his aerobioscope before the National Academy of Sciences. In 1909 the American Public Health Association adopted the Petri Sand Filter as the standard method of bacterial air analysis. Ruehle (22) suggested a slight modification of this method in 1915 which was adopted in the final report of the Committee on Standard Methods for the Examination of Air (23). As this is the standard recommended technic it is described in detail. A glass tube 15 mm. in diameter and 70 mm. long with a smaller tube 6 mm. in diameter and 40 mm. long, fused into one end is used as the filter. On the shoulder between the two tubes is placed a plug of cotton supporting a layer of sand 10 mm. deep. The sand is of such fineness that it passes a 100 mesh sieve, but not a 200 mesh one. The other end of the tube is plugged with a cork stopper bearing an outlet tube 6 mm. in diameter and 40 mm. long, bent at an angle of 45°. Five cubic feet of air are drawn through the filter. After filtration the sand is shaken into 10 cc. of sterile water and thoroughly agitated. Aliquot parts of this suspension are plated in nutrient agar. Brown (24) in 1917 suggested a further modification of this method in which the filter tube and a washing tube were fused to each other at an angle of 90° so that the whole operation could be carried on in one piece of apparatus. This method has not been widely used.

5. In 1908 C.-E. A. Winslow (25) described a modification of the Hesse idea. He drew air into two 2½ liter flasks connected in series and containing a layer of nutrient agar in the bottom. A known amount of air was then drawn through the apparatus, usually about 1 liter. The bottles were then incubated and the number of bacteria counted.

6. Rettger (26) in an effort to simplify the technic drew air through 5 cc. of sterile saline solution. The column of air was broken up into minute bubbles by a perforated glass bulb fused to the end of the intake tube. This suspension was then mixed with an equal amount of double strength nutrient agar and plated. The apparatus was also washed out with a second 5 cc. portion of sterile

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saline solution which was plated. This supplementary procedure was intended to collect any bacteria that adhered to the sides of the apparatus. W. J. McConnell (27) modified this method by inserting one tube inside another. The inner tube was covered with fine bolting cloth to break up the air stream that was aspirated through the saline solution in the tube.

7. McConnell (27) also devised a method of collecting bacteria with the Anderson-Armspach (28) dust determinator on filter paper. The filter paper was then cultured in the usual manner.

8. In 1933 Wells (29) described an apparatus for enumerating bacteria in air, which was based on the principle of direct centrifugal precipitation of the bacteria on nutrient agar. This method and the results that have been secured with it are described by Mr. Wells elsewhere (30).

As far as can be ascertained, these eight types of apparatus built around the three principles—precipitation, sand filtration and water filtration—constitute all the methods that have been developed for the enumeration of bacteria in air.

Relative Merits of the Different Methods

Several investigators have studied and compared the various methods. Their conclusions as to the relative merits of the different methods may be of value in interpreting the results obtained from the respective methods.

Soper (31) in a study of the air of the New York Subways in 1906 compared the open plate method of Koch with the Sedgwick aerobioscope, using fine sand as a filter. His figures showed:

	Subway	*Street*
Plate	500	1157*
Filter	3200	6500

* Exposed 15 minutes.

From these figures and other experiments he concluded that the filter gave the best quantitative estimate, but that for matters of comparison the plate method was adequate and much simpler.

When Winslow (25) presented his jar aeroscope he compared the fine sand filter and the coarse sand filter. The fine sand varied from 0.1 to 0.3 mm., while the coarse varied from 0.5 to 1 mm. He concluded that his culture-bottle method was the most accurate. He found that the coarse sand filter was open to gross errors, and the fine sand filter was more convenient but less accurate than his own technic.

The American Public Health Association Committee of Standards described the sand filter, as modified by Ruehle, as the standard method in 1917 (23). This method was based partly on research done by Ruehle (32) in 1915. He compared the saline aeroscope of Rettger, the standard sand filter at that time, and his modified sand filter described above as the standard method. By placing two pieces of apparatus in series he studied the efficiency of the different methods with the following results:

	Per cent
Standard Sand Filter	
Highest average efficiency	92
Lowest average efficiency	90
Rettger Saline Filter	
Highest average efficiency	97
Lowest average efficiency	93
Modified Sand Filter	
Highest average efficiency	99
Lowest average efficiency	96

He points out that the chief difficulty with the Rettger saline filter is in sterilizing it so that the saline does not condense on the tube and in keeping the stoppers from leaking. Also some difficulty is encountered from foaming. It hardly seems that this would be an efficient filter as Tyndall (9) pointed out in 1876 that dust and bacteria would pass right through water or sulfuric acid without being damaged unless the bubbles were very small. The former standard apparatus equipped with two rubber stoppers had to be sterilized by steam. This tended to cause the sand to cake and thus spoiled its efficiency as a filtering agent. Ruehle points out that the plate method and all methods depending upon precipitation of particles have the common fault that they enumerate not bacteria in the air, but the number of dust particles that carry single bacteria or the clumps of organisms.

McConnell (27) compared the Anderson-Armspach dust determinator (28), a water aeroscope of his own design, the standard sand aeroscope and the sugar aeroscope used by Sedgwick. He found that the filter paper method was efficient, but the technic was too difficult for routine use. His results show that the water aeroscope is ten times as efficient as the sand aeroscope. These comparisons of efficiency were made by blowing a suspension of *B. coli* and *Staphylococcus albus* into a hood for 10 seconds before each experiment. The air in the hood was kept in motion during the sampling. It seems that the regulation of the conditions is altogether too crude to utilize as a method for comparison of the efficiency of the various procedures. The sugar aeroscope was found very unsatisfactory because of difficulty in sterilization. With dry heat the sugar was caramelized and with moist heat it became a solid mass.

Criteria for an Aerial Bacteria Enumerator

In order to evaluate the various procedures listed above on a theoretical rather than an experimental basis the following criteria for an aeroscope have been set up:

The instrument must have the following characteristics: (1) Easy portability, (2) Simplicity, (3) Rapid and easy manipulation, (4) High efficiency, and (5) Wide range of applicability.

The plate method is portable and simple, but is of no value quantitatively. The number of bacteria falling on the plate in a given period of time is governed by chance only and is not under the control of the operator. Air motion over the plate is one factor that would have a great influence in the count. This method may then be considered a simple, quick, easy, inefficient method without quantitative value and may be used to give a rough comparison between two environments.

The methods of Hesse and Winslow have the decided advantage that there is no intermediate step between the collection of the sample and cultivation of it, e.g., the sample is taken directly on the final culture media. The apparatus as designed by Winslow is not portable. The Hesse tube is not accurate, as pointed out by Frankland. The range of applicability of these procedures has never been determined. In the laboratory,

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however, it seems that the Winslow bottle method would be useful in checking the efficiency of other procedures. This could be done by attaching the two or three bottles in series with the exhaust of the apparatus under observation.

The sand filters are portable and constructed on a simple principle, but they have several decided disadvantages. First, the sand must be graded and carefully sterilized to avoid caking. The most glaring deficiency in the sand filter method is that the results obtained do not represent the number of bacteria in the air, but only the number that lived after the process of filtration and until the culture was made.

The water filter is portable, simple to set up, and good claims are made for its efficiency. It has the disadvantage that there is an intermediate step between the collection of the sample and the plating of the sample on the nutrient media. This objection is not as important as in the case of the sand filter, as more bacteria probably live in saline solution than on sand. The efficiency of the saline filter is open to some doubt, since Tyndall showed that dust and bacteria in air bubbles could pass directly through water without being wetted. This was particularly true if the number of bacteria was large.

The Wells apparatus is portable, but demands an electric current for its operation. It is simple to operate and easily and quickly manipulated. It has the distinct advantage that the media upon which the bacteria are counted is the same upon which the sample is taken. The apparatus has a wide range of application, since any type of media desired—plain agar, blood agar, Endo's or any other special media—may be used.

Summary

In summary, the following conclusions may be drawn in relation to our present knowledge of bacteriology of the air and its relationship to air borne infection.

1. Bacteria are introduced into the air by extraneous forces. The principal source is from dust that contains dry bacteria and spores. Most of these bacteria are harmless to man. Most pathogenic bacteria that occur in the air come from human mucous membranes. These bacteria are introduced by the coughing or sneezing of bacteria-laden droplets of moisture from the nose and throat of human beings.

2. The number of bacteria in the air is dependent upon the activity in the environment and the amount of dust stirred up. The following observations tend to verify the conclusion:

(a) There are more bacteria in the air during the day than during the night.

(b) The number of bacteria in the air is increased by sweeping.

(c) The number of bacteria decreases as altitude increases and at sea.

(d) The number of bacteria in air is higher in dirty and untidy rooms than in clean rooms.

(e) The number of bacteria in air is higher in small, poorly ventilated rooms than in larger rooms.

(f) The number of bacteria varies markedly with season. The air during the dry summer months contains many more bacteria than during the wet winter months.

(g) The bacteria vary in numbers from day to day depending upon weather conditions, the numbers being highest on dry windy days.

(h) The number of bacteria in the air of a room is increased by activity in the room as shown in school rooms with the students drilling and in the smoking room of the House of Commons.

(i) The air in cities shows heavier bacterial pollution than the air of the country.

3. Well ventilated rooms show fewer bacteria than poorly ventilated rooms.

4. Pathogenic bacteria are so widely dispersed in the outside atmosphere as to be of no practical significance. They are probably of significance only in enclosed places of dense human congregation.

5. Air as a factor in the spread of disease is not as important as the early developments of the science of bacteriology seemed to indicate. One by one the various contagious diseases have been shown to be transmitted by other vehicles. Recent evidence indicates, however, that some diseases may be transmitted through the air as a medium.

6. Experiments under controlled conditions which attempt to study the length of life and the behavior of pathogens in the air is the next essential step in advancement of our knowledge of these matters. This approach to the subject has been Mr. Well's important contribution to this field.

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AIR-BORNE INFECTION AND SANITARY CONTROL*

William Firth Wells and Mildred Weeks Wells

IN THE dissemination of plant life, the atmosphere is nature's prime sower of the seed and thus vitally affects all living things. Air currents, by gripping the extended surfaces of winged larger seeds and the protuberances of the smaller pollens, lift, transport and release them at their destinations. As the size of particles decreases, the weight decreases more rapidly than the surface area and the tiny spores of molds and fungi require no special adaptation for air travel. Bacteria are even smaller, but since they have no power to invade the atmosphere except in association with other matter, their flight range is determined not by size but by the character of the matter with which they are associated.

"Dust and droplets wafted into the air include bacteria. The number of such temporary passengers on the wing depends upon the kind, the source and conditions which lift them into the air, their survival rate, the air currents which transport, disperse and dilute them within the atmosphere, the rate of deposition and the physical and chemical conditions of their atmospheric environment" (1).

The theater of operation of these phenomena is vast: micro-organisms have been found in polar flights and in the highest penetrations of the stratosphere. We are not concerned with this outer atmosphere except as a source of infinite dilution, and in this paper only the dense layer close to the earth's surface will be considered. Particularly in those semienclosed atmospheres wherein we live, dilution is restricted and the spread of parasites is facilitated. On the other hand, these ventilated spaces are also most subject to human control.

Perhaps a discussion of bacteria in air should begin with the pregnant researches of Louis Pasteur, which inaugurated the science of bacteriology and the germ theory of disease. His classic experiments on spontaneous generation, published in 1861 (2), proved that air was populated with microscopic germs which caused putrefaction and fermentation. This fact seemed to substantiate the universal belief that air was the vehicle of contagion, and for twenty years thereafter this thought motivated the work of Lister (3) and of Tyndall (4). Strangely enough, the perfection of bacteriologic technic during the last two decades of the nineteenth century, in which the specific agents of disease were identified, disclosed in rapid succession their transmission by other routes without demonstrating in air recognized pathogenic organisms. When Flügge (5) failed to recover

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nasopharyngeal organisms on plates exposed farther than a few feet from a person coughing and sneezing and concluded that they settled out in short distances and in brief time intervals, air-borne infection seemed almost eliminated. Meanwhile, sanitary bacteriology during the next twenty years, by demonstrating general bacterial contamination, seemed to justify the belief that such diseases as could not otherwise be accounted for were spread by direct or indirect contact. In the face of the growing momentum of contrary opinion based on this negative evidence, the case against air was dismissed with a Scotch verdict, and the theory of air-borne transmission of infection was well-nigh abandoned.

During the past five years, certain developments in the technic of air bacteriology at Harvard University have caused a modification of our views regarding the inability of air to transmit infection. The invention of an instrument (6) for the extensive exploration of and the practical experimentation on controlled atmospheres initiated these studies. The development of a technic for producing bacterial suspensions by atomizing cultures into these controlled atmospheres became an important factor in the experimental investigation. The technic so developed provided a means for the study of the dispersion of bacteria in air, and the effect of physical and chemical agents on their viability.

The Exchange of Nasopharyngeal Flora by Air

1. Droplets and Droplet Nuclei (7)

Droplets expelled into the air from the nose and throat in sneezing, coughing, and the like, do not necessarily, as was concluded from Flügge's experiments, fall immediately to the ground within a short distance from their source. This theory is based on an assumption of constant size, which ignores the important factor of evaporation. As droplets become smaller, the surface exposed to air resistance becomes relatively greater when compared to the weight or gravitational pull toward the earth, and droplets therefore, in accordance with Stokes's law, fall more and more slowly as the size becomes smaller and smaller. The rate of evaporation, which also depends on the surface area, becomes relatively more rapid as the droplet volume becomes smaller, and some size must exist smaller than which a droplet could not fall the height of a man without complete evaporation. This droplet size has been estimated as approximately 0.1 mm. The residues of droplets of this size, derived from physiologic solution of sodium chloride or from body fluids are, after evaporation, so small that their behavior in air is more comparable to a particle of smoke than to the droplets described by Flügge. They may be considered to float or drift with the slightest air currents and therefore to be in effect a part of the atmosphere itself.

This fact may be simply demonstrated by atomizing liquids into a dark enclosed chamber, such as our experimental tank, through which a strong beam of light is projected. Distilled water evaporates almost immediately, leaving no evidence in the beam. If the liquid contains substances in solution, the nuclear residues leave a fog on evaporation, which is clearly revealed by the tyndall

effect. The presence of salts suspended in air can be easily demonstrated by drawing the air through a Bunsen flame.

Liquid suspensions of micro-organisms may be atomized into the tank and their presence can be easily demonstrated quantitatively by the air centrifuge. It may readily be shown that they persist in diminishing numbers for hours or days.

Transmission of infection through the air may therefore take one of two forms, depending on the size of the infected droplet. The more obvious form, recognized by Flügge, is droplet infection proper. It applies to droplets larger than 0.1 mm. in diameter, which are rapidly removed from the air by gravity before they can dry and within a short distance from the source. The second form may be called air-bone infection and deals with the dried residues of infected

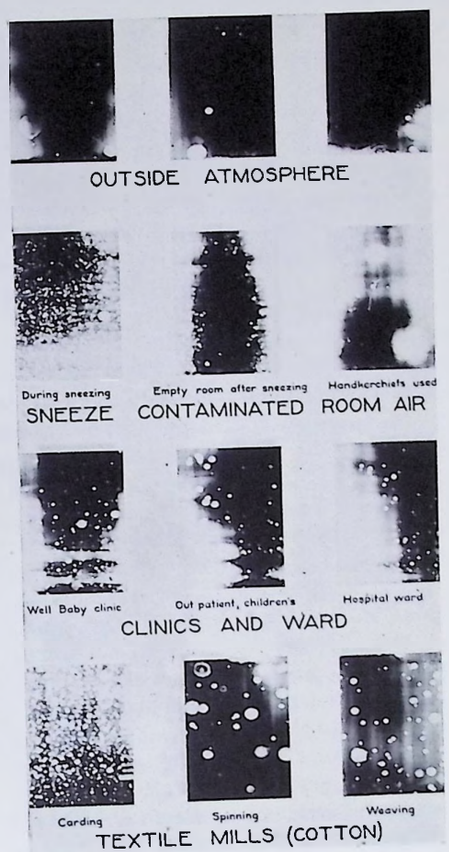


Fig. 1.—Bacteria in air

droplets, or droplet nuclei, derived directly from droplets less than 0.1 mm. in diameter, depending primarily on air for the buoyancy that keeps them suspended for longer times and carries them longer distances. Droplet infection may change into air-borne infection when larger drops settle, evaporate and are lifted into the air as dust.

The epidemiologic characteristics of droplet infection and droplet nuclei infection are by nature opposite. Droplet infection is essentially localized and concentrated, while infection broadcast by droplet nuclei is more dispersed and dilute.

The basic fact that micro-organisms can remain suspended alive in air for periods which may permit their wide dissemination has thus been demonstrated.

2. *Viability of Droplet Nuclei Infection (8)*

The interval of time spent in the air by Flügge droplets is too brief for significant change in the viability of infection, as it is also too brief for wide dissemination. Since droplet nuclei remain in suspension for long times and may drift considerable distances, the viability of the bacteria associated with them becomes an important factor in the spread of air-borne infection. The difference between the rate at which droplet nuclei are removed from the atmosphere by settling, and the rate at which infection disappears from the air into which they are expelled, depends on the rate of survival of micro-organisms attached to these nuclei. The disappearance rates have been determined for sixteen organisms, chosen to represent several different normal habitats and other characteristics of hygienic significance in the problem of air-borne infection.

The disappearance of the Pfeiffer bacillus within an hour was in sharp contrast with the long period of several days that B. subtilis persisted in the air of the chamber. Staphylococcus aureus disappeared more rapidly than B. subtilis, but since it was recovered after three days it may be classed among the more resistant organisms. The water-borne organisms, on the other hand, B. prodigiosus, B. pyocyaneus and B. violaceus, did not survive one day, how much less a time being undetermined.

Four organisms characteristic of the respiratory tract, pneumococcus type I, B. diphtheriae, Streptococcus haemolyticus and Streptococcus viridans, were recovered after two days, while none of the four organisms typical of the intestinal tract, B. coli, B. dysenteriae Hiss Y, B. typhosus and B. paratyphosus A, were recovered at the end of the first day or at the end of eight hours when samples were taken after this time interval. If the Pfeiffer bacillus may be excepted as a special case, this respiratory group of organisms may be regarded as decidedly more viable in air than the intestinal group of bacteria, in spite of the rapid decrease in both groups.

Bacteriophage active against the Hiss Y dysentery bacillus was recovered from air at the end of twenty-four hours and cultivations from the plaques demonstrated the identity of the bacteriophage. The rate of disappearance during the first three hours also resembles the behavior of bacteria in air. The viability of this bacteriophage was therefore greater than for the intestinal group and less than for the respiratory group of organisms.

The recovery of virus experimentally suspended in air was made possible through the collaboration of Dr. H. W. Brown, who had previously (9) become proficient in the identification of the virus of influenza. The lungs of a ferret infected with the Puerto Rico 8 strain (10) of influenza virus being used as the source of infection, filtered liquid suspensions of virus were atomized into the tank, recovered in liquids by the air centrifuge, and inoculated intranasally into ferrets. All the ferrets inoculated with the material collected from the air within an hour after suspension contracted influenza. None of the ferrets inoculated with samples collected from the tank an hour or more after suspension of the virus contracted the disease. On the basis of this exploratory study, in which the technic was evolved as it progressed, it is not believed that the viability end point of influenza virus has necessarily been reached (11).

The time and distance which infection from droplet nuclei may travel depends more on the viability of the organisms in air than on the settling rate. The differences in viability of the various microörganisms when suspended in air seem to be significant.

3. *Dust and Droplet Nuclei*

The slow rate of settling of nuclei produced by evaporating droplets distinguishes them from particles of bacteria-laden dust. It should be obvious that the number of particles that settle on a given area in a given time depends not only on the number of particles in the air but also on the rate at which they settle. Since the coarser particles settle more rapidly, more larger particles would settle on a given area in a given time than smaller particles assuming equal concentrations in the air, as determined by the centrifuge. The ratio between the plate count and the number in a given volume as determined by the centrifuge may thus be used to indicate the rate of settling and the equivalent size of suspended particles.

It has been found by tests on artificial humidification with bacteria-laden water that the nuclei of the evaporating droplets settle with extreme slowness as compared with the settling rate of ordinary atmospheric dust. A hundred times as many dust particles as nuclei settle on a plate for the same atmospheric concentration. Twelve out of sixteen eosin methylene blue plates remained sterile when exposed for fifteen minutes to air containing 250 B. coli in each standard sample of 10 cubic feet, as determined by the centrifuge. This shows the impracticability of Flügge's technic for determining the presence of micro-organisms in nuclei resulting from mouth spray. His tests showed that they remain suspended in the air rather than that they settle out in a short distance. With the centrifuge, however, they may be readily demonstrated.

These conclusions were corroborated under practical working conditions in a study of the bacterial contamination of the air of textile mills in Massachusetts (12). Much dust is lifted into the air of the breaking and carding rooms in cotton mills. Comparatively small amounts of dust are found in weaving rooms, but enormous quantities of water are required to humid-

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ify the air. The ratios of plate to tube counts in the dusty rooms was four times greater than the ratio in weaving rooms, which were heavily humidified, showing the high preponderance of dust in the former and of nuclei in the latter.

Little doubt can remain as to the adaptability of nuclei to be conveyed by air when it is found that they drift with so much greater readiness than the dust with which all are familiar.

4. Dispersion of Droplet Nuclei through Buildings

Wide distribution of "nuclei" in a building was demonstrated by inoculating with a culture of B. coli the humidifying water of a one-room air conditioner in the basement of the Harvard School of Public Health. This building does not have mechanical ventilation and it conforms in general design to the building of the National Institute of Health described by McCoy (13) in which psittacosis virus appeared to have been conveyed by air from the basement to upper floors. Numbers of B. coli were recovered from the ends of every corridor up to the top floor of the three-story building where the concentration reached approximately 1 per cent of that in the air-conditioned room.

Infected nuclei can therefore be dispersed by ventilating currents throughout a building, as was shown by the dispersion of nuclei from humidification with contaminated water.

5. Expulsion of Droplet Nuclei by Sneezing

These air-floating nuclei are peculiarly adapted to bear infected matter, and the physiologic processes of respiration provide an obvious mechanism for implantation on the nasopharyngeal tissue of a person breathing the air. There remains in the chain of evidence of air-borne infection the demonstration that droplets sufficiently small to evaporate completely are actually expelled into the air by expiratory processes and that such droplets may, during pathologic reactions, be infected.

The experimental demonstration that large numbers of nuclei, infected by organisms typical of the nasopharynx, are expelled in sneezing, forged the last link in this chain of evidence. By the simple procedure of broadcasting small amounts of "sneeze powder" into a room, a practical joke was turned into a conclusive experiment. Fifty sneezes were induced from a group of subjects in a standard air-conditioned room. Bacterial samples collected in the air centrifuge on blood agar tubes revealed thousands of alpha streptococci and M. catarrhalis. Even after the subjects had left the room, the air contained many hundreds per sample. The application of handkerchiefs to smother the sneeze showed marked results in preventing expulsion of microörganisms into the atmosphere. These results are illustrated in figure 1.

A convincing experiment was conducted under natural conditions in a demonstration of the air centrifuge to a class of twenty-five graduate students in a room of about 10,000 cubic feet capacity. The air centrifuge was placed at the speaker's table at least 10 feet away from the nearest person and the exhaust pointed not toward the class but laterally. The air centrifuge inspires continuously at about

the same rate as a person during the maximum phase of inspiration and may therefore be considered a mechanical subject. A small amount of "sneeze powder" was dusted into the exhaust stream of the air centrifuge, being thereby projected into the room more as in normal expiration than in the more violent act of sneezing. That the expired air carried the particles to the class after a lapse of several minutes was indicated by occasional sneezes during the next ten minutes. Sneezing had ceased before the second ten-minute tube was taken, following which the class was dismissed and a third sample taken. The first tube, taken during the interval of

TABLE 1

BACTERIA IN AIR

(Blood agar, 37°C.)

	NUMBER OF SAMPLES	AVERAGE NUMBER OF COLONIES PER 10 CU. FT.	
		Total	Alpha (haem.)
Outside laboratory:	14	23	0.0
Summer	17	13	0.0
Autumn	8	11	0.1
Winter	21	25	0.3
Spring			
Experimental:	21	20	0.0
Quiet	14	3090	2200
Sneezing	4	1440	920
Empty after sneezing	7	66	1.0
With handkerchiefs	18	65	1.3
College classrooms and laboratories			
Lecture hall:	2	91	0.0
Before lecture	2	438	3.5
After lecture			
Public schools:	13	99	5.3
Modern	14	261	10.8
Old	22	28	0.6
Theatre, modern air conditioned	28	728	13.3
Clinics, children's and infants' sick and well	13	247	2.9
Miscellaneous hospital wards	1	230	3.0
Operating room			
Textile mills (summer conditions):			
Cotton:	13	3090	0.0
Breaking and carding	10	366	0.0
Spinning	7	733	0.0
Weaving			
Woolen:	4	267	0.0
Dusty operations	7	112	0.0
Intermediate	7	363	0.0
Humidified	14	46	0.0
Outside factories			
Total samples	281		

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sneezing, showed, on incubation, many alpha streptococci. The second tube, taken after the sneezing had ceased, however, showed a very large increase, thus indicating that the organisms had become dispersed throughout the room and were returning to the machine. The third tube showed a marked decrease but still gave positive evidence of contamination. In this experiment, contamination of the air by the machine was evidenced by the sneezing, and contamination of the room by the sneezers was evidenced by bacterial colonies in the tubes. A perfect cycle was thus completed and little doubt can possibly be entertained that most of the persons in the room were infected by the machine and by one another.

Whenever a person sneezes, many thousand nasopharyngeal organisms remain suspended in the air, and in commonly occupied, enclosed spaces, the exchange of nasopharyngeal flora is inevitable.

6. Recovery of Nasopharyngeal Organisms in Normal Occupied Atmospheres

It is not necessary to employ experimental expedients to demonstrate the exchange of nasopharyngeal flora in occupied spaces. A little skill in the recognition of alpha streptococci on blood agar tubes makes their normal recovery during the winter a simple routine performance (14). Samples of air taken from well baby clinics, children's medical clinics, hospital wards, theaters, factories, school rooms and outdoor air confirms the deduction that the numbers of alpha streptococci correspond to the degree of contamination by the occupants, as shown in table 1. It would seem obvious that under conditions of crowding in enclosed rooms we are breathing one another's nasopharyngeal flora as we once drank each other's intestinal flora in our water supplies, and the consequences of such practices become a study in sanitary science.

We wish to resuggest (15) the alpha streptococcus, an organism normally present in the nasopharynx, for service in indicating the degree of nasopharyngeal contamination of air similar to that of B. coli in drinking water as indicating the degree of intestinal contamination, since the implied potentialities are analogous. An extensive study of the great diversity of inhabited atmospheres of New York City has been conducted during the past winter, and the results of 2,000 samples bear out this conclusion.

The sanitary analysis of air of normally occupied rooms establishes the nasopharyngeal contamination of our breathing air, as the presence of B. coli establishes the presence of intestinal contamination in drinking water.

Air-borne Infection and Air-borne Disease

1. Universality of Nasopharyngeal Infection

These bacteriologic experiments would seem to demonstrate a mechanism of air-borne infection that provides for the exchange of nasopharyngeal flora. The burden of proof of air-borne infection, which had hitherto rested on bacteriology, has been lifted, and there now rests on epidemiology the burden of disproof of air-borne disease. Except in the case of such manifestly widespread clinical diseases as measles and smallpox (uncomplicated by vaccination), in which intensive outbreaks seemed almost to require the possibility of air-borne transmission, such disproof did not seem difficult a quarter of a century ago.

It has seemed almost axiomatic that contamination of the air we breathe should bring about almost universal infection, although contamination of a common water supply does not necessarily do so. The quantitative factor of dilution could account for the occurrence of sporadic cases of air-borne respiratory infection, just as it accounts for sporadic cases of water-borne intestinal disease.

Nevertheless the widespread occurrence of clinical cases of measles and smallpox (in which infection is manifested by disease) almost requires the hypothesis of air-borne transmission. At the time when the indictment against air was dismissed, the extent of spread of infection was defined by the extent of the spread of clinical disease, in this definition the two being synonomous. While carriers had already been recognized and been assigned an important rôle as infectors in the spread of disease by contact, their rôle as infectees in the epidemiologic determination of the extent of spread of infection was disregarded. Means for tracing subclinical infection have since revolutionized the concept of the extent of spread of infection (16) through the nasopharynx, though much of this evidence has not yet been assimilated into our epidemiologic thought. The mass of evidence accumulated by tests for immunity and sensitiveness, for carriers, and by epidemiologic studies of age incidence, now indicates that many, if not most, of these infections spread as readily and as broadly as the virus of measles. Translated into infections, these tests may be interpreted as evidence that few children escape the nasopharyngeal infections, and probably most adults have been infected and repeatedly reinfected.

Where the clinical cases of these diseases represent only a small fraction of the infections, conclusions based on cases must be revised before being offered in evidence. It has been argued (17) that in the enclosed atmospheres of contagious hospitals, with known cases of nasopharyngeal disease, the incidence of secondary cases was too low to warrant the conclusion that the air of the building, shared by all, was infective. The factors of immunity, of subclinical infections and of preclinical infectiousness have been overlooked in the interpretation of the much quoted reports on hospital cross infection. When were the cases most infective, before or after coming to the hospital? Of the exposed, how many were already immune, what was the nonimmune population actually at risk per annum? How many were infected but reacted with an immunity response rather than the clinical disease? How much seed fell on stony ground?

The cases of "diseases of childhood", the total number of infections required to immunize a population to these diseases before maturity, and the repeated attacks of those diseases in which no permanent immunity is conferred reveal a universality of infection which falsifies the premises on which was based the conclusion that the air, breathed by all, cannot be infective.

If the total number of nasopharyngeal infections required to immunize

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a population before maturity is compared with the number of intestinal infections that would condemn a water supply as being highly dangerous, it might be concluded on epidemiologic grounds that the atmospheres of our common habitations are even more highly infective. It may be that the air of our schools, institutions and homes, where children mix freely in the highly infectious preclinical stage of disease, where many more harbor infection subclinically, where air is less diluted than in separate wards opening into common corridors, or even in wards where bed isolation is practiced, is more heavily infected than the air of contagious hospitals.

The universality of nasopharyngeal infection does not prove that it is air borne, but it meets the objection that, if air were infective, nasopharyngeal disease would be universal.

2. *Velocity of Spread*

The aptness of the theory of air-borne infection to account for disease transmission has never been questioned, and "the theory is reluctantly given up, since it is the easiest method of explaining the spread of readily communicable diseases" (1). Those, however, who have adopted the alternative theory of "contact" infection will point out the undeniable fact that the special conditions which have been set up for the spread of air-borne infection are likewise conducive to intimate contact. Just what is meant by the word contact as applying to the spread of infection should be defined in objective terms before the two theories can be contrasted.

If the more or less direct spread of infection from person to person, the quick transfer of fresh infective material, proximity in time and space between infected and noninfected, constitutes contact, then the condition of air-borne infection by breathing one another's air in semienclosed spaces would constitute a rather extended form of contact infection. The preceding discussion has not assumed the broadcasting of infection in the sense that wind-blown pollens causing hay fever are broadcast.

While these distinctions may reconcile those to whom the words "air-borne infection" might revive the ancient and exploded theory of miasms, failure to extend the concept of "contact" may lead to the breakdown of measures for the prevention of this type of infection. It is necessary therefore to distinguish the different phases of "contact," and it would seem that this might become possible by a statistical examination of the velocity of spread by the different phases.

If contact infection requires that an uninfected person touch an infected person in some particular manner, or touch something in a particular manner which the infected person has touched in a particular manner, or that the two be within the short radius of Flügge droplets during the brief interval of fall, the rate of spread would be limited by these circumstances. If the chance of infecting each individual is not large, the chance of simultaneous infection of many would be exceedingly small, and disease would limp in its spread. (Contact outbreaks of typhoid die out, not from exhaustion of inflammable material, but from difficulty of transferring the spark.) If, on the

contrary, the sneeze-infected air of a room were breathed by many persons over a considerable interval of time, simultaneous infection could be realized, and the velocity of infection would be ample to explain even the explosive pandemic of influenza in 1918–1919. If refinements in statistical methods can determine the velocity of subclinical infection, it may be possible to distinguish between these two modes of transmission.

Recognizing, of course, that all forms of contact work coöperatively in spreading infection, there is good reason to believe that only that phase which is called air-borne infection can be swift enough to explain the epidemic spread of nasopharyngeal disease in non-immune populations.

3. *Diseases as Biological Entities*

If infectious disease may be regarded as a biological entity requiring the continuous propagation of parasites through a chain of hosts (18), it would follow that a mode of transmission on which the continuity of the disease depended must postulate a means for the parasite to leave its discarded host, exist, and be transported to a new host into which it must gain entrance. The characteristics of diseases conveyed through the nasopharynx would seem to satisfy such postulates, as their pathology provides a means for infecting air, the etiology seems to indicate causative agents capable of existing in air, and physiology provides for the planting of the parasite on the respiratory passages of a new host. Their universality even at early ages indicates widespread infection clinically or subclinically, and the velocity of spread seems to be characteristically explosive.

If one compares as a group diseases whose portals of entry and exit is the nasopharynx with those whose entrance is through other portals, one finds marked group contrasts. The nasopharyngeal group may in these respects be contrasted with typical gastro-intestinal diseases: where frequent uncontrolled liquid discharges are conducive to the contamination of food, milk and water; where the organisms can readily survive, if not multiply, in these media, and appear unadapted to life in air; where the epidemiology makes it possible to incriminate such sources even though the organism cannot be found; and where control measures have dramatically demonstrated the soundness of the hypothesis.

They may be contrasted with the insect-borne diseases where discharge of the organism is not pathologically provided; where the organism cannot survive the rigors of environmental transfer, but the existence of which in the peripheral circulation adapts them to withdrawal through the proboscis of an insect, within whose body they are adapted to survive or even of necessity bound to sojourn; where the occurrence of the disease is perfectly circumscribed by the prevalence of the insect, and where control of insects inevitably stamps out the disease.

They may be contrasted with typical contact diseases such as the venereal diseases where external lesions are habitually brought into physical contact with susceptible tissue; where life of the pathogen outside the body is almost impossible; where any other explanation of transmission is regarded

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with scepticism, if not derision, by the specialist; and where prevention is limited by the power to control the contacts.

The argument that once all communicable diseases were attributed to air and that, the more perfect becomes our knowledge, the less air becomes implicated cannot in view of these differences be carried *ad absurdum.*

The more intimate our knowledge of the modes of transmission becomes, the more evident does it become that diseases are adapted to transmission by diverse routes and among these air transmission of nasopharyngeal infection may not be the least important.

4. Nasopharyngeal Infection Still Uncontrolled

Where the transmission of disease has been prevented by control measures, there can be little doubt as to the correctness of the theory of transmission. It may, therefore, be significant that those diseases which have so far defied control are those in which the causative agent enters and leaves through the nasopharynx. In an evaluation of the importance of diseases made by the United States Public Health Service (19), the only infectious diseases considered as of a first order of magnitude were influenza and pneumonia, and tuberculosis.

The Public Health Service figures show, in particular:

(1) More than 85 per cent of the deaths from infectious and parasitic diseases occurring in the United States in 1933 were from diseases in which the usual portal of entry of the causative microörganism is the nasopharynx.

(2) Of the important reportable diseases in 1933, the incidence of measles was highest, that of influenza second.

(3) Of the incidence of illness, based on nation-wide periodic surveys in 1928–31, colds and bronchitis, influenza and pneumonia, and tonsillitis, occupy the first three places in annual incidence, causing considerably more than half of the total cases.

(4) Among industrial workers during 1933, the largest single cause of illness of 8 days' duration was influenza and pneumonia.

(5) Nation-wide periodic surveys in 1928–31 show that influenza and pneumonia caused more days in bed than any other disease. Colds and bronchitis rank second, tuberculosis third. The diseases spread through the nasopharynx caused a total of 218 days in bed for every 100 persons, as against 167 days in bed from all other causes combined.

The predominance among infectious diseases of those transmitted through the nasopharynx challenges public health measures of control. Until the purity of our common air supplies can be established through sanitary control, the transmission of these diseases by air cannot be disproved.

IV. Sanitary Control

1. Effect of Ventilating Factors upon Dispersion and Viability

In view of the proved possibility of infectious matter being carried by air, reasonable efforts to free air supplies from living microörganisms are justified in the light of general sanitary principles. The great reduction of intestinal disease through water purification since the turn of the century might prompt us to hope that some of the diseases transmitted through discharges from the respiratory tract may be checked by methods of controlling air supplies. A study of the effect of ventilating factors on the dispersion and viability of microörganisms suspended in air* has already disclosed the efficacy of certain destructive agencies.

Experiments on the disappearance of B. coli in the recirculated air of an air-conditioned room were conducted as a preliminary to the investigation of textile mill humidification referred to previously (12). B. coli seemed to disappear much more rapidly from air when the spray humidifier was operating than when the air was circulated without the use of the spray. Further tests showed that the reduction in the number of bacteria did not take place in the spray chamber but after the air had returned to the room, indicating that humidity might increase the death rate of B. coli in the air. Increasing relative humidity from 45 to 90 per cent more than doubled the disappearance rate of B. coli from air.

By means of the technic developed in this study, experiments on other physical and chemical factors were undertaken with the technical assistance of R. F. Wagner. Ozone in tolerable concentrations was found to give effects of a similar order of magnitude; i.e., olfactory concentrations four times the threshold value raised the death rate threefold. Commercial germicidal sprays also gave somewhat similar results. Negative and positive ions produced no observable differences in disappearance rate. The bactericidal action of a quartz mercury vapor lamp, however, was of a higher order of magnitude (20).

The bactericidal effects of ultra-violet radiation on microörganisms suspended in air proved, therefore, to be of a higher order of magnitude than humidity, ozone or commercial germicides.

2. Effect of Ultra-violet Radiation

(*a*) *Physical Factors* (*21*). These results precipitated an intensive investigation of the physical and biologic factors governing the effect of ultra-violet radiation on microörganisms suspended in air.

The interrelationship of space and time involved in the application of light to the sterilization of large volumes of air presents mathematical problems hitherto unfamiliar either to sanitary science or to the science of illumination. In chemical disinfection, a relatively uniform concentration of active reagent is assumed for a disinfecting interval. In thermal sterilization or pasteurization, each organism is subjected to a fairly uniform temperature for a specified interval of time. Where light has been used in the sterilization of liquids, a relatively thin film of exposure is necessary for effective action, so that each organism may be considered to be exposed to a relatively uniform degree of intensity of light for an adequate time interval. In attempting to sterilize by ultra-violet rays the large volumes of air involved in practical ventilation, it becomes difficult if not impossible to maintain uniform light intensity throughout the ventilated space, or to maintain a constancy of exposure in so mobile a medium.

* A grant from the Milton Fund for studies on the effects of ventilating factors on dispersion and viability of microörganisms suspended in air was made by Harvard University.

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The first step in the solution of the time-space interrelationship was to develop means for determining the rate at which some test organism is killed at known distances from a given light, by means of which the killing power constant of that light can be readily computed.

Preparatory to a more thorough analysis, and also to experimental application of light, studies were undertaken in the tunnel system of the Harvard School of Business Administration. A quartz mercury vapor lamp was placed in the center of this tunnel, which was 100 ft. long, 8 ft. wide and 7 ft. high. Air inoculated with B. coli could be drawn down this tunnel at regulated velocities and the bacterial concentrations at different points determined by simultaneous sampling with three air centrifuges.

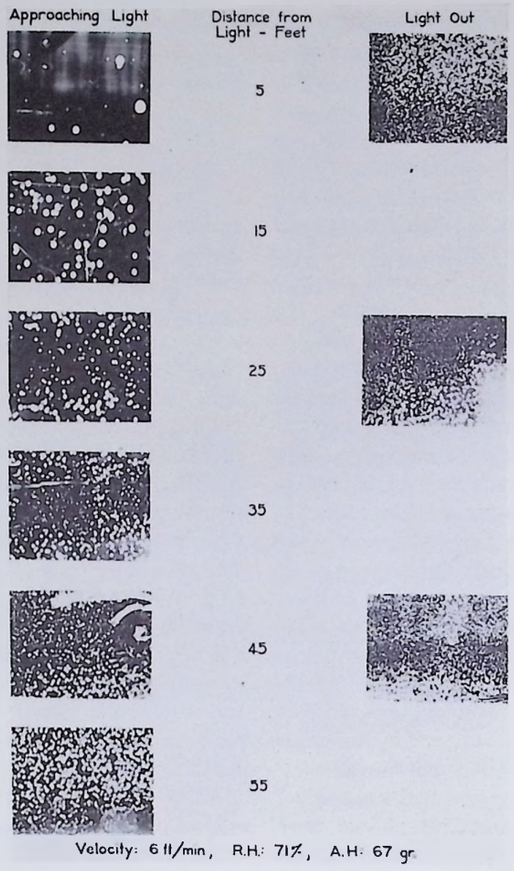


FIG. 2.—Bactericidal action of ultra-violet radiation on *B. coli* in air at different distances.

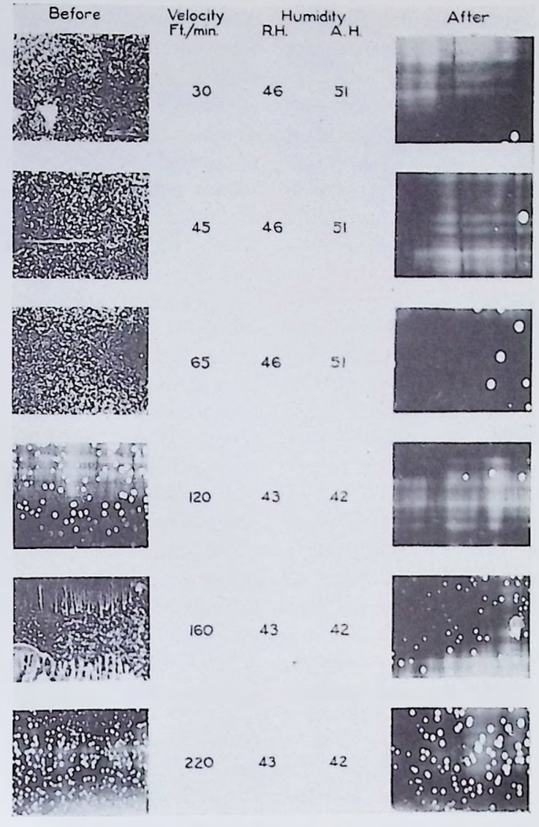


FIG. 3.—Bactericidal action of ultra-violet radiation on *B. coli* in air at different velocities. Passing light.

light. This cannot be done simply by exposing a quartz flask of air at some given distance from the light, because of the large volumes of air involved and the high cost of quartz. It was, however, possible to devise a dynamic method for exposing flowing air at predetermined distances from a given light for periods determined by the velocity of flow. The number of organisms killed in moving from point to point toward a light can be determined. The integrated products of the times of exposure multiplied by the distances from the light then bears a simple relationship to the distances of the two sampling points from the

The bacterial reductions at flows above 20 ft. per minute were too low for accurate determinations in approaching to within 5 ft. from the light. Measurable reductions in bacteria were obtained with low air flows, but these low flows could not be

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accurately measured. At 6 ft. per minute, bactericidal reductions could be determined and the flow measured with a reasonable degree of accuracy. The results of such a test are illustrated in figure 2. Marked reductions are apparent up to within 5 ft. from the light, and noticeable effects as far as 55 ft. from the light. Precise results could not be obtained by this method in the tunnel arrangement, though a more precise laboratory arrangement utilizing closer approach was later developed by Benjamin Whisler (22) in a study for a doctor's thesis.

Obviously the zone of greatest bacterial reduction lies within the sections 5 ft. before and beyond the light. By sampling simultaneously at points upstream and downstream from the light, marked reduction in this tunnel was observed at velocities up to 222 ft. per minute. The bactericidal effects in passing the light at six widely differing velocities under otherwise comparable conditions are illustrated in figure 3. More than half the bacteria were killed at velocities of 222 ft. per minute, and yet some survived passage at a velocity of 30 ft. per minute, which represents more than seven times the exposure.

Assuming the bacterial death rate to be proportional to the light intensity as given by the inverse square law for each point in space, it is possible to set up and integrate equations that can be tested by these experimental conditions.*

The values of $KI_0 \equiv K_0$, as given by these equations, with B. coli as the test organism, were found over the wide range of time-space variations, indicated by these tunnel experiments, to be constant within the errors expected from so simple an arrangement. Mr. Whisler's intensive studies with more refined apparatus confirmed the substantial validity of the assumptions and the practical applicability of the formulation. The values thus obtained for the constant K_0 justify the initial assumption which may now be modified and stated in the following form:

The total number of given organisms killed by a given light is proportional to the total quantity of light energy intercepted by the living organisms and approaches a maximum as the product of time and intensity for each approaches uniformity (23).

Humidity.—For constant atmospheric conditions the value of I_0 in these equations defines the killing power of a given source against organisms having a vulnerability defined by K. The results illustrated in figure 3 were thus obtained under relatively uniform humidity. Comparison with the results given in figure 4 reveals amazing differences in bactericidal effect with different humidities. The results obtained at flows of 65 ft. per minute shown in figure 3 are strikingly similar to the results shown in figure 4 for flows of only 6 ft. per minute. This ten-fold difference in killing power is the result of a difference in relative humidity between 45 and 90 per cent.

*The formulation for simple physical combinations are summarized: If N_0 = number of organisms before and N_1 = number of organisms after irradiation by light of lethal intensity I for time t, then $\log_e \frac{N_1}{N_0} = -KIt$; and at r distance from a source $I_0 = \frac{-KI_0t}{r^2}$; and in a sphere of R radius (source at center), maximum $= \frac{-3KI_0t}{R^2}$ for infinite mixing of air, and minimum $= \frac{-1.2KI_0t}{R^2}$ for zero mixing of air; and approaching a source at velocity v from $+\infty$ to r distance from source, $= \frac{-KI_0}{v\,r}$; and passing the source (from $+\infty$ to $-\infty$) on a straight line r distance from source, $= \frac{-\pi KI_0}{v\,r}$; and for a cylinder of R radius with source in axis (from $+\infty$ to $-\infty$), maximum $= \frac{-2\pi KI_0}{v\,R}$ for infinite turbulence, and minimum $= \frac{-1.24\pi KI_0}{v\,R}$ for stream line flow.

The numerical values of $\log \frac{N_0}{N_1}$ obtained in the tunnel experiments are plotted on figure 5 against the reciprocal of the velocity in conformity with the equations. It is seen from this chart that the results fall into two classes, each class represented by a straight line as would occur if K were constant for the class. The angle between the lines indicates a wide difference between the value for K for each class and it is seen that this dif-

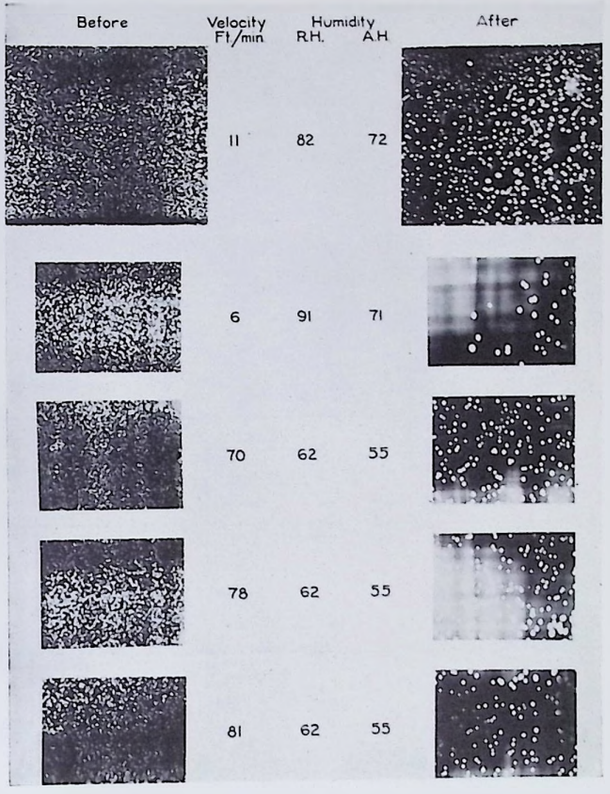


FIG. 4.—Bactericidal action of ultraviolet radiation on *B. coli* in air at different humidities. Passing light.

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ference corresponds to a difference in relative humidity, the killing power at low humidities being approximately ten times those obtained at high humidities. Since the inverse square law has been found to hold with high humidities as well as low humidities, the reduction in killing power appears to be due to interference with the bactericidal reaction on the bacteria.

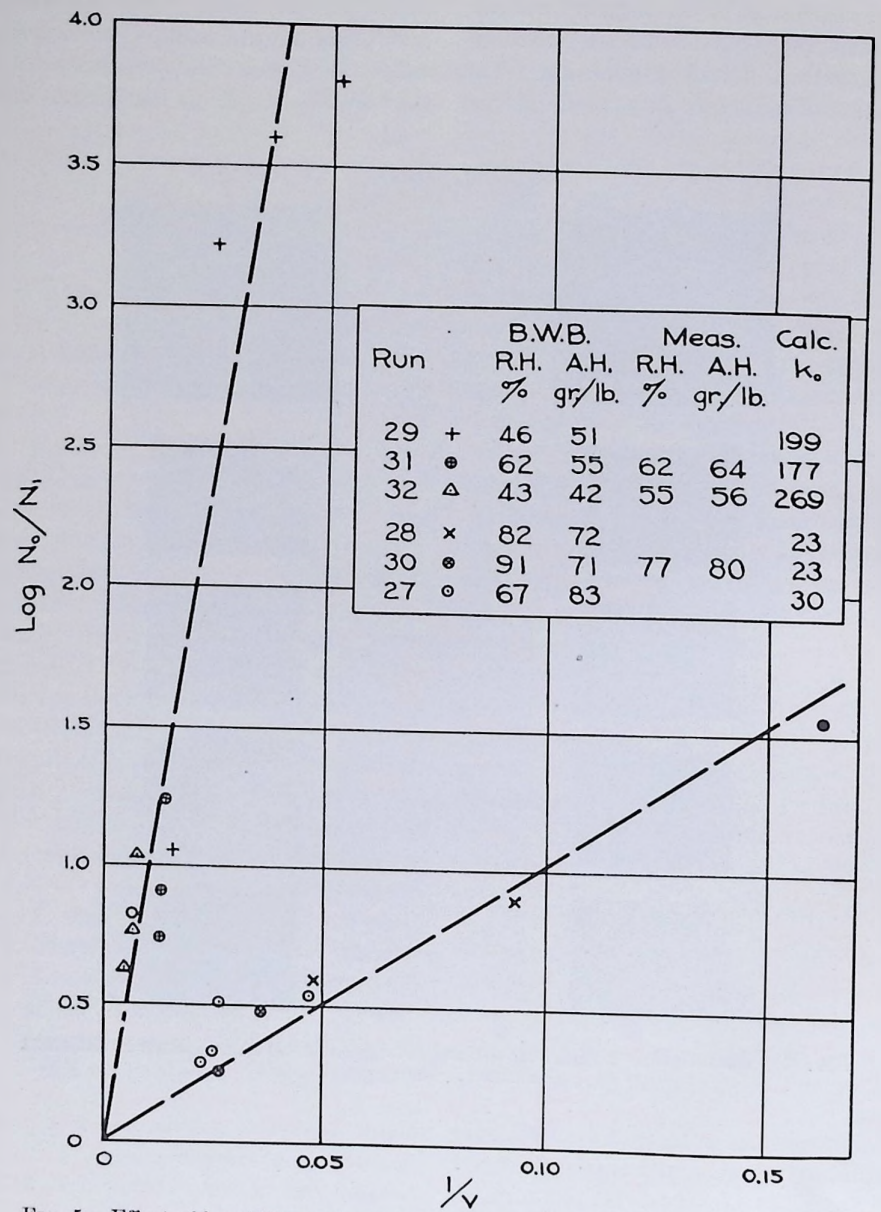


FIG. 5.—Effect of humidity on death of *B. coli* passing ultra-violet rays in tunnel

The results of the more intensive study by Whisler clearly corroborate the relation between the vulnerability of B. coli and relative humidity. The values of $K_0 \equiv KI_0$ drop precipitately between relative humidities of 55 and 65 per cent, above and below which the change is gradual, the values approaching constancy.

Obviously, humidity becomes a basic factor governing the bactericidal effect of ultra-violet radiations on bacteria suspended in air, the killing power for low humidities being many fold that observed at higher humidities.

Spectral Range.—Gates (24) has thoroughly investigated the lethal action of different wavelengths of light on bacteria smeared on agar plates. His conclusion that waves longer than 300 millimicrons are relatively ineffective has been confirmed for air suspensions of bacteria by filtering out these shorter waves. His conclusion that the maximum effect lies in a zone midway between 200 and 300 millimicrons would conform to the values of KI_0 obtained by lamps emitting different spectral ranges. The most efficient source among several types tested proved to be a 48 inch quartz Geisler mercury tube* emitting 90 per cent of its radiation as a wavelength of 254 millimicrons. Only 12 inches of a double arc gave a value for KI_0 of 910, at a relative humidity of 42 per cent, when tested against B. coli. Since this lamp consumes about 35 watts, the KI_0 approximates 50 per watt. If this value is applied in the preceding equations, it is seen that less than one colon bacillus per thousand suspended in several thousand feet of air would remain after irradiation with this light for 1 minute.

Those ultra-violet light sources which emit the largest proportion of radiant energy midway between 200 and 300 millimicrons are most efficient in destroying microörganisms suspended in air.

(*b*) *Biologic Factors.*—The bactericidal ranges of commercial ultra-violet lamps seemed to warrant experiments looking toward their practical application in sanitary air control. A therapeutic lamp was therefore set up in a clinic of the Children's Hospital, where the atmosphere had been found to build up a relatively high bacterial concentration during hours of active service. Preliminary tests, however, did not give the expected results. The lamp was found by test to be adequate and also proved in the clinic room to be effective against B. coli. If the presence of more resistant organisms was the explanation of these disappointing results, an important question was raised, since there is no hygienic significance in the elimination of B. coli from air. This study was therefore temporarily put aside until further information regarding the relative vulnerability of significant organisms to ultra-violet radiation could be ascertained. The equipment previously developed for determining the viability of droplet nuclei infection was therefore adapted to the study of the biologic factors bearing on the germicidal effect of ultra-violet radiation. Samples of air were withdrawn from the tank through siamized tubes to two Wells air centrifuges. One branch led directly to a centrifuge; the other branch included a small chamber enclosing a quartz Geisler mercury tube, by means of which the air passing to the second centrifuge could be irradiated with ultra-violet light.

Organisms in the tubes taken at the Children's Hospital both before

* Kindly lent by the Hanovia Chemical Manufacturing Company.

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and after irradiation of the air were observed to be predominantly sarcinae and staphylococci, owing probably to the nature of the activities of that particular clinic. These organisms are characteristic of the skin and were raised into the air by the dressing and undressing of the patients, together with the treatments given, which consisted largely of massage, manipulative exercises, etc. These organisms typically grow in clusters and are thrown into the air in masses, which may be a natural provision for the survival of organisms adapted to grow on surfaces, be rubbed off, and spread through the air to other surfaces. The relative coarseness of the suspended particles, as compared to droplet nuclei, was indicated by the ratio of bacterial counts on centrifuge tubes and on Petri plates, which was intermediate between the ratios found in the humidified weaving rooms and the dusty carding rooms of cotton mills (12).

The organisms first subjected to test in the experimental tank were the staphylococci and sarcinae isolated from the tubes taken at the Children's Hospital. The staphylococci were considerably more resistant than B. coli, sarcinae considerably more resistant than staphylococci. Alpha streptococci, on the other hand, were comparable in their vulnerability to B. coli.

The fact that the less vulnerable organisms were those which normally grow in masses and are separated only with difficulty suggested that their apparent resistance to light, as compared with those which separate naturally into individual unit cells, was due to this grouping. Streptococci, which divide in parallel planes, forming chains which are readily broken up, were comparable in their vulnerability to B. coli; staphylococci, which divide irregularly in more than one plane, resulting in cohesive grape-like clusters, were more resistant; while sarcinae, which divide in three planes at right angles to one another, forming packets with a minimum of eight cells, were still more resistant. To determine whether the manner in which organisms naturally group themselves was a prime factor in their varying resistance, cultures were grown in a revolving flask with suitable culture medium barely covering a layer of glass beads. Grinding during growth in this tiny ball mill, followed by prolonged centrifuging, provided a technic whereby suspensions consisting largely, though never entirely, of individual unit cells of streptococci and staphylococci could be tested against ultra-violet rays. Sarcinae, on the other hand, could not be broken down further than to the packet of eight cells, which seemed to constitute the basic unit.

In table 2 is given the vulnerability constant K for four organisms grown in the revolver, with B. coli for comparison. The differences in vulnerability between unit cells of streptococci and staphylococci, produced by this technic, and the naturally single cells of B. coli are within the limits of experimental error. The vulnerability constant for sarcinae, however, differs markedly from those for the other organisms. Presumably each of the eight cells in a packet is sufficient for reproduction, and it would be necessary to kill all eight to prevent a colony developing from a suspended packet.

The mathematical formulation employed in the derivation of the constant K for single cells must obviously be modified before application to multicellular groups of organisms. Under the conditions of the test, thirteen times as much light was required to destroy all eight of the cells grouped in a sarcinae packet as was required to kill each colon bacillus dispersed individually. This would conform to the assumption that the vulnerability of individual cells is likewise similar to that of the other organisms given in the table. A progressive increase in the vulnerability constant K during the course of the tests was observed for those organisms which tend to form clusters, but not for B. coli, as would be expected if the number of cells in the clusters is being reduced by natural death rate. The implied assumption that only one light unit is required to destroy one life unit, which underlies the mathematical formulation, thus appears to be satisfied.

Cell units of the organisms so far tested, therefore, have proved to be equally vulnerable to ultra-violet radiation.

The study of the biologic factors underlying the vulnerability constants is far from complete. Such factors as capsule formation, spores and pigment remain to be explored. Ultimately the vulnerability constants of pathogens will be independently determined. The fact, shown in table 2, that Staph. aureus and Staph. albus do not, in spite of the difference in pigment, differ markedly, suggests that the latter factor is not of the prime importance that might be imagined. There has not been enough work to indicate that more resistant organisms are not common. There is, however, sufficient evidence to indicate that B. coli is not peculiar in its susceptibility.

In the practical application of ultra-violet radiation it becomes evident that a distinction must be made between clumps and individual organisms, between dust and droplet nuclei. Air purification methods that depend on filtration or sedimentation may

TABLE 2

RELATIVE VULNERABILITY TO ULTRA-VIOLET RADIATION OF INDIVIDUAL CELLS OF VARIOUS COCCI SUSPENDED IN AIR
(*B. coli* = 1.00)

ORGANISM	NUMBER OF RUNS	VULNERABILITY	
		Constant	K
B. coli	20	1.00	
Strep. viridans	5	1.05	±.07
Staph. albus	5	1.18	±.07
Staph. aureus	7	1.21	±.20
*Sarcina lutea**	3	0.85	±.02

* The chance that all eight cells of a packet will be killed is the eighth power of the chance that an individual cell in a packet will be killed. If one-half of the cells in a packet lie in the shadow of the other half, and if the packet turns in such a manner that each cell shares equally the light and shadow, the chance of a cell in a packet being killed is one-half the chance where the cells are so distributed in space that no cell eclipses another. From the determination of the vulnerability of packets of sarcinae (0.083 when 66 per cent survived), the vulnerability constant of the individual sarcina cell has been computed as 0.85, if *B. coli* is given a value of one. Since, in the determination, packets flowed in a smooth stream past the light source in less than 2 seconds, it is doubtful whether each cell shared equally in light and shadow. Since exposure to equal quantities of light is the condition of maximum killing, the vulnerability of sarcina cells would be greater than is indicated by this computed value. The fact that doubling the intensity of the light increased the proportion of packets killed by only 7 per cent, would indicate that a constant proportion of cells were thus protected from the light, owing to a constant condition of flow, which was not affected by changes in light intensity. From the figures, it would appear that more than half of the packets survived because of protected cells, and the vulnerability constant of individual sarcina cells is greater than one. The importance of illuminating particles on various sides becomes apparent.

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be more effective against dust, and ultra-violet rays may be more effective against nuclei, the two being complementary and therefore effectively combined. Likewise, methods that are effective in testing for one type of suspended organism may be inappropriate for testing the efficiency of purification devices against the other type.

Virucidal Action of Light (11).—The persistent belief that air may transmit certain virus diseases made it important to determine whether bactericidal light would also destroy air suspensions of virus. Into the air of the tank were atomized the filtrates of lung emulsions of ferrets made ill with the Puerto Rico 8 strain of influenza virus. Simultaneous sampling under identical conditions of air as it came from the tank and after ultra-violet irradiation indicated a definite virucidal action of the rays. In two tests the ferrets that were inoculated with material recovered from unirradiated tank air suffered a typical attack of influenza, which was confirmed by virus neutralization tests. The ferrets that received material simultaneously recovered from the air of the tank under identical conditions, except for irradiation of the air, failed to show any symptoms of influenza, and virus neutralization tests subsequently showed no development of immunity.

The infectivity for ferrets of air suspensions of Puerto Rico 8 strain of influenza virus was destroyed by ultra-violet radiation.

V. Application of Sanitary Air Control

The question of air-borne infection will not be definitely answered until common air supplies are rendered free from nasopharyngeal contamination, just as endemic water-borne intestinal disease became apparent only with change from polluted to pure water supplies.

A solid foundation for sanitary air analysis has been developed, by which the purity of air can be determined, air contamination interpreted, and the efficiency of air purification processes tested. The practical effectiveness of certain devices that can be applied to the bacterial purification of air has been demonstrated. Others (25) have reported beneficial results following control of the bacterial content of the air of operating rooms. The experimental application of sanitary air control in hospitals, schools, and other gathering places is indicated.

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THE EFFECTS OF HEAT AND HUMIDITY UPON THE HUMAN BODY*

CECIL K. DRINKER

CONSIDERATION of the effects of heat falls into two natural divisions:

1. *The acute effects of encountering very high temperatures such as are met in many industrial processes and under natural conditions in such places as the desert regions of southwestern United States.* The temperatures with which we are concerned in this division of our inquiry are necessarily high. Brief exposures to temperatures of 200°F. are encountered in the steel industry. One hundred and fifty degrees Fahrenheit is frequently found in the stokeholds of coal-fired steamers. Outdoor temperatures of 100° to 125°F. were met at Boulder City, Nevada, and under such exposure men worked through regular shifts during long periods of time.

2. *The effect of residence in tropical climates.* By this is meant the gradual deterioration experienced by most northern white people who reside in the tropics. A tropical climate of the sort that interests us is characterized by little change. There are no seasons such as we have in the temperate zone. Monthly temperatures and temperature differences between day and night are slight. In the Marshall Islands for example, islands lying in the equatorial belt, the daily maximum temperatures for a year were between 88° and 91.5°F. and the daily minima between 75° and 77°F. It has been said of such places that "they possess more climate and less weather", but in spite of such qualification they are not so suitable for human residence as are the changeable regions of the temperate zone.

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THE PRINCIPAL PHYSIOLOGICAL FACTORS INVOLVED IN THE PROBLEM OF HEAT EFFECTS

It may be recalled first that the external environment with whose effects we are concerned is not in reality the environment in which the body cells live. We *exist* in a room, for instance, which may be hot or cold, dry or humid, dusty or gas-filled, in conditions which vary greatly from day to day as a result of natural phenomena or the vagaries or ineffectualities of human manipulation. We *live* in an internal environment characterized by great constancy in physical and chemical composition. This constancy is maintained, first of all, by certain physical and chemical factors inherent in the saline fluids which constitute the internal environment and, second, by certain bodily reactions designed to prevent abnormality. For example, the principal component of the internal environment is water. L. J. Henderson

(1) has summarized the peculiar fitness of water for its position in the human body. It is a singularly inert chemical "which does not easily attack the substances which in great variety dissolve in it. The chemical changes which do follow upon solution are not such as to produce substantial chemical transformations, and most substances can pass through water unscathed. The nature of water, then, is a great factor in the chemical stability, which, no less than the physical stability of the environment, is essential to the living mechanism." Further qualities of water, such as the high specific heat and the high latent heat of evaporation, are of extreme influence in keeping body temperature constant, and so one might go on enumerating qualities of the environment which are peculiarly potent in stabilizing it.

As an example of a physiological reaction which in its turn tends to maintain constancy, one may think of the simple increase in breathing accompanying exercise. This keeps the carbon dioxide content of cells and body fluids at a tolerable level, not far different from that at rest, and brings a sufficient increase in oxygen to prevent oxygen lack. Another extraordinarily constant feature of the internal environment is the practical neutrality of the fluids which bathe the body cells. Under normal conditions the hydrogen ion concentration is uniformly 7.3, which in the usual terms of normality means a solution with a hydrogen ion concentration corresponding to 0.000,000,05 N and a hydroxyl concentration of 0.000,000,2 N. Such a solution is faintly alkaline. Under extremely serious conditions the hydrogen ion concentration may rise to 0.000,000,1 N, but this comparatively slight change brings with it disastrous effects and can be endured but briefly. This essential neutrality of the body fluids is dependent both upon their chemical composition and upon physiological reactions which at once resist any tendency toward dislocation from the normal. Examples of the constancy of the actual environment in which the body lives might be further multiplied. Some have been enumerated here in order to emphasize the idea that the actual changes in the body which occur as a result of exposure to heat cannot be great, and that the reactions of the body to heat are in most instances expressions of the effort of the body to sustain the constancy of the internal environment.

Man is a warm-blooded animal. By this is meant that man possesses the possibility of physiologically regulating his body temperature so as to maintain it at a constant level. Warm-bloodedness is entirely essential for such constant, or rather uniform, degrees of activity as are required of man. He cannot suffer the variations of physical ability observed in creatures like frogs and snakes, which pass during the different seasons from inertness in the winter to the possibility of maximum activity in the summer. Muscular activity in cold-blooded animals is optimum at certain temperatures just as it is in man, but these animals are unable to maintain the internal environment at this temperature and suffer corresponding depressions in activity.

Warm-bloodedness is not absolutely perfect in man, and in children, par-

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ticularly in very small infants, it is less well developed. The premature infants cared for in our large hospitals require air-conditioned rooms with a fixed temperature in order to maintain body temperature at a constant level. It is interesting to contrast the temperature steadiness in infants kept under such modern conditions with what happens under ordinary circumstances of care (figure 1).

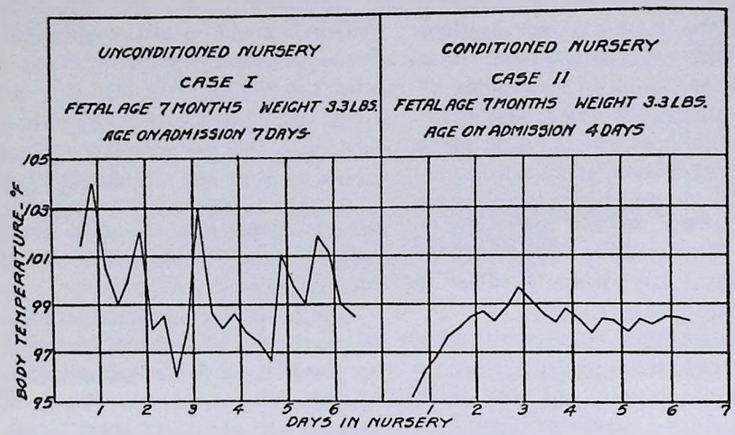


FIG. 1.—Fluctuation of body temperature in unconditioned and conditioned nurseries. Conditioned nursery, temperature 80–85°F., humidity 50–59 per cent, air movement 15 ft. per minute. (Fig. 7 from BLACKFAN, K. D., AND YAGLOU, C. P.: The premature infant. Am. J. Dis. Children, *46*, Part II, 1175. (1933))

The maintenance of body temperature in man depends upon the balance between heat production and heat loss. Heat is produced in the body by the oxidation of carbohydrates and fats, and the muscles are the most important heat producers since they constitute about one-half by weight of the soft parts of the body. Heat is, however, produced by all the glandular organs when active. Muscles properly innervated produce heat even while at rest. Since in oxidative processes heat and carbon dioxide are both produced, one may measure the production of either in order to obtain a picture of the metabolic state of the subject at the moment.

The final physiological mechanism concerned with heat effects is that of sweating (2). Sweating is of two sorts, mental and thermal. The former appears under emotional stress and is ordinarily confined to the palms, soles and axillae. Thermal sweating involves the entire body surface except the palms and soles, and is the variety of sweating which concerns us. It is generally thought that the cause of sweating is a rise in body temperature, but this is not the case. It has been shown that if a subject sits in a room where the temperature is 113°F. and immerses one arm in water at 41°F., the cooling effect of the water may lower body temperature measured rectally almost a degree but sweating

occurs normally. One can cause sweating by direct heating of the brain and spinal cord, but ordinarily sweat appears as a result of impulses generated in nerve endings in the skin. If a subject enters a room at 100°F., sweating does not begin for 10 minutes or more. This slow appearance of sweating seems to express the fact that the sweat apparatus is at first relatively insensitive to the stimulation of heat applied to the skin. It is found, however, that one of the adaptations man experiences as a result of prolonged exposure to heat is an increased ability to perspire. If subjects are suddenly exposed to high temperature in summer, sweating will begin much more rapidly than from the same exposure in winter. This increased "ability to perspire" is one of the few definite adaptations to high temperatures known to exist in man. Its utility for prompt cooling of the body is sufficiently obvious. When thermal sweating begins it is general, not limited to one part of the body. If one arm is heated sweat will appear all over the body when secretion begins in the heated part.

When a gradual rise in temperature is experienced the volume of sweat produced from a given area is at first fluctuant, as is shown in figure 2. If, however, the exposure is abrupt, fluctuations in sweat volume are not marked until the individual nears collapse. Once the sweat glands become active they rapidly reach maximum production. This is shown in figure 3, which pictures an extremely severe experience. After a brief period at 23°C. (73.4°F.) the temperature was raised abruptly to 53°C. (127.4°F.). The rate of sweat production measured for an area on the chest increased rapidly to a high level, where it was well sustained for about 50 minutes until the collapse of the subject. One may notice, also, the rise in rectal and pulse rate. The fact that the volume of sweat from

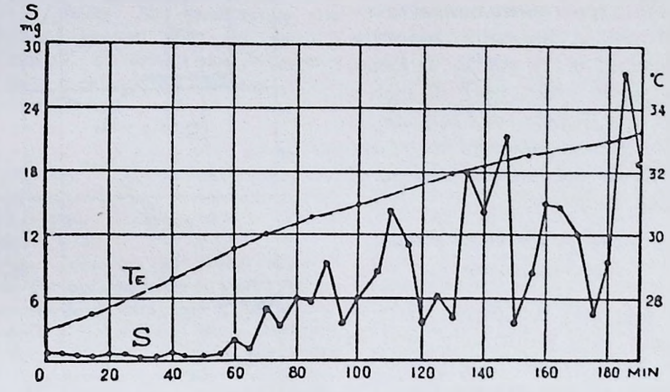


FIG. 2.—Fluctuations in the volume of sweat from a given area on exposure to a gradual rise in room temperature. *S*, perspiration on the chest; *Te*, room temperature. (Fig. 10 from Kuno (2).)

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the palm increased but slightly is in accord with the fact that this region is concerned with emotional and not with thermal sweating.

Sweat is a dilute fluid containing 0.1 to 0.5 per cent sodium chloride as the most important constituent. The amount of sweat produced at ordinary types of work in such a climate as Boulder City (95–120°F.) may be as high as 7.5 liters during the day. Assuming a sodium chloride concentration of 0.3 per cent, this should mean a loss of 22.5 gm. of salt. Since the average normal excretion of salt in the urine is in the neighborhood of 12 gm. in 24 hours, the degree to which work in such a climate may deplete body chlorides is clear and this depletion is one of the most definite and important effects of very high temperature.

The Effects of Very High Temperatures

The first and commonest disturbance met with industrially, and in severe heat exposure however encountered, is heat cramps (3). The most illuminating way to follow the development and treatment of heat cramps is through reports of the history and treatment of actual cases.

Case 1. Boulder City, Nevada, Six Companies Hospital (Talbott and Michelsen (4)):

Mr. J. F., a married white man of 42, entered the hospital on June 24, 1932, complaining of vomiting for 3 days and generalized muscle cramps for 12 hours.

Past history. Born in Nova Scotia, he has lived for the past 28 years in southwestern United States. He has never been in the tropics, has never noted any ill effects of heat, and prefers summer to winter. He perspires freely in a warm or hot environment and his skin tans easily. He came to Boulder City June 6, 1931, and has worked since that time in the Machine Shop situated on the edge of the city. He drank at least two quarts of milk daily during the first four months of his employment in the summer of 1931. In the fall his family moved to Las Vegas and he had virtually no milk after that time. He is a light meat eater, preferring fruits and vegetables and not especially addicted to the use of salt.

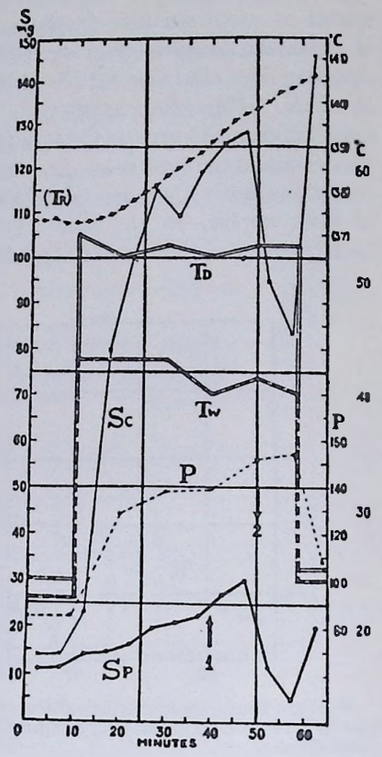


Fig. 3.—Sweating under sudden exposure to extreme heat and humidity. Stupor and collapse. *Sc*, volume of chest sweat in milligrams; *Sp*, that of the palm; *P*, pulse rate; *Tr*, rectal temperature; *Td*, dry bulb temperature; *Tw*, wet bulb temperature. At the arrow 1, strong palpitation was felt. At the arrow 2, stupor and dyspnea began. (From Kuo, K. W., Takahara, K., Adachi, J., and Saito, K.: Medicine, *22*, 1152 (1935). Also Fig. 16 in Kuno (2).)

Present illness. Three days ago he began to vomit and, while the vomiting has diminished in severity, only a small amount of food and fluid has been tolerated during this period. Twelve hours ago cramps in the muscles of his legs first appeared and since then they have caused pain in his arms, hands, and abdominal wall. Change of position will generally bring on cramps in the parts moved, although deep pressure or palpation is not painful. He voided small amounts of urine twice during the twenty-four hours before admission. He has continued to perspire freely in spite of the low fluid intake.

Physical examination. Temperature, 99.6°F.; pulse, 88; respiration, 16; blood pressure, 130/84. The examination was essentially negative. The eye grounds were normal. Chvostek's and Trousseau's signs were negative. No fibrillary twitchings were seen.

Diagnosis. Heat cramps.

Treatment. He was given, during the first 24 hours, two hypodermoclyses of 1500 cc. of normal saline and was allowed to drink 3000 cc. of milk. He received no other food or fluids.

Course. The cramps ceased after 6 hours. He was sent home on the 3d day on a diet containing a minimum of one quart of milk daily. He resumed work the third day after discharge. Frequent follow-ups revealed no muscle soreness or cramps during the next two periods of hot weather.

Comment:—This was a relatively mild case. Notice that the man vomited for 3 days and continued to perspire during this time. He lost both salt and fluid for 2½ days before cramps began. The treatment was not especially radical—salt solution under the skin and milk by mouth. Milk is one of the best sources of sodium chloride both for the treatment and prevention of heat cramps. It contains 0.3 per cent of the salt.

Case 2. (Talbott (3)):

Mr. J. D., a divorced, colored man of 38, entered the hospital on July 1, 1934, complaining of generalized cramps in his extremities and in his abdominal wall. On admission 45 cc. of blood was taken from the brachial artery.

Past history. Born in Virginia, he had worked steadily in the sheet mills for 14 years, up to 1929. In 1918 and 1928 he was treated for gonorrhea. He consumed moderate amounts of hard liquor but did not classify himself as a steady drinker. He had never been exhausted by the heat. Seven years ago he had generalized cramps in his arms and legs. They were not severe enough to cause him to seek medical attention and they subsided with treatment at home.

Present illness. The day of admission was the first sheet mill work the patient had had for 4 years. During that period he had only odd jobs of short duration. Two days before admission he consumed large amounts of alcohol, but had eaten his meals regularly. He slept well the night before admission. He ate a good breakfast and had a bowel movement before going to work. The day was hot, he worked very hard, perspired profusely, and had no appetite for lunch. At 3 P.M. he felt weak, became slightly dizzy, had a little nausea but did not vomit. Shortly after, he was transferred to an easier job. He began to have cramps in his arms and legs but was able to finish the shift. He had a shower bath, felt better, and went home. On his arrival home, he was seized with severe cramps in his extremities, his neck, and along his back. The muscles knotted up in hard bunches and became excruciatingly painful. The muscles in the abdominal wall became involved shortly afterward, and this was followed by vomiting. It became impossible for him to talk and he was brought to the hospital by ambulance at 7 P.M.

Physical examination. Temperature 99.4°F. p.r.; pulse 108; respiratory rate 20; blood pressure 100/72. His skin was warm and he perspired moderately. Nothing was discovered on examination that was unusual except the cramps. The patient appeared to be in extreme pain from cramps in his arms, legs, abdominal wall, and back. The cramps were intermittent in character and 2 to 3 minutes in duration. . . . On palpation

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the affected muscles felt stony hard. The cramped muscles were not tender to palpation nor could the cramps be massaged away. When the hands and arms were involved the affected member would be flexed with such force that it was impossible for the examiner to extend it, without some fear of breaking a bone. The deep reflexes were present.

Diagnosis. Severe heat cramps.

Course. The cramps did not subside with rest in bed, and 50 minutes after admission he was given 50 cc. of 50 per cent dextrose intravenously. The next 25 minutes, the cramps returned with greater severity than before. It was necessary for the patient to walk the floor to obtain slight relief. At 8:15 P.M. he was given morphine sulphate gr. ¼ by hypodermoclysis. There was little relief from the medication after 35 minutes. Two hundred and fifty cc. of 10 per cent dextrose was then administered intravenously. Shortly after the injection of this solution there was a period of freedom from cramps only to have them return in greater severity than before. The patient felt that he could no longer tolerate the pain and morphine sulphate gr. ¼ was repeated, followed at 10:30 P.M. by 800 cc. of normal saline solution intravenously. When about 200 cc. of the saline solution had been given, the patient relaxed, said that he had no more cramps and was extremely tired. He slept for 1½ hours after this. At midnight he had a very mild cramp in a finger and then slept until morning. There was no subsequent return of his cramps. He stayed in the hospital two days. During this time he gained 3.7 kgm. in weight and retained 438 m.Eq. of chloride.

August 4, 1934. He was interviewed and had been working two or three days each week since discharge. Two weeks before, after a period of unemployment he had mild cramps in his arms.

Comment:—This was a severe case in a sheet mill worker. Notice that he was alcoholic and that his difficulties began with nausea. On admission he was practically normal except for very severe cramps. Observe the failure of the treatment by intravenous dextrose, a measure often advocated and possibly useful if there has been prolonged vomiting but of no avail against the cramps. The immediate effect of the saline infusion was striking.

The treatment of cases of heat cramps depends obviously enough on replacement of the lost sodium chloride together with a suitable amount of water. These measures are specific and nothing can take their place. Alcohol, morphine, calcium salts, sodium bicarbonate, nitrites and other remedies have had their advocates, but no one of them is of avail.

Prevention of heat cramps is of greater importance than their treatment. Men at hard work under high temperatures must be in good physical condition. Alcohol and excesses of all sorts must be avoided. A sodium chloride intake of at least 15 gm. a day must be maintained. Particular care is necessary when the individual first begins to work. If facilities are available urinary chlorides may be quantitated and total excretion should not fall below 3 gm. a day. Food should be plentiful with no restriction upon protein. It is generally held that hot weather diets should contain little meat. It is, however, impossible to expect continued hard work upon a highly restricted protein intake and there is no logical reason for the reduction. Milk is extremely useful and should be supplied freely. Additional salt may be added to the drinking water, taken in tablets or added to the food. The first method is preferable and a concentration of 0.1 to 0.3 will suffice.

There is no doubt that men in good health achieve some sort of acclimatization when placed at work in such a climate as that of Boulder Dam. Little is known as to the nature of this adaptation. Two general facts comprise our knowledge upon the subject: first of all men sweat more readily as they become accustomed to the exposure to heat and, second, the sweat has a lower concentration of sodium chloride. The organism apparently learns to retain chlorides, since even on a high chloride intake the concentrations in the sweat remain low. Other types of adaptation, such as changes in the ductless glands, are too speculative for comment.

In addition to cramps there are other conditions which appear as a result of exposure to extreme heat, such as "heat exhaustion" and "heat stroke." Heat exhaustion is the milder of the two conditions. Patients feel weak and ill for several days. They usually have slight fever but the temperature may be subnormal. If put to bed and kept cool and quiet they usually recover in a short time, but such individuals should be carefully watched as they may readily become true instances of heat stroke. This latter condition usually comes on rather abruptly, but may develop over 2 or 3 days. Dizziness, headache, faintness, vomiting, a broad chain of symptoms such as might initiate a severe infection, characterize the onset. Sudden collapse and coma, with accompanying high fever are not uncommon. Temperatures from 106° to 110°F. occur. Delirium, neurological signs of various sorts, and hallucinations are noted if the fever continues for long. The pulse is rapid, the blood pressure low, and the breathing shallow and fast. The patient resembles one in surgical shock, except for the elevated temperature. Now and then, for reasons not understood, the temperature may be subnormal. Treatment consists in the use of cold packs or cold baths, stopping when the rectal temperature reaches 102°F. Salt solution should be given under the skin and water by mouth as soon as possible. The underlying cause of the condition seems to be abnormal stimulation of heat production as a result of the heating of the body. In very severe cases a variety of nervous sequelae may occur, and in all instances which recover there seems to be an increased susceptibility to the effects of heat.

Shattuck and Hilferty (5) have recently published an analysis of acute heat effects in various parts of the world. Their conclusions are as follows:

1. The death rates attributed to heat among European residents of Shanghai and among the population of the Republic of Panama are outstandingly high.
2. Heat effects are notably common in the United States and in Australia.
3. Soldiers from the British Isles stationed in India frequently suffer from heat effects.
4. The frequency of heat effects appears to differ markedly in various parts of tropical Africa. Cases appear to be decidedly more numerous in some of the British Colonies (Nigeria, Anglo-Egyptian Sudan, Nyasaland) than they are today in French or in Belgian territory.
5. In the Tropics in general, persons of European races are attacked far more often than are persons of the native races, but the latter are by no means immune. (Anglo-Egyptian Sudan.)
6. Males are far more liable to heat effects than are females.
7. Heat effects are comparatively un-

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common in the West Indies, in the British Isles, in Europe, in the Union of South Africa and in Japan.

8. Notably low rates are exhibited for Finland, Sweden, Ceylon, New Zealand and Lima (Peru). Deaths from heat are recorded as *nil* in Mauritius in the Indian Ocean.

9. There are outstanding fluctuations in heat effects in several countries in certain years. To explain these, it may be necessary to localize the cases sharply, to determine the climatic conditions from day to day in the places where the heat effects are most numerous, and to learn whether there had been marked coincident changes in occupation or mode of life among the victims.

10. It has been said that heat cases were common in the French Dependencies twenty years ago but that they have been few in recent years. Reports for the year 1933 from French Dependencies in Africa and in the Far East indicate a striking scarcity of heat cases.

11. The irregular world distribution of acute effects of heat which the data indicate may be, to some extent, fallacious. Incomplete reporting, different methods of recording or of classification, or incorrect figures for population might cause misleading irregularities in the figures.

12. Some real irregularities of distribution can, probably, be explained as due to climatic factors which are peculiar to restricted localities.

13. It is interesting to note that acute effects of heat are common in some parts of the tropics and not in others; and that the same is true of the temperate zones. These facts indicate the need of further study to explain the distribution of heat cases with reference to probable causes, climatic or other. Work on this problem will be undertaken in the near future.

The Effects of Residence in Tropical Climates

Of far more importance to man than the problems of the abrupt effects of high temperature are the slower and more subtle effects of prolonged residence in the tropics. Tropical diseases are no longer the reason why northern whites fail in the tropics. It is the gradual deterioration in health which whites experience that constitutes the real problem. The English have had the longest experience with the problem, yet Meredith Townsend, in his book "Asia and Europe," made the following statement: "Not only is there no white race in India; not only is there no white colony, but there is no white man who proposes to remain. No ruler stays there to help, or criticize, or moderate, his successor. No successful white soldier founds a family. No white man who makes a fortune builds a house or buys an estate for descendants. The very planter, the very engine driver, the very foreman of works, departs before he is sixty, leaving no child, or house, or trace of himself. No white man takes root in India."

Efforts have been made to contend that, barring tropical disease, life in the tropics is as filled with good health as is life in temperate zones. It is certain that this is not true. Deterioration is the rule, and 2 years is probably the longest safe period for tropical residence. Furthermore, it is safe to say that the effects of tropical residence are worse in the case of women and children than in men.

From the point of view of effects upon health, the climates of the tropics differ. Thus there are vast areas of swamp and forest, as in the basin of the Amazon; monsoon districts where climate is controlled first by the wet then by the dry monsoon; desert areas extremely dry; tropical islands where winds from the sea make life possible; regions of high altitude where the temperature may be entirely agreeable. All these situations differ, but all have one factor in common—lack of change.

A hill station in India may be cool, but it is an unbroken, unvarying coolness. Huntington (6), in a book "Civilization and Climate," makes a tremendous argument for weather changes as influencing human efficiency. He points out that racial dominance has always belonged to dwellers in the temperate zone. It is extravagant to refer such a fact to climatic change alone, but there is much of interest in Huntington's book.

Let us consider that we are dealing with residence such as that along the seacoast in northern Venezuela, a hot, moist situation and one of the utmost importance to this country because of the large oil fields. In such a region all the months of the year are hot (over 68°F.). There is a mean temperature of 85°F. and a high humidity. For such regions data are lacking as to the cooling power of the air katathermometer readings, in order to classify the region physiologically, but as yet such data are available for very few regions and over short periods of time.

Let us now list what one may expect to find in individuals who enter such a climate from life in a temperate zone.

1. *Basal metabolism.* The trend of events is best shown by Martin's (7) observations upon himself. During a voyage from London to Australia he measured his basal metabolism daily for the 35 days of the voyage, taking great pains to keep his food and exercise constant. Within a few days after encountering hot weather his basal metabolism began to fall, reaching a minimum on the fifth day of heat and remaining low until cooler weather was brought by the trade winds when it immediately rose to its previous level. The maximum difference between the hot and cold periods was 12 per cent. There is no question that in the case of this individual the tropical climate had a depressing effect on the basal metabolism. This result would seem to me to indicate the fact for healthy white men. One can, however, find reports of "increase" and "no change." This is due, I believe, to uncontrolled observation or unfamiliarity on the part of observers with the determinations being made.

Recently Mason (8) has made a very careful study of nine European and American women in Madras. In this city there is a mean annual temperature of 82.2°F. and a relative humidity of 72 per cent—a trying climate for whites. Three individuals showed a definite decrease in metabolism over control figures obtained in Boston, and a fourth the same change though less marked. In the most complete record—that upon Miss Mason herself—basal heat production fell markedly during the first seven weeks residence in the tropics, remained low during 5 years in Madras and rose to the original level on the return to Boston, being at the same point when measured 4 days after return. This subject lost weight while in Madras and during the period of depreciated metabolism. Her weight was, however, at its lowest point on return to Boston when the metabolism had gone up.

In four other subjects the metabolism changed not at all, and in one there was variation in either direction.

Three Indian women, teachers, on the same economic level as the Europeans, showed a decrease of 4.8 per cent in their metabolism in the tropics as compared with the same measurement in temperate zones.

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A significant feature of Miss Mason's observations was the fact that her subjects who showed a decrease in heat production of 7 to 12 per cent, either showed no rise in temperature or an insignificant rise, whereas in those whose metabolism remained normal there was an average increase in temperature reaching 0.7°F. One at once feels that individuals whose basal metabolism falls slightly are better adapted for tropical residence than are those who remain level or who experience a slight sustained elevation of the basal metabolic rate following the increase which comes with the first experience with the tropical climate. Sundstroem (9) found, in this relation, that the basal metabolic rate of rats fell when they were placed in tropical conditions. He noted that rats given thyroid did very badly when placed at high temperatures, and suggests that anything which consistently increases metabolism operates very unfavorably for the organism. On the other hand, forced exercise which induced brief periods of high metabolism did no harm whatsoever, which is consistent with the belief and, apparently, the fact that northern whites must exercise in the tropics if health is to be sustained.

2. *Temperature.* A slight increase is the rule. Temperature measurements are, as we have seen, of little value unless correlated with observations on the basal metabolic rate.

3. *Growth.* A weedy, long-legged type is the rule in the tropics. Height is attained more rapidly than in temperate regions and fatness is uncommon. Growth is most rapid in the hottest periods of the year. A tall, thin type is, perhaps, the best for tropical residence, having a maximum surface for heat loss in relation to body weight.

4. *Reproduction.* Fertility is apparently less in the tropics, both males and females being affected. Menstruation in white girls does not take place abnormally early, but the menopause comes sooner.

5. *Blood pressure, pulse rate and respiration.* A slight decrease in pulse rate and in systolic blood pressure are the rule, but the changes reported are very insignificant. Respiration tends to decrease in rate and the minute volume is somewhat higher. A slightly deeper breathing is more efficient for the individual and is thus an economy of energy. At the same time the increase in air breathed results in cooling due to evaporation of water.

6. *Blood volume.* It is obvious that the increase in sweating which is necessary must require a constant higher blood supply to the skin. If the total blood volume failed to increase this would result in a rather steady impoverishment of internal organs.

Barcroft (10) and his associates, in an expedition from England to Peru, found that blood volume increased as the tropics were entered. On their return to London they were able to make more precise measurements upon the matter. Subjects were confined in a psychrometric chamber and measurements were made of total blood volume, hemoglobin, oxygen capacity, and reticulated erythrocytes.

An example is given in figure 4. Blood volume rose abruptly during the night of the 23rd and 24th on first entrance into heat. The subject was quiescent at this time. The rise in blood volume was accompanied by a

fall in hemoglobin, indicating that this was a simple dilution effect, blood plasma being drawn into the capillaries from the tissues. On the 24th there was heavy exercise on a stationary bicycle. The hemoglobin and oxygen capacity rose, indicating entrance into the circulation of corpuscles heretofore stored.

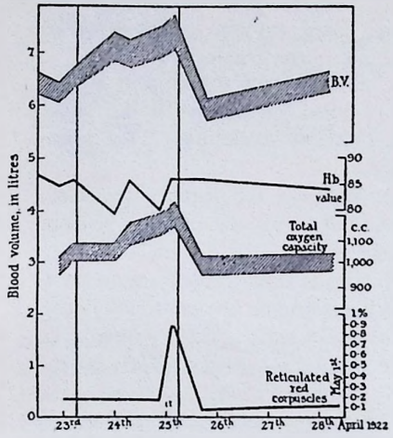


FIG. 4.—Blood volume, hemoglobin, total oxygen capacity, and reticulated red corpuscles in an individual subjected to high temperature. On the 23rd, surrounding temperature 14–15°C. (57.2°F.). The night of the 23rd and until the morning of the 25th the temperature was 32–35°C. (90.5°F.). (Fig. 3 from Barcroft *et al.* (10).)

Man ordinarily does not have all his red corpuscles in active circulation; he draws on a reserve in the spleen when necessary. Increase in reticulocytes is important in showing quick entrance of young forms in the circulation. In the individual represented in figure 4, blood volume increased from 6.4 to 7.1 litres, or 700 cc. in 2 days. At the same time the oxygen capacity rose from 1020 to 1130 cc., indicating a 10 per cent increase in circulating hemoglobin. These results have not been verified by others, so far as I know, and they are very fundamental. They mean that the organism is wetter and so is able to sweat more easily and plentifully.

In the case of a group working at Boulder Dam (Talbott et al. (11)) in 1933, with a higher environmental temperature, subjects reacted as follows:

1. First lost weight. Increased fluid intake, keeping urine volume constant but the specific gravity high, 1030 to 1035.

2. Sodium chloride in sweat greater in first few days of exposure. At same time less in urine.

3. Weight regained. Specific gravity of urine fell to 1015 to 1020. Sodium chloride in sweat fell. Sodium chloride in urine increased.

These changes, had determinations been made, would probably have added to them an increase in blood volume when the sodium chloride in the sweat fell and when the individual became adapted. At that time there would be retention of water held by the sodium chloride and weight would also increase.

Keeping cool in the tropics is preeminently a problem of water movement, and I have no doubt that exploration in the region indicated by the material discussed here would surely result in the accumulation of valuable knowledge. It is not enough to make determinations under immediate conditions of experiment in the laboratory. What is needed are comparative groups of studies on the same individuals under the same circumstances of diet and activity, before, on entering, and during residence in the tropics. It is necessary that these observations permit correlation of a number of changes. Thus it is not enough to make red cell counts and

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observations on weight and general nutrition. That is the sort of thing with which the past is filled. A definite schedule is needed, followed rigorously over 3 years at least and, if possible, the observations should be upon men, women, and children.

Let us construct such a schedule so far as our present indications go:

Weight
General appearance
Blond or brunette
Blood volume
Oxygen capacity
Reticulocytes
Chlorides in blood, urine and sweat
Urinary output
Effect of standard exercise periods and exercise tests
Psychological tests

These observations should be made at regular intervals prior to entrance in the tropics, during 3 years of residence and, if possible, after return to the temperate zone. In my opinion they would hold out opportunity for improvement in two directions: (*1*) Thorough knowledge of the real nature of the change which takes place in northern whites in the tropics might result in making it possible to adjust diet, salt and water intake so as to best meet the necessities of the situation. (*2*) The possibility of determining through a brief test period in a northern laboratory whether or not the individual would react well to the conditions of life in the tropics.

There are other observations which may be added to our analysis.

7. *Urine.* There should be little change in total output after the individual has become adapted. Water intake should be large enough to provide this. We have commented on variations in the chloride output.

There is no large volume of systematically controlled data on the subject.

8. *Acid-base equilibrium.* A slight alkalosis has been reported, particularly in persons of sedentary life. It disappears with the assumption of periods of exercise.

9. *Blood sugar* is apt to be low.

10. *Non-protein nitrogen* has been reported from northern Australia as increased. Our own investigators at Boulder Dam found it lower than normal, which seems more apt to be correct, since protein intake is likely to be low in the tropics.

11. Sundstroem reported a reduction of total *phosphorus* in the blood from northern Australia. This is unverified.

12. *Red cells* are slightly increased. *White cells* are decreased. Neither change is great.

Finally, in regard to effects on ductless glands and on the nervous system, little can be said. There seems to be little doubt that serious effects on the nervous system occur.

Children do well until about the third year. From 8 to 10 they begin to be weak and apathetic. They should be sent north at this time. We lack standard comparative intelligence tests on school children in Panama and Boston. It is said that memory, initiative, and application become bad after the tenth year. Children sent north should not be allowed to return until the twentieth year.

In the case of adults, weakening of the will power with laziness and the gradual development of vicious habits are notable. The observations in such directions are invariably vague and authorities are most contradictory. For example, certain missionary groups in the basin of the Amazon, leading a rigorously disciplined life, retain strength and vigor for years.

In order to succeed in the tropics white men must be willing to undergo discipline they would not subject themselves to in the north, and the very nature of the effects of the climate tends to break this down. We do not want to exercise and do not want to omit alcohol when we experience the enervating effects of high heat and high humidity.

The principles governing life are simple. No doubt they could be added to and made to fit our needs better had we some of the information I have pointed out as lacking.

1. Moderate amount of simple food.
2. Plenty of water.
3. Adequate salt intake.
4. Daily exercise.
5. No alcohol.
6. Adequate sleep.

All are provisions of prime simplicity and have been known in the main for years—a reflection on our medical handling of the problem.

Finally, a word as to humidity and sunlight. Neither of these factors possesses great specific importance; both act merely as aids in increasing the effects of heat. High humidity by diminishing evaporation of sweat and very hot direct sunshine may have important parts in intensifying heat effects but as direct factors they are being recognized as of little consequence.

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ABNORMAL AIR CONDITIONS IN INDUSTRY: THEIR EFFECTS ON WORKERS AND METHODS OF CONTROL*

C. P. Yaglou

IN MANY industries, workers are often exposed to adverse conditions of cold or heat ranging from well below 0°F. in artificial ice-making and kindred trades, to 150°F. or higher before furnaces and red-hot metals. The effects of these abnormal conditions on health, working capacity, accidents, sickness and mortality are reviewed in the first part of this paper. The second part deals largely with engineering and medical aspects of control.

Health of Workers in Cold Trades

General Effects of Cold on the Organism

Diseases due directly to cold are very few and rare in occurrence probably because the effect is largely mitigated by artificial control. The range of adaptability of man is enormous; with suitable clothing and proper nutrition, temperatures as low as −75°F. are encountered in polar expeditions and air flights with no apparent injury to healthy persons.

As a predisposing factor, however, cold may play an important rôle by increasing susceptibility to a number of diseases. More important than cold in itself are chilling drafts or great temperature changes, like those experienced in passing from a warm room to cold outdoor air. While a moderate variability of temperature is stimulating and probably beneficial, there is a happy medium beyond which extremes are destructive rather than constructive. In a warm room, according to the general belief, the mucous membranes of the turbinates and nasal septum are flooded with blood and lymph and covered with a thick secretion. Upon sudden chilling, as on going out to cold air, the blood vessels constrict and the mucous membranes become chilled but remain swollen with tissue lymph. The congested mucous membrane is deprived of fresh blood and lymph and this anemic condition is believed to offer a suitable opportunity for bacterial proliferation (1, 2).

Chilling of the body surfaces for short periods by drafts or insufficient clothing in a moderately cool room produces substantially a similar effect, in a less marked degree, by reflex vasoconstriction and diminished blood supply to the mucous membranes of the palate and oropharynx, the palatine tonsils, nasopharynx, and especially the nasal mucosa (3 to 7 incl.). In some instances of cutaneous chilling the temperature depression of the nasal mucosa was found to be more than 12°F. (4).

* From the Department of Industrial Hygiene, Harvard School of Public Health, Boston.

The condition of the vasomotor system may play an important rôle in the whole situation, for as is well known, a secondary reactive vasodilation occurs in healthy individuals during exposure to cold, with a rise of skin temperature, as shown by Lewis (8, 9), and Grant and Bland (10). Metabolism and heart action are increased, respiration becomes deeper, and the organism is better prepared to withstand the cold.

Reactive vasodilation does not appear during severe chilling of the body or in the ill or exhausted. Lewis's explanation is that larger arterial branches may be involved in the primary reflex vasoconstriction. Failure also results from degeneration of the arteriole sensory fibers. Under such conditions, ischemia persists and resistance of the mucous membranes may be lowered. Blood is diverted to the internal organs; and the metabolic rate does not increase sufficiently to avoid shivering.

In hypersensitive individuals, normal degrees of cold stimuli may induce exaggerated local or systemic reactions with manifestations of asthma, hives, vascular spasm, vomiting, headache, diarrhea, convulsions or syncope (11, 12, 13, 14).

The apparent inability of Kerr and Lagen (15) to transmit the common cold from carriers to susceptibles in an air-conditioned room may be largely explained by the control of predisposing factors. In these interesting experiments, 24 subjects with histories of winter colds in preceding years, but no colds during recent weeks, were exposed to infection from persons in the early stages of common cold. Infected and normal subjects stayed together in the conditioned room for 5 to 8 days. Although they ate, played cards and drank out of a common cup, sneezed at each other, none of the normal experimental subjects developed any sign of a cold.

A great number of investigations (1, 2, 5, 16 to 27 incl.) on animals and man would seem to indicate that prolonged exposure to cold and sudden changes in temperature lowers the resistance to infection apparently by depressing the defensive mechanism of the organism. This appears to offer a satisfactory explanation for the increase in the incidence of upper respiratory diseases during cold weather. But there is also a large volume of negative evidence (28 to 38 incl.) which weighs heavily against the positive evidence. Of particular interest is the extensive and thorough work of Chodousky (28), who experimented with many kinds of animals and pathogenic bacteria including pneumococci, Friedländer's bacillus, and diphtheria bacilli alone or with streptococci. He first chilled his animals in ice water and with cold drafts until their temperature (rectal) fell 2 to 13°F. He then infected the chilled and control groups by inhalation or injections of the virulent cultures, but found no difference in reaction, course of disease, or mortality between the chilled and control groups.

In another series of experiments Chodousky exposed himself to chilling drafts at temperatures between 36 and 54°F. immediately after hot or ice-cold baths. Despite the fact that he was 55 years old and subject to catarrh, bronchitis, and lumbago, he

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developed no sign of the so-called cold diseases.

More recently, Fleisher (29), Smillie (38), and others repeated Chodousky's experiments on themselves, with negative results. The inference to be drawn from all this conflicting evidence is that cold and chilling are not necessarily predisposing or exciting causes of upper respiratory infections, and that constitutional factors may play an important rôle. The truth of the matter is that the problem is very much involved and we know very little about it at present.

Although colds are never fatal, they may be followed by secondary, serious complications. Sinusitis, pneumonia, rheumatic fever, nephritis, endocarditis and a depressed vitality may result which predispose to other infections and accelerate the progress of organic diseases (39, 40).

Prolonged exposure to cold produces dryness of the nasal mucous membranes (2, 17, 19, 41) and a diminution of the sense of smell. The symptoms are those of simple atrophic rhinitis characterized by a loss of cilia and a thinning of the mucous membrane (42). The skin may also be affected; the more immediate effects are well recognized, especially by dermatologists (43, 44, 45).

The effects of prolonged exposure to cold and temperature changes on the general health are not well understood. An extra load is imposed upon the heat-regulating mechanism, digestion, metabolism, blood circulation, kidneys, and thyroid-adrenal apparatus (39, 46, 47, 48, 49), and indirectly, upon the nervous system (14, 49, 50). Mills (50) lays great stress on the effects of weather changes on the nervous system, for the individual must be constantly shifting from a feeling of exhiliration and restlessness induced by sudden drops in temperature and rising barometric pressure, to one of irritation and depression which comes with rising temperature and falling barometric pressure.

As a class, workers in cold trades are more than usually susceptible to respiratory diseases, bronchitis, pneumonia, catarrh and also rheumatism. Heavy muscular work in cold environments is held to be a predisposing cause of disease owing to the likelihood of chilling of the body surfaces (39, 40, 51). According to Kober and Hayhurst (40), acute nephritis of serious nature occurs among workmen habitually exposed to moist cold atmospheres, particularly in persons with a history of tonsilitis, pharyngitis, or scarlatina.

Rheumatic stiffness and pains of non-specific etiology for centuries have been ascribed to sudden changes in temperature, humidity, and barometric pressure (53, 54, 55, 56) which lead to local anemia, followed by hyperemia and exudation of fluid in the tissue spaces. In case of lowered vitality, resorption is hindered and fibrinous organization of such exudates may take place. Tissues once devitalized may become breeding places for organisms displaced from mucous membranes of the respiratory and alimentary tracts.

Considerable suffering is also caused by chilblains, and it would seem that the extra-heavy clothing used by workers for protection against cold aggravates the condition. Inadequate heat regulation of the human body is probably an important factor in the predisposition to rheumatic and other circulatory affections.

Occupational Morbidity and Mortality Statistics

Trustworthy morbidity and mortality statistics of workers in cold trades are very few, limited largely to a small number of outdoor occupations. The sources of information are principally the Registrar General for England and Wales, the United States Public Health Service, and a number of insurance companies and other interested agencies.

We must admit at the outset that aside from limitations in data the evaluation of any specific deleterious influence in industry is extremely difficult, owing to the simultaneous operation of many other direct and indirect influences, occupational, socio-economic, hereditary, environmental, constitutional and others. All these factors must be carefully scrutinized before conclusions are drawn, and such conclusions must always be held with reservations.

TABLE 1

MORTALITY OF OUTDOOR WORKERS FROM PRINCIPAL CAUSES COMPARED WITH THAT OF ALL OCCUPIED AND RETIRED MALES. AGES 20–65 YEARS. ENGLAND AND WALES, 1921–1923

(Courtesy, Registrar General, England and Wales)

OCCUPATION	SOCIAL CLASS	ALL CAUSES	PNEUMONIA	INFLUENZA	BRONCHITIS	RESPIRATORY TUBERCULOSIS	CHRONIC NEPHRITIS	VALVULAR HEART	"OTHER HEART"	CEREBRAL HEMORRHAGE	DIGESTIVE DISEASES
All occupied and retired males		100	100	100	100	100	100	100	100	100	100
(Death rate per 100,000)		(913)	(78)	(33)	(45)	(150)	(32)	(58)	(60)	(41)	(54)
Costermongers, hawkers, etc	V	166	198	109	269	229	150	146	166	102	127
Stevedores	IV	162	243	—	205	223	—	147	109	77	151
Other dock laborers	V	153	201	116	251	190	117	136	132	123	133
General and undefined laborers	V	144	169	133	195	165	127	150	127	126	117
Drivers horse drawn vehicles	IV	138	160	127	204	132	131	135	132	132	124
Shipyard laborers, etc	V	135	195	181	246	160	106	145	85	108	97
Bargemen and boatmen	IV	129	121	168	134	113	118	140	128	137	71
Coal-boat loaders and dischargers	V	123	196	159	198	102	117	121	131	98	—
Comparative mortality by social class. All occupations											
Upper and middle social class	I	81	83	83	27	49	97	57	103	88	—
Skilled labor	III	95	90	93	96	98	97	97	90	100	—
Unskilled labor	V	126	150	118	178	140	106	128	115	107	—

Huntington (57, 58), Besson (59), Greenburg (60) and others compiled a wealth of statistical data showing a definite inverse relationship between outdoor temperature and morbidity and mortality from pneumonia among the general population. In an analy-

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sis of disabling illness among 100,000 wage earners in different industries, Brundage (61) showed that respiratory diseases cause nearly one-half of all the disability due to illness, with the peak of incidence occurring during the three coldest months of the year. The second most important group of diseases from the standpoint of sickness frequency was the digestive group.

Brundage and Bloomfield (62) found an incidence of pneumonia among general laborers of a large steel plant exposed to outdoor weather with no other occupational exposure nearly 3.5 times as great as that in a control group not exposed to weather. Here it would seem that exposure to the elements had a causative relation to pneumonia, for a careful consideration of other influences failed to explain the wide difference in the incidence. An equally high pneumonia incidence was found among the chippers who worked in damp and drafty sheds.

TABLE 2

MORTALITY STATISTICS OF CHICAGO POLICE FORCE, 1901–1910

(After Hoffman, Courtesy Prudential Insurance Company)

PRINCIPAL CAUSES OF DEATH	DEATH RATE PER 100,000
Accidents	17.6
Pneumonia	15.5
Tuberculosis	12.9
Urinary Diseases	10.0
Heart Diseases	14.7
Digestive Diseases	6.5

Comprehensive mortality rates in outdoor occupations and among workers in open sheds are given in the Registrar General's report for England and Wales (63), from which the values in table 1 were taken. Although the British experience is not generally applicable in this country for a number of reasons, the data are especially valuable to us since there are no comparable mortality statistics in this country.

One particular point of incomparability requires specific mention. The surprisingly high mortality for bronchitis (chronic) in column 6, table 1, is largely due to international differences in certifying and classifying causes of death. In the United States, the certification of chronic bronchitis as a cause of death is discouraged, and deaths are classified according to certain fixed rules of the Census Bureau. In England, the opinion of the physician is usually followed, as Britten (64) points out.

It can be seen in table 1 that outdoor workers as a class have a high mortality from all causes, particularly from respiratory diseases, with rates significantly above those of all workers in the same social class. Exposure to bad weather conditions with wetting and chilling is probably one of the contributing causes in all groups. No doubt the mortality is influenced considerably by the conditions of life implied by these occupations, and is partly owing to excessive alcoholism and partly to the physically inferior types among such occupational groups as costermongers, hawkers, and drivers of horsedrawn vehicles.

Of particular interest in this connection is the mortality experience of the Chicago Police force (65), the data shown in table 2. Here we are dealing with an excessive respiratory mortality in a group of healthy picked men of average socio-economic status, whose chief occupational risk, apart from homicides, is exposure to inclement weather and irregular hours.

Corroborative evidence is found in the occupational mortality statistics of the Metropolitan Life Insurance Company for 1921–1923 (66). Among the occupations with high respiratory mortality, chiefly from pneumonia, are trades with general exposure to bad weather conditions (laborers, longshoremen and stevedores, hucksters and peddlers, roofers, policemen and others) but the data are not sufficient to stand out by themselves.

HEALTH OF WORKERS IN HOT TRADES

Limits of Adaptability to Heat

Healthy persons with inherited or acquired resistance to heat can withstand quite high temperatures in a day's work without demonstrable injury to health. The endurable limit of temperature depends largely on the physical activity, length of exposure and mode of living. In men at rest in hot weather clothing, little or no change in body temperature and pulse rate results until the effective temperature* (67) exceeds 85°F. The upper limit of air conditions to which healthy persons residing in temperate climates can adapt themselves in the course of a working day without serious discomfort or injury to health is approximately as follows:

Rest, or light sedentary work—90° effective temperature:
90° dry bulb; 100% Rel. humid.
105° dry bulb; 50% Rel. humid.
120° dry bulb; 20% Rel. humid.
Air movement under 25 f.p.m.

Work—80–90° effective temperature, depending upon the rate of work:
80– 90° dry bulb; 100% Rel. humid.
90–105° dry bulb; 50% Rel. humid.
100–120° dry bulb; 20% Rel. humid.
Air movement under 25 f.p.m.

With higher air movement the limits of temperature and humidity are considerably extended as indicated by the effective temperature charts. Within these limits a new thermal equilibrium is established at a higher body temperature level through a chain of physiological adjustments.

Exposure to more extreme conditions for any considerable length of time may result in a break-down of the heat-regulating mechanism. The body temperature, heart action, and the metabolic rate are then markedly increased and a vicious cycle results which may lead to serious physiologic damage unless the organism is promptly removed to a cooler environment.

Acute Effects of Heat

The acute effects of excessive heat take the form of heat cramps, heat stroke or heat exhaustion and are

* "Effective temperature" is an empirically determined index of the degree of warmth perceived on exposure to different combinations of temperature, humidity and air movement. It was determined at the Research Laboratory of the American Society of Heating and Ventilating Engineers (68, 69) using healthy trained subjects who compared the relative feeling of warmth of various air conditions in two adjoining conditioned rooms by passing back and forth from one room to the other. The scale of the E.T. index was arbitrarily fixed by the temperature of still and saturated air which induces a sensation of warmth or cold like that of the given condition. Thus, any air condition has an E.T. of 60° for instance, when it induces a sensation of warmth like that experienced in still air at 60° saturated with moisture. The E.T. index cannot be measured directly but is computed from the dry and wet bulb temperature and the velocity of air, using charts or tables (67).

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seen especially among boiler stokers, foundry men, steel workers, miners and others. The incidence in hot industries is still quite high (70, 71, 72, 73), although in a few instances it has been practically eliminated by the application of medical and engineering measures, as already explained by Drinker (74) and Dill (75).

Heat stroke and heat exhaustion have no occupational limitation, occurring quite frequently among the general population during heat waves. Every summer there are usually between 300 and 1000 deaths from heat stroke in the death registration area of the United States. In the recent heat stroke epidemic in the Middle West during the first half of July, approximately 4000 deaths were directly attributed to heat (76).

General Chronic Effects of Heat

More important than the acute effects are the chronic effects, manifesting themselves in increased morbidity and mortality and a lowered physical efficiency. Respiratory diseases and rheumatism appear to be the chief affections in all hot trades associated with exposure to great temperature changes.

Work in hot air induces active dilatation of the vessels of the respiratory mucous membranes and skin and a more or less passive congestion in the intestinal tract and other interior organs. On exposure to cooler air as during resting periods, the condition is reversed. The hazard does not differ from that in cold trades, the significant factor in both being not heat or cold in themselves but rapid cooling of the body surfaces.

The defense of the organism against heat rests again on a good heart and vasomotor system, capable of maintaining the venous and arterial pressure. Congestions in the intestinal tract may prove significant by reducing gastric secretion and the bacteriostatic action of the intestinal mucosa. The permeability of the intestinal wall is increased, allowing the passage of infectious organisms (77, 78, 79, 80). These are believed to be important factors in the increased susceptibility to intestinal diseases among the general population during summer heat waves.

In addition to these obvious effects, there is a chain of insidious and less well defined systemic disorders leading to degenerative changes and fatigue (Sundstroem (81), Rogers (82), Bazett (83), Strong (84), Sayers (85) and many others) which were dealt with in two previous papers (74, 75).

Effects of Warm and Humid Trades

Heat combined with high humidity is trying to workers in laundries, cotton mills, canneries and kindred trades where experience and observation indicate a special susceptibility to diseases of the upper respiratory tract and tuberculosis.

Physical examinations of certain occupational groups by the New York State Commission of Ventilation (2) show that workers subjected for long periods to high temperature and humidity, such as laundry workers, exhibit an unusually high incidence of atrophic rhinitis by comparison with a control group of students, as shown in table 3. Workers exposed to drier heat, as in boiler rooms, also show a high incidence but considerably less than the laundry workers.

In addition to the atrophic condition in the nose and throat, the New York State Department of Labor (86) in a study of steam laundries in New York reports prevalence of conjunctivitis, dizziness and headaches among the manglers and pressers as a result of abnormal heat conditions. The mortality from tuberculosis in the trade is high (66), owing partly to the physically inferior type of workers and also to the fact that a small number of operatives are exposed to infected materials.

In cotton spinning and weaving processes that are carried out in warm and humid atmospheres, statistics in this country and Great Britain show a high incidence of upper respiratory infections and a comparatively high mortality from influenza, bronchitis, and tuberculosis.

Physical examinations of workers in a representative Southern cotton-cloth manufacturing plant (87) in which air conditioning apart from humidification is not used, showed a striking incidence of nasopharyngeal catarrh, from 22 to 45 per cent by room. The rate of illness from all causes lasting less than 8 days was well above normal. As a rule the workers were under the average weight of American industrial workers, an observation which is well in accord with that of Pembrey and Collis (88) for British weavers.

Of particular interest is a comparison of mortality from respiratory diseases among cotton and wool weavers; the former, working in warm and humid atmospheres, and the latter under more or less normal temperatures and humidities. According to the report of the Registrar General for England and Wales (63) the cotton spinners, doublers and weavers suffer a mortality from bronchitis between two and three times as high as the wool operatives in similar jobs but under normal temperatures and humidities. In a similar analysis in cotton weaving alone, weavers in wet sheds had about three times the mortality from bronchitis and pneumonia of weavers in dry sheds.

TABLE 3

INCIDENCE OF CASES OF ATROPHIC RHINITIS IN CERTAIN OCCUPATIONS

(Courtesy New York State Commission of Ventilation, 1923

GROUP	NUMBER OF PERSONS EXAMINED	NUMBER OF CASES OF ATROPHIC RHINITIS	PER CENT OF ATROPHIC CASES
Students	58	2	3.4
Outdoor workers (truckmen, drivers, etc.)	27	5	18.8
Workers in dry heat (firemen, engineers, boiler makers)	26	9	34.6
Workers in moist heat (mangle workers and feeders)	32	21	63.0

Complaints are frequently heard from cotton weavers about the unhealthfulness of high humidities. Vernon (89) cites the results of a ballot showing 68,000 votes against "steaming," out of a total of 72,000. The usual contention of the workers is that their clothes get too damp in the mills and after going out in cold weather they contract colds, coughs, rheumatic and lung diseases (90). Yet a study of sickness records of about 20,000 cotton weavers, half working

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in dry sheds and half in wet sheds, within the same district disclosed no definite difference in the incidence or duration of disease between the two groups over a period of a single year (91). This was recently borne out in the study of Britten, Bloomfield and Goddard (87) in an American cotton cloth manufacturing plant. It is possible that both of these morbidity studies may not have been extended over a sufficient number of years to show chronic inability.

Tuberculosis is abnormally prevalent among cotton spinners. According to studies of the United States Bureau of Labor (92) the male operatives at Fall River have a death rate 29 per cent above the standard and the females 160 per cent above.

There is no way to tell how much of the ill health is due to adverse working conditions in textile mills and how much to the low economic status and the poor physique of men and women who engage in this kind of light work.

High humidities are also held responsible as an etiologic factor in skin infections. Bacteria applied to dry skin normally diminish in numbers very rapidly owing to inherent germicidal power of living skin. When the skin is moist, however, bacteria remain viable for much longer periods owing to a depression of self-sterilizing power (93 to 97 incl.).

From an examination of 200 cases of boils among coal miners, Fisher (98) came to the conclusion that the main causative factor, apart from individual predisposition, is a high wet bulb temperature which provides favorable conditions of heat and moisture for the vitality of staphylococcus and opens the sweat glands and hair follicles, thus facilitating the entry of the organism.

Effects of Hot and Heavy Occupations

In the very hot and heavy industries such as iron and steel, sugar refining, deep mining and others, experience in this country and Great Britain shows the worst respiratory incidence and mortality next to that seen in workers exposed to silica dust.

An investigation of the frequency of pneumonia among iron and steel workers by Brundage et al. (99) disclosed an incidence more than three times as high among the men exposed to radiant heat and wide temperature changes, with no other kind of exposure, as among a control group exposed to none of these conditions. High pneumonia incidence was also associated with abnormally high incidence of influenza and other respiratory diseases, all apparently related with exposure to heat and wide temperature changes, after a careful consideration of other possible socio-economic influences.

Cheek temperatures taken in this study on workers exposed to radiant heat were unusually high (100). In a particular instance a temperature of 111°F. was recorded on the cheek of a coke oven worker when exposed to an air temperature of 94°F., relative humidity of 24 per cent and an air movement of 250 F.P.M. When the man shifted to another part of the oven section he was exposed to a temperature of only 56°F. and his skin temperature fell to 75.5°F., a decrease of 35°F. In a blast furnace cast house with an air temperature of 33°F., the cheek temperature of the first helper rose from 68.2°F. before casting to 107.6°F. immediately after casting.

Corroborative evidence on morbidity is found in British studies by Vernon and Rusher (101) covering a group of 22,000 iron and steel workers over a period of 6 years. As can be seen in table 4, the steel melters and puddlers who work under trying conditions of heat head the list with 20 to 23 per cent more sickness than the average for all steel workers combined. The excess of illness experienced by the puddlers is due almost entirely to rheumatism and respiratory diseases (table 4) which appear to be associated with the custom of these workers of alternating periods of heavy work with periods of rest or light work. This exposes the men to sudden temperature changes and the risk of chills. To some extent the same applies to the steel melters and pitmen. Tin plate millmen, on the other hand, who work almost continuously throughout their shift, escape the risk of chills and show no excess sickness from respiratory diseases and rheumatism. Their excess of illness from "other causes" is ascribed to fatigue and a lowered resistance to disease in general (Vernon and Rusher (101)).

TABLE 4

SICKNESS AMONG BRITISH IRON AND STEEL WORKERS LASTING 3 DAYS OR MORE, ALL AGES, 16–70 YEARS (1913–1918)

(After Vernon and Rusher, Courtesy Ind. Fatigue Res. Board)

OCCUPATION	RHEUMATISM	RESPIRATORY DISEASES	INJURIES	OTHER CAUSES	ALL CAUSES
All steel workers combined	100	100	100	100	100
Steel melters, teamers, and pitmen	144	110	171	114	123
Puddlers	178	135	—	97	120
Tinplate mill men	—	105	114	121	112
Rolling mill men, soakermen, hot bankmen	—	—	129	110	108
Engine, crane and locomotive men	67	110	57	97	92
All other workers	89	95	71	93	91

Mortality statistics correspond with those of morbidity, as shown in tables 5 and 6. Despite the unusually favorable selection of workers in this industry, the mortality from respiratory diseases is among the highest of all occupations. In foundry workers especially the figures of the Metropolitan Life Insurance Company (66) disclose more deaths from this cause than from any other, a condition found in no other industry. The responsible factors are undoubtedly of occupational origin. Heavy manual labor combined with exposure to dusts and fumes and especially to extreme variations of temperature are probably the significant factors. These facts are corroborated by all mortality investigations into the hazards of this occupation (102, 103, 104).

It is interesting to note in table 5 that the mortality of all steel workers from all causes appears to be 5 per cent lower than the average for all occupied and retired. This does not,

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of course, imply that iron and steel manufacture is a comparatively healthy trade; the explanation lies in the fact that the industry selects and retains only the physically strong and healthy, whereas the group of all occupied and retired males includes many invalids and others who are physically unfit for heavy occupations.

The mortality from respiratory diseases, on the other hand, is about twice as high as that of the general male population, while that from tuposure to heat and temperature changes. On the other hand, the puddlers who customarily alternate short periods of strenuous work with "cooling off" periods, have the highest respiratory mortality of all steel workers.

Coal miners also suffer an unusually high morbidity and mortality from respiratory diseases. The experience of the Metropolitan Life Insurance Company is given in table 6, and is confirmed by other studies (105, 106) and by the statistics of the Registrar

TABLE 5

MORTALITY OF STEEL WORKERS IN 1913–1918 COMPARED WITH THAT OF ALL OCCUPIED AND RETIRED MALES IN 1910–1912 BETWEEN THE AGES OF 25 AND 65. ENGLAND AND WALES

(After Vernon and Rusher, Courtesy Indust. Fatigue Res. Board)

OCCUPATION	RESPIRATORY DISEASES	TUBERCULOSIS	CIRCULATORY DISEASES	ACCIDENTS	OTHER CAUSES	ALL CAUSES COMBINED
All males occupied and retired	100	100	100	100	100	100
Steel melters, teamers and pitmen	219	75	120	48	114	120
Puddlers	259	62	63	81	52	90
Tinplate millmen	149	33	50	159	54	69
Rolling millmen, soakermen, hot bankmen	216	46	68	167	92	101
Engine, crane, and locomotive men	169	58	104	109	64	89
All other workers	203	24	75	104	85	95
All workers combined	202	52	78	110	81	95

berculosis is about 50 per cent below the average. As the Registrar General points out (63) all these figures need some correction in view of the fact that the less vigorous men eventually drop out to the ranks of unemployed or change to lighter occupations thus lowering the morbidity and death rate of those remaining in the trade.

The low mortality of the engine, crane, and locomotive men (table 5) is attributed to their comparatively light work, involving no significant exGeneral for England and Wales (63). The undue prevalence of respiratory conditions is greatly influenced by injurious dusts and gases, excessive heat and humidity with sudden changes in temperature, drafts, strenuous work and general unsanitary conditions.

Miners working in deep and hot mines are particularly prone to rheumatism and suffer more than most factory operatives (53, 54, 107). In the Brandenburg Miners' Federation, rheumatism accounted for 90 per cent

of the cases which received invalidity benefits (107). Although rheumatism is often closely associated with exposure to unfavorable conditions of temperature and humidity, the use of penumatic drills in mines is generally believed to play an important part in the predisposition to articular degeneration.

TABLE 6

MORTALITY IN HOT INDUSTRIES FROM RESPIRATORY DISEASES. EXPERIENCE OF METROPOLITAN LIFE INSURANCE COMPANY, ON WHITE MALE INDUSTRIAL POLICY HOLDERS, 15–64 YEARS OLD (1922–1924).

(After Dublin and Vane, Courtesy U. S. Department of Labor)

OCCUPATION	PNEUMONIA—ALL FORMS	INFLUENZA	OTHER RESPIRATORY DISEASES	TUBERCULOSIS—RESPIRATORY MEANS
All occupations	100	100	100	100
Iron-foundry workers	220	182	117	105
Iron and steel mill workers	142	123	122	86
Coal miners underground	150	188	238	48
Miners underground, except coal	117	—	—	182
Boiler makers	124	—	—	85
Glass workers	121	—	—	124
Blacksmiths	120	105	34	76

In coal mines Vernon and Bedford (108, 109) found the time lost from sickness to vary with temperature. Records of 23,000 men in 10 collieries indicate that 63 per cent more time was lost from sickness by miners working at temperatures of 80°F. or higher, than by those working in a temperature of 70° or less.

There is also evidence that the mortality also varies with the underground temperature (110) as shown in table 7.

Abnormally high respiratory mortality rates are likewise found among brass foundry furnace men, glass workers, brick tile and pottery kiln oven workers; brewers (malting and brewing) workers in canneries and sugar refineries, gas workers, and others who are exposed to heat and abrupt temperature changes (40, 63, 66, 111, 112).

Britten and Thompson (113) observed organic heart defects more frequently in foundries; enlarged heart

TABLE 7

UNDERGROUND AIR TEMPERATURE (DRY BULB) IN RELATION TO DEATH RATES IN MINES OF THE WITWATERSRAND, 1915–16

(Courtesy Miners' Phthisis Prevention Committee, Johannesburg)

RANGE OF TEMPERATURE	NUMBER OF MINES IN EACH TEMPERATURE GROUP	TOTAL DEATH-RATE IN MINES OF EACH GROUP	PNEUMONIA DEATH-RATE
°F.			
66–68	2	13.1	5.1
69–71	14	15.7	6.9
72–74	20	16.4	7.6
75–77	9	17.9	6.5
78–80	8	20.5	8.5

in the steel, glass and gas industries; arterio-sclerosis in foundries steel and glass plants; and varicose veins in the foundry, steel and gas industries. Heavy physical work is a common factor in all these conditions, particularly when accompanied with exposure to intense heat and great temperature changes.

Of less importance to workers in hot trades are diseases of the digestive system (63) in which heavy work, improper food and excessive use of cold drinks are contributing causes.

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Excessive heat is also definitely known to increase the poisonous action of toxic dusts and gases, presumably by increasing the volume of respiration and hence the quantity of toxic matter breathed. Absorption through the skin may also be increased in a hot and humid atmosphere.

Effects of Heat and Cold upon Physical Work and Industrial Output

The muscular system of man works best within an optimum range of air conditions depending to some extent upon the type and rate of work and degree of acclimatization. Significant departures from the optimum affect the inclination for work and reduce the working capacity with development of fatigue and other untoward symptoms. The disinclination for hard work in hot atmospheres is believed to be a conservative and protective natural instinct.

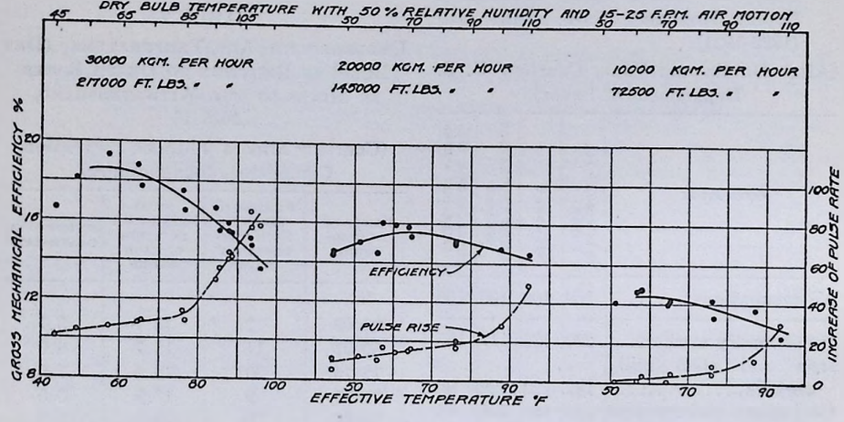


Fig. 1.—Mechanical efficiency of the human body during work under various air conditions. Experiments on an electric bicycle ergometer at constant speed.

The mechanical efficiency of the human body during work does not appear to be appreciably affected by moderate variations of temperature (114 to 120 incl.); only under unusually extreme conditions is the efficiency affected (120). It can be seen in fig. 1 that with loads between 10,000 and 20,000 kgm. per hr., variations in effective temperature between 45 and 95°F. (45–110°F. dry bulb) have but little effect on the gross mechanical efficiency. With a load of 30,000 kgm. per hr., there is a progressive reduction of efficiency from a maximum of about 18.5 per cent at 60°E.T. to about 14 per cent at 95°E.T. The loss of efficiency at the higher temperatures is associated with an abnormal rise of the pulse rate, approaching the limit of heart endurance, and with considerable discomfort and fatigue (fig. 1).

Working capacity is definitely and markedly affected even with comparatively small increases of temperature above the normal range. In experiments of the New York State Commission of Ventilation (?), 37 per cent more work was done in a temperature of 68°F. than in one of 86°, with 50 per cent relative humidity in both cases. In the experiments of the American Society of Heating and Ventilating Engineers (121, 122, 123) the greatest amount of work was performed between the limits 40° and 75°E.T. (fig. 2). As the effective temperature rose above 75°, the output fell progressively; twice as much work was done at an effective temperature of 70° as at one of 93°. In all observations shown in fig. 2 the subjects stopped work when they became tired but not exhausted.

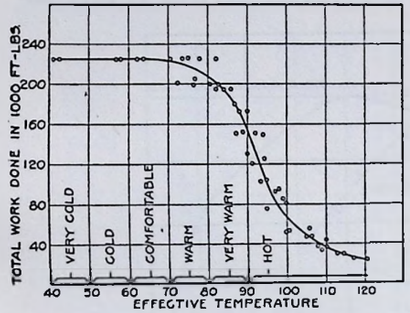


Fig. 2.—Average output of five men under various air conditions. Subjects raising weights by means of a rope and pulley. Rate of work 90,000 ft. lbs./hr. (After McConnell and Yaglou, courtesy Am. Soc. Heating and Ventilating Engineers).

Direct relationship between output and actual working conditions was obtained by Bedford and Warner (124) on 138 British coal miners working at depths from 540 to 2720 feet below surface. Their results are shown in table 8, arranged according to temperature in working places. Under normal air conditions it took the men about 8 minutes to fill a ten-hundredweight tub with coal, and the rest pauses aggregated about 7 minutes per hour. As the temperature rose with depth, both tub filling time and rest periods increased progressively, and the relative output consequently fell from 100 per cent under the best conditions to 59 per cent under the worst.

A similar experience is reported in American mines. In the Lake Superior iron mines where temperatures range between 80 and 90°F., with relative humidities close to the saturation point, the average miner works only one-half to one-third of his time (125). In one mine 4 men produced the same tonnage of ore as was produced by 9 miners in a similar place in the same mine 10° hotter (125).

In the hot metal mines of Montana, Sayers and Harrington (126) recount that 2 men working in the face of a drift in still air of 96° and 95 per cent relative humidity mucked about 12 tons per shift, whereas in a drift of an adjoining mine less than 1,000 ft. away where the temperature was 84° and the relative humidity 92 per cent, 2

TABLE 8

Working Capacity of Miners in Relation to Effective Temperature and Wet Kata Cooling Power

(After Vernon and Bedford)

Effective Temperature	Wet Kata Cooling Power	Rest Pauses	Tub Filling Time	Relative Output
°F.		minutes per hour	minutes	per cent
65.8	18.6	7.3	8.0	100
65.8	14.6	6.7	8.6	94
75.3	12.9	9.0	8.5	91
75.8	10.8	10.0	9.2	82
77.8	9.0	11.1	9.1	81
81.8	6.4	22.4	9.6	59

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men mucked more than 30 tons per shift.

Definite seasonal variations of output were shown by Huntington (57) in this country, by Vernon (127) in England, and by Yagi (128) in Japan. In Connecticut, the output of textile mill operatives is maximum during Spring and Autumn when the mean outdoor temperature averages about 60°F. (fig. 3). For heavier occupations involving exposure to high temperatures, as in tin plate manufacture, maximum output in Great Britain

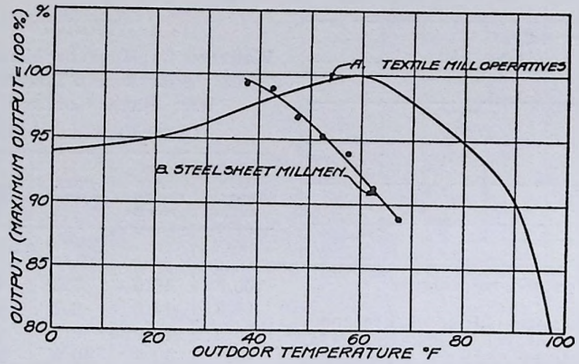


Fig. 3.—Seasonal variation of output according to outdoor temperature. *Curve A.* Output of textile-mill operatives in Connecticut. (After Huntington, courtesy Yale University Press). *Curve B.* Output of steel-sheet millmen in England. (After Vernon, courtesy Industrial Fatigue Research Board).

occurs in the cold months and minimum during the warm summer months (fig. 3). The reduction of output is small (2–6 per cent) where special means of ventilation are provided, and great (10 to 30 per cent) where reliance is placed on window ventilation alone (127).

Effect of Heat and Cold upon Industrial Accidents

Osborne and Vernon (129) have shown that the incidence of minor accidents among men and women in three large British munition factories reaches a minimum at about 67°F., increasing above and below that temperature (fig. 4). The rise at the lower temperatures is attributed to loss of manual dexterity, as the workers were handling metal shells and fuses with wet hands.

Under more adverse conditions in coal mines, studies by Vernon, Bedford, and Warner (108, 109) indicate a marked increase in the frequency of minor accidents with temperature; those causing less than 10 days' disability were three times more numerous at a temperature of 81° than at one of 63°. Major accidents, on the other hand, were not definitely affected by temperature.

In the Morro Velho Mine in Brazil, Davis (130) reported twenty fatal accidents in 16 months prior to the installation of cooling apparatus, and only six such accidents in the 16 months after the installation. The cooling apparatus reduced the dry bulb temperature in the working places (6,200 ft. below surface) from about

101° to 97°, and the wet bulb from 87° to 80°. Incidentally, the output of the workers increased 12 per cent after the installation of the apparatus.

Control of Abnormal Air Conditions

The control of industrial hazards associated with heat and cold is partly engineering and partly a medical problem involving four general lines of procedure, as follows:

(a) Change or mechanization of the process.

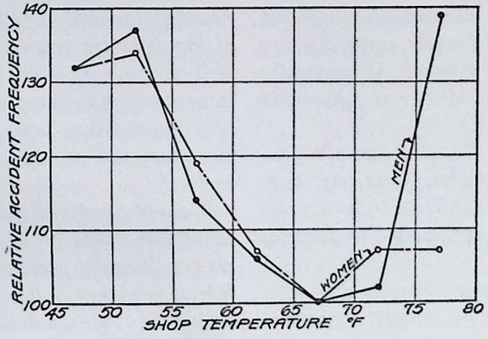


Fig. 4.—Frequency of minor accidents in relation to temperature in British munitions factories. (After Osborne and Vernon, courtesy Industrial Fatigue Research Board).

(b) Local control of the atmosphere surrounding the process.

(c) Control of the general atmosphere in the workrooms by ventilation or air conditioning.

(d) Preventive medical methods applied to the worker.

It is sometimes possible and feasible to change the process in such a way as to correct or ameliorate unfavorable working conditions. An example of this we find in the mechanization of the bottle-manufacturing industry which used to be a very unhealthy trade before the introduction of machine methods. The same holds true in the mechanization of malting and brewing processes in a few of the modern plants.

Under the second classification may be included the use of thermal insulation, screens for radiant heat, exhaust hoods or canopies, segregation and isolation of the offending process, or the enclosure of the entire process with more or less complete isolation from the general atmosphere of the room.

In a number of instances the abnormal conditions are dictated by the requirements of the process and it is often difficult to meet the requirements without interfering with the general atmosphere of the rooms. Unfavorable exposure becomes, then, a necessary evil, and all we can hope for is to alleviate the effects by preventive medical measures, selection and gradual adaptation of the workers, suitable clothing, short hours of work, suitable ventilation and air movement in warm environments, and proper personal hygienic habits. By means of medical supervision, predisposition and

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injurious physiological effects can be counteracted to a large extent and physical fitness maintained in most instances with little or no impairment.

In still other instances, such as laundries, steel mills, foundries, deep mines, etc., the abnormal conditions are incidental to the process and not only entirely unnecessary from the manufacturing standpoint, but injurious to the health and wasteful from the economic standpoint. It is in this field that proper insulation supplemented with ventilation or air-conditioning measures may prove valuable and often indispensable, but the extent to which such measures are being used at present is generally limited to the minimum requirements of the law.

Industrial ventilation and air conditioning are not always entirely effective and they often have to be supplemented with or superseded by medical methods.

Industrial air conditioning as it is practiced today is mainly concerned with the control of temperature, humidity, and cleanliness of air for the processing of certain materials or products that are affected by humidity or temperature, or both. The field of application is largely confined to the manufacture or processing of hygroscopic materials, such as textiles, foodstuffs, tobacco, paper, lumber, leather, chemicals, etc., in which the texture, strength, quality, weight, or moisture content are greatly affected by humidity and in many instances by temperature. There are more than 200 different industries in which certain ranges of temperature and humidity are desirable or essential from the economic standpoint, and in which the benefits of air conditioning can be evaluated on a monetary basis.

The human benefits are less tangible and in many instances difficult to prove, owing to the complexity of the problem. Industrial air conditioning in hot and humid trades solely for the comfort and health of the workers is at present a rare exception. Generally speaking, manufacturers until very recently paid little attention to personal factors unless forced to do so by law or by unbearable working conditions. Slowly but surely there has been during the past few years an increasing realization of the importance of the problem from the financial as well as from the health standpoint, largely owing to the gradual extention of compensation laws to disabilities caused by abnormal injurious environments.

The complexity of industry presents many difficulties in the solution of the air-conditioning problem which is different in every industry and every building. The possibilities and limitations of air conditioning as applied to three representative hot industries are discussed below.

Air Conditioning in Textile Mills

The art of air conditioning originated in the textile industry in which humidity plays a most important rôle. Successful application of controlled humidification methods has been instrumental in the gradual concentration of cotton mills near the source of raw material, whereas 20 years ago the plants were largely restricted to geographic areas having a high relative humidity.

The importance of humidity in textile plants is due to the fact that all

textile material, whether of animal, vegetable, or mineral origin is hygroscopic, containing a definite normal amount of moisture which varies chiefly with the relative humidity of the air and to some extent with the temperature. When the fibers are deprived of some of the natural moisture content, they invariably become stiffer and brittle, lose strength and pliability and cannot be worked readily and efficiently. An excess of moisture is not detrimental, except in the case of rayon and jute which weaken materially under excessive humidity, stretch more and become too plastic.

The effect of humidity on the strength of textile materials is considerable. The breaking strength of cotton thread "20 Denier" is according to Baker (131) 74 lbs. at a relative humidity of 40 per cent, and 92 lbs. at a relative humidity of 80 per cent or more. Thread of "35 Denier" has a strength of 35 lbs. at 40 per cent relative humidity, and 49 lbs. at 80 per cent relative humidity. Strength, resiliency, and stretching do not alter appreciably by humidities in excess of 80 per cent.

The main purpose of air conditioning in textile mills is, therefore, to maintain the normal hygroscopic moisture in the fibers by controlling the relative humidity, and in the case of rayon and jute by control of the temperature, also. Secondary purposes are to maintain constant machine speed through constant belt tension and to avoid accumulation of static electricity which weakens the threads by making the fibers fly apart.

Desirable or optimum air conditions for the processing of textiles depend upon the product and process. Wyatt (132) has shown that as the temperature in cotton-weaving rooms increases from 60° to 70°, and the relative humidity from 50 to 80 per cent, the number of yarn breakage decreases and the actual efficiency of production increases. But beyond a temperature of 70° to 75°, and a relative humidity of 80 to 85 per cent the efficiency begins to decrease because of the adverse physiological effects of atmospheric conditions on the weavers, as shown by significant increases in body temperature and pulse rates. While the number of yarn breakage keeps on decreasing practically up to the point of saturation, the ability of the workers to fix the breaks is reduced, with a reduction in the overall efficiency of production. Substantially, the same limiting values were obtained by Weston (133) in linen weaving. In silk weaving, on the other hand, Elton (134) found no significant variation of output with humidity.

In this country, the humidities recommended (135) in cotton weaving are somewhat lower than in England, being between 70 and 80 per cent. In the carding, combing, roving, and spinning of cotton, the relative humidity requirement is between 50 and 70 per cent, and this also holds for all processes in woolen and silk manufacture.

Generally speaking, these process requirements are not prejudicial to the health of the workers, and little or no trouble would be experienced if suitable equipment were employed to maintain these conditions. In a number of instances, application of air conditioning is claimed to have resulted in substantial savings of production costs and improvements in the general

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health of the operators (136, 137, 138, 139).

Observations of temperature and humidity in American cotton mills by Best (140) and by Britten, Bloomfield, and Goddard (87) disclosed temperatures between 75° and 100°, averaging rarely below 80° in the South even in winter time, with considerably higher figures in the summer time. The relative humidity in the weaving rooms was between 70 and 85 per cent and in the other departments between 50 and 65 per cent.

High temperatures in textile mills result from the following main causes:

1. Heat from power-driven machinery, practically all of which is liberated in the room.
2. Solar heat on exposed wall, roof and glass surfaces.
3. Body heat of operatives.
4. Heat from live steam used for humidification.

In some mills the waste heat liberated in the room is more than sufficient to offset the heat loss through the structure even in severe winter weather. In warm summer weather the temperature may rise to 95° or more.

Few of the mills are suitably equipped and far too few have mechanical refrigeration for cooling in warm weather. As a rule, the equipment includes direct or indirect humidifiers of the spray type for humidifying the air in cold weather, and for producing cooling by evaporation in warm and dry weather. The cooling effect is limited by the wet bulb temperature of the outside air, and the dry bulb temperature in the workrooms may be from 8° to 20° above the outdoor wet bulb. In warm weather the relative humidity required for the process must be maintained, but the dry bulb temperature is allowed to rise, often to an uncomfortable degree. Refrigeration appears to be the only remedy in hot weather. Solving the problem is not at all difficult in its engineering aspects but the cost of installing cooling equipment is considerable.

In small and old mills in which the extra cost may not be justified, working conditions may be alleviated by suitable insulation against solar heat substitution of water-spray humidification systems for the old-fashioned "steaming" method, an increase of ventilation rate and of air movement locally in the neighborhood of the workers by means of gyrating or oscillating fans. In the experience of Wyatt (141) the use of fans appears to increase the output of the looms when the temperature and humidity are high, without causing additional warp breakage.

Legislation in various countries fixes the upper limit of wet bulb temperature at which artificial humidification must cease. In Great Britain artificial humidification is forbidden when the wet bulb exceeds 75°F., and when it reaches 78°F. all work must cease.

Similar legislation was passed by some states in this country. The Massachusetts law fixes the same permissible maximum limits of humidity as the British regulation. It also requires pure water for humidification purposes and a good hygrometer in every workroom.

Special problems of localized exhaust ventilation arise in the cotton-carding rooms to guard against "cotton-asthma" (142, 143, 144), and in various departments of the artificial silk industry where injurious chemicals are employed (145, 146).

Air Conditioning in Mines

Air conditions in mines.—Abnormal air conditions in mines result from physical and chemical vitiation. Unless mines are thoroughly ventilated, the air becomes hot, humid, and stagnant, laden with dusts and often with dangerous gases. Conditioning of mine air becomes necessary, as a rule, in deep mines only. In shallow mines and pits, the problem is one of ventilation rather than air conditioning, and the object is primarily to remove explosive mixtures, dusts, gases, etc., to make the workings safe. This is particularly true of coal mines. The amount of air supply depends entirely upon the particular conditions existing in the mine. Nine states stipulate a minimum of 100 c.f.m. per person; 6 states require 150 c.f.m. per person in gaseous mines and 100 in others, other states demand from 100 to 200 c.f.m. According to Harrington (147) these values are entirely inadequate under certain conditions.

As mining operations proceed deeper and deeper, the temperature rises higher and higher owing largely to the combined effect of autocompression* and geothermal gradient of the rock. Observations in various mines show a rate of rise of 1°F. in from 60 to 250 ft. of depth depending on the locality. Additional sources of heat of considerable significance are machine drills, underground blasting operations, oxidation of pyritic materials, and of timber used for supports, body heat of the operatives and their lamps, etc. The heat is often associated with high humidities as most of the mines are usually wet. Even in exceptional mines, with comparatively dry shafts and drifts, the usual precautions taken for reducing the risk of silicosis by washing down the walls and roof tend to saturate the air and aggravate the heat problem.

In very deep mines (6000 ft. or deeper) the underground temperature remains, as a rule, practically constant throughout the year (see fig. 5) regardless of climatic changes on the surface as shown by Tillard and Ranson (148), Ranson (149) and others. The temperature in the working places may go up high and the humidity close to the saturation point, creating risk from heat stroke and greatly reducing the working capacity of the miners.

Air conditioning with refrigeration is necessary as a corrective measure, but the means to this end are not very effective in deep mines and under extreme conditions they may prove futile.

Possibilities and limitations of methods of cooling mines.—The increase of temperature and moisture content of the ventilating current in its course underground creates a most difficult problem in the cooling of deep mines. If air is cooled at the surface by using mechanical refrigeration the greater difference in temperature between rock and air will result in a greater heat absorption with considerable loss of cooling effect.

Observations by Davies (130) in the Morro Velho Mine, Brazil, show that uncooled air entering the mine at

* Maximum theoretical heating due to autocompression is 5.5°F. per 1000 ft. of depth.

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76° arrived at a level 6126 ft. below surface with a temperature of 101°; when cooled to 42° by refrigeration it reached the same level at 93°. An initial temperature difference of 34° at the surface decreased to 8° at the 6126 ft. level. If, on the other hand, the refrigerating equipment is installed underground, difficulty arises in getting rid of the heat from the condenser water. Heat absorbed from the mine air is simply transferred to the condenser water and must be got out of the mine in some way. Pumping the warm condenser water to the surface is economically impracticable owing to great frictional losses and high-power consumption.

A somewhat better method is using heat interchangers or cooling towers at the bottom of the upcast shaft for removing heat from the condenser water through the medium of exhaust air after it has served its purpose in cooling the mine. Although this method appears more promising, it does not offer a complete solution to the problem, for to cool the air effectively with gradually advancing workings, several units, preferably portable ones, must be installed at different working places underground, requiring considerable piping which interferes with blasting operations along stope faces, or near the development ends in drives and splits. The difficulties have been discussed quite fully by Tillard and Ranson (150) and others.

Various other methods of cooling mine air have been tried with limited or no success. Local underground cooling by means of ice was studied at the Village Deep Mine (150) by placing ice on traps inside the ventilating duct near the air outlets. The maximum reduction in air temperature was about 6°F. at the air outlet, but 15 ft. from the duct opening the temperature reduction was only 2 to 3°.

The use of dry ice, liquid air, and compressed air has been suggested but found economically impracticable except as a local expedient in dead ends. Chemical dehydration of mine air underground by means of calcium chloride or silica gel offers little hope of success because the adsorption process is accompanied by a marked rise in the temperature of the air; the latent heat of condensation is simply converted to sensible heat which must be removed from the air.

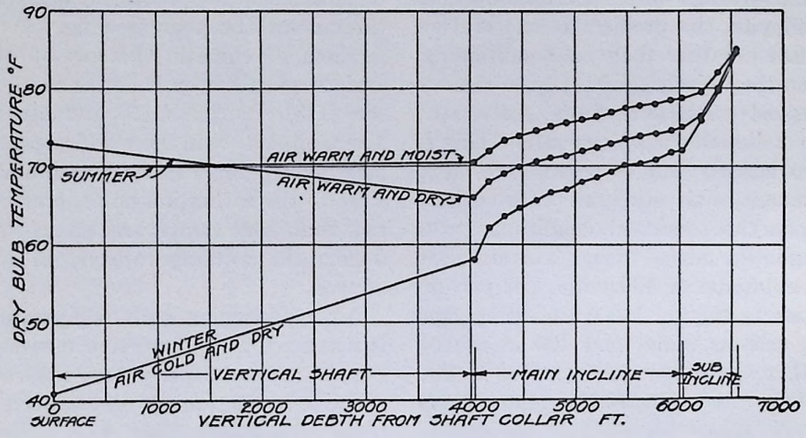


FIG. 5.—Air temperature at various depths in the Village Deep Mine (Witwatersrand, So. Africa) during different periods of the year. (After Tillard and Ranson, courtesy J. Chem. Met. Min. Soc. So. Africa).

A more recent suggestion by Hirschfelder (151) is the reduction of the humidity underground by the use of magnesium chloride ($MgCl_2$) solution which has a low vapor pressure. The more obvious disadvantages to such a scheme appear to be the possible effects of magnesium chloride on health, corrosion of metals, and the necessity for washing the ore before reduction treatment.

How effective air conditioning would prove in penetrating great depths is highly problematical. In the Rand gold field of South Africa there seems to be little hope for depths greater than 10,000 ft. unless some new method of refrigeration is found. Progress is now being watched with great interest in three mines, two of which have recently installed cooling equipment. Of particular interest in the installation at the Robinson Deep Mine on the Rand, the deepest mine in the world, with workings running more than 8000 ft. below the earth's surface. The air-conditioning system has a refrigeration capacity of 2,000 tons, capable of cooling 400,000 c.f.m. of air in order to overcome temperatures approaching 120° and allow access to rich veins of gold ore.

Haldane (152), Moss (153), Tillard and Ranson (150), Gibbs and Buist (154) and others believe that dry mining methods offer a practical solution in deep mines. They advocate keeping the air underground as dry as possible, in order to increase the evaporating power of the air, by substitution of dry-drilling methods with suitable exhausts, for the present wet-drilling methods. As an antidote for silica dust in the general mine atmosphere, Haldane suggests deliberately introducing carbon dust in the air in order to stimulate phagocytosis and in this way minimize the harmful effect of silica dust.

For the comparatively shallow mines in the United States, Harrington (147) and McElroy (155) believe that the most efficient method, at least for the time being, is the continual circulation of large volumes of fresh air from the surface. Ranson (149) and Whittaker (156) have shown by actual tests that an increase in the air supply not only reduces the time of contact between air and warm rock but it gradually cools down the rock to a significant extent. Material benefit will also result from concentration of air to the working places, and from exploiting air movement to the fullest practical extent. But too much air movement may prove harmful as indicated by certain observations of Vernon and Bedford (109) on sickness and accident rates of coal miners.

Ventilation and air-conditioning methods differ a great deal from mine to mine according to whether dust, or heat, or toxic gases constitute the chief hazard. Among the contributions to the engineering aspects of mine ventilation are those of Harrington (147, 157), McElroy (155, 158), Moss (159), and Weeks (160).

Medical aspects in deep mining.—

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With limitations in engineering methods, the practicability of ultra-deep mining in the future will probably depend to a considerable extent on the application of medical methods in selecting, acclimatizing, and taking proper care of the underground workers.

Individuals exhibit marked differences in their susceptibility to heat, as well as to cold and temperature changes. Some are capable of adapting themselves more easily than others, either because of greater resistance or because they have no circulatory or respiratory impairment affecting susceptibility. What may mean heat stroke to one may not affect another.

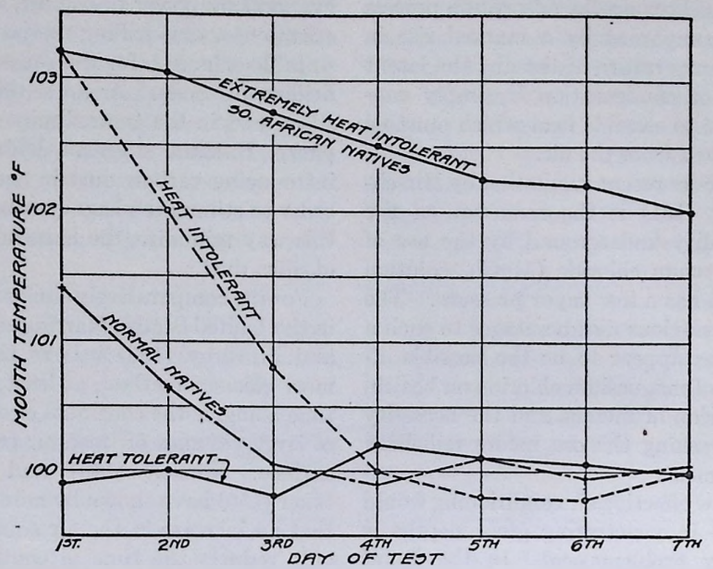


FIG. 6.—Typical reactions of new miners to "heat-tolerance tests" during probationary work periods. Chamber temperature 95°F., relative humidity 100%. Rate of work 9,000 ft. lbs./hr. (After Dreosti, courtesy J. Chem. Met. Min. Soc. So. Africa).

TABLE 9

MORTALITY OF NATIVES IN MEDICALLY SUPERVISED AND UNSUPERVISED MINES IN TRANSVAAL

(Courtesy Transvaal Mine Medical Officers' Association)

YEAR	UNSUPERVISED COAL MINES	SUPERVISED GOLD MINES
1924	13.59	9.99
1925	14.19	8.61
1926	13.25	9.05

The importance of acclimatization is duly stressed in a recent bulletin of the Metropolitan Life Insurance Company (76) dealing with the heat stroke epidemic in the Middle West last July. According to these statistics, a white person living in Wisconsin is approximately twenty times more likely to die from heat stroke than a white resident of Florida, and about ten times more likely than one in Virginia or South Carolina. Other states show differences proportional to differences in their climate.

Selection of heat-resistant workers from the natives and a system of gradual adaptation now in use at the City Deep Mine, in South Africa (161), proved very effective in reducing the incidence of heat stroke to practically nil. The system consists in an experimental chamber, equipped with rock, shovels, etc., where new natives are given probationary work periods in hot, saturated, and stagnant atmospheres comparable to those encountered in underground work. "Heat-intolerant" individuals are detected by excessive increase of body temperature and pulse rate, and given no employment in hot places. In the same chamber, "heat-tolerant" natives are gradually adapted to their future task in probationary periods of 4 to 14 days according to individual tolerance. Figure 6 shows typical reactions of "heat-tolerant" normal natives and "heat-intolerant" natives to a given task under comparable conditions, as observed by Dreosti (161).

Acquired adaptation was found to bestow no permanent immunity against heat stroke, being lost as rapidly as acquired in individuals staying away from work for a number of days.

If the acute effects of heat can be prevented this way by selection and adaptation of workers the chronic effects, such as respiratory diseases and rheumatism, may be controlled by proper habits of personal hygiene during and after work and periodic examination of the workers. The main factor appears to be avoiding chills during resting periods and on coming to the surface after work. Suitable working clothes with facilities for bathing and changing to dry street clothes are generally considered among the most important factors in a preventive system.

The value of medical supervision has been demonstrated in certain mines of Transvaal (162) by contrasting the mortality among natives working in well-supervised gold mines with that of natives in unsupervised coal mines. Except for the accident hazard, coal mining is generally recognized as a healthier occupation than gold mining, yet the mortality of the supervised gold miners was found to be consistently lower than that of the coal miners (see table 9).

Control of Heat Hazards in Hot and Heavy Occupations

Engineering methods.—The control of heat hazards in iron, steel, pottery kiln, foundry and other hot trades is primarily a medical problem and only secondarily an engineering one. The temperature in the vicinity of furnaces and red hot metals where men work may be between 90 and 200°F., while farther away from the source of heat it may be as low as 50° in cold weather and still lower in open sheds. The work is mostly intermittent with alterations of heavy manual labor, under trying conditions, with resting periods for cooling off. This in fact constitutes the chief industrial hazard. Sometimes a portion of the body is exposed to intense radiant heat inducing copious perspiration while other portions are subjected to cold drafts. Steep temperature gradients near the

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furnaces or hot metals create powerful drafts of air to which men are exposed.

The first attempt in environmental control should be directed toward effective insulation of the main sources of heat and the shielding of the workers from radiant heat rays by interposition of stationary or movable screens, fire chains in front of open furnaces, and by the use of face screens or masks with suitable goggles, when the workers must face intense radiant heat. Introduction of modern labor saving mechanical appliances would help a great deal in sparing the workers from heavy work and unfavorable exposure.

It would obviously be impractical, often futile, to attempt to control the general atmosphere by ventilation in winter time or by artificial refrigeration in warm weather. The problem of cooling the workers themselves while hot and perspiring is also a difficult one from the physiologic standpoint. Blasts of cold air are most uncomfortable and dangerous owing to the likelihood of chills. The chief trouble appears to be with the heat regulating mechanism of the body which cannot adjust itself as the cold draft is apt to chill the side of the body exposed to it while the opposite side is still uncomfortably hot.

Local cooling of the workers by means of moderately cool currents of air directed laterally or downward upon the body gives fair results, as good as can be expected under the circumstances. "Man cooling" fans are often employed instead of the conventional duct distributing systems. In warm summer weather, the air supplied to the workers may be moderately cooled by saturating it adiabatically in a conventional type of spray air washer and blowing the saturated cool air directly upon the workers through a system of air pipes, as described in detail elsewhere (163). This is all the cooling the workers can safely stand.

Medical methods.—In the prevention and treatment of acute and chronic heat effects, the industrial physician has accomplished much in decreasing sensitivity by prophylactic measures applied to the workers, by control of fatigue, diet, alcoholic habits, etc., and by periodic examination of the workers for the detection of early symptoms and the institution of prompt remedial measures.

Still greater possibilities would seem to lie in the selection and gradual adaptation of the workers according to their physiologic response to heat and sudden temperature changes so that only resistant individuals are put to work in hot places, as is now being done in South African Mines with considerable success (161).

The importance of suitable working clothes, facilities for shower baths and dressing rooms for changing to dry clothes before going out after work cannot be overstressed in view of the high incidence of pneumonia and rheumatism in hot trades.

Speaking from broad experience, Kober and Hayhurst (39), Vernon and Rusher (101) and others intimate that the workers are often more to blame than the employers for the high morbidity and mortality in their trades; their negligence in changing wet clothes is generally believed to be a potent cause of rheumatism and their pernicious habit in passing suddenly from an overheated atmosphere to cold outside air is a strong factor in the predisposition to respiratory diseases.

For the same reasons, open yards where the general laborers work should be provided with shelters against rain and snow. Suitably heated rest rooms should be available for men engaged in intermittent work and the employees should be instructed and induced to make use of these provisions for their own good.

Summary

Abnormal air conditions in hot and cold trades are shown to affect working capacity, accident liability, sickness, and mortality. Although heat or cold *per se* are the causes of acute conditions, chronic effects appear to be largely due to sudden temperature changes and the liability of chilling the body while warm and perspiring.

Respiratory diseases and rheumatism are the chief affections in hot and cold trades associated with exposure to great temperature changes. Unusually high respiratory illness and mortality is seen especially among heavy manual workers, outdoor laborers, iron and steel workers, miners, and others.

In the control of acute and chronic effects, ventilation and air-conditioning methods are not always effective and they often have to be supplemented or superseded by medical methods. Much has been accomplished by industrial physicians in decreasing sensitivity to abnormal environments by prophylactic methods applied to the worker, by control of fatigue and hygienic habits, and by periodic examination of the workers for detecting early symptoms, and instituting prompt remedial measures.

Still greater possibilities would seem to lie in the selection and gradual adaptation of workers according to their physiological response to heat or cold and sudden temperature changes, so that only tolerant individuals will be allowed to work in such trades.

The complexity of industry presents many difficulties in the solution of ventilation and air-conditioning problems which differ in every industry and every building. The possibilities and limitations of air conditioning as applied to three representative industries (textile mills, mines, and steel mills) are briefly discussed.

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THE PHYSIOLOGICAL EFFECTS OF HIGH PRESSURES*

Louis A. Shaw

When men have been working under high air pressures, the return to normal atmospheric conditions is frequently attended by disorders known as compressed-air illness. Compressed-air illness is caused by the conversion of dissolved nitrogen into free nitrogen. The liberation of this free gas into the tissues and blood forms bubbles which, when sufficiently profuse, may block the circulation. The character of the symptoms produced is subject to wide variations, depending upon the quantity and distribution of the bubbles.

Nitrogen in Supersaturation

What exactly is the mechanism by which nitrogen bubbles are formed in the blood and tissues of the body? If a beaker of water is subjected to a pressure of 2 atmospheres, equilibrium will ultimately be established between the supernatant gases and the gases dissolved in the water. Now if the pressure is suddenly dropped to 1 atmosphere, some of the dissolved gas must escape from the fluid in order to establish a new equilibrium. Will this excess gas leave the fluid as dissolved gas, or will it effervesce and rise to the surface as bubbles? When the partial pressure of a dissolved gas exceeds the barometric pressure upon it, the dissolved gas tends to effervesce, but under certain conditions gases may be held in a state of supersaturation.

It has been found that man can tolerate sudden decompression from pressures of 2 to 2.3 atmospheres absolute, i.e., from 15 to 19 lb. gauge, without manifesting any symptoms of compressed-air illness. At 15 lb. pressure the partial pressure of nitrogen dissolved in the blood and body fluids is about 1173 mm. When the barometric pressure is reduced to 760 mm. the partial pressure of the nitrogen held in supersaturation is, therefore, 1173 − 760 = 413 mm. If all this nitrogen in supersaturation were liberated into the blood and tissue fluids as gas bubbles its volume would approximate 700 cc. It seems highly improbable that any such volume of free nitrogen in the body could be tolerated. There can be no doubt, therefore, that the blood and body fluids can, within certain limits, hold nitrogen in a state of supersaturation. But when these limits have been exceeded, bubbles will form.

If time were permitted, decompression could be carried out so slowly that the barometric pressure is never permitted to fall below the partial pressure of the dissolved nitrogen, thereby making bubble formation an impossibility. I have not even calculated the length of time this would take, but it is certain that the time involved would render work under compressed air wholly impractical. The rate at which the excess nitrogen in the body is eliminated is proportional to the pressure difference of the nitrogen on the two sides of the alveolar membrane, i.e., between the pressure of nitrogen in the blood flowing through the pulmonary capillaries and the pressure of nitrogen in the air of the lungs. This pressure difference constitutes an effective pressure head, which is the crux of all decompression operations. In order to keep this pressure head maximal we must take advantage of the capacity of the body to hold nitrogen in a state of supersaturation. As we have just seen, a man may be released from pressure while the partial pressure of nitrogen in his body is about 1173 mm. Nitrogen pressures in the tissues greater than this may cause compressed-air illness. Since the very essence of successful decompression is to keep just within the limits of safety, and since a gas held in a state of supersaturation is very unstable and unpredictable in its behavior, it follows that we must be prepared for accidents.

Distribution of Bubbles

The character of the symptoms of compressed-air illness is conditioned by the volume of the bubbles and by their position within the body. We have no means of determining the volume of the bubbles present in the organism, either living or dead. Studies of the position of the bubbles, either post mortem or in the anesthetized animal, have not been carried out with the systematic thoroughness which the subject deserves. The most comprehensive study of this subject to date is that made by Boycott, Damant and Haldane in 1908 (1), using goats as the experimental animal.

These workers found that if an animal was killed while still suffering from compressed-air illness and examination made immediately, one could observe the state of affairs which *probably* existed during life. It was found that bubbles were present in great numbers in the right heart and in the venous blood throughout the body. Only a few of these bubbles pass from the right side of the heart, through the pulmonary capillaries, into the left side of the heart. As a consequence comparatively few bubbles are found in the arterial blood.

It is reasonable to suppose that the same forces which produce bubbles within the blood stream should be operative in producing bubbles in all the body fluids, both intracellular and extracellular. In order to ascertain if this were the case, Boycott, Damant and Haldane made microscopic examination of histological sections from various organs, glands, muscles, etc., for evidence of nitrogen emboli existing outside of the blood vessels, lodged either within the cells or between the cells. Strangely enough, the only extravascular bubbles observed were those existing between the fat cells of the cord and between the cells of the fatty deposits. No bubbles were found between the non-fatty cells. In no instance were bubbles ever found within the cells. It is diffi-

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cult to explain why the blood draining the tissues should be full of bubbles, while none are found within the cells. The absence of emboli within the cells must signify that bubbles form in the blood at a lower nitrogen pressure difference than in the tissue fluids.

Behavior of Bubbles

Although much valuable information concerning the behavior of nitrogen bubbles in the body has been derived from post mortem studies, these findings must be accepted with certain reservations, since bubbles which were *not* present during life may form after death, and bubbles which *were* present during life may have disappeared before the examination was made. Because of technical difficulties no satisfactory means has yet been found which enables us to make direct observations of bubbles in the living body. Our information regarding their origin, migrations and final disappearance must, therefore, be derived for the most part from a study of the physiological effects produced.

Following decompression the partial pressure of nitrogen in the tissues falls rapidly. It follows, therefore, that if bubbles are going to form, they should most likely do so soon after decompression when the supersaturation pressure is maximal, and for the same reason we should expect the symptoms of compressed-air illness to occur immediately after decompression if they are going to occur at all. This is not the case, however, and one of the most characteristic and perplexing aspects of compressed-air illness is the time interval which intervenes between the moment of complete decompression and the onset of symptoms. In 46 cases of compressed-air illness, reported by Shilling, Polak and Hansen (2), the maximum time interval was 420 minutes and the average interval was 59 minutes. This delay in the onset of symptoms, though unimportant clinically, may throw some light upon the behavior of bubbles within the body.

Migration of Bubbles

When bubbles forming in the tissues pass into the general circulation they will be carried to the lungs. If these bubbles are able to pass through the pulmonary capillaries, then with each circuit of the blood through the tissues some of the bubbles may stop in the systemic capillaries causing a gradual obstruction of blood flow. In this manner free gas may pass from a position in which it is innocuous to a position in which it causes circulatory blockage. This process may involve an appreciable time interval.

The foregoing hypothesis, however, is open to much criticism because it has been shown that under certain circumstances the pulmonary capillaries, with respect to gas emboli, act as an effective filter which prevents bubbles passing through the lungs into the arterial blood. Van Allen, Hrdina and Clark, in 1929 (3), showed by experiments on dogs that air injected into the veins does not succeed in passing through the pulmonary capillaries, but is held by the pulmonary arterial tree and gradually disappears into the alveoli. Ilyin (4) injected 2000 cc. of air into the jugular vein of dogs at a rate of 30 cc. per minute without fatal results. Escape by diffusion of gas through the capillary walls at any such rate as this seems quite impossible, because the concentration of gases in the bubble quickly becomes identical to that in the alveoli. The evidence points to the extrusion of air bodily from the bubble directly into the air spaces of the lungs.

When air was introduced through the pulmonary vein, Van Allen (3) found that very small quantities were fatal. Death was caused by blockage of both the coronary and the cerebral circulation. Some of the air thus injected passed through the systemic capillaries and appeared again in the right heart. Van Allen found that the tolerance to air entering the right heart was approximately fifty times as great as the tolerance to air which enters the left heart. Although the behavior of minute bubbles which are evolved from a solution undoubtedly differs from gas admitted through a cannula, Van Allen's experiments are significant in so far as they point to the filtering action of the pulmonary capillaries and to the serious effects produced by such gas as may pass through this filter.

That small quantities of free gas do pass through the lung capillaries following decompression is indicated by the post mortem findings of Boycott, Damant and Haldane who found a few bubbles in the left heart and arterial blood. Although, for reasons already given, post mortem evidence is not conclusive evidence, it nevertheless indicates that the lung is by no means a perfect filter. It would be unwise to underestimate the serious consequences which might result from even very small quantities of gas in the left heart.

There is yet another way in which bubbles may cause injury by moving from one position to another. One might suppose that bubbles floating freely in the circulating blood would be carried along by the current and caught in the pulmonary filter. If these bubbles are formed at the moment decompression is complete, they should reach the lungs and be caught in the pulmonary filter within the time necessary for the blood to move from the tissues to the lungs. Van Allen has shown that this is not the case however, since the movement of bubbles is conditioned largely by considerations of gravity. Even where the current is swift, bubbles may remain stationary in a bend of a vessel, or, should gravity so dictate, they may move in a direction opposite to that of the current. Thus muscular movements or a change in bodily position long after decompression may liberate free gas from a position of safety, whence it is carried to the lungs. If this gas should collect in the pulmonary vessels more rapidly than it can be eliminated, the result may be serious.

Bubble Gases

Whereas the bubbles which accumulate in pulmonary capillaries may escape directly into the alveolar spaces, those which form in systemic capillaries must pass by diffusion into the surrounding tissues, from which they are then taken up in solution by the circulating blood and carried to the lungs. When a bubble first forms in the tissues it is composed of 100 per cent nitrogen, which then becomes diluted by the inward diffusion of the water vapor, carbon dioxide and oxygen which are dissolved in the surrounding blood and tissues. The partial pressure of the gases dissolved in the arterial blood is approximately

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that of the alveolar air, and is therefore equal to barometric pressure. But the partial pressure of the gases dissolved in the venous blood and tissues is always less than the barometric pressure owing to the utilization of oxygen by the tissues. To the extent that the partial pressure of the tissue gases is less than barometric, the partial pressure of nitrogen in a bubble will be in excess of that of the tissues, and therefore the nitrogen tends to pass from the bubble into the tissues until absorption is complete.

TABLE 1

PARTIAL PRESSURE OF GASES DISSOLVED IN ARTERIAL BLOOD, VENOUS BLOOD OR TISSUES AND THAT OF GASES IN A BUBBLE IN BLOOD DRAINING THE TISSUES.

GAS	ARTERIAL BLOOD	VENOUS BLOOD AND TISSUES	BUBBLE IN VENOUS BLOOD OR TISSUES	pN_2 IN BUBBLE MINUS pN_2 IN TISSUES
1 Atmosphere Absolute = 760 mm.				
	mm.	*mm.*	*mm.*	*mm.*
H_2O	47	47	47	
CO_2	40	48	48	
O_2	100	38	38	
N_2	573	573	627	54
Total	760	706	760	
3 Atmospheres Absolute = 2280 mm.				
H_2O	47	47	47	
CO_2	40	48	48	
O_2	420	41	41	
N_2	1,773	1,773	2,144	371
Total	2,280	1,909	2,280	

Table 1 shows the partial pressure of the gases dissolved in the arterial blood, the venous blood or tissues, and the partial pressure of these gases in a bubble which is in the blood draining the tissues. We have assumed that the partial pressure of gases in arterial blood is the same as that of alveolar air. Although the partial pressure of carbon dioxide and oxygen of venous blood varies in different tissues, we have adopted the average value, i.e., the partial pressure of these gases in mixed venous blood. The partial pressure of carbon dioxide and oxygen in the tissues themselves we may assume to be approximately the same as that of venous blood. The calculations of partial pressures which follow from these assumptions can, without doubt, be made with sufficient accuracy to show the manner in which nitrogen passes from a bubble into the surrounding blood or tissues. It will be observed that as the air pressure increases, the pressure difference between the nitrogen in the bubble and the nitrogen in the tissues also increases. Thus at 1 atmosphere absolute this pressure difference is 54 mm., while at 3 atmospheres absolute it is increased to 371 mm. This effect is shown graphically in figure 1.

Bubble Growth by Accretion

Although bubbles will be absorbed when the dissolved nitrogen throughout the body is in a state of equilibrium, this is not the case when the equilibrium is disturbed by a sudden fall in the air pressure. We have already seen that in actual practice when a man is released from pressure, the partial pressure of nitrogen in his body is about 1173 mm. or more. At the same time the partial pressure of nitrogen in a bubble under 1 atmosphere of pressure is about 627 mm. Therefore, nitrogen will tend to flow by simple diffusion from the tissues into the bubble, causing it to expand. Expansion will proceed until the partial pressure of the nitrogen in the tissues has been reduced to that of the bubble. We have estimated that this process may take as long as 3 hours, during which time bubbles will continue to increase in size. It becomes apparent, therefore, that bubbles which at first may be too small to cause symptoms of compressed-air illness may produce deferred symptoms by their subsequent growth by accretion.

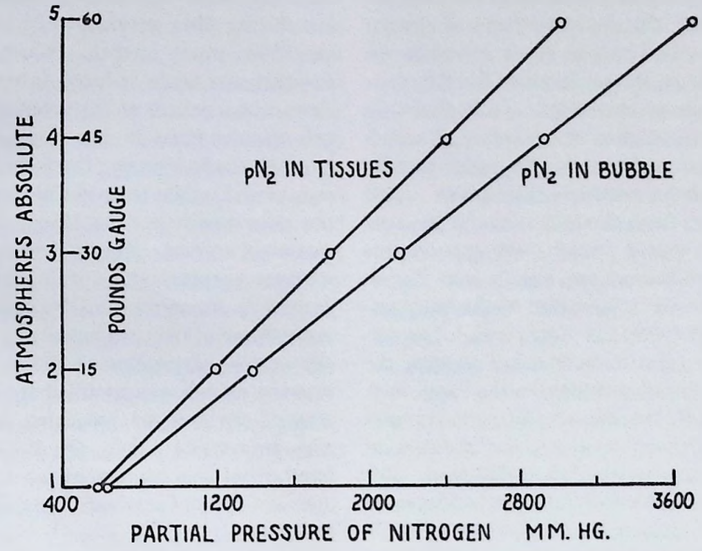


FIG. 1.—Increase of pressure difference between nitrogen in bubble and nitrogen in tissues with increased air pressures.

TREATMENT

Recompression not only reduces the volume of gas emboli in the tissues, thus tending to restore the normal circulation of blood, but it also raises the partial pressure of nitrogen in the bubble above that of the surrounding tissues so that the free gas is absorbed. It is clear that if bubbles are not absorbed under pressure they will return to their former size when the air pressure is again lowered, which in turn causes a recurrence of the original symptoms. It is essential, therefore, that absorption, if not complete, should at least be adequate to prevent a return of symptoms. The weakness in our present methods of recompression is inadequate absorption of free gas and the consequent recurrence of symptoms.

Emboli in Pulmonary Capillaries

While free gas trapped in systemic capillaries must escape through the tissues, where it is taken up by the blood and carried to the lungs, free gas which is trapped by pulmonary capillaries escapes directly into the

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lungs. As already pointed out, there is a tendency for the free gas in pulmonary capillaries to pass bodily through the capillary walls into the alveolar spaces. Nevertheless, if the diffusion process could be accelerated much would be gained. While air is breathed absorption of free gas by diffusion should be virtually in abeyance because the partial pressure of gases in the bubbles becomes approximately equal to that of gases in alveolar air. On the other hand, if oxygen is breathed instead of air, nitrogen will pass from the bubble into the nitrogen-free air of the lungs. It is also true that the higher the pressure at which oxygen is breathed, the more rapidly will the absorption take place. This follows from the fact that the pressure head under which nitrogen passes from a pulmonary bubble into the alveolar air is increased as the barometric pressure is increased. For example, if a man breathes oxygen, the pressure of nitrogen in the lungs is 0. Now if the barometric pressure is 1 atmosphere absolute, the pressure of nitrogen in a bubble is 627 mm. But if the barometric pressure be increased to 3 atmospheres absolute (30 lb. gauge), then the pressure of nitrogen in the bubble becomes 2144 mm. In one case the nitrogen in a bubble diffuses into the lungs under a pressure head of 627 mm., and in the other case the pressure head is 2144 mm. Therefore, breathing oxygen at 3 atmospheres of pressure should cause the nitrogen in a bubble to pass out by diffusion 3.4 times as rapidly as breathing oxygen at 1 atmosphere of pressure.

I shall not discuss man's tolerance to oxygen further than to say that men have breathed oxygen in this laboratory under a pressure of 3 atmospheres absolute, or 30 lb. gauge, for as long as 3 hours without ill effects. The effect of breathing oxygen in absorbing pulmonary emboli has been proved by experiments on dogs. We found that pulmonary embolism in dogs produced a high degree of oxygen unsaturation in the arterial blood. This condition was relieved by recompressing them at a pressure of 3 atmospheres absolute, some of the dogs breathing air during this period, while others breathed pure oxygen. When the pressure was again reduced to normal, there was a return of the arterial oxygen unsaturation in the dogs which had breathed air during the recompression period, while the arterial blood of the dogs which had breathed oxygen remained normal. This indicates that, whereas pressure alone was sufficient to relieve the symptoms by reducing the volume of free gas in the pulmonary vessels, absorption of the bubbles into the alveoli was insufficient, in the case of the animals breathing air, to give permanent relief. On the other hand, relief was permanent when oxygen had been breathed during compression.

It is very generally conceded, however, that free gas in the pulmonary capillaries responds very favorably to recompression and is more easily dissipated than the free gas which is trapped in the systemic capillaries. We may assume, therefore, that any treatment that is successful in coping with tissue bubbles will automatically take care of gas trapped in the lungs.

Emboli in Systemic Capillaries

When free gas is present in the tissues the rate of absorption, other things being equal, is a function of the pressure head under which nitrogen passes out of the bubble into the tissues. As we have seen, the pressure head increases as the air pressure increases. On the other hand there is an element of danger arising from the use of high air pressures when there is free gas in the tissues. As the air pressure rises the partial pressure of nitrogen in the tissues rises. If the bubbles have not been completely absorbed there is danger, when the air pressure is again lowered, that the partial pressure of the nitrogen in the bubbles will fall below that of the tissues, causing nitrogen to pass from the tissues into the bubble. Under these circumstances the bubble will again expand and tend to offset the benefits derived from recompression. In the event that the bubbles have been completely absorbed by recompression, decompression would offer no difficulties. But the fact that symptoms do so frequently recur leaves no doubt of the incomplete absorption of free gas by the recompression methods in current use.

Although there is not as yet a standardized procedure for absorbing gas emboli by recompression, a procedure frequently used is to recompress to the original exposure pressure and then decompress, allowing twice the schedule time. It has been suggested that it might be advisable to use an air pressure in excess of the exposure pressure for a few minutes only, and thereby so reduce the size of the tissue bubbles that they would be swept out of the capillaries into the general circulation and be disposed of in the lungs.

We very much doubt that bubbles can be displaced from capillaries by this method. When dogs suffering from "bends" following exposure to a pressure of 50 lb. gauge were recompressed to 75 lb. for a few minutes, we found that when decompressed again, there was an immediate return of the same symptoms, indicating that the bubbles had not been dislodged from the original location. If free gas could be dislodged from the capillaries in this manner, the remedy for compressed-air illness would be comparatively simple, but we doubt that this method will prove of practical value.

In the absence of any standardized method of treating compressed-air illness, I should like to make the following recommendations. First, recompress to a pressure of 30 lb. gauge for 2 or 3 hours. Then reduce the air pressure to 20 lb. for 1½ hours, during which time pure oxygen is breathed instead of air. The exact time necessary to bring about complete absorption of free gas can be determined only by experience and experimentation. But the method proposed is essentially simple and is designed to promote bubble absorption and at the same time overcome the possibility of re-expansion of any unabsorbed gas as the pressure is reduced to atmospheric. The pressure head under which nitrogen passes from a bubble into the tissues when this system of recompression is employed is shown in table 2. We may assume that the partial pressure of nitrogen in the tissues at the end of decompression is approximately equivalent to that which exists at 2 atmospheres of pressure or 1173 mm. When the air pressure is raised to 30 lb. the partial pressure of nitrogen in a bubble becomes about 2144 mm. Thus the nitrogen will pass out of the

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bubble under a pressure head of 2144 − 1173 = 971 mm. But at the end of 3 hours the pressure of nitrogen in the tissues gradually comes into equilibrium with the increased air pressure, rising to about 1600 mm. The nitrogen pressure head then becomes 2144 − 1600 = 544 mm. The air pressure may then be lowered to 20 lb. while the subject breathes pure oxygen. At the start the pressure of nitrogen in the tissues is 1600 mm. while the pressure of nitrogen in the bubble is 1640

TABLE 2

PRESSURE HEAD UNDER WHICH NITROGEN PASSES FROM A BUBBLE INTO TISSUE UNDER RECOMPRESSION AT 30 LB. FOR 2-3 HOURS, THEN UNDER 20 LB. PRESSURE FOR 1½ HOURS. (PURE OXYGEN BREATHED DURING THIS LATTER PERIOD.)

pN_2	GAGE PRESSURE 30 LB. AIR 2 TO 3 HOURS		GAGE PRESSURE 20 LB. OXYGEN 1.5 HOURS	
	Start	Finish	Start	Finish
	mm.	*mm.*	*mm.*	*mm.*
In bubble.....	2,144	2,144	1,640	1,640
In tissues.....	1,173	1,600	1,600	600
Difference...	+971	+544	+40	+1,040

mm., and at the end of 1½ hours the pressure of nitrogen in the tissues will have fallen to about 600 mm. The air pressure may now be lowered rapidly to atmospheric without fear of further bubble formation, since, by virtue of the oxygen inhalation, the pressure of nitrogen in the tissues is approximately normal.

In formulating table 2, it is necessary to bear in mind that our data are based upon calculations rather than upon direct evidence. The estimation of the partial pressure of nitrogen in the tissues and in bubbles under conditions of equilibrium has already been discussed. Estimation of the rise and fall of tissue nitrogen during changes of the partial pressure of nitrogen in the lungs is based in part upon nitrogen elimination curves constructed in this laboratory, and in part upon the theoretical curves of Boycott, Damant and Haldane. Notwithstanding the possible errors involved, there can be little doubt that the recompression schedule suggested is on the safe side, i.e., at all times the pressure of nitrogen in the bubble is higher than the pressure of nitrogen in the tissues, thus promoting bubble absorption and guarding against bubble expansion.

The theory that the recompression pressure should be equal to, or higher than, the exposure pressure which caused the symptoms seems erroneous. Free gas in the tissues will behave in the same manner whether it results from exposure to high or low pressure. So long as the partial pressure of nitrogen in the bubble is raised above that in the tissues absorption *must* take place. These conditions will be met by the system recommended. There can be no good reason for raising the pressure during recompression above 30 lb. unless this pressure fails to relieve the symptoms. When symptoms persist at a pressure of 30 lb. it is probably indicative of very massive embolism and the case should be considered serious. When recompression demands pressures in excess of 30 lb. much difficulty will be encountered in decompressing again in the event of incomplete gas absorption. Therefore, the recompression time must be increased as the pressure is increased in order to make doubly sure

of gas absorption before the air pressure is lowered.

Table 3 has been constructed to demonstrate the difficulties and the excessive time involved in decompressing a man who has been recompressed at pressures greater than 30 lb. We may assume that the subject under consideration is suffering from compressed-air illness, that his symptoms fail to disappear until the air pressure is raised to 60 lb., and that he remains at this pressure for 3 or 4 hours. If the bubbles have been completely absorbed at this pressure, then decompression may proceed in the routine manner. But the chances are great that absorption is not complete. How, then, can decompression be effected so as to avoid the expansion of such residual free gas as may still exist?

At 60 lb. the partial pressure of nitrogen in a bubble is 3661 mm. At the end of 4 hours the partial pressure of nitrogen in the tissues will approximate the saturation value for 60 lb., i.e., 2973 mm. The next drop in the air pressure must, therefore, be of such a magnitude that the pressure of nitrogen in the bubble does not fall below the pressure of nitrogen in the tissues. We find that at an air pressure of 46.5 lb. the nitrogen pressure in a bubble will be just equal to the nitrogen pressure in the tissues. At this air pressure the partial pressure of nitrogen in the arterial blood is 2438 mm. If time be permitted, the pressure of nitrogen in the tissues will fall to the level of the pressure of nitrogen in the blood and a new equilibrium will be established. It is determined from our nitrogen elimination curves that attainment of 100 per cent equilibrium would require 5 or 6 hours, but to reach 50 per cent equilibrium would take only 1 hour. The latter method constitutes a great saving in time and has therefore been adopted. During the first stage, then, one half of the excess nitrogen in the tissues is given up and the nitrogen pressure falls to 2705 mm.

In the second stage, the air pressure is lowered to 41 lb., at which pressure

TABLE 3

SHOWING STAGES OF DECOMPRESSION FOR A SUBJECT WHO HAS BEEN RECOMPRESSED AT 60 LB. FOR 3-4 HOURS

STAGE	GAGE PRESSURE	pN_2 IN BUBBLE	EXPOSURE TIME	INITIAL pN_2 IN TISSUES	pN_2 IN ARTERIAL BLOOD	FINAL pN_2 IN TISSUES
	lb.	*mm.*	*min.*	*mm.*	*mm.*	*mm.*
	60.0	3,661			2,973	2,973
1	46.5	2,973	60	2,973	2,438	2,705
2	41.0	2,705	60	2,705	2,200	2,452
3	36.1	2,452	60	2,452	2,025	2,238
4	31.8	2,238	60	2,238	1,838	2,038
5	27.9	2,038	60	2,038	1,682	1,860
6	24.5	1,860	60	1,860	1,550	1,705
7	21.4	1,705	60	1,705	1,425	1,565
	20.0	1,640		1,565		

the partial pressure of nitrogen in a bubble is equal to that of the tissues. During this stage the nitrogen pressure in the tissues falls from 2705 mm. to 2452 mm. In this manner we proceed by seven stages of 1 hour each until the 20 lb. stage is reached. Oxygen must then be used for 1½ hours, as previously recommended, before reducing the pressure to atmospheric.

Slow as this procedure may be, any attempt to hasten decompression will lower the nitrogen pressure in the bub-

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ble below that of the tissues, resulting in bubble expansion. Indeed, hasty decompression from high air pressures may result in a volume of free gas that is even greater than the initial volume which we have tried to absorb. Failure to recognize this fact is undoubtedly the cause of many disasters.

Summary

The cause of compressed-air disease is discussed with special attention to the formation, distribution and behavior of nitrogen bubbles. Methods of treatment are outlined; recompression followed by decompression in pure oxygen in the last stage is suggested.

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INDUSTRIAL OPERATIONS IN COMPRESSED AIR*

Ole Singstad

Introduction

THE industries in which operations are carried on in compressed air are in general those involving work of some nature below the water surface where the pressure of air is used to counteract the hydrostatic pressure. In some cases these involve activities directly in the water, and in others in earth or water-bearing material at depths either below the free surface of a superincumbent body of water, or below the level of ground water. The operations themselves may be classified as diving, caisson and shaft sinking, and tunneling.

Diving is employed in harbor, dock, pier and breakwater construction, in some of the pearl and sponge fisheries, in salvage work, in naval repair and emergency work, and in some cases in connection with the unwatering of flooded mines, shafts, and tunnels. Under-water explorations, observations, and photography are made with the aid of certain types of diving apparatus.

Shafts and caissons sunk under compressed air may be used in connection with the construction of bridge piers and abutments, building foundations, mine shafts and tunnel shafts.

Subaqueous tunneling is now generally carried on under compressed air, with or without the use of the tunnel shield, and is employed in connection with the construction of rapid transit, railroad, vehicular, and sewer tunnels.

Historical

It is thought by some that the art of diving was employed commercially and in engineering work a thousand years before the Christian era. Aristotle mentions a metallic vessel which retained air beneath it when lowered into the water, and records that the diving helmet was used as part of the war equipment of Alexander the Great. It has been suggested that the helmet was a clay pot of some description. Divers are supposed to have removed obstructions and loosened anchors and cables at the siege of Tyre, 333 B.C. It is recorded that Alexander the Great descended into the sea in a device called a "colimpha" which kept one dry and also admitted light. Divers are said to have been employed in removing obstructions at the siege of Syracuse, 215 to 212 B.C. Julius Caesar describes a varnished leather apparatus for diving and Pliny states that in war manoeuvers, the Roman and Greek navies employed divers who breathed through tubes which extended to the surface, where the inlets floated.

Roger Bacon is credited with the invention in 1240 of a contrivance resembling a diving bell which enabled men to work under water. The "De

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Re Militari" of Vegetius, 1511, depicts a diver wearing a helmet from which a tube leads to a float on the surface.

In 1538, as described in Kaspar Schott's "Technia Curiosa," 1664, an experiment was conducted at Toledo before Emperor Charles V, in which two Greeks with a lighted torch descended into the water in a large "kettle" suspended mouth downward by ropes, and emerged with the torch still lighted.

At the beginning of the 17th Century, Venetians are credited by Fignier with the use of a diving apparatus called a "cornemuse" or "capuchan." The device consisted of a tube which at one end expanded into a helmet covering the head, and to the other end of which a bellows was attached. An exit tube in the helmet extended to the surface.

In 1609 Lovini, an Italian engineer, devised a large leather tube, stiffened with iron hoops and braced in a vertical position to an iron frame. The tube was equipped with leather chambers and with windows. The diver thrust his head into the tube while sitting on a suspended platform. A somewhat similar device is described by Kessler in "De Secreto," 1616. This was called an "aquatic doublet," was made of leather and hoops, and was fitted with windows and weights.

Lord Bacon in "Organi novi Libri" describes a diving apparatus which consisted of a metal bell which was lowered onto a tripod set up so that a diver working on the bottom could place his head under the bell to get a fresh supply of air.

P. Mersenius in his "Tractatus de Magnetis Proprietatibus," 1638, speaks of a submarine boat. Robert Boyle in "Experiments Physico-Mechanical", 1647, states that a boat constructed by Cornelius Van Debrell, a Dutch physician, was used and rowed under water in the river Thames by order of James I; that it carried 12 rowers and passengers. A chemical liquor, the fumes of which would restore vitiated air, was said to have been invented by Van Debrell's son-in-law. This boat is mentioned by Wilkins in "Mathematical Magazine," 1648.

The air pump was invented by Otto Von Guericke in 1650.

In 1665, George Sinclair recovered treasure from a ship of the Spanish Armada, sunk off Mull in 1580; he used a lead diving bell 3 ft. high and 3 ft. wide under which was slung a foot rest of lead upon which the diver stood with his body in the bell. In 1667, an American, William Philipps, used this means to salvage gold from an English ship sunk off San Domingo in 46 ft. of water.

In 1682 "De Motu Animalium" states that Borelli developed a theoretical idea of a closed diving dress which proved to be impractical. It consisted of a metal helmet and buckskin dress. The diver carried a cylinder and piston with which he could regulate his specific gravity so as to ascend or descend as desired.

In 1685 John Christ Sturmius constructed a wooden bell 13 ft. to 14 ft. high reinforced with iron hoops. The diver sat in this contrivance and signaled to the top with a rope. Sturmius suggested the use of bottles of air to replenish his supply.

The use of bellows to supply air to diving bells was suggested by Denys Papin in 1691.

John Lethbridge of Devonshire, England, devised, in 1715, a diving chamber encasing all but the arms. This was successful in 10 to 12 fathoms of water. Lethbridge stayed for periods up to 34 minutes in 10 fathoms. The Lethbridge device is described as an engine "of wainscott," 6 ft. long, 2½ ft. in diameter at the head and 18 inches in diameter at the feet, reinforced with iron hoops, with two holes provided for the arms and a 4 inch diameter observation glass, 1¼ inches thick. Two air holes were provided. These were stopped by plugs while the diver was submerged. Air was conveyed through one of the holes with a bellows to replenish the supply. The "engine" would have been somewhat similar to the modern diving dress if an air pump, flexible pipe and exit tube were provided. The Lethbridge diving machine was improved in 1798 by Kleingert of Breslau; the feet and hands were free and an auxillary air reservoir was provided.

The first practical diving bell was invented by Dr. Edmund Halley, Secretary of the Royal Society, and is described in "Philosophical Transactions," 1717. The bell was constructed of wood covered with lead to add weight, built in the form of a truncated cone, 3 ft. in diameter at the top and 5 ft. in diameter at the bottom, 8 ft. high. A lense and tap were provided at the top. Air was supplied by alternately raising and lowering two lead lined barrels. Dr. Halley and four others remained down in this device for 1½ hrs. in 50 to 60 ft. of water. Dr. Halley's paper is entitled "The Art of Living Under Water by Means of Furnishing Air at the Bottom of the Sea in Any Ordinary Depth." In it the statement is made that for depths up to 3 fathoms, bellows and lead pipes will answer for furnishing the air supply. Efficient air pumps were lacking for greater depths. Charles Spalding made some improvement in Halley's bell in 1775. In 1778 the force pump displaced the barrels in this type of bell. Spalding and his son were suffocated in their bell in 1788.

It is recorded that a tube apparatus was used up to 1784 by pirates in the Black Sea for concealing themselves from the enemy.

John Smeaton, a British engineer, is credited with the design of the modern diving bell. He built a bell to use in the construction of the Hexam bridge, Northumberland, 1788, which employed a force pump. The bell was not entirely submerged and was surmounted by the pump. His later invention, 1790, designed for the Ramsgate Harbor works was similar to modern bells. This bell was 4½ ft. high, 4½ ft. long, 3 ft. wide, weighed 5,000 lbs. It accommodated two men. Brize-Fradin is credited with making improvements in the diving bell in 1808, cooling the compressed air with ice and introducing caustic soda as a carbon dioxide absorbent.

Augustus Siebe devised the "open dress" diving suit in 1819. This consisted of a metal helmet and shoulder plate attached to a water-tight jacket. A tube extended from the helmet to an air force pump. The jacket over-

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lapped the undergarment, forming a trap through which air escaped as the fresh supply was pumped down from above. If the diver lost his footing and fell in this dress he was in danger of drowning as water would enter his helmet through the opening between jacket and undergarment. This difficulty was eliminated in the "closed dress" developed by Siebe from 1830 to 1837. This is the type of diving dress in general use today.

Marc Isambard Brunel is credited with the invention of the tunnel shield in 1818. The shield was first used in tunneling in free air. In 1830 Lord Cochrane conceived and patented the idea of using compressed air in shaft and tunnel work in water-bearing ground, "an apparatus for compressing atmospheric air within the interior capacity of subterraneous excavations". With this scheme he proposed the use of an air lock to permit the passage of men and material in and out of the tunnel without loss of air pressure. Lord Cochrane did not put his scheme into operation, but its use was developed by others. M. Triger, a French engineer, employed compressed air in 1839 to sink a $3\frac{1}{2}$ or $4\frac{1}{2}$ ft. diameter tube 70 ft. in length, through quicksands in the valley of the Loire, near Chalonnes, France, for a coal mine. This cylinder was provided with an air lock. Pazerne, in 1844, constructed a vessel which was used on government works at Cherbourg. It contained an upper chamber and a lower working chamber, admitting 8 men to excavate. The device could be pushed about with poles. Air was pumped into it; caustic soda was used to purify vitiated air. It could be raised or lowered by emptying or filling certain chambers. In 1845 M. M. B. Pol and T. J. J. Watelle used compressed air in the working of a mine at Douchy, Dept. du Nord. In 1850, air was used by Hughes and Cubitt in constructing the piers for the Railroad bridge over the Medway, between Rochester and Chatham. Bouhy recounts in "Annales des Travaux publiques de Belgique," 1848, that compressed air was used at a mine at Strepy-Bracquegnies, Belgium. Compressed air was used about 1856 in sinking shafts for the coal mines of Eischweiller, near Aix-la-Chapelle. Foundations for bridge piers and abutments were constructed by the pneumatic caisson method in 1858–59, for Quarantine Bridge at Lyons, the bridge at Macon, the bridge chain over the Thiess, in 1863 for the bridge at Argenteuil, in 1868 for the St. Louis Bridge across the Mississippi, and in 1871–72, the Brooklyn Bridge.

In 1879 compressed air was used in tunneling at Antwerp and by D. C. Haskin in the Hudson River Tunnel. Haskin in 1874 patented a scheme for using compressed air to prevent the sudden breaking in of water while tunneling in water-bearing ground. Haskin's Hudson River attempt was temporarily abandoned some time after a "blow" in which 20 lives were lost. When work on Haskin's tunnel was resumed in 1888 by Pearson & Son, compressed air was used in conjunction with a steel tunnel shield equipped with six hydraulic jacks for driving it ahead.

During the last 35 years the use of the shield and compressed air in subaqueous tunneling has advanced from the status of hazardous pioneering to that of a safe, efficient, standard method of construction. Its use and development have been most notable in the New York City area, where, since 1900, eighteen important subaqueous projects have been successfully completed using this method of construction, and where, at the present time, more such projects are being planned.

Diving Equipment and Diving

The principal items of the modern diving apparatus, as described in the Diving Manual of the U. S. Navy Department, are the dress, breastplate, helmet, airhose, air control valve, weights, telephone equipment, gloves, overalls, and air pump.



Fig. 1.—Rear view of diver in modern flexible suit and helmet. (Courtesy, New York Public Library)

The dress, which encloses the entire body except the head and hands, is flexible, constructed of rubber between layers of cotton twill. Elastic rubber cuffs form water tight joints at the

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wrists. The neck is fitted with a rubber gasket, to which the breastplate fastens.

The breastplate and the helmet are constructed of tinned copper. The helmet has windows at front, sides, and top, and is provided with an air inlet and non-return safety valve at the back, to which the air hose is attached. It is also provided with a spring and screw controlled air escape valve by which air pressure in the suit and bouyancy are adjusted. A supplementary relief valve permits a fine adjustment of buoyancy.

The air line consists of flexible hose, of half-inch internal diameter made up in lengths which are coupled together. The flow of air into the helmet may be adjusted by the air-control valve interposed in the hose near the helmet.

The weights consist of a weighted belt and of leaded shoes, which produce negative buoyancy when the suit is moderately distended with air. Telephone cable and life line are combined. Signals may be given by the life line if the telephone is out of order. Waterproof gloves may be worn to provide protection from the cold. The overalls protect the suit from wear and by means of straps, prevent the helmet from rising over the diver's head when the dress is distended with air. Pumps may be manually or power operated. Gages on the pumps indicate the pressure and the water depth.

The diver descends by means of the "shot rope," which is attached to a heavy weight, previously lowered. A "distance line" about 60 feet long is attached to the bottom of the shot rope by which the diver can guide his return to make his ascent.

Under-water operations and observations are also made in the self-contained dress, in the helmet alone with air supply pumped from above, in rigid pressure-resisting watertight devices permitting descent to great depths in atmospheric pressure, and by the naked diver. Another form of contained apparatus has been specially devised for use in escape from submarines.

The self-contained dress and submarine escape appliance both employ soda-lime which absorbs the carbon dioxide from the exhaled air. In the self-contained dress the oxygen is replenished from a supply carried in a tank by the diver. The submarine escape appliance, designed for short periods of submergence, provides a rubber bag of oxygen with a mouth piece, into which one breathes during ascent to the surface.

The type of diving apparatus which keeps its occupant at atmospheric pressure out of contact with the external water pressure is represented by the Neufeldt and Kuhnke diving shell and by the Beebe "bathysphere." The former, successfully used in salvage operations in depths up to 525 feet, permits some operations to be performed by its occupant upon external objects. The latter is a hollow cast steel sphere containing ports from which observations may be made. This contrivance, lowered from a vessel on the water surface, has reached a depth of 3028 feet.

In sponge and pearl fisheries in warm, tropical seas, naked divers often work in depths of 60 to 70 feet, and it is reported that some have descended to depths of 120 to 130 feet. The equipment of these divers consists of a stone to descend with, a horn clip on the nose, oiled wads in the ears and an oiled sponge in the mouth.

In all the types of diving equipment described above with the exception of the "bathysphere" and the diving shell, and with the exception of the submarine escape apparatus, the diver descends into pressures above normal for the purpose of performing some useful work, whether it be to inspect, observe, or to perform manual labor. If he performs manual labor, he may use only his bare hands or the usual manual tools, or he may use pneumatically operated tools, the hydro-oxygen torch, or high pressure water hose. He may be provided with artificial illumination, or may have to grope in the twilight or darkness of the depths in which he is working. The resistance of the surrounding water and the impedance of clumsy apparatus greatly increase his energy output and slow down his progress.

For every foot of submergence in sea water an unprotected body is subjected to about 64 pounds pressure per square foot of surface. In the case of the helmeted diver who is supplied air at approximately the pressure of the surrounding water, an internal body pressure equal to that of the air in the helmet is developed through the solution of compressed air in the body fluids. This takes place through the lungs and circulatory system.

In the case of the naked diver, the opinion has been expressed that there is probably a certain partial equalization of pressure produced in the air in the lungs and other body cavities by the cupping and ascent of the diaphragm. It is consequently advised that this kind of diver make his descent with the lungs well inflated. Underinflation might result in displacement of the heart. The naked diver's air supply is limited to that in his lungs, and his stay below the surface of the water is consequently limited to the length of time that he can hold his breath without becoming asphyxiated. The ordinary time limit is about one minute, but may be increased by practice and by deep breathing just before diving. Dr. Leonard Hill has recorded that he and Martin Flack experimented with the idea of breathing oxygen just before submergence, with results indicating that the time below water could be extended by this method to several minutes.

The type of apparatus described as consisting of a tube and helmet with a free-air supply obtained through the tube, the end of which floated on the water surface, while apparently making available plenty of fresh air, would, in any appreciable depths, subject the diver to full water pressures without balancing internal pressures, and make the physical effort necessary for breathing very difficult.

The diver in rubber suit and helmet is exposed to many dangers, some of which are directly related to his atmospheric environment.

If the diver's air supply is inadequate, or interrupted, he will probably suffer from the effects of asphyxia. A diver requires, for any given condition of rest or exertion, the same volume of air measured at the pressure at which he is working, because the absolute partial pressure of carbon dioxide controls his breathing. If, at atmospheric pressure, 6 per cent carbon dioxide in the air causes distress and 10 per cent a tendency towards unconsciousness, at a depth of 33 feet, or an absolute

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pressure of two atmospheres, 3 per cent and 5 per cent carbon dioxide would produce the same results respectively. A man at rest on the surface requires about ¼ cubic foot of air per minute. This requirement is increased with hard work. If the partial pressure of carbon dioxide does not exceed 3 per cent of an atmosphere there is no danger of the effects of asphyxia. The oppressed breathing experienced by some divers at the greater depths is not due to water pressure but to insufficient ventilation producing excessive carbon dioxide in the helmet. It is considered that 1.5 cubic feet of air per minute at the absolute pressure at which the dive is made is essential.

Some of the contributing causes to asphyxia have been insufficient capacity of pumps for the depth, breakdown or inefficient operation of the pumps, stoppage or loss of the air hose. In one instance moisture in the air supply condensed and froze in the inlet valve of the helmet of a diver working in salt water just below freezing temperature. Such a condition requires that the air supply be freed of moisture.

The diver in the rubber suit has his head incased in a rigid helmet and his body in a flexible suit. For a man of average height in erect position there is a difference of hydro-static pressure between head and feet of about 2½ pounds per square inch. Ordinarily the pressure in the helmet is maintained equal to the hydro-static pressure at about chest level. This facilitates breathing. Under these normal circumstances there is a small differential of pressure between part of the body and the helmet. If pressure is accidently lost in the helmet, or if the diver falls suddenly to a greater depth of water, even a comparatively small increase in this differential may result in a tendency for the body to be squeezed into the helmet, resulting sometimes in instant death or serious injury.

During the process of returning to normal pressure, or much more often, some time after returning, the diver may be subjected to one or more of the symptoms of compressed air illness. These symptoms may range from the less serious pains in muscles, joints, or bones, to permanent paralysis or death. To prevent compressed air illness, the diver's stay on the bottom is shortened as the depth increases, and the time taken to ascend is governed by a schedule which is worked out on the basis of depth and time down.

Accidental "blowing up" occurs when the exhaust valve does not function properly or if the valve is improperly adjusted. The dress becomes inflated, buoyancy positive, and the diver rises quickly to the surface. Such rapid ascent may result in compressed air illness. If the suit is partially inflated and the diver overturns in rising he may float helplessly head downward. Water in the dress in this position might cause drowning. Overturning is prevented by lacing the legs of the suit to prevent entrance of air into this part of the dress.

Ear pains may be experienced during descent. They are due to pressure on the ear drums resulting from lack of equalization of pressure in the inner ear. Inner ear pressures are adjusted through the Eustachean tubes and if these are clogged by a catarrhal condition it may be impossible to balance pressure and if descent is continued the ear drum may be ruptured. Under ordinary circumstances the Eustachean tubes may be made to function by swallowing, or by distending them with air forced from the back of the mouth.

The normal tension of oxygen in the air is about 21 per cent of an atmosphere. If 70 per cent or more of an atmosphere exists and submergence is for too long a period, "oxygen poisoning" may result, evidenced by irritation of the lungs and other symptoms. In deep diving, oxygen poisoning may be prevented by reducing the percentage of oxygen in the air supply.

Many of the dangers that beset the helmeted diver are functions of depth and tend to limit both the depth and duration of the dive. The diver in helmet alone has reached 60 feet. The diver in helmet and flexible suit, still supreme among divers from the standpoint of useful output, has reached a maximum depth of 306 feet.

Compressed Air Shafts and Tunnels

The principle involved in the use of compressed air in the construction of shafts and tunnels is the exclusion of water with air pressure. In application, the fundamental requirements of this use of compressed air are: (1) an adequate source of compressed air; (2) conveyance of the air from source to point of use; (3) an air chamber where the desired operations are carried on, and in which the compressed air is confined at the required pressure; (4) a method of entrance into and exit from this chamber of materials and men, without loss of pressure.

In modern practice the first consists of a power operated compressor plant; the second, of pipe lines leading from the compressor plant to the tunnel or caisson; the third, of a confined space formed in some types of work by sheeting driven into the ground and a roof or air deck constructed on this enclosure; in caissons consisting of the working chamber, enclosed with the cutting edges, walls and air deck of the caisson; and in tunnels the portion of tunnel enclosed between heading and bulkhead; and the fourth, caisson or tunnel locks, each essentially a two-doored air-tight chamber interposed between the working chamber and the open air. The lock doors close against gasketed frames, swing towards the air chamber. One is between the open air and interior of the lock, the other between lock and air chamber. By closing the door adjacent to the open air and raising the lock pressure to air chamber pressure, the inner door previously held closed by unbalanced pressure may be opened, and entrance made into the workings. Exit is made by reversing the process. Muck and material locks and man locks are used as the respective designations imply. In their present form, locks in tunnel use are generally horizontal riveted or welded steel tubes of cylindrical or elliptical section placed in the tunnel bulkhead with the doors and frames enclosing each end. The types used in caissons vary. The "T" type used for men, consists of a structure similar to a tunnel lock but with one end solidly enclosed, entrance to the caisson working chamber being through a door in the bottom of the lock leading into a vertical steel shafting equipped with a ladder descending into the working chamber through the air deck. There are also various vertical types, with doors at top and bottom

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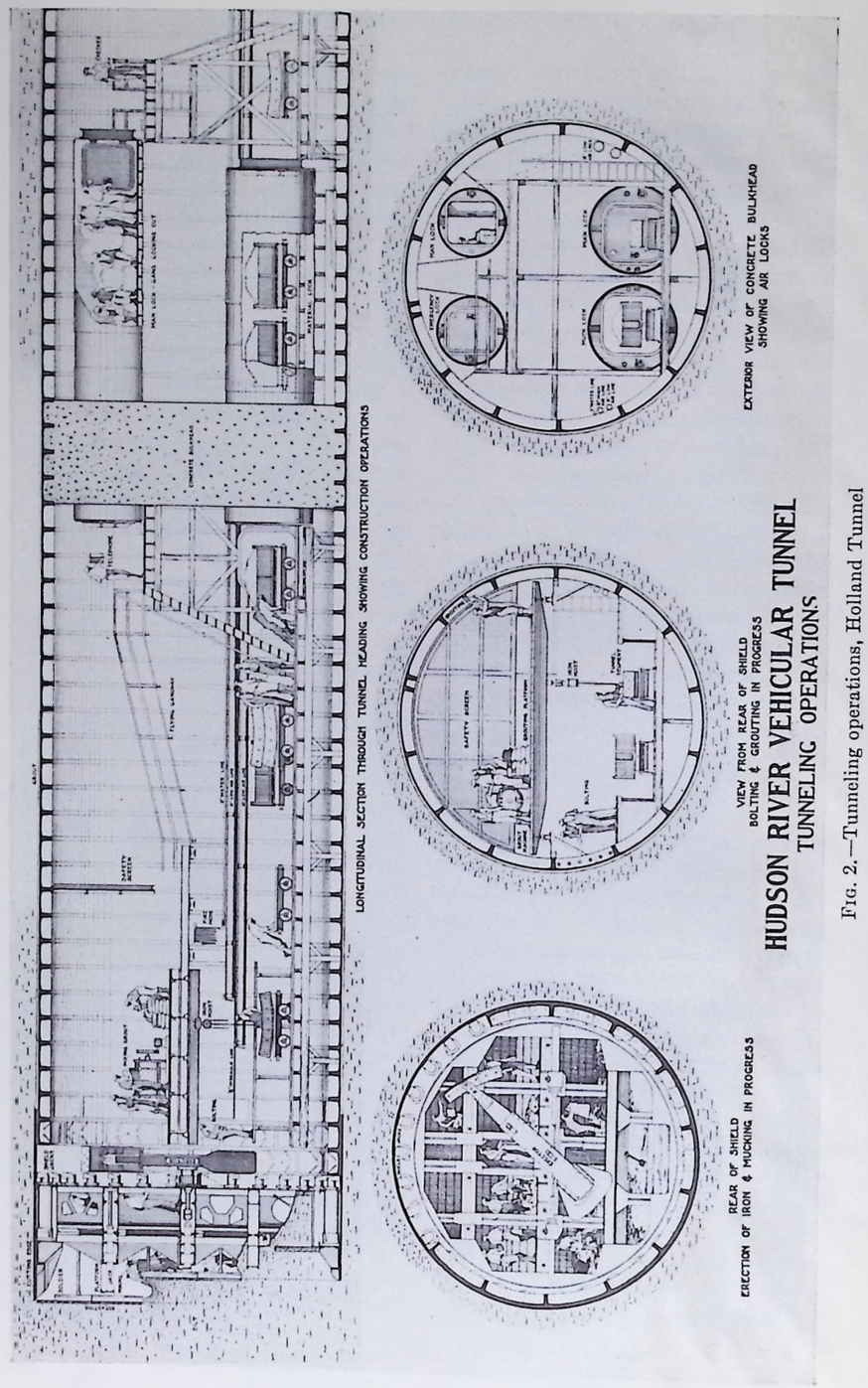


Fig. 2.—Tunneling operations, Holland Tunnel

or bottom and side, used for muck and materials and in some cases, as man locks.

After placing the air deck, fitted with the necessary service lines and locks, on the sheeted shaft type of structure, excavation may be carried below water level under air pressure.

In the caisson type of construction, a box or cylinder of steel or other material, provided with a working chamber, is constructed on the site of the shaft or pier or, if the site is under water, may be constructed on land, launched and floated to the site where it is sunk to the bottom. In either case the caisson may then be sunk to the required elevation by allowing it to descend as excavation proceeds.

The size of the tunnel, character of material, type of lining, and other considerations determine the method of tunneling to be used. During the past 50 years, over fifty tunnel projects have been successfully completed with the use of compressed air, constituting over 60 miles of tunnels varying in size from about 6 feet to over 30 feet in diameter. Any appropriate tunneling method may be used in conjunction with compressed air but the method often best adapted is that employing the tunnel shield. While the caisson is, in effect, a modification of the diving bell which can be sunk through earth and rock as well as water to a desired elevation, the shield might be considered a horizontal adaptation of the caisson.

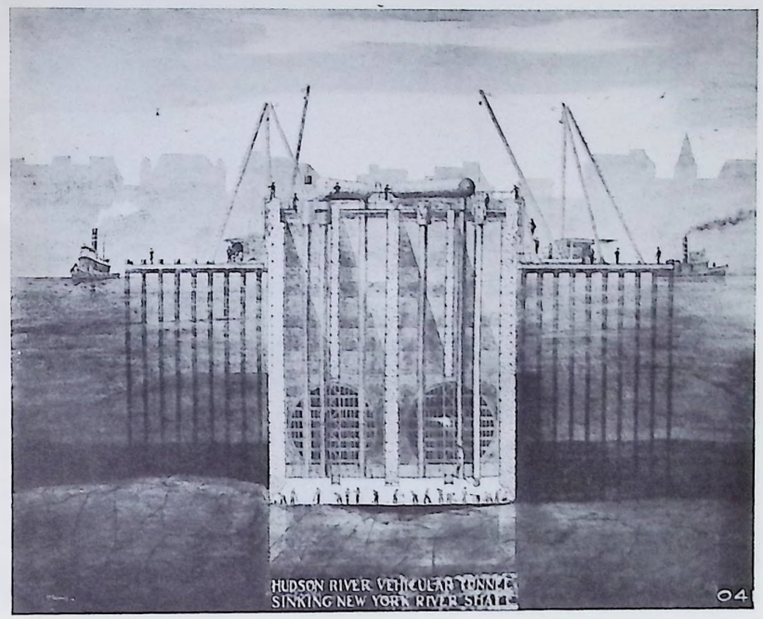


Fig. 3.—Caisson sinking, Holland Tunnel

The tunnel shield is generally cylin-

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drical in shape and when in this form is used in connection with driving a tunnel of outside circular section. It consists of a steel skin, to the front edge of which are attached cast steel segments forming the cutting edge. The intermediate section is reinforced with a circular girder and horizontal and vertical partitions forming the pockets of the shield. The tail of the shield is a plain continuation of the steel skin, in the protection of which the primary lining of the tunnel is constructed, and which overlaps a portion of the completed lining. The lining best adapted to this type of tunneling is composed of flanged cast iron circular segments which are swung into position by an hydraulic erector carried on the rear of the shield, and bolted together to form a complete ring of lining, adding the length of the ring (often 30 inches in modern practice) to the tunnel length. The shield carries hydraulic jacks housed in the circular girder in the intermediate section, which react against the face of the completed lining to force the shield ahead and to provide space in the tail for the construction of another ring of lining. Depending on material and conditions, the entire face may be breasted down as excavated, or only a part of the upper portion may be breasted. In rock or earth and rock, a bottom heading may be driven in advance of the shield. In Hudson River silt and similar materials, the shield may be bulkheaded and all or part of the excavation be accomplished by displacement as the shield advances.



FIG. 4.—Drilling rock in caisson working chamber, Midtown Hudson Tunnel

The compressed air worker or "sand hog" pursues his duties in the air

chamber clothed and equipped with the same freedom as in "free" air. The modern sand hog has many mechanical devices at his disposal. He is aided with the shield, hydraulic erector, electric haulage systems, electric hoist and mono-rail, pneumatic tools such as the "mule" for running down nuts on bolts and the pneumatic chipper, for caulking. In the Midtown Hudson Tunnel, now under construction, the arduous work of tightening bolts (see figure 5) by hand was practically eliminated by the use of hydraulic bolt tightening machines; as in the Holland Tunnel, the shield was bulkheaded and the small percentage of muck admitted into the tunnel was deposited on the bottom by electric conveyors with little manual handling, to be removed later with the use of air-operated shovels.



FIG. 5.—Tightening bolt with ratchet wrench, Holland Tunnel

The compressed air caisson and tunnel worker, similar to the diver, is

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threatened with possibilities of illness or accident which are functions of the pressures in which he works.

In "locking in" the sand hog swallows and "blows" to equalize the inner ear pressure with the external. "Blowing" consists of holding the nose and distending the Eustachian tubes by compressing the air in the back of the mouth. If the Eustachian tubes are obstructed, pain will be felt, caused by the cupping of the ear drum by the excessive external pressure. The lock tender, who manipulates the valves of the lock to compress or decompress the air in the lock, will close the inlet valve and slack off the pressure when signaled that any one in the lock is so "blocked." If an individual cannot "clear" his ears, he is returned to normal air. No one with a cold or with ear trouble should attempt to enter compressed air.

In both tunnels and caissons a "run" of material and water may result from a drop of pressure below that required. If a serious run develops, the tunnel or caisson may be quickly filled or partly filled with material and water, in which case the workmen are in serious danger of being buried or drowned. The compressor plant must be capable of maintaining the required pressures, with an ample emergency reserve. Air lines should be in duplicate and provided with check valves to prevent them from acting as exhausts in case the plant pressure drops or fails. When the tunnel heading extends under a waterway, an emergency runway is provided as high in the tunnel as head clearances permit, extending from the working face to an emergency lock placed high in the bulkhead. A safety screen may be provided, maintained near the heading, extending from crown to spring line, to act as a trap, in case of flooding, when the water rises to its lower edge.

The working face of the tunnel is approximately vertical. The hydrostatic head at the top of the face is consequently less than that at the bottom. In some kinds of ground this unbalanced head, as it is called, is a source of considerable danger. This danger is reduced by depositing a clay "blanket" on the waterway bottom over the tunnel heading of sufficient thickness to counterbalance, at least, theoretically, whatever excess of air pressure over water pressure may be developed at the top of the tunnel face. Shields have been devised with enclosed chambers or pockets in which air pressures were to be carried according to the water pressure at the level of each pocket, but this scheme proved impracticable. If, for any reason, the air pressure in the tunnel suddenly overcomes the resistance of the superincumbent water and material, a rush of air from the tunnel results, which is called a "blow." Workmen at the face when a blow occurs are in danger of being swept out of the tunnel into the surrounding material or carried through material and water to the surface. Marshall Maybie, a compressed air worker on the East River Tunnels, had this experience and survived. Two companions who were carried out with him were not so fortunate as to reach the surface alive. Maybie has continued in his occupation in spite of his experience, and was last so employed as a gage tender on the Midtown Hudson Tunnel. A blow may so reduce the air pressure in the tunnel as to be closely followed by a run, with accompanying flooding.

Air under pressure has a corresponding concentration of oxygen that greatly stimulates combustion and increases the fire hazard. This should be safeguarded against in the tunnel by providing adequate water lines with hose and hose connections, by forbidding smoking, and by keeping the tunnel as clear as possible of combustible material. In the Fulton Street-East River Tunnel a salt hay bulkhead while being compressed by advancing the shield developed frictional heat sufficient to cause it to ignite, with resulting damage to equipment, injury to some of the workmen, and loss of progress.

The problem of adequate ventilation in compressed air caissons and tunnels is seldom a difficult one. There is generally enough air leakage at the face, caisson cutting edge, caisson air deck, etc. to meet ventilation requirements. The air inlet should be maintained as near the heading as possible. Blow pipes and exhaust valves with risers may provide additional ventilation when required, as when explosives are used, or when burning with the oxy-acetylene torch is in progress. The use of pneumatic tools might be considered as contributing to good ventilation. Air intakes at the compressor plant should be devised to provide as clean and pure an air supply as possible. Cooling devices may be used to keep air chamber temperatures moderate. Samples of air should be taken frequently and analyzed; if the carbon-dioxide content is excessive, corrective measures should be taken.

The earlier tunnels and caissons presented greater problems of ventilation and sanitation than those of more recent years. Candles, lamps, and open gas flames used for illumination tended to vitiate the air and fill it with soot. Animals were used for haulage purposes in some of the workings. Modern tunnels and caissons are lighted with electricity. Animals are not permitted in the air chambers.

Oxygen poisoning is unimportant in tunnel and caisson work where working periods are restricted and where pressures are 50 lbs. per sq. in. or less.

The compressed air worker in tunnels and caissons is affected by compressed air illness as is the diver. The extensive use of compressed air in this kind of work during the last 50 years with thousands of workers employed, makes the problem of cause, prevention, and treatment of compressed air illness of extreme importance.

Compressed Air Illness

The evolution of the modern theories and practices in connection with compressed air illness began about 100 years ago.

According to Dr. Andrew H. Smith, a Dr. Hamel, a Russian, observed in connection with diving bell work at Howth, Dublin, in 1820, that a certain workman felt so accustomed to the atmosphere of the bell that he was uncomfortable under normal pressure.

It is recorded that Triger, a French engineer, reported having observed that two workmen employed in sinking a pneumatic cylinder under his direction near Chalonnes in 1839 were affected with pains in arms and legs about half an hour after coming out of the caisson.

M. M. B. Pol and T. J. J. Wattelle,

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while working a mine at Douchy, France in 1845 made note of some of the dangers of working in compressed air from observations on 64 men who were employed in about 36 lbs. per sq. in. air pressure, working two 4-hour shifts per day and taking from a quarter to a half an hour to decompress. Pol noted:

Increased danger in proportion to pressure.

Ill effects in proportion to period in the air, and rapidity of decompression.

One case indicated return to compressed air.

Dr. Francois noted, in connection with the bridge works over the Rhine at Strasbourg, that men who decompressed too fast "sometimes fell as though struck by lightning." He provided woolen vests for the men to wear after leaving the air chamber and established the following decompression rules:

PRESSURE	DECOMPRESSION TIME
¼ to ½ atmosphere	4 to 5 minutes
1 atmosphere	6 to 7 minutes
1½ atmospheres	10 minutes
2 atmospheres	12 minutes

J. B. Green, an American diver, contributes to the history of compressed air illness in his pamphlet published in 1861, entitled "Diving or The Wonders of the Deep." Green records that he was paralyzed after making a dive and makes the following comment:

"There have been many conjectures in regard to the cause of my paralysis. Some attribute it to my meal; others to the pressure of the water. There is one thing which I shall mention as having something to do with it. The pumps which were used for forcing air into the armor were of brass, and with each movement of the pumps, I could plainly taste and smell the copper in the atmosphere I breathed."

As a further contribution to the historical record of compressed air illness in connection with diving, Henry Siebe in "Conquest of the Sea," 1873, observes:

"A man at all sanguinous should ascend rather slowly; the brain being suddenly relieved of pressure causes a sudden rush of blood to the head. . . ."

Siebe listed men who should not dive as:

1. Men with short necks and florid complexions.
2. Men who have headaches.
3. Men who have coughed up blood.
4. Men who have had palpitation of the heart.
5. Pale men.
6. Men with blood shot eyes.
7. Men who drink hard, have had venereal disease, rheumatism, or sun stroke.

He recorded the death of a Greek diver who ascended from 30 fathoms in 7 minutes: "He immediately began to expand and die."

Dr. A. Jaminet, in 1871, published a paper entitled "Physical Effects of Compressed Air and of the Causes of Pathological Symptoms Produced on Man, by Increased Atmospheric Pressure Employed for the Sinking of the Piers in the Construction of the Illinois and St. Louis Bridge over the Mississippi River at St. Louis, Mo."

Dr. Jaminet records that this work, started in 1869, was carried to a depth of 115 ft. as against the previous record depth for a caisson of 65 feet. He describes 78 cases of compressed air illness among which there were 8 deaths. In pressures up to 50 lbs. per sq. in., three 2-hour shifts per day were worked, with rest periods of 2 hours between shifts. Dr. Jaminet noted that the workmen began to be affected at a pressure of 24 lbs. per sq. in. and to be seriously affected at 34 lbs. per sq. in. Dr. Jaminet advised, "Avoid too sudden a transition from normal atmosphere to an over-condensed one." He further felt that one should come out of the air *quickly*, and ordered the following schedule:

COMPRESSION	DECOMPRESSION
1 minute per 3 lbs.	1 minute per 6 lbs.

This concept of decompression is contrary to modern ideas and practice. More rigid physical examination of workmen and a reduction of working time reduced the number of cases of illness in a group of 140 men, and limited fatalities in this group to one, in spite of the decompression schedule.

Dr. Andrew H. Smith has recorded, in 1873, his experiences as surgeon to the New York Bridge Company during the sinking of the Brooklyn Bridge caissons. He is credited with being the first to suggest the use of a medical lock with which to treat compressed air illness with recompression. E. W. Moir, in 1890, actually instituted the medical lock for recompression at the Hudson Tunnels, where it was successfully used.

Many theories as to the cause of compressed air illness have been advanced, among then that blood under pressure reacts to cause injury upon decompression; that wastes in the body accumulate in harmful amounts when one is subjected to the rapid oxidation produced by breathing compressed air; that high pressures cause direct injury to organs and interfere with their normal functioning. The theory of air embolism, now generally accepted, has been substantiated by many experiments on men and animals. Nitrogen dissolved in the body under pressure forms bubbles on sudden decompression and so obstructs the circulation. Paul Bert, a French physiologist, is credited with establishing this theory and definitely stating it in "La Pression Barometrique," 1878.

Dr. Edward Levy in U. S. Bureau of Mines, Technical Paper 285, recognizes air embolism as the cause of compressed air illness, and lists the following symptoms:

1. *Affections of the central nervous system.* Disturbances of the central nervous system may be either motor or sensory, due to the pressure of air emboli upon the brain or spinal cord.

2. *Localized pains.* Localization of pain depends on whether the gas emboli are present in the muscle fiber, tendon sheath, bone, or nerve terminal.

3. *Vertigo.* Dizziness is the result of gas emboli in the middle ear or may be caused by disturbances of the central nervous system.

4. *Chokes.* Difficult breathing is due to bubbles of gas forced through the pulmonary arteries into the lungs.

5. *Unconsciousness or collapse.* Unconsciousness or collapse is usually caused by large quantities of gas distributed generally throughout the circulation.

Compressed air illness is now dealt with on the job by the practical application of the following ideas:

1. *Medical supervision* by qualified physicians with compressed air experience.

2. *Selection of men by qualifying physical examination.*

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Dr. Levy in the paper mentioned above, states that the essentials are normal lungs, normal kidneys and a good heart; and in older men the blood pressure must not be too high. He does not consider age and obesity as of as much importance as heretofore has been given them. Contractor's doctors generally will not pass a man with no previous experience in compressed air who has reached the age of 40 years or more; old hands are not so limited. The continuance of a man in compressed air work will depend on his medical record. Some men have a disqualifying sensitivity to compressed air illness, which often cannot be determined except by trial in compressed air.

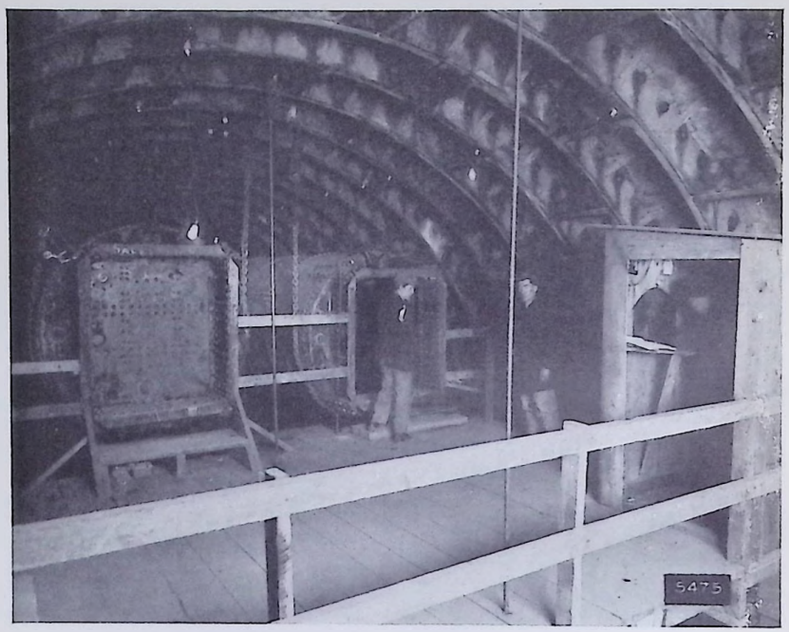


FIG. 6.—Checking into tunnel (manlock on right; emergency lock on left), Holland Tunnel

3. *Limitation of hours of work in compressed air* is practiced by the application of definite schedules of work and rest for various pressure ranges. It is generally recognized that shortening the stay in compressed air as the pressure rises reduces the number of cases of compressed air illness. There is no one schedule in universal use at the present time although tunnel and caisson working schedules have been established by legislation in some instances.

4. *Slow decompression*, allowing time for the blood to become desaturated without the formation of nitrogen bubbles, is perhaps the most important measure used in the prevention of compressed air illness. Safe rules for decompression should be established and rigidly enforced. In the past there has been a tendency on the part of compressed air workers to consider decompression rules as an encroachment on their personal liberty and to disregard them if given the opportunity. Compressed air workers now more generally realize the importance of slow decompression and coöperate accordingly. Decompression rules are also made more effective by competent lock tenders, by using checkers to make a record of all those entering and leaving compressed air when pressures are above a certain amount, and by the use of a recording gage on the man lock. In some regulations the uniform method of decompression is favored and in others the stage method. Decompression may be further modified by the use of intermediate bulkheads to provide sections of tunnel which carry pressures stepped down from the heading pressure. Exercise aids decompression by stimulating the circulation which increases the rate of desaturation. Exercise during decom-



FIG. 7.—Gang decompressing, Midtown Hudson Tunnel

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pression is advised, and for this reason the lock should be of large enough proportions to permit it. The lock should also be properly heated to prevent chill when decompression is in progress. When more than one bulkhead is used it is generally agreed that benefit is derived in walking from one lock to the next.

The theory of stage decompression was advanced by Dr. J. S. Haldane, British Admiralty expert on compressed air illness, as a method of safely accelerating desaturation, and thus obtaining a more nearly complete desaturation in a given time. Diving tables computed on this theory were issued by the British Admiralty in 1907, and have been used by divers of the British Navy and the United States Navy since that time. Haldane's method of stage decompression employs a drop to one half the absolute pressure at a fast rate; in caisson and tunnel work in the United States, this has been modified to a rapid decompression to one-half the gage pressure.

In deep diving, decompression may be facilitated by use of the Davis submersible decompression chamber. Instead of the diver having to hang onto the "shot rope" or decompression ladder in the cold and dark while making his ascent, he enters this device, a cylindrical lock, which is suspended at a depth corresponding to the pressure at which slow decompression is to start. The lock, with pressure maintained within, is hauled quickly to the surface, where the proper slow decompression time is taken under ideal conditions. If operations are being conducted from a boat, this device permits moving the position as soon as the lock is aboard.

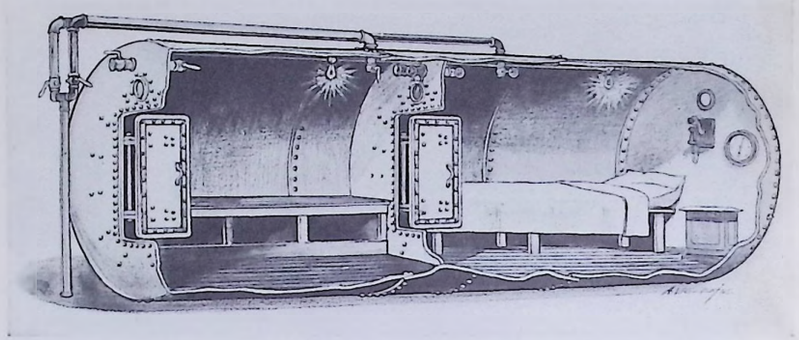


Fig. 8.—Drawing showing interior view of medical lock

5. *The hospital lock* has been used universally on compressed air work since its introduction by Moir on the Hudson Tunnels. Recompression and slow decompression is the recognized treatment of compressed air illness. It should be used as soon after the onset of the illness as possible. In theory, the bubbles of nitrogen causing the trouble are forced back into solution by putting them under pressure, and desaturation accomplished without their reformation by decompressing at a very slow rate. Use of twice the normal time or more to decompress is recommended. Some advocate a return to maximum pressure, some to one-half the maximum absolute pressure, and others to two-thirds the maximum gage pressure at which the subject worked.

The compressed air worker should be provided with an identification badge, plainly stating that in case of illness he be taken immediately to the medical lock for treatment, the location of which should be given.

6. *Complete records* of all cases of compressed air illness should be made. It is difficult to obtain a 100 per cent record, as the compressed air worker often fails to report his case for fear the record might affect his employment but the more severe and therefore more important cases are probably all reported.

Safety Codes for Work in Compressed Air

Rules and regulations governing work in compressed air have been adopted by eight states of the Union up to the present time. These are New York, New Jersey, Massachusetts, Pennsylvania, Wisconsin, Ohio, Maine and California. The last adopted its regulations in 1933.

California, Massachusetts, Maine, and New York are now in accord as to hours of labor and decompression schedules. Hours of labor and decompression schedules were originally established in New York by an act of the Legislature in 1910, and were as follows:

Hours of Labor

Gage Pressure	Time under Pressure	Interval between Shifts
lbs. per sq. in.		
0–27.99	8 hours less interval	30 minutes
28–35.99	2–3 hour shifts	1 hour
36–41.99	2–2 hour shifts	2 hours
42–45.99	2–1½ hour shifts	3 hours
46–49.99	2–1 hour shifts	4 hours

No employee to work in more than 50 lbs. per sq. in. except in emergency.

Decompression Schedule

Uniform decompression at the rate of 3 lbs. every two minutes up to 36 lbs. per sq. in. For working pressures over 36 lbs. per sq. in. the rate was 1 lb. per minute.

These schedules have since been modified from time to time. The following schedules were adopted by New York in 1922, by Massachusetts in 1930, by Maine in 1931, and by California in 1933.

New York, Massachusetts, Maine and California Hours of Labor

Two shifts only to be worked during 24 hours with an interval in open air.

Maximum working pressure (except in emergency)—50 lbs. per sq. in.

Gage Pressures	First Shift	Interval	Second Shift
lbs. per sq. in.			
0–18	4 hours	½ hour	4 hours
18–26	3 hours	1 hour	3 hours
26–33	2 hours	2 hours	2 hours
33–38	1½ hours	3 hours	1½ hours
38–43	1 hour	4 hours	1 hour
43–48	¾ hour	5 hours	¾ hour
48–50	½ hour	6 hours	½ hour

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New York, Massachusetts, Maine and California Decompression

Decompression to be by the stage method, dropping to ½ maximum gage pressure at the rate of 5 lbs. per minute and completing decompression at a uniform rate so that the total time consumed shall be not less than that computed using the maximum pressure and the rate given:

GAGE PRESSURES	RATE
lbs. per sq. in.	
0–15	3 lbs. per minute
15–20	2 lbs. per minute
20–30	3 lbs. in 2 minutes
30 or over	1 lb. per minute

Some of the existing variations from these schedules are:

Wisconsin: Hours of Labor for Tunnel Work

GAGE PRESSURES	FIRST SHIFT	INTERVAL	SECOND SHIFT
lbs. per sq. in.			
0–21	4	½	4
21–30	3	1	3
30–35	2	2	2
35–40	1½	3	1½
40–45	1	4	1
45–50	¾	5	¾

Wisconsin: Decompression (Tunnel Work)

GAGE PRESSURES	UNIFORM RATE
lbs. per sq. in.	
36 or less	3 lbs. per 2 minutes
Above 36	1 lb. per minute

Wisconsin's schedule for hours of work in caissons is the same as the present schedules of New York, Massachusetts, Maine, and California. The decompression schedule now in use in Wisconsin for caisson work is as follows:

GAGE PRESSURES	MINIMUM NUMBER OF MINUTES TO DECOMPRESS
lbs. per sq. in.	
0–10	1
10–15	2
15–20	5
20–25	10
25–30	12
30–36	15
36–40	20
40–50	25

Wisconsin's schedules were established in 1930. Pennsylvania's rules for caissons and tunnels established in 1922, prescribe the same hours of work as Wisconsin's rules for tunnels. The corresponding Pennsylvania decompression schedule is the same as that of New York.

The New Jersey rules as published in 1931, prescribe the same hours of work and intervals for tunnels and caissons as those of New York; the decompression schedules for tunnels and caissons are respectively the same as those for Wisconsin.

Wisconsin provides a stage *compression*, with stops at every 5 pounds to determine if any one in the lock is blocked.

The American Standards Association is preparing a Proposed American Standard Safety Code for work in compressed air. The pressure shifts and intervals of work for each 24-hour period, in this proposed code, are the same as in the present code of New York. The decompression schedule for this proposed code will be written following receipt of information based on tests now being conducted by the Navy Department. One of the questions to be decided by these tests is

that of the relative merits of fast decompression (5 lbs. per minute), as used in the present application of the stage method, and the uniform rate method of decompression.

The codes of the various states are fairly uniform in other requirements.

In general, lock tenders, gage tenders and checkers must be provided. Recording gages must be placed on man locks when pressures are over 17 lbs. per sq. in. First class sanitary conditions must be preserved in the air chambers. California and Massachusetts prescribe the use of after coolers and limit working temperatures to a maximum 85°F. The American Standards Association's proposed code limits temperatures where work is in progress to from 70°F. minimum to 85°F. maximum. The States that have codes are uniform in requiring that electric illumination only be used in the air chamber; that an adequate supply of pure air be brought close to the heading, with a check valve provided on the free end of the air pipe; that exhaust valves be provided to clear the air in the heading after a blast; that a telephone or other suitable means of communication between the air chamber and the contractor's office be established. Two or more locks must be provided when the size of the tunnel permits and there are 15 or more men in a gang, one of the locks to be for the exclusive use of the men. The locks must be of sufficient size to prevent cramping of the men when decompressing, (generally specified as 5 feet or greater in diameter). Caisson man locks must be placed above water level. Intermediate bulkheads and safety screens are to be provided when conditions require their use.

The State codes generally specify that the compressor plant must be good and sufficient to meet emergencies as well as ordinary requirements, and must be provided with two independent sources of power, duplicate air lines and emergency units.

Fire prevention and blasting rules are also included in the codes of some of the States.

Medical rules are fairly uniform and provide that a qualified physician with compressed air experience be put in charge to enforce provisions requiring: (1) a qualifying physical examination of each new man; (2) a test in the compressed air of each new man; (3) re-examination of any one absent from work for 10 days or more; (4) regular re-examination of all air workers; (5) alcoholics to be barred from work in compressed air; (6) a complete record of all physical examinations and cases of compressed air illness; (7) adequate and healthful dressing room facilities; (8) a medical lock 5 to 6 feet in diameter and a physician in constant attendance when pressures exceed 17 lbs. per sq. in. gage; (9) the serving of hot coffee to men on return from the air chamber.

Ontario, Canada, published a code in 1926 which covers most of the regulations enumerated above. The working period schedule of this code follows the Pennsylvania and Wisconsin schedule for tunnels very closely; a stage decompression the same as that of the New York code is required. Decompression rules must be observed by those that stay in pressures of from 15 to 27 lbs. over 30 minutes, or in 27 to 31 lbs. over 15 minutes, and for all those who enter 31 lbs. or more. For pressures of 22 lbs. per sq. in. or more,

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the men must remain on the job for one hour after decompressing.

In Great Britain, the Committee on Regulations for Work Carried Out under Compressed Air, appointed by the Council of The Institution of Civil Engineers on April 30, 1935, in a report submitted January, 1936, recommend working periods and decompression rates as given in their tables 1, 2 and 3.

The Committee favor the single working period schedule as against the two period schedule now generally practiced, and are of the opinion that extending the stay in compressed air beyond the period in which the body becomes almost entirely saturated (considered to be 4 or 5 hours), does not add materially to the danger of compressed air illness, provided that adequate time be given for decompression. They recommend the use of a decompression chamber in connection with tunnels and caissons which are too small to provide for the decompression rates prescribed, the gang to leave the working chamber quickly and to enter the decompression chamber immediately for proper decompression.

An interesting comparison may be made between the total decompression times obtained by applying the Committee's decompression schedule to New York's hours of work schedule and the decompression times provided by the New York regulations.

TABLE 1

TIMES OF WORKING PERIODS—ONE WORKING PERIOD PER SHIFT

AIR PRESSURE (GAGE)	TIMES
lbs. per sq. in.	
0–25	One working period not exceeding 8 hours, including half-hour meal time
25–40*	One 6-hour period, including half-hour meal time
40–50*	One 4-hour period, with meal during decompression

* With 25 to 40 pounds pressure, men should be kept for 40 minutes after decompression before leaving the works, and with 40 to 50 pounds pressure they should be kept for one hour. In cases such as sinking caissons, where only a few shifts are required at pressures somewhat higher than those stated above, the longer working period may be continued.

TABLE 2

TIMES OF WORKING PERIODS—TWO WORKING PERIODS PER SHIFT

AIR PRESSURE (GAGE)	TIMES
lbs. per sq. in.	
0–25	Two 4-hour working periods with ¾ hour interval including decompression time
25–40*	Two 3-hour working periods with 3 hour interval including decompression time
40–50*	Two 2-hour working periods with 4 hour interval including decompression time

* See note to table 1.

PRESSURES	PERIOD IN AIR, HRS.	DECOMPRESSION TIME, MINUTES		
		N. Y. State	Committee	Committee (Experienced Men)
0–15	4	0–5		
15–18	4	7½–9		
18–20	3	9–10		
20–22	3	13⅓–14⅔		
22–26	3	14⅔–17⅓	6–10	4⅔–7⅓
26–30	2	17⅓–20	14–23	10–16
30–33	2	30–33	30–38	20⅔–26
33–38	1½	33–38	(29–40½)*	(20–27½)*
38–43	1	38–43	32–44	22–30
43–48	¾	43–48	(30–36)*	(20⅔–24⅔)*
48–50	½	48–50	27	18⅔

* Interpolated.

J. A. Hawkins, D. Sc., and Lieutenants Shilling and Hansen of the United States Navy have recently suggested a revision of the diving table which would materially reduce the time of ascent for the various depths and times of submergence. This suggested revision is based on 2,143 experimental dives in submarine escape apparatus, in which the simulated rate of ascent was kept constant at 50 ft. per minute, while the time of exposure was varied during each run for a given depth.

Table 4 is compiled from data given by Dr. Levy in his Bureau of Mines paper supplemented by later data which he has very kindly furnished from his records.

It has been recognized for some time that helium, which is about half as soluble as nitrogen and diffuses more rapidly, may be substituted for the nitrogen in the air to the advantage of divers and compressed air workers.

TABLE 3

DECOMPRESSION TIMES FOR VARYING PERIODS OF EXPOSURE IN COMPRESSED AIR

GAGE PRESSURE IN THE WORKING CHAMBER, LB. PER SQ. IN.	REDUCED IN 2 MINS. TO GAGE PRESSURE, LB. PER SQ. IN.	FURTHER UNIFORM REDUCTION TO ZERO (GAGE PRESSURE) TIME IN MINUTES									
		For working periods of 6 hrs. or more		For working periods of 4 hrs.		For working periods of 3 hrs.		For working periods of 2 hrs.		For working periods of 1 hr.		For working periods of ½ hr.	
		Time in mins.	Mins. per lb.	Time in mins.	Mins. per lb.	Time in mins.	Mins. per lb.	Time in mins.	Mins. per lb.	Time in mins.	Mins. per lb.	Time in mins.	Mins. per lb.
22–24	4	10	2½	8	2	4	1	0	0	0	0	0	0
24–26	5	20	4	15	3	8	1½	5	1	0	0	0	0
26–28	6	33	5½	27	4½	21	3½	12	2	4½	¾	0	0
28–30	7	45	6½	35	5	28	4	21	3	7	1	0	0
30–32	8	52	6½	44	5½	36	4½	28	3½	12	1½	0	0
32–34	9	59	6½	50	5½	45	5	36	4	18	2	4	½
34–36	10	70	7	60	6	55	5½	40	4	20	2	5	½
36–38	11	82	7½	72	6½	66	6	50	4½	27	2½	8	¾
38–40	12	96	8	84	7	78	6½	60	5	30	2½	12	1
40–42	13	104	8	91	7	85	6½	65	5	33	2½	13	1
42–44	14	112	8	105	7½	98	7	77	5½	42	3	14	1
44–46	15	—	—	112	7½	105	7	82	5½	45	3	15	1
46–48	16	—	—	128	8	120	7½	88	5½	48	3	20	1¼
48–50	17	—	—	136	8	127	7½	102	6	59	3½	25	1½

When men selected in view of previous experience in compressed air without having shown serious symptoms are employed, the Committee consider that the above times for uniform decompression may at the discretion of the Superintending Engineer in charge on the works be progressively reduced to two-thirds of the above figures. The effect of each reduction on the incidence of cases should be carefully noted and successive reductions regulated accordingly. The number of cases requiring recompression in any one week should not be allowed to exceed 2 per cent of the number of decompressions.

Synthetic helium-oxygen mixtures have been used experimentally in tests conducted under the joint supervision of the U. S. Public Health Service, the U. S. Bureau of Mines and the U. S. Navy Department in an attempt to produce an atmosphere for work under pressure that would eliminate

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or lessen the danger of compressed air illness. A large number of experiments using very high pressures, have been conducted on animals. These were supplemented by actual diving tests. It is recorded in "Chemicals," November 22, 1926, that it was concluded that an atmosphere could be made that would permit decompression in a third to a quarter of the time required for air and also that the deleterious effects of oxygen poisoning could be prevented.

Helium was used in 1921 in the treatment of compressed air illness on board the U. S. S. *Falcon* while salvaging the submarine, *S-51*, sunk near Newport, R. I., in 135 ft. of water.

The supply of helium is still limited so as to make the cost of any extensive use of it in the prevention of compressed air illness in tunneling prohibitive.

Compressed air illness prevention by expelling nitrogen from the system by breathing oxygen before and during decompression is also receiving attention. No practical application of this method has ever been attempted on tunnel work.

TABLE 4

COMPRESSED AIR ILLNESS. TUNNELS BUILT WITH THE AID OF COMPRESSED AIR IN THE VICINITY OF NEW YORK CITY

TUNNEL	YEAR	CONTRACTOR	MAXIMUM PRESSURE	NUMBER OF DECOMPRESSIONS	CASES OF BENDS	DEATHS
			lbs. per sq. in.			
Hudson-Manhattan	1879 1903–1907	Hudson Cos.	42	?	1,573	3
Battery-Joralemon	1902–1908	N. Y. Tunnel Company	42	?	674*	14
North River-Penn.	1903–1909	O'Rourke Engr. Constr. Co.	28	?	490**	?
East River-Penn.	1904–1909	F. Pearson & Sons, Inc.	42	557,000	3,692	20
Clarke St.	1914–1919	Flinn-O'Rourke Co.	37½	761,405	292	1
Montague St.	1914–1919	Flinn-O'Rourke Co.	34½			
14th Street	1916–1921	Booth & Flinn, Ltd.	39½	388,096	270	0
60th Street	1917–1921	P. McGovern & Co.	47½	211,960	118	1
Holland Tunnel	1920–1927	Booth & Flinn, Ltd.	47	756,565	528	0
53rd St.	1927–1930	P. McGovern & Co.	41	280,019	278	0
Fulton St.	1928–1933	Mason & Hangar Co. Inc.	47½	406,583	243	0
Harlem Riv.	1928–1932	Geo. H. Flinn, Corp.	24	88,135	3	0
Rutgers-Jay	1930–1933	Mason & Hangar Co. Inc.	43	234,747	182	0
Midtown-Hud.	1933–	Mason & Hangar Co. Inc.	45	120,652	39	0

* Figure for the 5 months for which records were kept.

** These were well marked cases.

The last five tunnels were constructed under the existing New York State code for work in compressed air. Compressed air work for the last ten was under the medical supervision of Dr. Levy.

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CARBON MONOXIDE POISONING*

CECIL K. DRINKER

IN THE space of a lecture such as this it is manifestly impossible to review the entire subject of carbon monoxide poisoning—one involving physiological problems of the greatest intricacy, medical problems, and pathological problems of equal size and difficulty. As a consequence, I shall deal with aspects of the carbon monoxide situation which have interested me personally—in which I have been personally involved.

Carbon monoxide is an extremely ancient poison, as old as man's use of fire. Descriptions of poisoning appear in the medical literature in Greece, in Rome, in the medieval medical literature and so on to the present time. Its modern history, however, began in the middle of the 19th century when Claude Bernard recognized the true manner of its action. He realized that it was an asphyxiant and that it acted by excluding oxygen from the blood. This is the essential action of carbon monoxide and possibly, though recent work gives us reason to think there may be a little more, the only action.

First, I will recall for you certain physiological matters which are absolutely fundamental and which must be carried in mind. The blood is a mixture of a watery fluid carrying various substances in solution and red blood cells. The blood plasma—that is, the fluid of the blood, red cells excluded—is capable of carrying extremely little oxygen to the body—only 0.36 cc. per 100 cc. of plasma. The whole blood—that is, the blood containing the red cells filled with hemoglobin,—can carry 20 cc. per 100 cc. of plasma.

Barcroft has pointed out that if it were not for the possession of hemoglobin and this extraordinary property of loose combination and transport of oxygen man would never have been capable, if he was to have any activity at all, of reaching a size much greater than that of the smaller insects. And if he had no hemoglobin at all and, somehow or other, had reached his present size, his capabilities of activity would be below that of a lobster. So that hemoglobin in the red blood corpuscles is of fundamental importance to mammals.

How does the hemoglobin act in relation to holding and combining with oxygen? This is best illustrated by what is called the dissociation curve of hemoglobin shown in figure 1. This figure is of a family of dissociation curves. The percentage of saturation of hemoglobin with oxygen is plotted vertically, and horizontally the pressures of oxygen in millimeters of mercury to which the hemoglobin solutions were exposed. At an oxygen pressure of 100 mm. mercury the

* From the Department of Physiology, Harvard School of Public Health, Boston.

hemoglobin is practically completely saturated, that is, it is carrying in the neighborhood of 20 cc. of oxygen in each 100 cc. of solution. The curve marked *40* is most representative of what takes place in the body at sea level. It happens that under such normal conditions the partial pressure of oxygen in the lungs is about 100 mm. mercury. In the time of movement of blood through the lungs practically complete saturation with oxygen occurs. But there is a large margin of safety; thus, if the oxygen pressure is only 50 mm. mercury, the hemoglobin is 80 per cent saturated.

To illustrate: Suppose one is called to work in a mining property in Peru, 14,200 ft. above sea level. At that height the partial pressure of oxygen to which the blood is subjected as it goes through the lungs is 54 mm., corresponding to the reduction of general barometric pressure. Even then the blood is over 80 per cent saturated. In men working at this altitude the blood was found to be 87 per cent saturated with oxygen, a sufficient degree of oxygenation to permit active work in most individuals and a comfortable, reasonable life. As one goes higher the situation becomes worse. In the Everest expeditions trouble is encountered when 17,000 ft. is reached. Acclimatization is necessary in most of us at 14,000 ft. and at about 10,000 ft. the body will begin to show evidence of

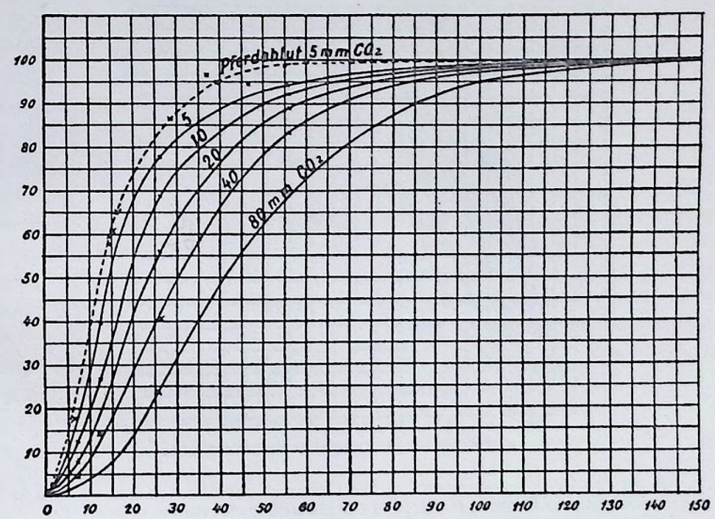


FIG. 1.—A series of curves representing the ability of solutions of hemoglobin to hold oxygen under different oxygen pressures when carbon dioxide under different tensions is also present. *Ordinates*, percentage saturation of hemoglobin with oxygen; *abscissae* partial pressures of oxygen in millimeters of mercury. Partial pressures of carbon dioxide used in each sample above curves. (From Bohr, C., Hasselbalch, K., and Krogh, A.: Skandin. Arch. f. Physiol., *16*, 402 (1904).)

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change in individuals who are becoming adapted.

While the ability of the blood to take up and hold oxygen is dependent to a very great degree on the partial pressure of oxygen in the surrounding air, it is also dependent on other things, than 80 per cent. The further significance of the carbon dioxide effect is best appreciated after a glance at figure 2, which is a similar set of dissociation curves using carbon monoxide instead of oxygen. The curves are very similar to those with oxygen, and

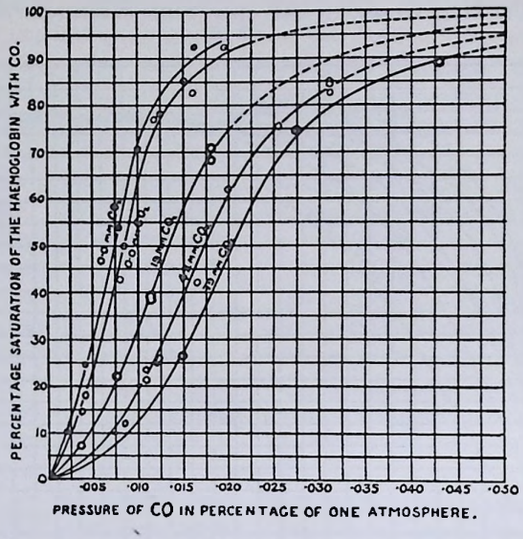


FIG. 2.—A series of curves representing the ability of solutions of hemoglobin to hold carbon monoxide under different pressures of the gas and under different tensions of carbon dioxide. *Ordinates*, percentage saturation of the hemoglobin with carbon monoxide; *abscissae*, partial pressures of carbon monoxide in percentages of one atmosphere. Partial pressures of carbon dioxide used in each sample above curves. (From Douglas, C. G., Haldane, J. S., and Haldane, J. B. S.: J. Physiol., *44*, 275 (1912).)

and of these the carbon dioxide situation is most important. Our family of curves in figure 1 shows the effect of carbon dioxide on the ability of the blood to take up and hold oxygen. As the carbon dioxide in the environment increases the curves shift to the right. At 50 mm. of oxygen pressure and 5 mm. of carbon dioxide, the hemoglobin is above 90 per cent saturated, but when 40 mm. of carbon dioxide are present at 50 mm. of oxygen pressure the saturation is less the effect of increasing amounts of carbon dioxide is quite the same.

Suppose now we give an individual who has been poisoned with carbon monoxide 7 per cent carbon dioxide to breathe. This will increase the carbon dioxide in the air of the lungs to a marked degree. It will force carbon dioxide into the blood and will cause the blood to be proportionately less able to hold carbon monoxide and so will induce more rapid elimination through the lungs. This is one of the

fundamental reasons why the carbon dioxide treatment of carbon monoxide poisoning is both rational and successful. When carbon dioxide is given to patients with carbon monoxide poisoning, we employ 7 per cent carbon dioxide and 93 per cent oxygen. The high concentration of oxygen assures as complete as possible saturation of the available hemoglobin with oxygen. To illustrate: Suppose we have a patient who has 60 per cent of his hemoglobin saturated with carbon monoxide. He now has 40 per cent available to transport oxygen. It is essential, if he is to recover, that he secure the full 40 per cent saturation in each passage of the blood through the lungs. We assist in this by increasing the oxygen in the air from 20 per cent, the normal content, to 93 per cent. It is also true that in the presence of such high concentrations of oxygen as this the release of carbon monoxide from its combination with hemoglobin is facilitated. We add the carbon dioxide in order to push the carbon monoxide out of the blood as rapidly as possible and to deepen the breathing so as to bring in as large a supply of oxygen as the individual is capable of obtaining.

It was pointed out by Haldane in 1912 that carbon monoxide is from 290 to 300 times more readily taken up by hemoglobin than is oxygen. This, of course, accounts for the fact that such low concentrations of carbon monoxide become poisonous.

There are other facts about carbon monoxide poisoning which are essentially physiological. There can be no doubt that if pure carbon monoxide is breathed, that is, carbon monoxide generated in the laboratory from the action of sulfuric acid on formic acid, man and animals will experience a slow increase in the red cells of the blood. If for days and weeks we maintain a 20 per cent saturation of the blood with carbon monoxide, individuals in this condition have 80 per cent of the available hemoglobin for oxygen transport, which is plenty for ordinary use. But, under these circumstances, it will be found invariably that the red cells increase somewhat from in the neighborhood of five million to six or six and one-half million.

In actual industrial practice we do not meet pure carbon monoxide. It is mixed with a great variety of substances. One can find in the literature records of both increases and decreases of red cells in man exposed to an environment such as that of the ordinary public garage. The decrease is apparently due to the fact that the gas in such places frequently contains material of the general type of benzene. The same is true of illuminating gas. Since these substances tend to decrease the number of red corpuscles, in certain individuals who are non-resistant, low grades of anemia may appear.

In recent years Barcroft and his collaborators have brought out the fact that when an individual is poisoned with carbon monoxide the spleen contracts and forces into the circulation the reserve of red cells which it invariably carries. In this splenic contraction we have an immediate reserve for providing the blood with all the oxygen carriers that the body can give us, and this is probably of some importance in serious cases of acute poisoning.

The question of chronic severe

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anemias in connection with chronic carbon monoxide poisoning arises in the medical literature frequently. Pernicious anemia has been described as the result of carbon monoxide poisoning. An example of the sort of thing that one may expect was reported from Norway in 1912. A physician attended three children of the same family who he thought had pernicious anemia. One died. The others recovered after it was found that a coke-burning stove in the house was generating 0.04 to 0.05 per cent carbon monoxide and the hazard corrected. One of these children had less than a million red cells per cubic millimeter of blood. There can thus be no doubt that severe anemia follows exposure to carbon monoxide, but that this can cause true pernicious anemia is not the case.

The acute effects of poisoning by carbon monoxide are not things that most of us see except experimentally, and the course of events as poisoning progresses is naturally enough unfamiliar to us. The best account of what happens to an individual poisoned with carbon monoxide from minute to minute has been given us by Haldane in the description of an heroic experiment he did upon himself and which I quote here:

EXPERIMENT VII (HALDANE)

Percentage of CO (in air breathed) = 0.21. Duration 71⅔ minutes.

After 16 min. Pulse 91. No symptoms.

After 20 min. Blood taken. Distinctly a little pink. *Saturation* 17 per cent.

After 34 min. Very slight feeling of fulness and throbbing in head.

After 37 min. Fulness and throbbing more distinct.

After 40 min. Blood distinctly pinker than last specimen. *Saturation* 39 per cent.

After 43 min. Feeling decidedly 'abnormal.' Slight hyperpnea and marked throbbing.

After 45 min. Pulse 104. Breathing distinctly deeper.

After 54 min. Feel very decidedly abnormal. Vision seems not so good. Slight feeling of giddiness.

After 59 min. Hyperpnea more distinct. Beginning to look pale yellowish, and 'as if ill.'

After 61 min. Blood taken again. Pinker than last specimen. *Saturation* 44.5 per cent.

After 63 min. Feel worse shortly after making any movement in my chair.

After 65 min. Hyperpnea marked, and slight confusion of mind.

After 71 min. Blood taken. Very pink tint, slightly more so than last specimen. *Saturation* 49 per cent. Stopped experiment. Vision dim. Limbs weak. Had some difficulty in getting up or walking without assistance, movements being very uncertain.

After 2 min. from time of stopping. Could walk fairly straight across the room. Could write on black board, but letters not formed as usual, and some mistakes in spelling, etc. Felt confused.

After 5 min. Felt a little better.

After 6 min. After walking four times up and down the room I staggered and nearly fell. On going on I was very unsteady, often nearly falling, and grasping uncertainly at various objects for support. Vision also very indistinct. I seemed to see things, and yet not recognize their details. I could not read until after a rest. The exertion caused considerable hyperpnea, but this was not much noticed, as the other symptoms were so much more prominent.

After 12 min. Said over the German numerals correctly up to 25. Still rather unsteady, and nearly fell when turned round.

After 13 min. Attempted to walk along the line of one of the boards of the floor. Did so with much difficulty and great staggering and waving of arms.

After 15 min. Immediately after the last exertion, and while still very confused, I was given oxygen to breathe out of a bag. The effect seemed to be distinct. After three or four seconds everything seemed to clear up suddenly, and I was able to walk steadily up and down the room carrying the bag. Face also was said to improve in appearance, and no longer to look so 'sickly.' I breathed the oxygen for two minutes, and on ceasing continued to walk, and soon again became unsteady and confused.

After 22 min. from time of stopping. On walking quickly up and down the room I got very unsteady, and could not see distinctly, or hear the noise of a tap except faintly. At this point I again began to breathe from the oxygen bag, and the effect seemed distinct. After three or four seconds the confusion of mind and of perception disappeared completely, and I was able to run up and down the room with the bag, without any return of the confusion of mind. On stopping the oxygen I again began to feel confused after about a minute of walking. On trying to run vision rapidly became dim, and movements uncertain. Breathing the oxygen seemed once more to produce the same good effect, and it was also noticed that my voice seemed to become more natural.

After 35 min. The symptoms now became much less marked.

During the whole of the evening after this experiment I suffered from headache, but had no nausea or marked loss of appetite. Within two hours of the experiment I ate dinner as usual. During the succeeding day I had slight headache.

Haldane's experiments indicate that in man increased breathing begins when the blood is about 30 per cent saturated with carbon monoxide. Obviously the length of the period of hyperpnea will depend on the concentration of the gas in the air breathed which will govern the time the subject can survive. It is thus fair to expect that patients poisoned quickly by high concentrations of carbon monoxide, but removed from the gassy atmosphere just before the blood carbon monoxide reaches a fatal level, will suffer but a brief period of increased breathing and a consequent less degree of disturbance in regard to carbon dioxide and the acid-base equilibrium of the body fluids than will patients poisoned slowly by low concentrations of carbon monoxide. These latter will receive especial benefit from inhalation mixtures containing carbon dioxide.

When the carbon dioxide method of treatment of carbon monoxide poisoning was advanced by Henderson and Haggard about 1920, they produced experiments which showed that in animals poisoned by carbon monoxide the breathing increased and, as a consequence, the normal carbon dioxide content was reduced so that by and by the blood showed less carbon dioxide than it should. They felt that this situation had something to do with the failure of breathing and a decided amount to do with the general abnormality of the animal. I have watched many cases of human carbon monoxide poisoning, usually too late in the situation to see this breathing increase, usually after profound unconsciousness had occurred and when the individual was on the way down hill rapidly. But Haldane's experiments on himself showed that in the early stages of the poisoning this increase in breathing, beyond the control of the individual, does occur and it must deplete the body of carbon dioxide—a clear reason for the inclusion of carbon dioxide in resuscitation mixtures.

Let us now see what happens in an animal when carbon monoxide poisoning develops to a fatal point. Figure

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3 is an abbreviated record of an experiment upon a cat caused to inhale Boston illuminating gas and air for 40 minutes. At the time breathing ceases in the first asphyxiation shown in the upper group of tracings, the condition of the circulation is still excellent, and the same thing is true in the second experiment shown in the lower tracings. As poisoning progresses and the breathing begins to fail, the systematic irregularity seen in these two instances is often broken and breathing

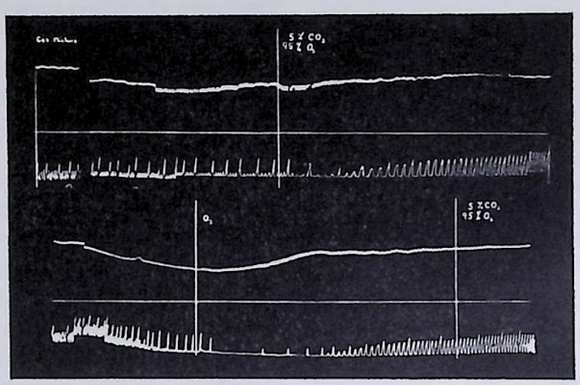


FIG. 3.—*1*, curve of blood pressure; *2*, base line for blood pressure; *3*, respiration. Normal conditions of blood pressure and breathing are shown in the upper left hand corner. Reading to the right and covering a period of 40 minutes carbon monoxide was inhaled. At the vertical line the gas was shut off and oxygen and carbon dioxide given. The bottom tracings are similar and show a second asphyxiation.

becomes a series of gasps of varying size. Breathing stops before the circulation fails; this is practically invariable unless there is a decided cardiac lesion in the patient. After the stoppage one probably has, at the most, not more than 8 minutes before artificial respiration must be supplied; otherwise the circulation will collapse and death will invariably ensue.

That situation explains why we rarely find cases of carbon monoxide poisoning who are wholly without breathing. One must catch them before many minutes have passed. Most patients are breathing poorly but still are breathing, and our experience has indicated that it is extremely advisable to give such persons artificial respiration in order to increase the volume of air breathed when the inhalation mixture is first administered.

Acute fatal carbon monoxide poisoning necessarily causes nerve lesions. These lesions, in summary, consist in dilatation, stasis, perivascular hemorrhage and edema, changes occurring diffusely through the brain. The edema is particularly severe. It is perineuronal and perivascular. With this there is nerve cell damage which varies in different parts of the brain, the cortex, corpus striatum, dorsal vagal nuclei and dorsal areas of the medulla being most affected. These latter facts account for the occasional Parkinson's sequelae. But damage may be diffuse through the entire brain and in some cases in the spinal cord which accounts, in its turn, for

the development of symptoms not dissimilar to those of multiple sclerosis.

These are the admitted and necessary facts in connection with fatal cases of carbon monoxide poisoning.

A long experience in New York City, the greatest reservoir of this type of poisoning in the world, however, convinces me that few cases survive severe poisoning who show very much the matter with them. There is apparently an extraordinarily small margin between damage which is necessarily fatal and survival. People are either killed or the damage has not occurred to a sufficient degree to register itself in the future at all. During the past year, with Dr. Shillito of Columbia and Mr. Shaughnessy in charge of the emergency work of the Consolidated Edison Company of New York, I have had opportunity to make an investigation as to this question of nerve lesions following poisoning and it has, as I myself have experienced, a good deal of medico-legal importance. People who have had a mild gassing and subsequently appear with every possible variety of neurological symptoms and claim that these date from the event of the poisoning are numerous and troublesome, and we desired to find out whether their claims had any substantial background.

TABLE 1

CARBON MONOXIDE CALLS MADE BY EMERGENCY SQUADS OF VARIOUS GAS COMPANIES IN METROPOLITAN NEW YORK AREA*

YEAR	COUNTIES OF NEW YORK, BRONX, QUEENS AND WESTCHESTER		COUNTY OF KINGS		TOTAL
	Resuscitated	Dead	Resuscitated	Dead	
1925	†	†	444	209	653
1926	1,039	444	554	261	2,298
1927	872	398	473	291	2,034
1928	968	461	553	254	2,236
1929	1,106	545	645	269	2,565
1930	1,038	496	490	218	2,242
1931	989	494	795	289	2,567
1932	1,064	463	659	297	2,483
1933	892	408	613	239	2,152
1934	964	387	414‡	148‡	1,913
Total.....	8,932	4,096	5,640	2,475	21,143

* From Shillito, F. H., Drinker, C. K., and Shaughnessy, T. J.: J. A. M. A., *106*, 669 (1936).

† No figures available.

‡ Returns incomplete.

The Consolidated Edison Company of New York maintains twelve emergency crews in all parts of Manhattan and nearby. Men on 24 hour duty are equipped with the best possible means for immediate resuscitation work and all are thoroughly well trained. In addition to this, they are trained to keep records as to the condition of patients, so as to report on pulse and respiration. Such records supply data on the immediate event of

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poisoning and, furthermore, data on the number of poisonings occurring during a certain period of time.

Table 1 shows the number of cases occurring during 10 years. Observations began early in 1925, when the emergency service was operating uniformly and satisfactorily, and run through 1934. During that time there were 21,143 cases of carbon monoxide poisoning. These cases, if severe, are sent to such general hospitals as Bellevue and then, if they develop sequelae, are distributed through the Metropolitan District to the mental hospitals. We could feel confident that if there were in those 21,000 individuals any serious number of mental or neurological sequelae they would find their way to the mental hospitals in the district. Very few of the people poisoned by carbon monoxide are wealthy or capable of private care. All of them, sooner or later, gravitate to one of the charity hospitals for mental or nervous cases.

During the same period of years these mental hospitals had 81,659 admissions of mental and neurological cases, as shown in table 2. Dr. Shillito and Mr. Shaughnessy searched the records with the assistance of the staffs of the hospitals with the utmost care. Out of this search they were able to find 39 admissions in 10 years who were sent to the hospital with nervous or mental diseases dating with certainty from the carbon monoxide episode. To these 39 cases, four others have been added which occurred before or after our 10-year period. Table 3 displays them all.

Obviously, from the nature of the pathology of carbon monoxide in fatal cases, we may expect diffuse distribution of lesions and we may expect a certain number to suffer mentally. It is, however, quite clear that the number of cases of carbon monoxide poisoning that show nervous or mental sequelae is exceedingly small and that such after-effects never appear unless poisoning has been exceedingly severe.

There is a further interesting aspect of the problem, namely, the number of people showing sequelae that are reasonably permanent who showed a clear period after the poisoning—a clear period of from 7 to 23 days. That is, they were badly poisoned in every case and then were apparently well, but after a week or more something began to happen. An illustrative case is as follows:

TABLE 2

TOTAL ADMISSIONS IN TEN YEAR PERIOD IN MENTAL HOSPITALS SERVING NEW YORK METROPOLITAN AREA, INCLUDING PSYCHOSES DUE TO CARBON MONOXIDE INTOXICATION*

FISCAL YEAR	STATE HOSPITALS						TOTAL	CARBON MONOXIDE CASES
	Manhattan	Brooklyn	Hudson River	Central Islip	Kings Park	Rockland		
1925	2,529	1,043	717	1,321	1,221		6,831	2
1926	2,221	1,274	793	1,324	1,098		6,710	1
1927	2,363	1,406	734	1,667	1,119		7,289	4
1928	2,317	1,529	788	2,020	1,277		7,931	1
1929	2,297	1,523	819	2,008	1,107		7,754	1
1930	2,317	1,629	841	2,017	1,302		8,106	8
1931	2,223	1,606	907	2,170	1,150	1†	8,057	7
1932	2,358	1,543	829	2,027	1,290	795†	8,842	4
1933	2,004	1,917	721	2,261	1,663	1,457†	10,023	4
1934	2,531	1,895	634	1,933	1,551	1,572†	10,116	7
Total....	23,160	15,365	7,783	18,748	12,778	3,825	81,659	39

* From Shillito, F. H., Drinker, C. K., and Shaughnessy, T. J.: J. A. M. A., *106*, 669 (1936).

† Exclusive of transfers.

TABLE 3

INCIDENCE AND TYPE OF NEUROLOGIC LESIONS OCCURRING FOLLOWING CARBON MONOXIDE POISONING*

	NUMBER OF CASES
1. Showing muscular hypertonia (increased reflexes, perhaps clonus and positive Babinski) (1 shows signs after 2 yrs.).....	9
2. Showing hypertonia and some degree of peripheral neuritis (2 permanently).....	5
3. Showing parkinsonism (3 permanently).....	4
4. Showing parkinsonism and some degree of peripheral neuritis..	1
5. Showing only peripheral neuritis.	4
6. Showing no neurologic signs.....	10
7. Dying before complete neurologic examination.....	10
Total.....	43

* From Shillito, F. H., Drinker, C. K., and Shaughnessy, T. J.: J. A. M. A., *106*, 669 (1936).

Case Illustrating Clear Period

A woman, aged 51, a Danish housewife, did not have a contributory past history. She was found unconscious from illuminating gas exposure and removed to the hospital, where she remained unconscious for from 40 to 50 hours. After 5 days she was discharged from the hospital, apparently entirely recovered from the gas poisoning, except for a little weakness. In 2 weeks, however, her gait became unsteady and her mental state changed from clarity to confusion and bewilderment. She was admitted to another hospital for observation. There it was found that she was mentally confused.

On the 52nd day she was transferred to the Hudson River State Hospital. On physical examination on admission no remarkable changes were noted except on the neurologic side. In this respect there was a noticeable blank, expressionless appearance to the face. The knee jerks were increased. There was a coarse tremor of the hands. Skin sensitivity to touch, cold and heat was diminished over the entire body. Mentally the patient was abnormal. She was anxious and disoriented. There were no hallucinations or delusions. Urinalysis showed a specific gravity of 1.021, a faint trace of albumin and no sugar, and the sediment was clear. The Wassermann reaction was negative.

On the 59th day the progress note said that the patient had cleared mentally so that she was well oriented and more interested. She complained of vague pains over the body.

On the 94th day the progress note said that the patient felt that she was thinking more easily. She was mentally clear on examination. On the 116th day all neurologic signs, including the diminished skin sensitivity, had cleared.

On the 123d day the patient was paroled.

On the 266th day the patient reported that she was feeling better every day. She was going to movies and the like.

On the 490th day she got her permanent discharge papers.

The diagnosis was psychosis due to drugs or exogenous toxins (illuminating gas) and confusion.

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The explanation of such clear periods is difficult. It probably depends on what is observed if one ties off a good part of the circulation to the head of an animal. Such animals are often very much more normal, both pathologically and in their ability to get about, immediately after recovery from the anesthetic, than they are a week later. Apparently, at the end of the 7th or 10th day, there is a reaction in connection with the repair of the damage which results in edema and in further interference with blood supply. It is at that time that acute symptoms may appear. This may be the case in these individuals who have been poisoned by carbon monoxide. They suffer from some neurological damage at the time of the asphyxiation. Then, as they attempt to repair the damage, further degrees of edema and lack of blood supply occur and it is at that time that symptoms begin.

Treatment

Finally, a few words about treatment. The inhalation treatment of oxygen and carbon dioxide came to us about 1921. We are beginning to know something of what can be accomplished by it provided other measures are also instituted. I think that what I now have to show you indicates the result not only of a very well administered treatment, but also a correlation of technic between the emergency crews of the New York gas companies, police and firemen, and certain other things in connection with the education of the public. It seems undeniable, however, that better technic in immediate treatment has resulted in some of the improvement which we can see. Table 4 shows the trend of suicidal and accidental deaths from carbon monoxide during 9 years. Accidental deaths are beginning to be reasonably few. The total deaths also seem to be coming down with a fair degree of significance, but we cannot control the incidence of suicide, and carbon monoxide poisoning will probably be a very favored method of suicides as long as we use gas.

All through that period, New York had the same medical examiner, Dr. Charles Norris, so that the medical data come from the same source. And we had the same methods of treatment from 1926 until we reached 1929, when we changed the concentration of carbon dioxide in the gas mixture from 5 to 7 per cent. Figure 4 shows the cases treated by the emergency men year by year. Early in 1929 we changed to 7 per cent carbon dioxide from 5 per cent. You see there are 1,128 total cases of which only 40 died following treatment, and that seems to continue to improve.

TABLE 4

Deaths from Illuminating Gas Poisoning in New York City. Statistical Report of the Chief Medical Examiner of the City of New York*

Year	Suicides	Accidental	Total (Suicide and Accidental)
1926	371	812	1183
1927	457	611	1068
1928	520	567	1087
1929	582	502	1084
1930	616	413	1029
1931	636	298	934
1932	649	262	911
1933	531	197	728
1934	462	213	675

* From Drinker, C. K.: Am. Gas Assn. Monthly, *12*, 444 (1935).

It was the only change of which I know. The 7 per cent of carbon dioxide has since this time been adopted all over the world and is, I think, a large enough amount. We have used 10 per cent during the past 2 years in certain situations but are unable to observe that it gives us in the least degree a better result than the 7 per cent, and those of us who have breathed carbon dioxide persistently in the laboratory know that 10 per cent carbon dioxide is capable of causing severe headache. So I have felt that 7 per cent is the safe place to stop.

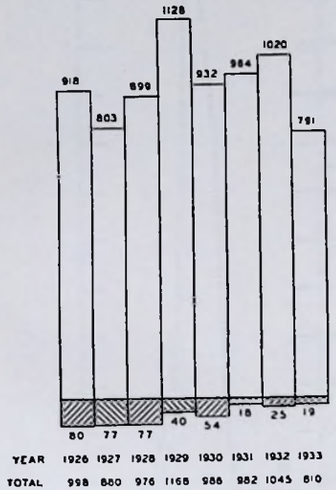


Fig. 4.—Columns indicate the total number of cases of carbon monoxide poisoning treated by emergency crews in New York by years. Shaded areas give the number of deaths occurring in treated cases. Early in 1929 the 5 per cent carbon dioxide and 95 per cent oxygen used for inhalation was replaced by 7 per cent carbon dioxide and 93 per cent oxygen. From Drinker, C. K: Am. Gas Assn. Monthly, *12*, 444 (1935).

The reasons for changing to 7 per cent are easy to demonstrate and are shown in figures 5 and 6. Each of these curves represents an individual. In figure 5, from the beginning of the curves to the vertical line each subject is breathing air and the amount of air breathed is measured in litres per minute, the average being somewhere around 10 litres per minute. At the vertical line they have been put on 5 per cent of carbon dioxide in air. The breathing changes, but on the same mixture individuals breathe differently. One subject experiences comparatively little increase in breathing from 5 per cent dioxide. Obviously a 5 per cent mixture would not do him very much good if he were poisoned. When, however, we change to 7 per cent carbon dioxide, then we invariably get a tremendous increase in breathing such as you see in figure 6, B. We were unable to find any one who did not react with an increase of breathing of substantial magnitude to 7 per cent, and so selected that concentration.

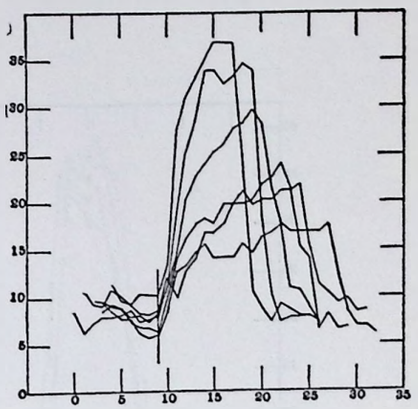


Fig. 5.—Response of six young men to inhalation of 5 per cent carbon dioxide in air. *Ordinates*, minute-volume in liters; *abscissae*, time in minutes. (From Heller, E., Killiches, W., and Drinker, C. K.: This Jour., *11*, 293 (1929).)

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Some one will certainly ask about methylene blue, which has appeared and, I should say, disappeared. I cannot see from the laboratory data that have been provided that it has much place in carbon monoxide poisoning, though it may be of use in cyanide poisoning, and there are reports recently of substantially bad reactions. It is a difficult drug to keep stable and it is possible that some of the poor results have been due to the use of methylene blue which has not any properties which are worth while. But, in any event, it has not justified itself as a remedy and we have nothing better to offer at the present time than proper use of artificial respiration combined with the inhalation mixture, artificial respiration being given in all cases where the breathing seems to be weak.

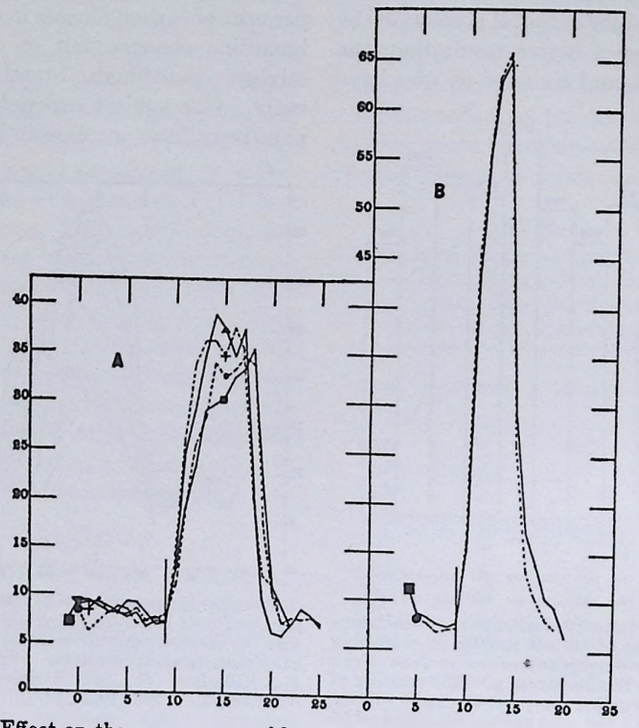


FIG. 6.—Effect on the same person of breathing 5 and 7 per cent carbon dioxide. A: ■ = 5.02 per cent carbon dioxide in air, March 15, a.m.; ● = 4.94 per cent carbon dioxide in air, March 15, p.m.; ▲ = 5.02 per cent carbon dioxide in air, April 5, a.m.; ✚ = 5.05 per cent carbon dioxide in air, April 5, p.m.
B: ■ = 7.01 per cent carbon dioxide in air, April 29, a.m.; ● = 7.01 per cent carbon dioxide in air, April 29, p.m. Vertical lines in both curves indicate beginning of carbon dioxide inhalation. *Ordinates*, minute-volume in liters; *abscissae*, time in minutes. (From Heller, E., Killiches, W., and Drinker, C. K.: This J., *11*, 293 (1929).)

There is a tradition that individuals who were breathing at all should not

be given artificial respiration because somehow or other the operator and the patient got out of time and the respiratory center became confused, and the individual had to relearn his breathing as he recovered. That theory may be disregarded.

The thing that these people need is a large supply of air in the lungs as quickly as possible. If they get it and they are breathing at all, they will probably recover; they should be given artificial respiration at once if there is the least doubt that the inhalation mixture is not getting into the lungs in a proper amount. As soon as it does, the breathing will pick up and take care of itself.

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TOXIC ORGANIC VAPORS AND GASES*

JOHN H. FOULGER

SINCE 1828, when Wöhler synthesized urea and laid the foundation of organic chemistry, the number of new carbon compounds has reached the hundreds of thousands. As a rough estimate, about 25 to 30 per cent of these are liquids or gases at room temperature. But although they are a minority in number, yet as a source of harm, gases and liquids are a majority. Very few chemical processes are carried out without a solvent, either as the reaction medium or in separation of the reaction products. Every use of a liquid involves the possibility of vapor formation. In many new processes a vapor phase is deliberately produced, since the molecules of a vapor, being more widely separated than those of the liquid, offer a greater chance of collision with molecules of other vapors in a mixture and therefore greater reactivity and a higher yield of the reaction product. The possibility of hazards from vapors therefore is increasing rather than decreasing.

If toxic, these organic materials are capable of producing the most insidious hazard which we encounter in industrial medicine. Vapors and gases are usually invisible and often devoid of odor. Their toxic effects are often produced without warning of exposure. They will penetrate by diffusion all parts of a room in which they are liberated. Many vapors will be condensed upon surfaces with which they come into contact, especially moist surfaces. Thus they may collect on the skin of the worker or may accumulate in clothing in quantities far greater than those found in the air.

To realize the nature of the dangers from toxic vapors and gases we must recall the routes taken by materials introduced into the body. Substances ingested may exert a local action upon the mouth and the digestive tract, or if devoid of such action may be absorbed in the intestines. Such absorption is usually variable, influenced not only by the physico-chemical properties of the material but by its reaction with the enzymes of the digestive tract as well as with food and by-products of food digestion. After absorption the major portion of this material passes into the portal circulation and may be detoxified by the liver cells. Materials introduced rectally, if absorbed, mostly pass into the inferior vena cava and so to the right heart. Approximately one-third may pass directly to the portal circulation and the liver. But substances inhaled can pass rapidly into the blood stream and so to the heart and general circulation; often they pass especially rapidly to the central nervous system. In such cases the detoxifying action of the liver can play but a very small

* From the Haskell Laboratory of Industrial Toxicology, Wilmington, Delaware.

part. The action on the heart or on the central nervous system can be more rapidly induced than by any other route except direct injection into the venous blood stream. Therefore, other things being equal, a toxic material may often be relatively more dangerous if inhaled than if ingested.

The absorption of a toxic material presented as a vapor can be stopped if the worker be removed from the atmosphere containing it. Absorption of a vapor through the alveolar walls depends, among other things, upon its partial pressure in the lungs. It will continue as long as this partial pressure is greater than that in the blood stream. In this connection Claude Bernard used a very interesting lecture experiment. Sulfuretted hydrogen, inhaled by a dog, is rapidly fatal, but if injected intravenously—of course with due precautions against gas emboli—it is harmless because the partial pressure in the lungs is much lower than that in the blood and the gas is rapidly exhaled. We all now realize the difference in our ability to control anesthesia produced by inhalation of ether or nitrous oxide compared with our control of that induced by injection of a barbiturate.

Of course, vapors which must be taken into the respiratory tract if they be present in air, are not necessarily always absorbed into the blood and tissues. Absorption will depend upon their solubility and their chemical reactivity. Many materials will be precipitated by the moist secretions of the upper respiratory tract or may penetrate as far as the alveoli and there be precipitated. Then, if they have no irritative action, they may merely act as foreign bodies. As such they may produce coughing and reflex attempts to remove them, or they may be inert for a long time and be destroyed slowly by the action of the tissues upon which they are deposited. Other vapors having irritant action may produce local reactions which, while causing serious respiratory embarrassment, will prevent absorption into the system. But still others may have no local action and may be so soluble that they pass directly into the blood stream. Here they may produce immediate changes in the composition of the blood, interfering with its oxygen carrying capacity, or they may be without action until distributed to the tissues.

Thus the general possibilities of hazards from inhaled gases or vapors are: —fairly mild respiratory embarrassment such as might be caused by a foreign body; upper respiratory, bronchial or pulmonary irritation, or all three, leading to acute respiratory distress with pulmonary edema and hemorrhages, cyanosis, asphyxia and death; respiratory distress and cyanosis following changes in the oxygen carrying capacity of the blood; and finally, toxic conditions produced by materials which do not affect respiration but whose action is first evidenced by malfunction of the brain, heart, liver, kidney or other organs.

Vapors of the less volatile materials or even of volatile materials in a humid atmosphere, may often produce a hazard by skin absorption. Such are quite often insoluble in water and are precipitated by contact with moist surfaces such as skin and clothing wet with perspiration. If fat soluble, they may be absorbed through an intact skin. If not fat soluble, absorption

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may occur through the ever-present small lesions of the skin or through lesions produced by chemical action of the material itself. In either case the hazard may be important. It must always be remembered also, that a vapor, when inhaled, must pass into the nose and mouth. There it may be condensed and swallowed with the saliva, causing a hazard by oral route. Sometimes air analysis may detect vapors in such low concentrations that risk by inhalation is of minimal importance. Yet risk of intake by other routes may still exist and lead to serious results.

There are considerable difficulties in the study of hazards due to organic vapors and gases. In the first place, since they may be present in the air in very low concentrations (except when containers or pipe lines are broken) special methods of air sampling must be used. Usually the methods involve either condensation of the material in tubes immersed in freezing mixtures or adsorption of the vapor by activated charcoal. The method employed must be governed by the properties of the gas or vapor but also must be suited to its detection and estimation. The procedure of collection must be as simple as possible as must also be the method of analysis.

It is in the matter of analysis that we are faced with the greatest difficulty. The majority of hazards from organic compounds result from their use as solvents. Now a solvent is not chosen for its chemical activity but for its ability to disperse materials placed in it. Solvents, therefore, are substances of relatively low chemical reactivity under the conditions in which they are used. They are usually aliphatic hydrocarbons or their halides, alcohols, ester or ethers. While, as groups, it is possible to differentiate and estimate these compounds, it is extremely difficult to identify, and much more to estimate, individual members of the groups. This fact is not always realized by the chemist. Dealing as he does with large samples, he can often use some physical property, such as boiling point, for identification. But in air sampling one's total sample, collected by an air flow of 10 liters per minute throughout an 8-hour day, may be a matter of thousandths of a cubic centimeter of the liquid from which the vapor is formed. Fractionation by physical means is impossible. So also, in many cases, is identification. Thus one might estimate the total halogenated hydrocarbon vapor in air by passing the vapor-air mixture through a red hot tube and collecting the hydrochloric acid formed in silver nitrate solution. But as yet we have no means of saying whether the halogen compound is trichlorethylene or carbon tetrachloride, or whether it is a mixture. We might obtain this information from the operator of the process but still we cannot estimate the relative values of each component in a mixed hazard. For this reason, in medical studies of the industrial risk of certain processes we must not jump rashly to conclusions and ascribe to one agent alone effects which are possibly the result of the activity of more than one agent. A mixed hazard is especially liable to occur with halogen or sulfur compounds. Such substances, if they come into contact with hot metal or open flames, decompose to give not only toxic inorganic gases—hydrochloric acid and sulfur dioxide—but also volatile organic compounds such as phosgene. These, being irritants, cause respiratory disturbance and also by the damage which they do to alveolar membranes, facilitate the absorption of the materials from which they are produced.

Protection against organic vapors can usually be obtained by adequate ventilation. In devising systems of ventilation the physical properties of the vapor and its mother liquid must be considered. For instance, if the vapor be heavier than air, ventilation will best succeed in removing it at a level below the shoulders of the workers, keeping the concentration low at the face level. It is ridiculous to use forced ventilation *above* a tank of liquid producing heavy vapor—the result is merely to facilitate vaporization and increase the concentration at a level which it would not normally reach. Yet such a scheme has been used in plants in which halogenated hydrocarbons are employed in cleaning metal parts.

The most dangerous exposures to organic vapors occur in the breaking of containers or pipe lines or in the careless opening of vats while the contents are still at a high temperature. If it is ever necessary to open tanks during an operation the workers should be adequately protected not only with an air-line respirator but with goggles and gloves. A similar protection should be given when any accident occurs throwing large concentrations of vapor into a small space. Ordinary respirators are often inadequate protection against vapors. Many organic vapors—especially metallo-organic compounds—are not easily adsorbed by the materials used in general service respirators. Even if they are adsorbed it must be remembered that the capacity of these respirators is limited. They can only deal adequately with low vapor concentrations. This is a simple matter of physics. No adsorbing medium will take up molecules unless they come into close contact with it. Frequency of contact is dependent upon the surface area of the adsorption agent and the concentration of the material to be adsorbed. Efficient adsorption only occurs when the surface is large compared with the number of molecules of vapor in unit-space.

Since vapors may produce a hazard by skin absorption—the result of collection on clothing or on dirt on the skin—cleanliness of body and clothing is necessary. Plenty of soap and water is a good mode of protection. But the soap must not be abrasive or so alkaline as to cause skin irritation for this would increase the risk of vapor absorption by producing lesions which are places of entry for toxic material.

It is obvious that in the present state of our knowledge protection against toxic organic vapors is dependent upon mechanical methods—adequate ventilation applied in a manner consistent with the physico-chemical properties of the vapor; cleanliness of the skin and clothes at all times; and in emergency, the use of respirators of such a type that the worker breathes air from a special source, never contaminated with the vapor. If such precautions be followed, the hazards will be reduced to a minimum. Finally, unless there be adequate information as to

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the toxicity of a given vapor (and at present this information is very restricted) all vapor should be regarded as toxic and all precautions taken for protection.

First aid measures in poisoning by organic vapors and gases will depend considerably upon the properties of the toxic material. First, however, the victim must be removed from the site of exposure. This will lower the vapor tension in the alveoli and not only stop absorption but often allow exhalation of vapor already absorbed. If the vapor be irritant, great care must be taken in using any form of artificial respiration. Manual methods are very likely to produce pulmonary edema or increase it if already present as a result of the action of the vapor. Cardiac failure may follow. The best treatment for poisoning which affects respiration is usually absolute rest with continued medical observation for 24 to 48 hours. Oxygen or oxygen-carbon dioxide mixtures may be used to control respiratory difficulties. Venesection may help considerably in reducing pulmonary edema. Heat will combat shock.

Many of the results of poisoning by organic vapors and gases may not appear soon after the exposure. Toxic action upon the liver, kidney, bone marrow or central nervous system may be delayed. Continued clinical observation is necessary with, of course, suitable laboratory tests, but it must be remembered that laboratory tests are usually only positive when considerable tissue damage has taken place—when the tissue reserve is greatly depreciated.

Our information on the pathology of poisoning by organic vapors is defective. Most studies contain information about liver or kidneys but very little about changes in the heart and almost none concerning the central nervous system. It is very important that the central nervous system should be studied more intensively, not only in laboratory experiments with animals but by thorough autopsies on industrial fatalities. Only by careful clinical and pathological observation can we overcome our ignorance of a source of industrial risk which is rapidly increasing in importance.

TOXIC DUSTS AND FUMES*

LAWRENCE T. FAIRHALL

FROM the point of view of industrial toxicology the distinction between toxic dusts, fumes, and gases is not very sharp. In industry one may find (and often does) that workers are exposed to a toxic substance in both a dusty and a gaseous form. For instance, where mercury is carelessly spilled on floors it becomes ground to a state of extremely fine subdivision and under certain conditions may be breathed as dust, while the vapor tension at room temperature is such that it also exists in the atmosphere in the gaseous form. On the other hand, some dusts, in themselves quite inert, may serve as carriers for a toxic substance. Fume occupies a position intermediate between dust and gas and is more or less synonymous with smoke. Certain substances such as zinc oxide may give rise to toxic action when inhaled as fume and yet be relatively inert when inhaled as dust.

In spite of many suggestions, no very satisfactory classification of toxic dusts has been made. This is not surprising in view of the fact that toxicity itself is a very elastic term. Perhaps for practical purposes it might be useful to say that one dust is more toxic than another, but so many factors are involved, such as degree of subdivision or particle size, retention, and individual susceptibility, that such a distinction after all is not very useful. As an instance of this one might cite the fact that air dusty with ragweed pollen can be and is breathed by numbers of people without the realization that it varies in any way from air at other seasons, while to those susceptible it causes the greatest distress. Similarly, in industry there appear to be varying degrees of susceptibility to such substances as tetrachlorethane, chlornitrobenzene, and several of the metallic dusts.

With the exception of silica, particle size plays a less important rôle than would be expected. In the case of metal fume fever the size of the particles is, of course, important but this is in general a minor industrial hazard. Probably the reason that most of the toxic dusts react with less reference to the degree of subdivision is largely due to their greater solubility or reactivity. Nonetheless, the particle size of any toxic dust should receive consideration.

The damage arising from the inhalation of toxic dust may be either local or remote and depends upon whether the material is a protoplasmic poison, whether it is caustic in reaction, or whether it is absorbed into the blood stream and carried to other centers which are affected in turn. Thus, bichromate dust commonly perforates the nasal septum, tar dust

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produces lung tumors, while ultramarine is quite inert to the lung tissue and chiefly affects the liver. In general, the toxic dusts produce remote rather than localized effects and for precisely this reason it is important in industry that these effects—often giving rise to very obscure symptoms—should be looked for early before extensive damage has occurred. This places a great burden of responsibility upon the employer. Frequently, however, instead of meeting the problem this way the easier course is taken of increasing the rate of labor turnover.

The toxic dusts and fumes of outstanding importance in industry, if we except silica and asbestos, are not particularly numerous. Arsenic, mercury, lead, phosphorus, manganese, cadmium, zinc, hexavalent chromium compounds, fluorides and silico-fluorides, certain dye stuff intermediates, and other organic compounds, claim our immediate attention. This by no means closes the list for we have caustic dusts such as certain basic salts, calcium and barium hydroxides, and tar dust, numerous merely irritating dusts and fumes, and such dusts as wool sorters and jute handlers are exposed to and which carry a marked mortality due to anthrax and tetanus. The latter are certainly difficult to classify as toxic dusts yet are nonetheless dangerous to those exposed to them.

Phosphorus fume as a cause of industrial disease is commonly thought to have disappeared with the severe legal restrictions against the use of yellow phosphorus in match factories and its substitution by red phosphorus and more particularly the sesquisulfide (P_4S_3). However, Ward (1) has shown that yellow phosphorus is still being used in certain fireworks factories. The use of this type of phosphorus in these establishments and also in the manufacture of rat poison together with the occasional appearance of cases of phosphorus poisoning in hospitals show that an industrial hazard, although a minor one, still exists.

Lead, because of its great importance in industry, its known effects as fume, and the degree and ease of control that can be exercised, has received by far the most attention amongst hygienists. To discuss it here is merely retelling an old story. Due to the widespread knowledge of the hygiene of lead and the measure of control that is possible, lead is losing ground from the point of view of toxicological importance. Hoffman (2) points to a decided decrease in lead poisoning in the United States. This decrease has been brought about probably by adequate ventilation more than by any other one factor. The elaborate safeguards against the oral ingestion of lead compounds which the older hygienists evolved are of far less importance than protection against breathing lead dusts or fume. Lead absorption is always greatest among those exposed to freshly-formed lead fume. For instance, in burning lead (a very hazardous trade if the worker is unprotected) it has been found that lead absorption occurred in 100 per cent of the cases examined (3), whereas, in spray painting only 44 per cent indicated lead absorption. It is interesting to contrast these real industrial hazards with pseudo-hazards that are announced from time to time. For instance Lipkovich (4) calls attention to a certain American typewriter having a lead cushion upon which the type bars fall when completing their back stroke. He states that he found lead poisoning symptoms to a greater extent in the typists using this machine than in other workers.

The fact that lead poisoning as such is lessening does not mean that prompt and energetic measures against industrial exposure are unnecessary. The prevalence of lead poisoning in any plant or a sudden outbreak of lead poisoning in any industrial work is as much a reproof to the hygienist as an outbreak of typhoid fever from a city water supply.

Although arsenic does not occupy a place in industry to compare with many other hazardous substances, its properties give it a high rating among the toxic dusts. Injury from it is definite and very often fatal. Only a rapid labor turnover keeps the number of reported cases low. Even so, in a study of 42 workers in Paris green made in 1917 by the New York Department of Labor (5) practically 60 per cent had definite symptoms of arsenic poisoning. The toxicity of arsenic and its compounds varies greatly. The dust of metallic arsenic is said by many to be quite innocuous while arsine and many organic arsenic compounds in gaseous form are extremely toxic. Of a number of cases of exposure to arsine reported by Guelman (6) 20 per cent had a fatal outcome. Arsine is quite different in its action from the dust of arsenical salts and compounds. Cases of poisoning occur from time to time in pickling metals where the arsenic is present either in the acid or in the metal, in cleaning acid storage tanks where washing has been incomplete, or in the gases evolved from storage batteries in submarines. Several cases of this latter type have been reported. Before legal restrictions were imposed, cases of poisoning with fatal outcome were reported on ships transporting ferrosilicon where the latter had become wet. In some of these cases phosphine as well as arsine was the offender. While arsenic is no longer used in the manufacture of coal-tar dyes a source of arsenic poisoning exists in the reduction of intermediates by other metals, such as zinc, magnesium, and iron, where the arsenic exists as impurity either in the metal or acid. Bomford and Hunter have recently shown that even quenching material containing arsenides with water has caused arsenical poisoning and deaths (7).

Arsenic is used in enormous quantities at the present time for the preparation of lead arsenate which is taking the place of copper arsenite, or Paris green, for spraying fruit and vegetables. Furthermore, the packaging of this material calls for dry packing instead of the paste form formerly used. This naturally makes the handling more hazardous.

As I have already mentioned, the action of arsenic salts or compounds in general is different from that of arsine. The latter causes vomiting in most cases, albuminuria, jaundice, and produces a hemolytic effect on the red blood cells. Fatal termination is frequent. Arsenical dusts, on the other hand, usually produce troublesome skin lesions—first of all an

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edematous condition with inflammation and eventually ulceration. Wherever the dust comes into contact with the skin and is held by perspiration, in folds (as around the edges of respirators), ulcers develop. Perforation of the nasal septum is common. That slow absorption does occur is evidenced by bronzing and in severe cases gastric symptoms occur.

The very uncomfortable effects of exposure to arsenic dust probably more than anything else lead to the rapid labor turnover, so that statistically, poisoning from arsenic dusts does not appear to be as serious as it really is.

Poisoning from antimony dust or fume is rare in industry although it has been reported with reference to type founders (8) and the experimental changes produced in animals by antimony, namely, a decrease in neutrophils and an increase in mononuclears, are similar to the typical blood picture of type founders.

Mercurial poisoning in industry seems to center rather in the inhalation of mercury vapor rather than in mercury dusts although in the hatters furriers' industry dust probably is a contributing cause. Of the 259 cases reported in 32 years in Great Britain between 1899 and 1931, 47 cases were reported amongst hatters and the remaining 212 cases in industries in which mercury fume or vapor would seem most likely the causative agent. Absorption by the skin of mercury as compounds or as metallic mercury in finely divided form is also a possible means of invasion. The commercial installation of mercury boilers is a potential source of mercury poisoning through leakage.

Poisoning by mercury where it is not acute is slow and insidious and while chronic mercurial poisoning does not lead to a rapid death, its impairment of tissue function is so drastic that the worker is in worse case than with many of the other industrial poisons. Mercury is constantly giving off vapor and thus it contaminates the air where it is exposed. Thus, the concentration of mercury in air saturated with mercury vapor is 1.84 parts per million at 20°C. and 8.5 parts per million at 40°C.

Obviously, the degree of saturation depends upon the temperature, pressure, rate of air exchange, and amount of surface exposed. Since mercury vapor is very heavy, it tends to collect on the surface and hinders further volatilization in still air.

Recently, Alfred Stock (9) has suggested a novel means of protection against mercury vapor. He has effectively demonstrated that activated charcoal impregnated with about 5 per cent of iodine will protect against mercury vapor and suggests the use of this material in gas masks. The impregnated charcoal can also be sprinkled upon open areas or cracks contaminated with metallic mercury, thus fixing the mercury vapor in a sense and preventing its further distribution.

Manganese and zinc poisoning are of less interest to the industrial toxicologist—the one because of its rarity and the other because chronic poisoning apparently does not occur. According to Schwarz and Pagels (10) in their investigation of manganese poisoning, examination of the blood for anemia gives certain indication of poisoning.

Similarly, tellurium and selenium,

industrial silver, and thallium dusts are as yet of no great industrial interest. Thallium fume, however, is extremely toxic and in this connection I would like to point out a source of exposure small, it is true, but not mentioned so far as I know in the literature of industrial toxicology. In the spectrographic analysis of materials arcking causes a surprising amount of fume. The great usefulness of the spectrograph has become increasingly apparent and is spreading rapidly particularly in industrial establishments. The spectrographer conducting routine tests with metals and other substances is frequently exposed to a much greater degree of fume than would be anticipated. Close work over freshly formed fume might well prove troublesome. The amount of fume given off in arcking a small bit of metal is often very noticeable.

Many new alloys are being developed entailing the use of unusual metals and the processing of these might repay attention. Beryllium steel has such remarkably valuable properties that it will doubtless receive more attention commercially. In the preparation of this metal a certain amount of dust is continually given off by the molten salt electrolytic baths. This dust consists variously of sodium silico-fluoride, barium fluoride, beryllium oxide, and beryllium fluoride. Experiments by Weber and Engelhardt (11) have shown that the dusts of all these compounds are toxic to animals. Our information is very poor concerning dusts and fumes from other metals and compounds that, although only a few years ago were rare or unknown, are becoming commercially important — indium, rhenium, gallium, titanium,—to mention only a few. Probably these and many others are quite innocuous, but experience in industrial hygiene, heretofore, has been in the direction of cure rather than prevention. An existing industrial hazard—a minor one it is true—is that of boiling out automobile radiators with oxalic acid. Oxalic acid is carried into the air to such an extent that unless the ventilation is good one is quickly driven from the room. So far as I know no very careful study of the effect of inhalation of oxalic acid over extended periods of time has been made. The body possesses no mechanism for rendering oxalic acid innocuous beyond elimination as oxalate.

I would like particularly to call attention to the possibility of injury or death from inhalation of cadmium fume—either metal or oxide—but particularly the latter. Cadmium melts at 320.9°C., a few degrees lower than lead (327°C.). It not only has a great degree of resistance to corrosion, but also has physical qualities much superior to other metals as a protective agent. The great increase in the use of cadmium not only for coating marine hardware but also for many fittings that were formerly zinc coated has presented a new problem in hygiene. Heretofore, exposure to cadmium has been very slight and was confined to the relatively small amount of metal annually reduced and to the small amount of cadmium yellow pigment manufactured. Some cases were reported by Stevens in 1921 (12) of cadmium absorption by men in a zinc smelter in Wales and a fatality was reported in 1923 of a worker in a

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plant making cadmium yellow who had been exposed to cadmium fume.

From animal experiments done in our laboratory a few years ago (13) we were able to show that cadmium oxide fume made by burning metallic cadmium in oxygen is extremely toxic. The metal burns readily, giving off a dense cloud of brown smoke which remains suspended for some time. Exposure of cats to this smoke for 15 minutes resulted in a severe reaction followed by death. In a case of overheating of cadmium in a foundry a few months ago dense clouds of cadmium oxide smoke were given off to which two workers were exposed. Both were affected and one died within a few days.

Dust injury from exposure to chromium in industry is largely confined to dust from handling the chromates or to spray from chrome-plating vats. Other processes in which workers are affected are those in which the skin comes into contact with a liquor as in tanning vats or in dyeing, rather than exposure to dust.

Whatever the source of injury from exposure to chromium compounds, the effect is largely local; systemic symptoms are rare and so far as I know no case terminating fatally has been reported except where the compound has been administered internally.

Since 1927 the new industry of chromium plating has widened exposure to chromium. Here the worker is exposed to spray or mist carried into the air by bursting bubbles over the plating vats. Because of the rapidity with which ulcerations appear, the labor turnover in this industry is said to be high. Ulcerations may be apparent in as short a time as 2 weeks.

Chromic acid and its salts attack the skin. The unbroken skin is not affected, but the slightest break furnishes a means of entrance. Once started the effect is progressive resulting in the well-known "chrome holes" or "chrome ulcers". These are very painful and may require months to heal. In addition to this, perforation of the nasal septum is common and has been found, in fact, in more than half those engaged in chrome plating.

The toxic action of chromium is confined to the compounds of hexavalent chromium. Trivalent chromium salts show none of this toxic action. In recent experiments (14) we were able to give cats as much as 1,000 mgm. as phosphate or as carbonate in their food per day and caused them to inhale up to 200 mgm. of carbonate over a period of 17 weeks without causing illness, loss of weight, or tissue damage. The contrast in toxic action between trivalent chromium and hexavalent chromium compounds is very marked.

With reference to exposure to toxic organic dusts there appears to be less definiteness. A certain amount of dust occurs in conveying, packaging and bagging, drying and dusting of material from floors, and workers are often exposed to fumes of various kinds. But in general, workers in such plants are exposed to gas or vapor and the toxic hazard is due to this rather than to dust. Of cases reported of injury or death following inhalation of the dust of organic compounds we find paranitraniline, the dinitrobenzenes, chloro-nitrobenzenes, trinitrophenol, and nitronaphthalene chief among the offenders. Eye damage due to inflammation of the cornea

by methyl violet dust has occurred with workers exposed to this dye. Tumors of the bladder, both benign and malignant, which have been found to occur in workers in aniline or aniline colors are not at all unusual. These appear as a rule only after long periods of exposure and it is difficult to say whether ingestion of small amounts, inhalation of dust or fume, or skin absorption is the most significant factor producing the toxic effect. Particularly irritating and dangerous is the inhalation of dust from paraphenylene diamine compounds. The paraphenylene diamine derivatives not only cause a severe form of dermatitis where the dust comes in contact with the skin, but also produce acute inflammation of the mucous membrane of the respiratory passages.

The degree of exposure to toxic fumes in general is probably greatest in the chemical industry and this is significant because this is one of our key industries. The number of workers in the chemical and allied industries according to the U. S. Census for 1925 (15) was 72,000. However, there are additionally great numbers of men in contact with the products or by-products of chemical manufacture in the petroleum, rubber, metal and other industries.

While the foregoing discussion has been confined to workers exposed to toxic dusts one must not overlook widespread exposure of large bodies of people to either constant small amounts or accidental large amounts of dust or fume. Thus, Dunn and Bloxam (16) point out the relatively large amount of zinc, lead, copper, manganese, and arsenic in the soil and herbage of areas surrounding coke ovens and other industrial establishments.

Liesegang (17) refers to the presence of sulfur oxides in atmospheric air as affecting health. However Miessner (18) is inclined to think that the danger from sulfuric acid, lead, and arsenic fumes from smelters is largely exaggerated. The material is deposited on grass, it is true, but is also frequently washed off by rains. There is more danger from the hydrofluoric acid fumes from artificial fertilizer plants, as animals grazing in the neighborhood of these plants develop a softening of the bones. Bloomfield and Isbell (19) have demonstrated the presence of lead dust and fumes in the air of streets and automobile repair shops of large cities. The cause of various allergic disorders has been traced to atmospheric dust by Murphy (20), who was able to show that definite relief was apparent when sensitive individuals occupied quarters equipped with air-cleaning devices.

An interesting effect was reported obtained by Campbell (21) who exposed mice to dust from tarred roads. This dust contained about 2 per cent tar. Cancer of the skin developed in 70 per cent of those surviving long enough and the incidence of primary adenoma of the lung was increased tenfold over that of the controls. Correlation of these facts with the undebated increase in tumors of the human lung is difficult, if not impossible, at present. The mice were, of course, exposed to excessive dusting —much more than is the case with humans breathing tar-dusty air.

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Collection and Analysis

The collection and analysis of dusts and fumes usually present problems of an individual nature. In general, however, the evaluation of the amount of a toxic constituent is not difficult. One point should be emphasized above all and that is that the sampling of a dust is quite as important as the analysis. Those who have given careful study to dust and fume fully realize this, of course. The haphazard collection of two or three air samples will give no information of value. It is necessary to plan the sampling very carefully with respect to source and type of dust and fume, air drift and disturbance as well as establishing exposure stations.

It is impossible in this short discussion to review recent methods of dust sampling (22–34), the physical evaluation of dust (35–40), or the chemical examination of dust and fume (41–45). I shall content myself, therefore, by mentioning only a few scattered points. For the determination of a given constituent the impinger method is still by far the most relied upon. Since particle-size distribution is so important numerous methods have been evolved to facilitate these determinations. Brown and Yant (38) have evolved an ingenious projection method for particle-size distribution and number concentration determination. The dust particle images are projected at a high, known magnification onto a ruled translucent screen while the observer, stationed in the rear of the screen, determines number, concentration by direct area counts, and comparison with known screen areas. Green (27) has devised a clever method of causing a measured volume of air to stream slowly past an electrically heated wire, the dust being deposited uniformly on cover slips in a way convenient for mounting, counting, and measuring of the deposited particles. Green finds it to be practically 100 per cent efficient for all particles of pathogenic importance.

With reference to the size of industrial dusts, Bloomfield (36) has obtained data of greatest value for comparison. Of 18,000 outdoor particles which he measured, nearly all were below 1 micron in size, while of 6,000 industrial dusts, 69 per cent ranged between 1 and 3 microns.

For the chemical detection of constituents, the conventional procedures have been used with such modifications as the nature of the dust required. Jötten and Sartorius (43) find a shift in relative composition with size and insist that the determination of free, insoluble silica is insufficient as a means of estimating the risk from a particular dust. For the detection of tar in dusty air Heller (40) collects the dust on a gelatin film and exposes this to chloroform vapor. Under the microscope the tar particles then appear surrounded by a brown ring. In detecting free metallic particles in dust Ward (45) treats the ether-washed dust on a slide with silver nitrate. Wherever metallic particles are present a silver tree is seen to develop.

Where a more extensive knowledge of the composition of a dust is needed, somewhat larger samples and careful microchemical procedure are necessary. The quantitative evaluation of a given constituent is frequently a matter of special investigation.

Toxic Evaluation

The purpose of industrial dust or fume investigations is to determine the presence and amount of a harmful constituent in the air which the workers breathe. This necessitates a knowledge of the harmfulness or toxicity of the foreign constituent. And this, frequently, is where a difficulty lies. In a gross sense we can, and in the past have, used experience as a guide and the older literature of industrial toxicology is largely, therefore, a collated collection of post mortems. Unfortunately, this is of little use when a new or little-known substance becomes commercially exploited. The rapid growth of domestic refrigerating units calling for low boiling liquids, the great growth of commercial solvents, the large-scale utilization of organic compounds which only a few years ago were laboratory curiosities have placed a great responsibility upon those who have been concerned with the health of workers.

It is the function of the toxicologist to determine the injuriousness of a substance, in a gross sense, to search out the tissues or organs affected, to discover what effect this has on the current or future life of the individual and finally, to find a safe minimum of exposure, if such exists. The factor of safety that he introduces is, unfortunately, not susceptible to that mathematical accuracy with which the engineer is concerned in building a bridge or steel building. The human animal is too complex, too variable. Since human individuals cannot (except in a few instances) be used for experimental work, one must rely on animal experimentation. There, too, one is confronted with a difficulty as it is sometimes difficult or unwise to interpret data obtained on animals in terms of humans. Therefore, it frequently requires slow and intelligent accumulation of much evidence to establish what may seem to be rather trivial points. The accumulated evidence eventually gives us a rather clear picture of what damage results from exposure to a given toxic substance.

The response of tissue or of the animal itself to contact with toxic substances is studied in a variety of ways, by intravenous or subcutaneous injection, by inhalation, ingestion, or application to the skin surface. Local tissues may show no response as Petrov (46) has shown with respect to ultramarine. This pigment, a double silicate of aluminium and sodium in combination with sodium sulfide, is physiologically inactive with reference to the respiratory system. However, anemia, degenerative changes in the kidney due to hydrogen sulfide poisoning, and even death of test animals may follow inhalation. Observation of the respiratory system alone, therefore, in such a case is insufficient evidence to show that such a dust is inactive.

On the other hand, tissue response at the site of contact may often give very valuable information, indeed. Thus Sayers, Miller, and Yant (47) were able to show a very striking response of interperitoneal tissue to various dusts introduced as foreign bodies.

The method of intravenous injection, formerly employed more than at present by toxicologists, is not particularly reliable. It was thought that this gave a more nearly true

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quantitative index of toxicity than any other means. One may produce typical tissue changes in this way, it is true, but many otherwise inert or harmless substances may act as severe poisons when introduced in this way.

In many ways inhalation is undoubtedly an ideal method of establishing toxicity—particularly of borderline substances—because it is a mode of entry against which nature has built up but little defense. In its quantitative aspects it is not yet altogether satisfactory, but that is a matter that is under active investigation at many centers.

In view of the many difficulties confronting one in giving a numerical value to toxicity, attention might be drawn to the so-called index of toxicity, *ct*, which is frequently used (48). *c* represents concentration of injurious substance in terms of milligrams per cubic meter of air and *t*, the time of exposure in minutes. The toxicity is then rated as proportional to the product *ct*. However, much more exact information than we now have will have to be obtained before we can freely use such a toxicity constant.

The inhalation of dust or fume more than other types of industrial exposure tends to produce *chronic* poisoning. *Acute* poisoning by inhalation is mostly caused by poisonous gases. In chronic poisoning we have an accumulation of poison taking place which is often unsuspected until symptoms of illness become apparent. This is rather important in a legal sense, for the sudden absorption of poison in quantity to produce immediate damage or death is rated as an accident, whereas chronic poisoning which also may end in death is generally accounted an illness. The distinction is, of course, very thin in many cases and non-existent in others. That there should be any distinction at all, however, seems at first thought to be unnatural. The reason for it, of course, is because of our difficulty in evaluating toxicity. We need to know not only the nature of the poison but also its effects, both qualitative and quantitative, upon the organism.

With reference to the quantitative aspect, a great deal has been accomplished with reference to minimum lethal dosage and the fatal amount of poison may be stated roughly in terms of the weight in kilograms of an animal or man, for instance.

The definition of toxicity in a qualitative sense is much more difficult. Here one is confronted with varying susceptibilities of individuals. After some experience with poisons one is inclined to be quite as unkind towards the idea of susceptibility as towards the idea of resistance. Very often one or the other disappears in the light of careful experiment. Cushny (49), for instance, states that the so-called resistance of arsenic eaters to arsenical poisoning breaks down entirely when soluble arsenic compounds are ingested. However, susceptibility is a factor to be reckoned with and one should be careful in haphazardly transferring experience gained from one species of animal to man or to other animals without further experiment.

The reason that inhalation of fume or dust may produce poisoning so definitely is because the material is carried into the body in such a way that the entire circulatory system may be involved, whereas toxic substances absorbed from the alimentary tract are to a much greater extent blocked by the very effective excretory mechanism of the liver and kidneys.

All inhaled particles are soluble, at least to a small extent. The solute may be harmless or toxic. If harmless, cell activity is stimulated so that phagocytes remove the dust. If the solute is toxic the viability of the phagocyte is affected and an ineffective accumulation results. At the same time, further solute may diffuse into neighboring tissues setting up an irritation and subsequent fibrosis. Obviously, the nature as well as the solubility of the solute is a factor of importance, but of two substances of about equal toxicity, the more soluble form causes the greater damage. However, a substance of such very low solubility even as silica may ultimately produce extensive injury.

While so much excellent work has been accomplished in the detection and control of fume and dust hazards, there still remains a vast and most interesting field for exploration with respect to the transport and ultimate activity of these substances in the organism.

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THE CAUSATION OF PNEUMOCONIOSIS*

PHILIP DRINKER

THERE are four different types of reaction produced in man by the inhalation of dust. The first and most important are the pneumoconioses, such as silicosis and asbestosis, which cause specific lung pathology and often are followed by pulmonary tuberculosis. The second type of reaction is caused by toxic dusts like lead, cadmium, and radium. A third type of malady follows the inhalation of finely divided metallic fume particles such as zinc oxide and is known as metal fume fever. Finally, the fourth reaction, allergic in character, is caused by breathing organic dusts such as pollen and certain types of pulverized wood and flour. In all four instances dust inhalation can be the sole cause of the disability but with the toxic dusts characteristic reactions result from swallowing as well as from inhalation. The latter route, however, is much the more important.

In the present instance we are concerned only with the pneumoconioses which result solely from the action of inhaled dust upon the lung tissue. Of necessity then, the dust particles must be small enough to float about in the air and be carried by rather slight air currents; otherwise they cannot be inhaled.

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is a shortening of Zenker's original *pneumonokoniosis*. Zenker (1) depicted lungs definitely damaged by dust particles, but today pneumoconiosis is generally used to describe any lung which has been dusted to more than the normal degree—there need not necessarily be demonstrable lung pathology. Silicosis, asbestosis, anthracosis, anthraco-silicosis, and similar terms indicate the different causative agents (silica, asbestos, and coal) in various kinds of pneumoconiosis.

The International Silicosis Conference in 1930 (2) defined silicosis as a "pathological condition of the lungs due to the inhalation of free silica (SiO_2)". The American Public Health Association (3) described it as a "disease due to breathing air containing silica." Sayers and Jones (4) state that "from the viewpoint of etiology, the harmfulness of a given dust containing free silica is directly influenced by the number of particles of free silica less than 10 microns in diameter that it contains". Collis has claimed for years that free silica, especially quartz, was the all-important factor. In summarizing his South African experience, Watkins-Pitchford (5) wrote in 1927 that dusts other than silica could "give rise to such non-permanent and relatively harmless conditions—one can hardly call them diseases—as anthracosis, aluminosis, siderosis etc"

In figure 1 are shown data from Collis indicating the etiological importance of free silica. The U. S. Public Health Service's data (6), shown in table 1, emphasize still further the importance of free silica.

Silica.—Silica occurs most commonly as the mineral, quartz, which is a natural contaminant of most ores, occurs in many rocks, and is found in a fairly pure state as beach sand, chert, flint, sandstone, gritstone, ganister, quartzite, and jasper.

gested by Badham (7) to describe a lung fibrosis caused by dusts in which silicates and not free silica predominate. The distinction between free and combined silica is best shown by a simple example: A granite dust (8) might have the following mineral composition:

	Per cent
Feldspar (orthoclase)	70
Quartz	25
Mica (muscovite)	5
	100

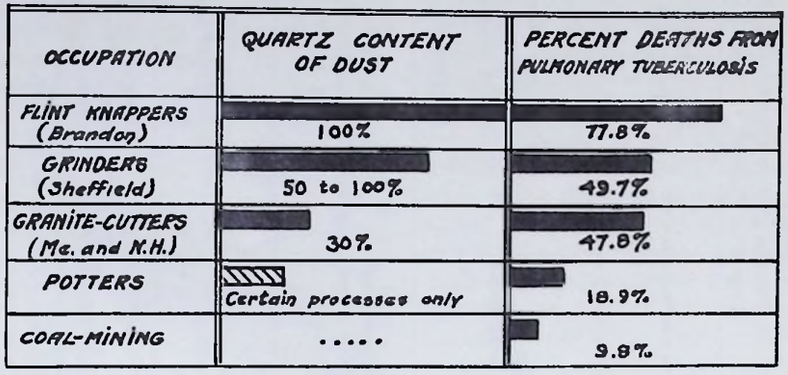


FIG. 1.—Mortality from pulmonary tuberculosis in various dusty trades. (After Collis)

Quartz is a hard crystalline mineral which is weakly birefringent, that is, its two indexes of refraction are near together. Chemically it is very inert and inactive. In fact its hardness and inertness are the two properties which make it especially useful in industry. Other varieties of pure silica such as opal, which is non-crystalline, have not as yet been appraised hygienically and there are no statistical studies to show the relative potency of the various forms of pure silica.

Silicates.—Silicatosis is a word sug-

Chemical analysis of this granite would give the following result:

	Per cent
SiO_2 (total)	72.55
Al_2O_3	14.80
K_2O	12.42
H_2O	0.23
	100.00

Recently Jones (9) showed that sericite was the outstanding common mineral constituent of a considerable series of lungs he analyzed. Sericite is a variety of mica with the formula

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TABLE 1

SUMMARY OF THE SIX DUST STUDIES BY THE U. S. PUBLIC HEALTH SERVICE SHOWING THE DUST CONCENTRATION, COMPOSITION AND THE RESULTING HAZARD*

INDUSTRY	AVERAGE DUST COUNT IN MILLIONS OF PARTICLES PER CUBIC FOOT	AVERAGE PERCENTAGE OF FREE SILICA (QUARTZ)	OTHER CHARACTERISTICS OF DUST	DEGREE OF HAZARD UNDER CONDITIONS AS OBSERVED IN EACH STUDY
Granite cutting:				
Hand-pneumatic tool operators	59	35	Balance mostly combined silica	Great excess of pulmonary tuberculosis after 15 years or more exposure; silicosis in from 2 to 10 years. Silicosis after prolonged exposure; no excess of tuberculosis
Surface-machine operators, etc	36			
General air	20			
Less than general air	9			Negative except for occasional nondisabling silicosis
Anthracite coal:				
Rock drillers	82	31	Siliceous rock	Data insufficient; other studies show severe hazard
Miners and miners' helpers	232	1 5	Carbon and inorganic matter	Dyspnea and other signs of pneumoconiosis; excess sickness from respiratory conditions; excess mortality from influenza, pneumonia and possibly tuberculosis
Bituminous coal:				
Rock drillers	78	54	Sandstone	Data insufficient; other studies indicate severe hazard
Loaders and machine men	112	1.2	Carbon	Generalized fibrosis chiefly linear in character; excess mortality from influenza and pneumonia
Cement	26	6–8	Primarily lime	Some early pneumoconiosis; excess of disease of upper respiratory tract and of influenza
Cotton-cloth manufacturing	7	?	Vegetable and silica	Negative
Silverware manufacturing	5	1.7	Metal and other	Negative
Municipal	4	?	Not determined	Negative

*After Thompson, et al.

$K_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O$. Its occurrence in nature is widespread but the quantities actually found are much less than those of quartz. It has not been shown that sericite, without quartz, will produce silicotic pathology; all investigations along such lines have been negative.

Asbestos is the only silicate at present recognized as causing pathology which is definitely and distinctly different from that due to silica alone. The condition known as asbestosis, like silicosis, predisposes to tuberculosis but to a much less degree. Since, however, asbestos is handled by far fewer persons than are dusts containing free silica, asbestosis is much less common than silicosis.

Asbestos is not a true mineral but is a name applied to any mineral which is easily separable into more or less flexible fibers. In this country, the commonest asbestos is the fibrous variety of serpentine in the form of the mineral chrysotile, $3MgO \cdot 2SiO_2 \cdot 2H_2O$.

Other silicates such as talc, $3MgO \cdot 4SiO_2 \cdot H_2O$, which resembles asbestos chemically, shale, kaolin, $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$, feldspar, and pure mica have been studied in both the field and the laboratory. The pathology they produce is much less significant than that from quartz and the fibrosis rarely is disabling.

Carbon.—An extensive examination of coal miners' lungs was made by Cummins and Sladden (10) as the result of which they wrote that "coal is only retained in large amounts when there is a really high silica content" and "we believe that in the absence of the silica factor there would be, under modern mining conditions, no serious degree of anthracosis. . . ." Men who were engaged in trimming coal ships with virtually no quartz exposure but undoubtedly with very heavy dust exposure, showed some fibrosis but it was not considered disabling (11).

The study made by the U. S. Public Health Service (12) in the anthracite mining district of Pennsylvania adds much weight to statements quoted from Cummins and Sladden, namely, that the harmfulness of a coal dust varies with the silica which contaminates the coal.

Haldane considered that coal dust might even reduce the severity of a quartz dust exposure; he suggested actually blowing coal dust into a mine with high quartz content as an antidote for the quartz dust (13) but no serious attempt apparently was ever made to test the validity of Haldane's claims. The recent statistical analysis of lungs autopsied in the Pittsburgh district (14) shows beyond doubt that city air, contaminated by an unusual amount of coal dust, does not produce a disabling fibrosis. Many of the lungs were markedly pigmented but the pathology found was not, in general, significant.

Calcium and magnesium carbonates.—These substances occur in nature as the minerals calcite, $CaCO_3$, magnesite, $MgCO_3$, and dolomite, $CaCO_3 \cdot MgCO_3$. Limestone and marble contain high percentages of calcite while the bulk of the rock from which cement is made consists of these carbonates. All three minerals are a great deal more soluble in water and in body fluids than is quartz. Furthermore the solubility of all three substances increases greatly if the solvent is saturated with carbon

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dioxide, a condition which occurs in the lung fluid which wets inhaled dust.

The several studies which have been made on calcium carbonate dusts indicate that the dusts are not harmful probably because they are so readily dissolved (8).

Gypsum.—This mineral, $CaSO_4 \cdot 2H_2O$, is very common and is mined and milled all over the civilized world. It is an essential ingredient of ordinary plaster and is now used extensively as a wall board. When partially dehydrated it again takes up water readily, but in neither that state nor as the native substance has it been shown to be harmful (15). It is an interesting fact that pure limestone (quartz free), dolomite, and gypsum are recognized universally as the dusts safest (hygienically) to blow into soft coal mines to prevent explosions.

Iron Oxides.—The mining of iron, next to coal, is perhaps the mining industry in which the greatest number of men are employed throughout the world. The ore generally is hematite, Fe_2O_3, but other oxides, and sometimes the sulfide, pyrites, FeS_2, are handled on a considerable scale. As a result of the improvements made in machine-tool steel, it is possible today to see iron dust created by work on lathes, drills, and the like. Yet there are no data to indicate that iron, in the absence of silica, causes pathology in any way comparable to silicosis. However, lungs which have been heavily dusted with iron in any form are generally colored distinctively and were called by Zenker (1) *siderotic.*

Estimation of Dust Exposure

The effect of any inhaled dust varies more or less directly with the duration of the exposure, the dust concentration and the volume of air breathed. In the case of the gas, carbon monoxide, our knowledge of the relationship of these factors is sufficiently exact to permit the use of a simple rule (16) for predicting the effects of breathing various gas concentrations under various conditions. Unfortunately, one cannot estimate or predict the severity of dust exposures with any such nicety.

In cases where men work for a number of years at different jobs with differing degrees of dustiness Bloomfield and DallaValle (17) compute exposures by averaging dustiness in these various jobs over the total period in question. In their anthracite coal dust study they found that computations so made agreed well with the results of the physical and x-ray examinations of the men. A typical example of their method of computing dust exposure is reproduced in table 2.

The advantage of these estimates lies in their simplicity and the fact that they have proven useful in correlating dustiness with physical examinations. The error in such calculations is that the effects of dust do not vary exactly, but only very approximately, with the dust concentration and with the exposure. Thus, Mavrogordato (18) writes that "Lesions of silicosis in a mild degree can be produced in an animal by 30 hr. exposure to intense dust clouds, and one is inclined to suspect that it is intermittent exposure to relatively dense clouds that is the deciding factor in producing the disease in susceptible human subjects." These momentary excesses of dustiness Mavrogordato named *dust floods.* Bloomfield and DallaValle's calculations of necessity ignore dust floods and use only figures of average dustiness.

The Value of Dust Samples

The purpose of dust sampling is to make possible the control or elimination of dustiness rather than to obtain a precise measure of dust concentration. Conditions may vary greatly almost from moment to moment and only occasionally are they reasonably constant during a working shift. In general, then, it is advisable to give the results of the final estimate with an indication of the expected variation. "Thus, as a means of classifying processes according to their respective health hazards, it appears to be unnecessary to arrange them in concentration groups closer than 100 per cent, *i.e.*, 0 to 5, 5 to 10, 10 to 20, 20 to 40, etc." (8). Such an arrangement is consistent with the few American data we now have on standards of dustiness and is in reasonable agreement with Mavrogordato's "figures of merit" as obtained by konimeter samples.

A great deal of time can be saved by ignoring samples which are obviously too dusty—it is as well to take the sample for a matter of record but it is absurd to work long over it if it is certain to be vastly in excess of the objective. Mavrogordato dismisses such samples with the laconic symbols "T.M.C." (too many to count).

TABLE 2

Example of Method Used in Determining an Employee's Total Dust Exposure*

Occupation	Years in occupation	Average dust concentration, millions per cubic foot	Millions of particle years per cubic foot
Slate picker (dry breaker)	2	380	760
Patcher (dry mine)	2	71	142
Mule driver (dry mine)	3	71	213
Miner's laborer (chamber)	3	480	1440
Miner (chamber mining)	15	480	7200
Section foreman	5	7	35
Totals	30		9790

$$\frac{\text{9790 millions of particle years per cubic foot}}{\text{30 years}} = \text{326 millions of particles per cubic foot}$$

* After Bloomfield and DallaValle.

On the other hand, it is well to have records which indicate that the environment is as clean as is desired. In our own experience the ignoring of such samples has raised difficulties in proving in court that adequate dust control had been enforced. There is no doubt whatever that, in the United States at least, dust samples now have a very definite place in depicting working conditions to compensation boards or to a court. Under the circumstances, it is very unwise in making surveys to ignore the clean places.

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Methods of Sampling

Dustiness is given gravimetrically if the dust is to be determined chemically and by counts if the chemical determination is especially difficult. Thus, lead is always recorded in milligrams per cubic meter but dust which may cause silicosis is given in particles per cubic foot or per cubic centimeter.

Sometimes one may wish to convert one set of readings into the other. If the dust particles are perfectly uniform and of definite shape such as spheres or cubes and of known composition the conversions can be made with precision. In such a case, it does not matter how dustiness is recorded. But in practice the dust particles are never uniform in size and rarely in composition. Conversions are, therefore, apt to be misleading. For practical work, 1 mg. of fine quartz as collected by the impinger contains 300 million particles (by the light-field counting technic).

A great deal of energy is being wasted in deciding which dust sampling method is best. The rapidity with which new methods are appearing, each claiming unusual points of merit, indicates that standardization is unlikely. An international agreement on a reference standard would be welcomed by all working in this field but, at present, such an agreement seems to be far off.

In the United States the impinger technic is most used, largely because our only extensive field data come from the Public Health Service whose workers favor this instrument. If one wishes to compare his results with those of the Public Health Service he must copy their technic. But copying the Public Health Service's technic for the sake of the legal prestige thus gained has its drawbacks. We know of one case where a gasoline motor-driven generator and electric pump mounted on a mine car and hauled by tractor, with three men in attendance, resulted in obtaining only four samples in one day.

In South Africa where dust sampling has been done on a scale far beyond anything attempted elsewhere the konimeter and sugar tube both have been used. In England great hopes for the new thermal precipitator have been advanced but the results published so far have added nothing significant to the data already available from methods which are less accurate. In Australia several different instruments including Owens' counter have been used while the results coming from Germany were obtained by filter methods and by a modification of Owens' counter.

In our own studies we use several different methods according to the problem. There is every reason to encourage rapid methods which are particularly applicable to routine control and to discourage the widespread use of the impinger technic except for occasional check-ups. The impinger has little to recommend it in control work while a light portable instrument, such as the konimeter, has already proven its value in practice.

Composition of Air-Floated Dusts

It is rarely that one meets exposures to pure silica; generally the dust is a mixture of which the original composition either is fixed, as in granite, or variable as in most foundry and mining operations. But the composition of the dust breathed from a mixture is seldom the same as that of the parent material.

If a dust arises from the grinding or comminution of a comparatively pure substance, such as beach sand, the resulting material must have substantially the same chemical and mineralogical analysis in all stages of particle subdivision. But if a complex material like granite is ground and the dust then scattered in the air, samples of different particle size will have very different composition.

Many examples of the changes in composition of air-borne dust can be found in the literature to prove these statements but it is interesting that the facts generally have been ignored. Thus, in this country, investigators frequently sample and count air-borne dust by the impinger technic and then for chemical and mineralogical analyses take samples of material which has settled on rafters which will have a quite different composition. To make bad matters worse, samples for mineralogical and chemical analysis usually have not been graded into various sizes.

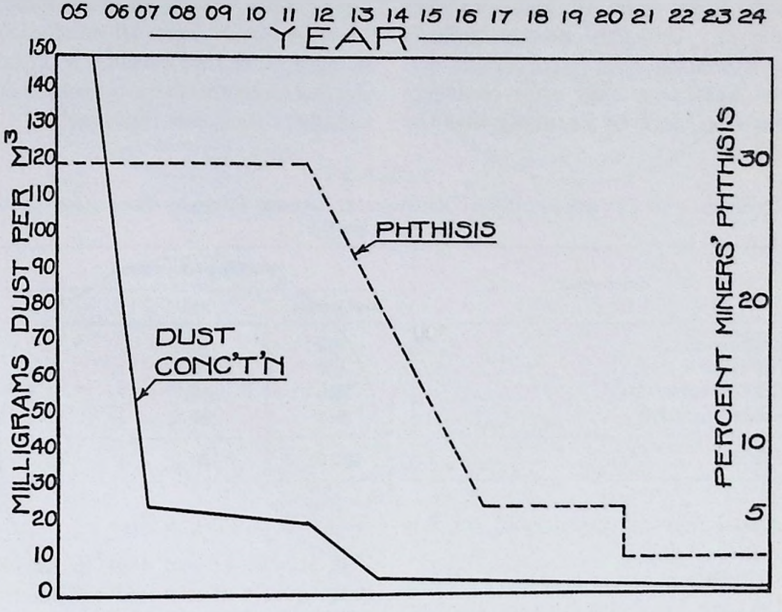


Fig. 2.—Dust control and silicosis in South African gold mines (adapted from Mavrogordato).

Jones (19) has given indisputable proof of the carelessness of which most of us have been guilty in recording the composition of air floated dusts. In support of Jones' contentions an interesting example is given by Drinker and Hatch (8) for foundry dusts. "A good molding sand is made up of about 80 per cent quartz in the shape of coarse particles; the bulk of the re-

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maining material is clay in the form of fine particles which coat the coarse quartz grains. The chemical composition of the finer fraction (say below 10 microns) of material in foundry sand is markedly different from the composition of the coarse fraction." Thus, the original material contains about 76 per cent quartz, while particles above 10 microns have 85 per cent quartz and those below 10 microns have only 19 per cent (see table 3). Under the present methods of estimating dust composition and dust hazards a large error obviously would be made by assuming that the original material represented the fine air floated dust.

TABLE 3

COMPOSITION OF COARSE AND FINE FRACTIONS OF UNUSED FOUNDRY SAND (CONTAINING NATURAL BOND)

CONSTITUENT	PERCENTAGE BY WEIGHT		
	Total sample	>10μ	<10μ
Combustible	2.3	0.7	12.7
HCl soluble	5.5	1.6	30.5
H_2SiF_6 soluble (clay)	16.0	12.7	37.5
Residue (quartz)	76.3	85.0	19.2
Total	100.0	100.0	100.0

Another example is given by Jones (19) from the South African "banket" —large crystals of quartz held together by fibrous sericite. In figure 3 are illustrated the changes in dust composition which he noted as the dust was allowed to settle, as it would in practice. Obviously, the quartz content decreases as the sericite increases. Jones remarks that "when a wall built of quartz boulders is pulled down, the bulk of the dust comes not from the quartz boulders but from the mortar."

It would be interesting to know what changes in the composition of Barre granite, of 35 per cent original quartz composition, and of various coal-silica mixtures take place on settlement in air. Obviously, changes will occur (probably great changes) but they have not been measured as yet although we have all welcomed the figures of reasonable dustiness suggested by the U. S. Public Health Service for the two industries in question, granite cutting and coal mining. Their analyses were all made from samples which had settled out on rafters, and no samples were separated into various particle size fractions.

Particle Size

It is well known that in silicotic lungs dust particles under 3 microns vastly outnumber those which are larger. It has been alleged that the respiratory mechanism, the lungs, and the phagocytes are mostly responsible for this size grading. However, it is easy to show that the size grading is done in the air before the dust is breathed and not later in the human body. That is, we find an excess of small particles in the lungs simply because that is the way that they occur in air. It is physically impossible for any but particles below 5 microns

to remain afloat in air long enough to be carried about by gentle air currents and to be inhaled. It is perfectly true that the alveoli are large enough to admit particles 100 or even 200 microns in length and that such particles are occasionally found in lungs (20). But the reason that they are found in lungs so infrequently is that they rarely remain in air more than momentarily. Bloomfield (21) has recorded hundreds of measurements of air floated dusts. His average sizes are all of the order of those found in lungs and in phagocytes.

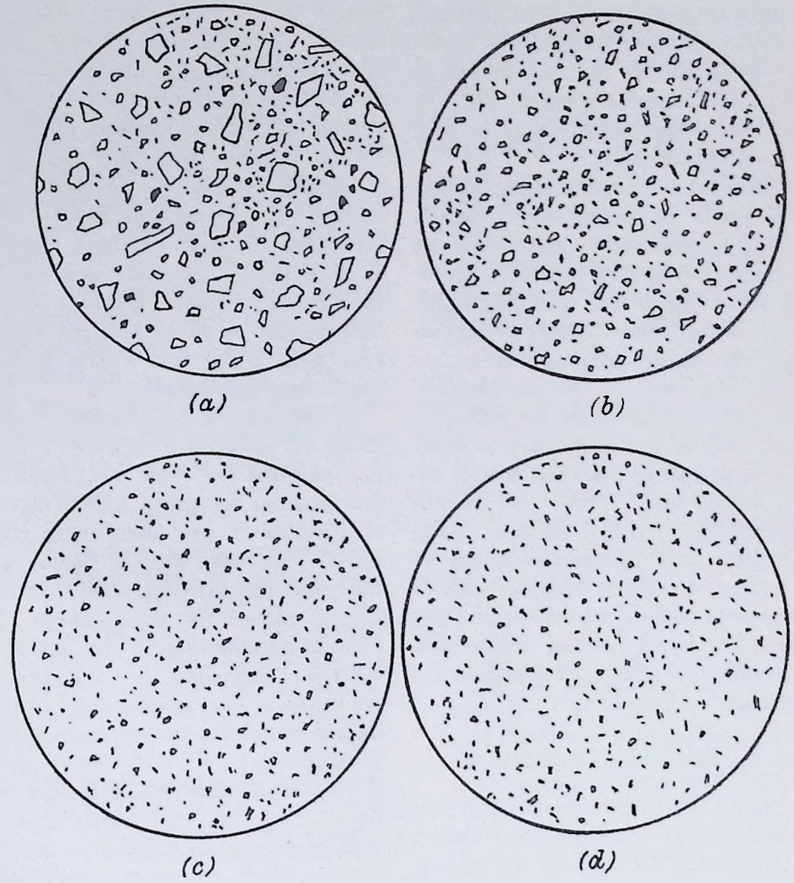


FIG. 3.—Sketches illustrating the increase in the ratio of fibers of sericite to quartz particles at different periods after blasting in a Witwatersrand gold mine. (*a*) about 15 minutes after blasting; (*b*) about 1 hour after blasting; (*c*) about 2½ hours after blasting; and (*d*) about 3 hours after blasting. (After Jones, courtesy Inst. Mining and Metallurgy.)

Gye and Kettle (22) showed that colloidal silica was extremely toxic and that it could initiate fibrosis. It

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is claimed occasionally that the damage done by quartz particles is due entirely to those which approach the colloidal in size. Usually particles possessing colloidal as distinguished from crystalloidal properties are considered to be less than 0.1 micron in size. All colloidal particles are so small that they can be measured only ultra-microscopically.

There is no evidence indicating that appreciable or significant quantities of ultra-microscopic quartz can be made by any known process of grinding or comminution, including blasting. In fact, the difficulty of preparing even small specimens of quartz below 0.5 microns is considerable. Furthermore, there are no published data indicating the relative potency of quartz particles in various sizes below 3 microns. Under the circumstances, then, there is no good reason to blame colloidal particles as the initiators of the silicotic nodule when it has been demonstrated again and again that such nodules can be produced by particles approximating the common bacteria in size.

Standards of Dustiness

Under one name or another the plant or mine manager always wants an objective for his dust control program. It serves no useful purpose to evade the issue on the ground that precise figures are not available. Probably they never will be. The practical man argues, very properly, that if dust is the cause of silicosis there must be some degree of dustiness or of air cleanliness which is safe. Having been told that silicosis is a disease caused by breathing silica, the practical operating man naturally expects of the physician or hygienist some objective of air cleanliness, call it by whatever name one likes.

In this country the U. S. Public Health Service studies have furnished the only published data we have from which we may suggest dust standards. In the case of Barre granite it was pointed out that a dustiness of 10–20 million particles per cubic foot was reasonably certain not to cause disability. The coarse dust, in this case, contained about 35 per cent quartz. In their recent anthracite coal study the Public Health Service found that counts of 50 million per cubic foot, with 5 per cent quartz in the coarse dust, seemed safe.

In the case of pure quartz Cummings (4) suggests a figure of 5 million particles per cubic foot which is not far from the South African figure of 1 milligram per cubic meter (figure 3). We have then 50 million for dust with less than 5 per cent quartz and 5 million for pure quartz. It is very questionable if one has any right to interpolate for the quartz percentages between 50 and 5 but the figures certainly invite such interpolation.

These standards do not answer the question of the plant which handles dust of no proven pulmonary significance. What standard should the manager of such a plant take as his objective or need he take any precautions at all? We cannot give him any standards but we can only suggest that he investigate one of the many plants which has reduced dustiness without waiting for any physiological justification. Generally the manager and workmen of a clean plant will uphold eloquently the advantages of dust control.

It is only in South Africa that dustiness and silicosis have been correlated routinely over a considerable period. There they realized at the outset that dustiness would not be controlled properly unless measured and recorded routinely. Concerning the results of their procedure, Irvine (23), Chairman of the Miners' Phthisis Medical Bureau in 1934, stated that "No 'New Rand Miner' who has entered the industry since August, 1923, i.e. 10½ years ago, has as yet contracted silicosis. These facts demonstrate that the engineering and medical measures which have been directed against silicosis have achieved a very significant degree of success." It would be hard to devise a more eloquent or complete proof of the advantage of dust sampling and of dust standards.

Summary

The various pneumoconioses and their causative agents are discussed. Silicosis and asbestos are definite diseases; in anthraco-silicosis and various silicatoses one sees modifications of normal lung conditions. The effects of carbon, or carbonates, of gypsum and of iron oxides are also discussed.

Methods of estimating dust exposures of a workman includes the taking of dust samples from the work place and interpreting the results during the man's total period of exposure. Errors which have been made from estimating the composition of dust from samples which have settled upon rafters instead of using samples taken from the air, are emphasized.

Permissible dust concentrations need not exceed 50 million particles per cubic foot for dust with very low quartz content or 5 million for pure quartz. In defense of the use of standards of dustiness the experience in South Africa where such standards have been applied successfully for many years is cited.

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CLINICAL ASPECTS, DIAGNOSIS AND TREATMENT OF PNEUMOCONIOSIS*

W. Irving Clark

THERE are two types of dust which may cause some degree of pneumoconiosis; these have been termed inert and active dusts. The determination as to whether or not a dust is active or inert has been reached by pathological examination of the lungs of those dying of pneumoconiosis, by clinical studies, especially x-ray, and by animal experimentation.

Review of Animal Experiments

The study by animal experimentation has been particularly valuable as it provides a method of determining the effect of a given dust upon the living tissues and a comparison with the effect of similar exposure to other dusts. The animals used have been white rats, rabbits, guinea pigs, monkeys, fowl, cats, and, for some experiments, tadpoles and fish (1, p. 44).

The methods used have been:

1. *Dusting.*—This consists in exposing the experimental animal to a "high concentration of dust (up to 10 or 12 billion particles per cu. ft. of air, dark-field) to produce maximum effects in short time." This method might be called the normal breathing method.

2. *Injection of suspensions of dusts.*—This consists in injecting suspensions of dusts into various parts of animals to detect the capacities of different dusts to provoke reaction in the tissues. Results are obtained more rapidly than by dusting but do not correctly show the natural development of disease in the lungs.

The dust suspensions may be introduced into the animal by:

1. Intratracheal or bronchoscopic injections.
2. Intraperitoneal injections (Miller-Sayers method (2)).
3. Subcutaneous injections.
4. Intravenous injections—showing the effects of the dust on the extra-pulmonary viscera.
5. Intracutaneous injections—for gross reaction.
6. Intra-lymphatic injections—for reaction of lymph node cells (3).

All animals tested either by dusting or by injection showed a tissue reaction to silica. This reaction was typified by the formation of fibrotic nodules except in the cold blooded animals where there was necrosis followed by some fibrosis. Changes in susceptibility of animals to tuberculosis as a result of the effects of various dusts have also been studied, and the activating effect of silica demonstrated.

The effect of the inert dusts upon the animal tissue was found similar to that of any foreign body. There was reactionary enlargement of lymphatic nodes, slight fibrotic reaction immediately surrounding the injected dust

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but no continuation of this fibrosis and no formation of nodules. The exact pathology noted was scattered or clumped cells containing the inert dust lying in the alveoli, slight inflammation or no inflammation of the adjacent walls, a slow accumulation of dust-containing cells in the lymph nodes with enlargement of the nodes, and a deposition of dust about the lymphatics of the lung or pleura. When inert substances were injected intravenously, intraperitoneally or subcutaneously, there was no reaction beyond that of any foreign body (2).

As a result of such experiments which have been repeated in many parts of the world, it is believed that of all suspected dusts only silica has a specific action upon animal tissue which results in fibrotic nodulation. Asbestos fibres produce a peculiar reaction in the lung which is different from silica. Following the inhalation of asbestos dust there are formed "cuffs of more dense connective tissue about the terminal bronchioles" (1, p. 46). Contraction and collapse of the alveoli supplied by the affected bronchioles occurs. This is followed by induration and fibrosis of the collapsed alveoli, presenting the picture of diffuse fibrosis of parts of the affected lung with persistent foci of normal air spaces.

Silicosis

The Committee on Pneumoconiosis and the Committee on Standards of the American Public Health Association (4) adopted in 1932 the following definition: "Silicosis is a disease due to breathing air containing silica (SiO_2) characterized anatomically by generalized fibrotic changes and the development of miliary nodulation in both lungs, and clinically by shortness of breath, decreased chest expansion, lessened capacity for work, absence of fever, increased susceptibility to tuberculosis, (some or all of which symptoms may be present) and by characteristic x-ray findings."

I. Pathology of Silicosis

Dust particles after reaching the lung alveoli may remain quiescent for a considerable period as is the case with the inert dusts, or they may penetrate the lymph spaces in small numbers. The bulk, however, are phagocytosed, that is engulfed, by wandering endothelial cells which at first, lining the wall of the alveolus, become detached, and then, having taken up the dust particles, pass by ameboid movement through the walls of the alveolus into the lymph spaces. The cells now slowly migrate to the minute lymph islands which guard the entrance to the small lymphatic vessels, pass through these, thence to the lymph vessels, and finally are caught by the large group of lymphatic glands which form part of the hilus or root of the lung. These wandering cells are commonly called dust cells.

The piling up of cells and the reaction of the glands blocks the free circulation of lymph so that the dust cells tend to move slowly toward the lung roots, blocking the lymph vessels and later the minute lymph masses which guard the entrance to the lymph vessels. The dust cells which are killed by the silica disintegrate and free the silica dust for further injury to the neighboring tissues. The reaction of the tissues to silica is the production of fibrous tissue. Thus fibrous tissue forms along the lymphatic vessels which accompany the blood vessels of the lung, invades the septa between the lobes, and spreads its shoots into the lung tissue itself. The minute masses of lymphatic tissue become fibrotic nodules and these, as time goes on, increase in number to such an extent that, combined with the fibrous tissue of the former lymph channels, conglomerate masses of fibrous tissue are formed, blocking off large portions of the lungs. The blocking of the lymph flow toward the hilus increases the spread of dust cells to the pleura and eventually leads to fibrosis of this structure.

The fibrotic nodule is characteristic of silicosis. It is a small, discrete hyaline mass surrounded by apparently normal lung. It does not exceed 6 mm. in diameter. "Occasionally some of these nodules may show microscopic foci of central necrosis" (1, p. 146).

This increasing amount of fibrous tissue obliterates the alveoli and provokes a compensatory enlargement of the alveoli elsewhere. This condition of enlargement is called emphysema. As the amount of air space is insufficient to permit the normal oxygen-carbon dioxide interchange of the lungs required by the body, the effort of the heart to pump blood fast enough may promote enlargement of that vital organ. This, however, if it occurs, is a terminal condition infrequently observed, as the patient usually develops pulmonary tuberculosis or dies of an intercurrent disease before this stage is reached. It must be remembered that only one-fourth of one lung is necessary for life, and that the amount of fibrosis must be enormous to restrict the lung capacity to this extent.

II. Symptoms

The effect of the underlying pathology upon the workman is at first too slight to be detected by physical examination and the worker shows no symptoms. While there is a pathological condition present, it is to all intents and purposes harmless, in that if it does not progress rapidly it may not provoke symptoms during a worker's life, or only during the last decade. Even respiratory disease of another nature, such as bronchitis or even pneumonia, may occur with recovery during this period.

As the condition progresses, however, more and more of the lung tissue is converted into fibrous tissue, and the patient begins to show certain symptoms. He complains of shortness of breath when he goes up-hill and says that he notices his heart beat on exertion. He also mentions a cough which is at first dry and infrequent, but which gradually becomes moist and frequent. With the cough he raises scanty, stringy sputum which is sometimes discolored. The sputum is never large in amount unless he catches cold and develops bronchitis. At this stage an attack of bronchitis does not disappear but becomes chronic. During this period the silicotic may complain of pain in the chest due to pleurisy or to epigastric pain, anorexia,

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and morning vomiting. While he is able to work, the victim cannot carry on his usual tasks and seeks lighter work.

Slowly the shortness of breath increases, the patient has poor lung expansion, and his color becomes pale and his lips bluish.

At this stage pulmonary tuberculosis is a frequent complication. When this occurs, the cough becomes more severe and continuous, the sputum free and moist, areas of dulness to percussion are noted, râles are heard over the chest on physical examination, and cavitation may be detected. Tubercle bacilli may or may not be present in the sputum. Many of these cases are able to carry on light work for years before finally succumbing. Hemorrhage from the lungs occasionally occurs.

During the early stages when perivascular, peribronchial, lymph node reaction is present there are only indefinite physical signs. Irvine (5) describes these as follows:

> 1. A certain lack of elasticity of the chest wall during movements of respiration together with
> 2. A somewhat reduced air entry, and
> 3. A characteristic alteration of the inspiratory murmur from the normal vesicular character to a higher pitched or "harshened," thinned and commonly somewhat shortened type, the expiratory murmur although somewhat prolonged remaining fainter than the inspiratory.

There is little change in these signs as the disease progresses. "The percussion note is somewhat flattened without being definitely dull especially posteriorly. Breath sounds have more definite characteristic thinning, the expiration being longer and fainter" (6). With the advent of tuberculosis the physical signs are those of that disease.

III. X-ray

The most important evidence of silicosis is obtained by x-ray. While a flat film gives valuable information, an accurate diagnosis requires a stereoscopic set of films. In many cases a lateral film is desirable in order to determine the amount of emphysema present and the size of the heart. Fluoroscopic examination is of interest in cases where diaphragmatic adhesions are suspected or shown on the film.

The old classification into first, second and third stages has been recently changed to a more descriptive nomenclature. The conditions noted on the film are now called:

1. Stage of perivascular, peribronchial, lymph node proliferation. Irregular exaggeration of linear markings.
2. Stage of nodulation.
3. Stage of fibrosis with conglomerate masses.
4. Any of above stages complicated by shadows characteristic of tuberculosis.

The first is not considered as diagnostic of silicosis as it may occur in persons who are in good health or in a number of pathological conditions which have nothing to do with silicosis.

The stage of nodulation is pathognomonic of silicosis but may be confused with films of miliary tuberculosis.

The stage of fibrosis with conglomerate masses may be confused with fibroid phthisis.

IV. Diagnosis

Diagnosis is made upon:

1. Occupational history with estimated length of exposure, quality of dust and quantity of dust.
2. Physical examination.
3. X-ray examination.
4. Presence or absence of tuberculosis as a complication.

Of these measures the first and third are most important. Probably the most difficult thing to decide is whether or not tuberculosis is present. Absence of fever and maintenance of weight, with absence of physical signs suggesting active inflammation in the chest, is indicative of simple silicosis.

The absence of tubercle bacilli from the sputum is inconclusive, as many cases of silico-tuberculosis fail to show bacilli in the sputum.

V. Progress

Silicosis once established in the lung has a strong tendency to progress. This appears to be owing to the toxic properties of the silica particle. What causes this toxic action is still in doubt. "Experiments and human pathological material indicate that in high concentrations silica is toxic and kills tissue; prolonged action of lower concentrations cause proliferation and fibrosis" (1, p. 46).

In spite of the fact that quartz is generally recognized as relatively insoluble, there is great rapidity of development of body reactions to silica. "Possibly unexplored properties of silica, electrical charge, adsorption etc., are concerned" (1, p. 48). This progressive tendency has been noted by Irvine, Böhme, Russell and others (1, p. 28).

The question is not what is the present condition of the silicotic, but how rapidly it will advance and how far. This is a serious problem in industry, for a worker having no symptoms and an early stage pathology by x-ray, may develop a disabling silicosis or a complicating tuberculosis. It is, therefore, possible for a worker to contract his disease while working for one employer and to develop symptoms many years later while working for another. If the work he is doing for the second employer involves exposure to an inert dust the employer may have difficulty in proving that this was not the cause of disability.

One of the striking differences between the effects of the inert dusts and silica dust is the lack of progress of pathology in the former as compared with the latter. Böhme (7) found that silicosis progressed after removal from exposure in 20 per cent of the cases diagnosed as having silicosis grade 1, in 40 per cent of the cases in grade 2 and in practically all the cases in grade 3. The experience of the State of Wisconsin, however, suggests that silicosis detected at an early stage in many cases will not progress if the worker is transferred to non-dusty work (8) though the reports of Watkins-Pitchford (9) and Britton and Head (10) make this somewhat doubtful.

Infection may play a part in the development. In fact, it is the frequent and serious complication of silicosis, and of the common infections, pulmonary tuberculosis is by far the most serious.

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Tuberculosis may develop early or late in the disease. In those who have an inactive focus in the lung, the silica dust may change the condition to one of activity, or in cases of well-developed silicosis, tuberculosis may be superimposed upon the silicotic fibrosis.

Thus Kettle writes, "harmful dusts if inhaled into the lung may excite to activity a latent tuberculosis infection; they may exaggerate an active tuberculosis lesion or a coincident infection; and they may render the lung less able to cope with a superimposed infection" (11).

The course of silicosis with a secondary tuberculosis is usually slow and without the usual symptoms of intoxication and may be carried for years without serious impairment of working capacity.

While tuberculosis is the most frequent complication and cause of death, other infections do occur. On the Rand pneumonia is a common cause of disability and death. Pope and Zacks found pneumonia occurring with great frequency among foundry workers in Massachusetts. Proske and Sayers have confirmed Cummings' discovery of fuso-spirochetal organisms as a cause of infection among miners in Picher, while chronic bronchitis with asthma is fairly common (12, p. 47).

Collis and Yule (13) compared the mortality experience of an occupational group exposed to silica dust with that of the general population, and with that of an occupational group exposed to dust not containing silica. As a result of the study, they concluded that silica is a body poison like lead. Even though it exerts its primary injurious effects on the respiratory tract, the silica slowly invades the body, involving the circulatory system, the nervous system, the digestive organs, the kidneys and liver, and eventually causes death through its harmful effect upon one or another of these organs.

Asbestosis

"Asbestosis is a pneumoconiosis caused by the inhalation of asbestos dust. It is distinct from silicosis both in its pathology and clinically. Asbestos is a hydrated magnesium silicate containing no free silica but about 44 per cent of combined silica, 43 per cent magnesium, nearly 13 per cent of water and traces of iron and nickel" (14).

I. Pathology of Asbestosis

Asbestos dust differs from other inhalable dusts in that it exists in thread-like fibres in which the diameter may be very small (5 microns or less) but which may be many microns in length.

These dust fibres do not appear to enter the alveoli. They are stopped at the neck of the alveolus where they are phagocytosed or penetrate the tissues. Acting specifically or merely as a foreign body they become surrounded first by mononuclear phagocytes, later by giant cells and last by fibrous tissue. There is no migration in dust cells to the lymphatics and lymph nodes as is seen in silicosis. The newly formed fibrous tissue contracts, constricting the neck of the alveolus so that no air can enter. Collapse of the alveolus follows and subsequent fibrosis.

In this way the lower parts of the lungs are filled with interstitial fibrosis and the air space markedly diminished. A compensatory emphysema may occur in the upper part of the lungs. Thickening of the pleura over the lower half of the chest is almost always present. Tuberculosis as a complicating factor is not common.

The asbestos fibre after it has become fixed at the neck of the alveolus frequently develops into a "curious body," the asbestosis body of Cooke (15). This is a long, narrow, cylindrical body, golden yellow and translucent, often with rounded ends like a dumbbell. These asbestosis bodies are found on autopsy and occasionally in the sputum. As similar bodies may occur in lungs not exposed to asbestos dust, the finding of these bodies is not diagnostic of asbestosis unless accompanied by a definite history of exposure to asbestos dust.

II. Symptoms of Asbestosis

The symptoms of asbestosis, like those of silicosis, are cough and dyspnea. With the cough there is sputum which may or may not contain asbestosis bodies. Hemoptysis is rare. There is loss of weight in the advanced cases, and marked reduction in the vital capacity and in chest expansion. The patient's face has an "earthy" look.

In advanced cases the dyspnea is out of proportion to the physical signs, being very severe, and is accompanied by blueness of the lips and occasionally by clubbing of the fingers. The fingers frequently show "asbestos corns" from the penetration and irritation of fine spicules of asbestos which are detached from the asbestos in handling.

III. Physical Examination

The patient, if an advanced case, shows loss of weight. The chest is emphysematous, and respiration is shallow, expansion being frequently less than 1 inch. The percussion note is one of dull tympany but with no definite dullness. The breath sounds are distant and expiration prolonged. The heart is normal in size, but lateral x-ray may show an anteroposterior enlargement.

IV. X-ray

This shows a fine mottling of a "ground glass" quality over the lower half of the chest. There is often an obliteration of the costophrenic angle and pleural thickening, shown particularly in the interlobular pleural on the right. The lateral view may show well-marked compensatory emphysema. A spot of tuberculosis at either apex is occasional but rare.

Still later in the course of the disease the appearance is that of a very fine stippling that obliterates most of the natural markings. The pleural shadow is definitely thickened. In some of the advanced cases the heart is enlarged and radiating from it into the lung fields is a series of heavy fibrous bands. This picture has been referred to as "porcupine heart."

Anthraco-Silicosis

This disease occurs among hard coal miners and is commonly known as miners' asthma. It is caused by the inhalation of large amounts of dust consisting of a mixture of anthracite coal and quartz, the quartz coming from the rock in which the coal is imbedded.

The pathology consists of a clogging of the lymph spaces with carbon particles which invade the upper lobes especially. Accompanying this is a linear or nodular fibrosis due to the

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inhaled silica particles. When large areas of the lung are involved there is a compensatory emphysema.

I. Symptoms of Anthraco-Silicosis

The cardinal symptom of anthraco-silicosis is shortness of breath, which explains the term "miners' asthma." With this there is cough and sputum. The cough may be dry and the sputum scanty but if infection in the form of bronchitis is present, the sputum is muco-purulent and colored with coal dust. As in silicosis, tuberculosis is a frequent complication.

The physical signs are similar to those of simple silicosis or of silicosis with infection. Diagnosis is made largely by x-ray which gives a picture very similar to that of simple silicosis. The U. S. Public Health study on this problem (16) suggests that the true lung injury is due to the silica inhaled rather than to the carbon particles. Carbon has been found to be harmless when inhaled in the form of smoke and by animal experiment.

Inert Dusts

I. Pathology

The inert dusts are relatively harmless. They may increase the frequency of respiratory disease when inhaled in large amounts, but this has not as yet been proved statistically. Workers inhaling these dusts develop a mild fibrosis which follows the course of the lymphatics along the broncho-arterial tree and is accompanied by enlargement of the trachial lymph nodes. This reaction which is very slow, after a number of years may progress to a moderate amount of interstitial thickening. The pleura may be thickened and there may be diaphragmatic adhesions. These later manifestations only appear after many years of constant exposure to a high concentration of dust.

II. Symptoms Caused by Inert Dusts

The symptoms of the pneumoconiosis of inert dusts are negligible. If the exposure has been long and the dust discharge abnormally heavy, there may be some dyspnea on moderate working. This is not usually severe enough to interfere with the worker's normal activities and may be caused by degenerative changes of the heart due to advancing age, as much as to the pathology of the lung. There is no evidence that the inert dusts, unless mixed with an active dust, can produce disability.

III. X-ray Picture, Physical Examination and Diagnosis

The x-ray picture is that of perivascular, peribronchial, lymph node thickening which does not progress. Some diaphragmatic adhesions may show in cases with long exposure to heavy concentrations of dust. Serial pictures fail to show nodulation or the massive areas of fibrosis which characterize silicosis.

The physical examination of those exposed to inert dusts is usually negative. In a few cases where there has been prolonged exposure to great quantities of dust there may be some restriction of chest expansion and signs of emphysema.

The diagnosis is made by physical examination, occupational history, and x-ray.

A typical inert dust is that of the artificial abrasive, aluminum oxide. This material is widely used in grinding wheels and for polishing, sand paper, etc. In the year 1929 over 71,000 tons were sold or used in plants in the United States and Canada (17).

The use of aluminum oxide creates a certain amount of dust. The effect of this dust has been studied by Clark (18) and Simmons clinically and by Gardner (19) on the experimental animal.

In a factory where artificial abrasives and grinding wheels are manufactured, Clark has studied the effects of inhalation of this substance for 25 years. He believes that in factories which provide proper dust removal, the continuous inhalation of artificial abrasive dust extending over many years of work does not produce the symptoms or present the x-ray findings of crippling fibrosis of the lung; that the number of cases of pulmonary tuberculosis does not greatly exceed the number normally present in the community; and that workers using wheels made of artificial abrasive or using this substance for polishing or other purposes run but slight risk of pneumoconiosis if excessive dust is removed by exhaust systems.

In spite of the fact that clinical and experimental evidence points to the relative harmlessness of the inert dusts, an effort should be made to keep the dust count around 20 million particles per cubic foot of air. This will make working conditions much more satisfactory to the worker and will reduce the hazard of respiratory disease.

Treatment of Pneumoconiosis

The only method of treatment of the pneumoconioses is prevention. Dust in quantity must be eliminated from industry wherever possible, and in most operations this is feasible. In a few where it is not, protective devices such as respirators or positive air pressure helmets must be used by the worker.

When a worker is found upon examination to have lung fibrosis it is wise to keep him at work in a non-dusty department. While his lung condition, if it is due to silica or to asbestos dust, will progress slowly, many years of profitable work are before him unless infection intervenes. As dyspnea increases, lighter work must be provided. If tuberculosis complicates the picture and the patient develops tubercle bacilli in the sputum, he must be isolated from other workers, but even then may be able to do light outdoor work. In more severe cases where there is temperature, all work must, of course, be stopped.

Exposure

The rapidity of development of silicosis and of asbestosis depends upon the amount of dust inhaled and the percentage of free silica (SiO_2) or of asbestos in the dust.

In men exposed to heavy dust clouds with a high concentration of silica, silicosis has developed in as little as 2 years, but under the usual exposures of mining and of industry where the free silica usually varies from 13 to 35 per cent, the development is slow and symptoms do not appear for 15 or more years.

In the case of asbestosis, the development of symptoms is more rapid, 5 to 8 years being the usual required time of exposure.

Efforts are now being made to correlate the exposure with the pathology, as shown by x-ray, and with the physi-

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cal signs. In other words, an effort is being made to determine standards of permissible amounts of dust in the working air for both the inert and the harmful dusts. Such standards will be of the greatest value to industry in its effort to reduce its dust hazard to a minimum.

Epidemiology

I. Silicosis

The danger of inhaling inorganic dust has been recognized for centuries, but careful study of the effect of such inhalation was first instituted in South Africa and culminated in the International Conference on Silicosis held in Johannesberg in 1930.

In 1933 Van Siclen (20) published an estimate of the health hazard from dust in the mines and allied industries of the United States. In his study he found that of 7722 men examined in the Tri-State zinc-lead district of southwest Missouri in 1927–28, 5704 were classified as negative for lung disease, 1362 had signs of first stage silicosis, 253 had second stage, and 32 had third stage. The remainder showed signs of tuberculosis with or without silicosis.

In Butte mines (Montana), of 1018 miners 42.4 per cent showed definite signs of dust injury to the lungs.

In the Lead-Deadwood district mines in South Dakota the sickness rates per thousand for respiratory disease was two and a half times greater than in general industry, while the tuberculosis rate was almost ten times greater.

Grouping the various industries studied, Van Siclen found that in metal mining about 62,228 workers were exposed while among those engaged in non-metallic mining or quarrying, 23,665 had a respiratory hazard.

The prevalence of silicosis in the general population was studied by Lanza and Vane in 1934 (21). They cite the following occupations as constituting a definite silicosis hazard:

1. Anthracite-coal and metal mining, quarrying.
2. Certain manufacturing industries such as potteries, glass works, and plants manufacturing granite, sandblasting.
3. Construction work—rock drilling, handling sand and gravel.

Their rough estimate of the number of workers exposed to silica dust to a harmful degree in the United States is upward of 500,000.

A careful study of 2,600 granite and foundry workers has recently been made by Pope and Zacks (22) in which correlation of the duration of exposure to dust and the incidence of silicosis was determined. Their conclusions are as follows:

1. In representative groups of both granite and foundry workers in Massachusetts the frequency of silicosis and of silicosis with tuberculosis was found to be positively correlated with the duration of exposure to dusts containing free silica and to concentration of such dusts in the occupational environment.
2. Among the granite workers examined silicosis alone was found in 15.2 per cent and silicosis complicated with tuberculosis in 7.6 per cent.
3. Tuberculosis is the cause of death in over one-third of all granite workers, a proportionate mortality three times that in foundry workers and four times that in all males of 20 years and over.

In 1907 Summons of the Miners' Phthisis Committee of Australia reported that gold miners there who contracted silicosis died of tuberculosis

(23). "The initial studies of silicosis by workers in South Africa were started by a demand made upon health authorities to determine the cause of the excessive mortality from tuberculosis which was increasing at a rapid rate among the miners there."

Russell found an excessive number of deaths from tuberculosis in his Barre, Vermont study of the health of granite workers (24) and Gardner (25) believes that at least 75 per cent of those who develop silicosis contract tuberculosis.

TABLE 1

Silicosis and Asbestosis in Great Britain, through 1934*

	Number of deaths	Average age at death	Duration of employment in years		
			Maximum	Minimum	Average
Silicosis	261	55.4	60	2.3	34.8
Silicosis with tuberculosis	315	52.5	67	2.0	32.0
Asbestosis	41	41.0	27	1.5	12.9
Asbestosis with tuberculosis	26	38.0	29	0.8	9.9

* J. C. Bridge: Report of Chief Inspector of Factories and Workshops, London, 1934, chapter 3.

II. Incidence of Asbestosis

The health hazard of asbestos dust has only been recently recognized. The Regulations for the Asbestos Industry in England have been in force for only 4 years. Bridge (26) says: "Over a number of years" (number not specified) "the deaths from asbestosis reported to the Department and compiled in 1934 numbered 41 while those from asbestos and tuberculosis numbered 26". (See Table 1.) Wood and Gloyne began their studies on pulmonary asbestosis in 1928 and published results of the study of 100 cases in 1934 (27). Most of these cases worked in the same factory. According to Wood, "pulmonary tuberculosis is so often associated with asbestosis that it seems probable that the association is more than accidental".

Gardner (1, p. 51) says that many autopsies show a combination of tuberculosis with asbestosis and other silicate dusts but "that surveys of living American workmen show no great excess of this infection", while Lanza (28) in a study of dust conditions in asbestos mines and mills in Canada and in fabricating plants along the Atlantic seaboard found in his study of 126 workers by x-ray that 67 were diagnosed as having asbestosis in some form, but that no predisposition to tuberculosis due to asbestos dust was indicated. Clark and Drinker (29) in summing up present beliefs say that while a secondary tubercular infection is not uncommon in asbestosis, it is far less frequent as a complication than in silicosis.

Summary

1. Pneumoconiosis is a disease resulting from the inhalation of inorganic dust.

2. The two pneumoconioses which produce disability are silicosis and asbestosis.

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3. The pathology of silicosis is characterized by the presence of fibrotic nodules scattered through both lungs, and that of asbestosis is characterized by an interstitial fibrosis involving the lower half of both lungs.

4. The symptoms of silicosis and asbestosis are similar, the most important being dyspnea.

5. The most common complication is pulmonary tuberculosis which in silicosis is a frequent cause of death.

6. The diagnosis of both silicosis and asbestosis is made largely by a correlation of history and symptoms with the x-ray examination.

7. The treatment of pneumoconiosis is preventive and symptomatic.

8. The course of silicosis and of asbestosis is slow but eventually leads to incapacity due either to the disease itself or to a complication, frequently chronic pulmonary tuberculosis.

9. The number of workers exposed to harmful mineral dusts in mining and in industry in the United States has been estimated as 500,000.

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DESIGN OF EXHAUST HOODS FOR DUST-CONTROL SYSTEMS*

THEODORE HATCH

A SYSTEM of local exhaust ventilation for the control of industrial atmospheric contaminants—dusts, fumes, vapors and gases—consists of four principal parts: exhaust hoods, piping, air-cleaning plant and source of suction. Each part must be selected to perform its required function with respect to the successful operation of the system as a whole. Of the four, however, the exhaust hood undoubtedly demands the most careful design since the degree of control secured depends more upon the shape and location of the hood and the rate of air flow through it than upon any other factor.

The selection of exhaust hoods, their location in relation to the point of dust generation, and the determination of the required rate of air flow through the hood to effect adequate control have been almost entirely empirical matters. Certain simple rules of design have been employed that arose out of the experience in a few industries, notably woodworking and grinding. In recent years, however, the industrial dust problem has assumed hygienic and economic aspects entirely beyond the limitations of those industries in which the dust has only a nuisance value. Dust control measures must be applied in many plants where conditions bear very little relation to those encountered in industries such as the two mentioned above. The cost of occupational disease compensation justifies the use of the most basic engineering methods of investigation and design of control equipment.

FUNDAMENTALS

One simple way to maintain a safe concentration of dust in a confined space housing dust-generating processes is to introduce enough clean air from outside to dilute the concentration down to the safe level. Thus, by the most elementary calculations, if 10^{12} dust particles are escaping into the air each minute† and if 10^7 particles per cubic foot of air is the permissible concentration, then $10^{12} \div 10^7 = 10^5$ cubic feet of clean air must be introduced per minute for each machine. This is a minimum ventilating rate which assumes perfect mixing of the dusty and clean air and is obviously impractical. Improvement is gained by introducing the clean air at or near the dust sources with exhaust outlets located so as to sweep the contaminated air away. This is the crudest kind of local ventilation and is objectionable chiefly because the workers are exposed to undesirable drafts.

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† This number of particles smaller than 1.0 micron are produced by a rock drill during one minute of operation.

True local exhaust ventilation has for its purpose the control of contamination at its source. Its function is to create sufficient air movement toward the exhaust opening to counteract the tendency of the dust to escape to the surrounding atmosphere and proper hood design demands that this be accomplished with the least possible air flow and power consumption.

Dispersion of dust into the atmosphere. Dust particles, generated by whatever means, require energy for their dispersion from the point of origin into the surrounding atmosphere. Physically, this is provided in only two ways: (1) Dynamic projection due to the kinetic energy of the particles themselves, imparted to them during their formation and (2) Dispersion by means of air currents created by the operation of the machine or otherwise set up in the zone of contamination.

The counter forces set up by the exhaust hood for the purpose of preventing the dispersion of the dust must be directed toward two different forms of energy. It is clear, therefore, that proper hood design depends upon an understanding of the relative magnitude and the manner in which these forces act. The first lends itself to approximate mathematical analysis which yields certain important conclusions:

A particle with a mass M thrown off with an initial velocity V_0 possesses the kinetic energy

$$KE = \int_0^{V_0} MV dV = MV_0^2$$

Its motion through still air is resisted by a frictional force which varies with the type of motion according to the general equation

$$R = Ka^n \rho \gamma^{(2-n)} V^n$$

where R = resisting force,
a = particle radius,
σ = particle density,
ρ = air density,
μ = air viscosity,
γ = kinematic viscosity of the air = μ/ρ,
n = 1.0 for streamline motion and 2.0 per turbulent motion,
K = 6π for the streamline region and 1.35 for turbulent motion (assuming spherical particles).

Neglecting the force of gravity, the projected particle will travel along a straight path with decreasing velocity until at a certain distance S the kinetic energy will be destroyed, i.e., the particle velocity will become zero. Thus:

$$\int_{V_0}^{0} RdS = -M \int_{V_0}^{0} VdV$$

Substituting the two values of R and integrating, one obtains:

$$V = V_0 - \frac{9}{2} \cdot \frac{\mu}{\sigma} \cdot \frac{S}{a^2} \text{ (streamline)} \ldots . \text{ I}$$

$$V = V_0 e^{\left(-\frac{1}{3} \cdot \frac{\rho}{\sigma} \cdot \frac{S}{a}\right)} \text{ (turbulent)} \ldots \text{II}$$

When the particle is projected into an opposing air current rather than into still air, the value of S is reduced since

$$R = f(V_a + V_p)$$

whereas KE remains a function of V_p alone (V_a and V_p are the opposed velocities of the air and particle respectively). Assuming V_a constant and $n = 2.0$ and substituting the new

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value of R in the equation, the following relationship results:

$$\frac{-k\rho}{4/3\pi a\sigma}\int_0^S dS = \int_{V_0}^{V}\frac{V_p\,d\,V_p}{(V_p+V_a)^2}$$

whence

$$\frac{\rho}{3\sigma}\cdot\frac{S}{a} = \log_e\left(\frac{V_a+V_0}{V_a}\right) = \frac{V_0}{V_a+V_0} \quad ..\text{III}$$

Examples.

I. Assume: $a = 5\mu$; $\sigma = 2.65$; $\mu = 18.1 \times 10^{-6}$; $V_0 = 1000$ cm./sec.
Determine S when $V = 0$.
Substituting in equation I: $S = 0.8$ cm.

II. Assume: $a = 0.5$ mm.; $\sigma = 2.65$; $\rho = 1.2 \times 10^{-3}$; $V_0 = 5000$ cm./sec.
Determine S when V has a negligible value (10 cm./sec.)
Substituting in equation II: $S = 2075$ cm.

III. Assume: $a = 0.5$ mm.; $\sigma = 2.65$; $\rho = 1.2 \times 10^{-3}$; $V_0 = 5000$ cm./sec. (10,000 ft./min.).
Determine V_a when the distance S out to zero velocity is 30 cm.
Substituting in equation III: $V_a = 9300$ cm./sec. (18,600 ft./min.).

The results obtained in these three examples are not absolutely correct since the equations do not hold over the entire range indicated by the limits V_0 and 0. Nevertheless, they are of the correct order of magnitude and thus demonstrate two important principles:

(1) Microscopic particles are not dispersed by dynamic projection more than a very short distance through still air.

(2) Large particles, which are easily dispersed by virtue of their own kinetic energy, cannot be captured within a reasonable distance by an opposing air stream having a velocity low enough to be practical.

It follows, therefore, that the important force of dispersion to be overcome by the air flowing into the exhaust hood is the movement of the dust-laden air and not the motion of the dust itself; the problem is to capture the contaminated air, not to remove the contaminating material from it (1). The scattering of large particles can be prevented only by erecting suitable barriers against which the particles impinge or by causing them to travel directly into a collecting hood.

Hood Design

Reducing the dispersion of dust-laden air involves two steps: (1) Eliminate or otherwise control all possible sources of air motion around the dust-producing process, and (2) All air motion that cannot be eliminated must be changed in direction and made to flow into the exhaust hood, i.e., any outward velocity potentials must be opposed and exceeded by the flow gradient toward the suction opening.

Generally, little or no attention has been given to the first step—eliminating sources of air motion—although it is often a more important part of hood design than the simple selection of a suction opening and the determination of the required rate of air flow. In fact, more effective reduction of the latter with consequent saving in power and cost frequently results from this first step than is secured with the most elaborate design with respect to the manner in which air flows into a hood. A few illustrations will make this clear.

Bagging machine. Dust-laden air escapes at fairly high velocities through the pores of the cloth bag as the air within the bag is displaced by the sudden inrush of powder. A considerable air movement is required toward the exhaust hood to capture it. The most effective way to reduce this required air velocity is to replace the cloth bag with a collapsed paper bag from which no air is forced when it is filled.

Granite-surfacing machine. On the down-stroke of the pneumatic hammer which actuates the cutting tool, the air in the lower part of the cylinder of the machine must escape and can do so only through the annular space around the shank of the tool. Thus, a high-velocity blast of air strikes the stone at the point of dust generation with consequent active dispersion of dust-laden air. A minor change in the machine permits the air to escape through the sides of the cylinder and thus eliminates an important force of dust dispersion. A reduction of more than 50 per cent in the required air flow through the exhaust hood for effective dust control has been reported following this simple change.

Grinding wheel. A rotating grinding wheel acts like a fan, drawing air in at its axis and throwing it off at the periphery. A properly designed hood should utilize this fan action to create air motion *toward* the exhaust outlet. I have seen numerous hoods, however, out of which air flowed even when the exhaust fan was running because of the outward air motion established by the rotating wheel. One simple way to minimize this fan action is to place stationary disks close to the sides of the grinding wheel.

All sources of air motion cannot be eliminated by these direct means nor can general rules of procedure be formulated. The best measures are generally suggested from the nature of the sources. It is helpful in this connection to classify the important sources of air motion into four groups (2):

(1). Motion produced inherently by the operation of the process itself.
Examples. Air thrown off by the fan action of a rotating grinding wheel; escape of air from a container as it is filled with a powdered material.

(2). Air movement generated incidentally to the operation of the machine.
Examples. Escape of air past worn pistons on pneumatic tools; vibration of machinery.

(3). Drag of air in the wake of large particles dynamically projected from their source, as from a grinding wheel.

(4). External sources of air movement. *Examples:* Convection currents; motion due to the operation of nearby machines, belts, etc.

Aerodynamic design. The second step in the design is to select the shape and location of the suction opening and fix the rate of air flow into it so that all remaining air movement in the zone of dust generation will be toward the hood. This can be accomplished with any kind of suction opening provided air is drawn into it at a high enough rate. Proper design, however, demands that it be done with the highest aerodynamic efficiency, i.e., with the least possible rate of air

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flow and power consumption. This requires a knowledge of the laws governing the flow of air into exhaust openings. The following general rules should be observed (3):

(1). Enclose the process as completely as possible and provide internal baffles to guide the air flow where it is most needed.

(2). An exhaust hood which does not enclose the process should be placed with its opening as close as possible to the point of dust generation since the air velocity in the zone of hood influence decreases approximately with the square of the distance from the face of the hood.

(3). Shape the hood to conform with the shape of the area of dust production so as to secure reasonably uniform air velocity over this area. For a given required air velocity at the point of dust generation, the velocity at the hood opening should be as low as possible. This is contrary to the common idea that the hood suction should be high.

(4). Provide flanges wherever possible to reduce the air flow from ineffective areas where no dust is produced.

(5). Locate the hood opening, or part of it, so as to receive directly any dust that is thrown off along a well-defined path, thus utilizing the directional energy of the material for its own capture.

Determining the required rate of air flow. The air flow requirement of an exhaust hood is commonly determined from a certain value of static suction at the hood throat which has been fixed by past experience and written into State codes (although the required values vary from one State to another). The relation between the two is given by the equation:

$$Q = 4000\, Af\sqrt{h_s}$$

where Q = rate of air flow into the hood, cu. ft./min.
A = area at hood throat, sq. ft.
f = coefficient of restriction which varies with hood design.
h_s = static suction at the hood throat, inches of water.

Thus, if $h_s = 2.0$ inches; $f = 0.7$ (average value) and $A = 0.196$ (6 inch pipe), then $Q = 775$ cu. ft./min.

One notes that Q is a function of A and f as well as of h_s and complete specifications must therefore include these factors. Some State codes specify branch pipe sizes but all assume an average value of $f = 0.7$. The chief criticism against the use of the static suction index arises from the fact that f may depart considerably from 0.7 and as a matter of fact, may easily vary from 0.95 for a well-designed opening to as little as 0.3 for a poorly shaped and constructed hood. Thus, a variation of 300 per cent in the value of Q may occur for constant values of A and h_s.

Recently, the velocity pressure in the branch pipe has been proposed as a better index of hood operation since with it the variable coefficient of restriction is not required, thus

$$Q = 4000\, A\sqrt{VP}$$

where VP = velocity pressure in the branch pipe, inches of water. An important disadvantage of this index compared with static suction is that a great deal more skill is required in its determination. A pitotstatic tube must be employed and great care taken to make the readings in a section of pipe in which steady flow obtains. This condition is frequently absent in a short branch pipe possessing sharp bends, or changes in area.

Basically, neither the velocity pressure nor the static suction in the branch pipe should be employed as indices of hood operation since high values do not necessarily mean high efficiency of dust control. The velocity pressure should be determined by the velocity required to convey the collected dust and any increase over this simply represents wasted energy. Thus, if the transporting velocity is 4000 ft./min., then VP should not exceed 1.0 inch of water. If Q is not large enough to provide adequate control, improvement should be secured by increasing the area of the branch pipe and not by raising the velocity pressure. In the same way, it is poor design to increase h_s when the desired value of Q can be obtained with less power consumption by increasing A and f. A State code which specifies 5 inches static suction does not necessarily insure better dust control than another which permits as little as 2 inches; it simply requires greater power consumption for the same amount of work done. It is not the manner in which the air travels within the branch pipe but rather the conditions of flow into the hood opening that determines the collecting efficiency.

The required rate of air flow into a hood is properly determined by two factors: first, the necessary air velocity at the point of dust generation, and, second, the shape and location of the hood with respect to the dust source, since these determine hood efficiency.

TABLE 1

MINIMUM AIR VELOCITIES REQUIRED TO CAPTURE CERTAIN INDUSTRIAL DUSTS

INDUSTRY	PROCESS	REQUIRED AIR VELOCITY		CRITERION	REFERENCE
		At point of origin	At face of hood		
		ft./min.	*ft./min.*		
Granite cutting	Pneumatic hand tool	200		Reduced conc. to safe level	(5)
	Surfacing-machine	1500		Reduced conc. to safe level	(5)
	All tools		1500	Reduced conc. to safe level	(6)
Grain elevators	Elevator boot and head, garner		500	Visual test	(7, 8)
Paint spraying	Spray booth		50–200*	Reduced conc. to safe level	(9, 10)
Sand pulverizing	Bagging machine	400		Reduced conc. to safe level	(11)
	Elec. welding	100–200		Visual test	(12)

* Depending upon the nature of the work and the size of the object being sprayed in relation to the size of the hood.

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(1). The *required air velocity* in the the area of dust production depends upon the magnitude and direction of the air motion to be overcome. These cannot be calculated directly; the designer must form his estimates upon past experience, although very limited data are available. The minimum velocity necessary to overcome natural convection currents is 50–100 ft./min. Vertical convection currents over hot bodies are higher and are best determined by actual measurement. The required air velocities for most processes are between 100 and 500 ft./min. as the few figures in table 1 show. In the new Wisconsin code the necessary velocity is put at 170 times the specific gravity of the collected dust, but shall not be less than 500 ft./min. The density and size of microscopic particles has nothing to do with their dispersion and it is therefore doubtful if this specification is justified. The rule yields figures, however, that are high enough to insure successful operation in most cases and to this extent it is superior to the static suction index.

(2). The *required rate of air flow* may be calculated when the velocity requirement outside an unobstructed hood is known. Thus, according to DallaValle's equation (4):

$$Q = V\,(10X^2 + A)$$

where Q = rate of air flow,
V = air velocity at point of dust generation at X distance from the hood,
A = area of hood opening.

If the air velocity necessary to collect the dusty air is 200 ft./min., for example, and the condition of the process fixes a 4 in. x 12 in. hood a distance of 6 inches from the dust origin, the value of Q calculated by this equation is 533 cu. ft./min.

If the hood is flanged, the actual value of Q is reduced 30 per cent below the calculated value and a similar reduction may be assumed when the hood lies on a flat surface instead of in an unobstructed position.

The rate of air flow into a hood over a tank or table may be readily calculated by another equation developed by DallaValle (13):

$$Q = 1.4\,PDV$$

where P = perimeter of the hood,
D = distance from edge of hood to edge of the surface over which it is suspended,
V = required air velocity through the open area below the hood.

The rate of air flow into an enclosing or semi-enclosing hood must be sufficient to do two things: prevent the escape of dust through openings into the hood, and develop sufficient air motion within the hood to prevent undesirable settling out of the dust. In hoods over storage bins or mixing tables, however, the air velocity must not be high enough to lift and carry away valuable material. For semi-enclosing hoods, Q can be calculated by means of the simple relationship:

$$Q = VA$$

where A is the cross-sectional area of the hood at a point for which V is known, as, for example, in a paint-spraying booth.

Experimental determination of Q. Undoubtedly, the best way to determine the proper value of Q is by direct experiment under actual working conditions. The process is roughly isolated from others so as to be free from outside contamination and is operated with experimental hoods. The rate of ventilation is varied and correlated with the resulting dust concentrations. From the curves thus obtained one selects the best hood and determines the minimum ventilating rate necessary to keep the dust concentration below the maximum permissible level.

Direct investigation in this manner is not always practical although the cost of the experimental study will frequently pay for itself through the more efficient and economical design of equipment thus secured. A less expensive method is to employ a small "probing hood" for estimating the required air velocity. The hood, with known velocity characteristics and operating with a known rate of air flow, is held at various points in the zone of dust production and moved up until the velocity is high enough to turn the dusty air into the hood. The distance is measured and the velocity quickly calculated by means of DallaValle's equation for an unobstructed hood. The total rate of air flow is estimated from a series of such readings.

Summary

Dispersion of microscopic dust particles away from a dust-producing machine depends upon the movement of the air into which the particles are thrown and not upon their mass or the velocity with which they are projected. Consequently, the function of the exhaust hood is to overcome the outward movement of dust-laden air (and draw it into the hood) and not to separate the dust from the air in which it is suspended. The problem properly involves two steps: first, eliminate or reduce as much as possible all air movement in the zone of dust production; second, select the proper shape of hood, locate it to operate with maximum efficiency, and determine the minimum rate of air flow through it necessary to draw all dust-laden air into the exhaust system. Some simple rules of procedure and elementary equations for calculating the desired rate of air flow are given, although the experimental determination of the latter under actual working conditions is recommended as the most satisfactory means of establishing the necessary capacity of the exhaust system.

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RESPIRATORY PROTECTIVE DEVICES*

CARLTON E. BROWN†

THE problem of providing suitable respiratory protection in industrial, civil, and military activities is increasing in extent and complexity. Some of the conditions responsible for this are: The rapid development and growth of such air-contaminating industrial processes as abrasive blasting, spray coating, metallizing, welding, and pneumatic drilling; the increased knowledge of the harmful effects of inhaling atmospheric contaminants; the tendency of legislative bodies to make industrial disabilities compensable; and the fear of the widespread use of chemical warfare in the event of another war.

These conditions are stimulating much interest and many improvements in personal respiratory protective devices. Although, in general, the use of other preventive or control methods is preferable to the use of respirators, there are situations in which the use of respirators is desirable if not essential. Respirators should be used in emergency situations, in providing protection where general methods are not available, in intermittent exposures of short duration, and in protecting a small number of exposed persons in isolated places.

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DEVELOPMENT AND DESCRIPTION

There are a number of different kinds of personal respiratory protective devices, differing in operating principles, constructional details, and intended fields of use. These devices were developed either to protect against new kinds of harmful or objectionable atmospheric conditions or against common atmospheric conditions which new knowledge showed to be harmful.

Ancient Respirators

Probably the development of the first respirator was due to the presence of harmful or irritating dusts. The relation between cause and effect of irritation by dust is so obvious that probably the idea of using some medium over the nose and mouth to filter out dust from the inhaled air occurred to the ancients even before the time of Pliny the Elder (23–79 A.D.) who described the use of loose bladder skins over the face to protect against the inhalation of vermilion dust (1). The use of fibrous materials over the face to protect against the inhalation of dust generated in various mining operations was mentioned by Agricola (2) in the 16th century.

The necessity for furnishing air to divers led to the development of hose-type devices in ancient times (3).

The details of these early devices are not known, but they probably consisted of a head covering to which was attached a hose through which the wearer inhaled air by means of his lungs alone. Positive-pressure air supply devices, bellows, were used to force air through the hose to the wearer as early as the beginning of the 17th century.

The dust respirator and the supplied-air respirator of the type used in diving were the only types of respirators available until relatively recent times, certainly within the last hundred years.

Modern Respirators

For protection against irrespirable atmospheres far from a source of fresh air

About the middle of the last century the pressing need for a portable self-contained apparatus that would furnish protection in any atmosphere, particularly for rescue work and fire fighting in mines, led to the development in 1853 of a supplied-atmosphere respirator (4) similar in principle to that of the present oxygen breathing apparatus.

This type of device has been brought to a high stage of development largely through stimulation by governmental mining agencies in various countries, particularly in the United States, Germany, England, and France. The common form of the present apparatus consists essentially of a cylinder of compressed oxygen and a regenerator or chemical for removing carbon dioxide from exhaled air. The entire apparatus is carried by the wearer who inhales oxygen from a bag that is supplied automatically with oxygen from a cylinder. The exhaled air passes through the regenerator, where the carbon dioxide is removed and the unused oxygen enters the breathing bag where it mixes with oxygen from the cylinder. Obviously no respiratory equipment will protect against the absorption through the skin of such harmful atmospheric contaminants as hydrogen cyanide (5) or against skin irritation by high concentrations of such gases as ammonia and sulfur dioxide. The length of the service life period of protection of this apparatus depends upon the oxygen supply and the absorptive capacity of the regenerator. The amount of oxygen and the regenerator chemical must be limited in order to keep the weight of the device within reason. The United States Bureau of Mines does not approve respirators of this type weighing more than 40 pounds (6). The most common oxygen-breathing apparatus, the 2-hour type, weighs about this much, and the service life period of protection is at least 2 hours for a wearer doing strenuous work, or longer if he is engaged in less difficult work. This is the type of respirator recommended for mine rescue work, since it permits the wearer to travel a considerable distance from an assured supply of fresh air and return to fresh air before the oxygen supply is exhausted. In this general category there are also half-hour respirators weighing about half as much as the 2-hour device. These are used in fire fighting, in the metallurgical industries, and in certain operations in mining where the wearer does not

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have to travel far from an assured supply of good air.

For protection against the inhalation of low concentrations of gaseous contaminants

Although the need for a light, portable self-contained device for protection against the inhalation of gases was recognized as early as 1870 by John Tyndall, the eminent English scientist, who devised a "firemen's respirator"(7), it was not until the world war that the need for such respirators became acute. Intensive research was devoted to developing a suitable respirator of this type. In this country the work was done for the Army under the direction of the United States Bureau of Mines, which had had much previous experience with respirators for use in mines and the mineral industry. This research work was directed toward the development of suitable chemical absorbents for the gases, mechanical filters for the particulate contaminants, canisters that would have low resistance to inhalation, and properly fitting facepieces. Toward the end of the war respirators with very high filtering efficiency and reasonably comfortable to wear were available. Respiratory equipment for military purposes is receiving much attention in the press, particularly in some of the European countries.

After the war, accidents and deaths from the use of army gas masks in industry for protection against gases such as carbon monoxide and ammonia, against which they provided no protection, led to the development of respirators for protection against all kinds of gases and vapors encountered in industry.

For protection against irrespirable atmospheres near sources of fresh air

The rapid increase in the use of organic substances, such as gasoline, benzene, carbon tetrachloride and acetone whose vapors are harmful to breathe, introduced new types of atmospheric hazards against which none of the available equipment was suitable. Since organic vapor gas masks would protect only against low concentrations (less than 2 to 3 per cent in air) of organic vapors, they were not suitable for protecting against the high concentration of vapors encountered. As for oxygen-breathing apparatus, the service life period was too short and the weight, skill required to operate, and expense were too great for it to be practical for many of the situations in which respiratory protection was required. It was finally determined that some form of a hose-type supplied-air respirator would be best for furnishing long-time protection against high concentrations of harmful organic vapors. The present device consists of a hand-operated blower, a large-diameter hose (internal diameter about 1 inch), harness, short length of flexible breathing tube, and full facepiece. Among the reasons for using a hand-operated blower are: The presence of the operator of the blower gives reasonable assurance that the intake of the blower will be located in fresh air regardless of any change in wind direction or other factor which might change atmospheric conditions while the wearer of the device is exposed, and the operator of the blower can draw the wearer to safety if necessary by means of a life line attached to the harness or in exceptional circumstances by the hose. The blower of this respirator is so designed that when not operated the wearer can draw air through it and the hose by means of his lungs alone. The hose must not be permeable to organic liquids, as some of the important uses of this respirator are in oil fields and in cleaning out tanks that have contained organic liquids. The maximum length of the hose is limited so that the wearer will not be able to travel too far from an assured supply of fresh air.

For protection against particulate contaminants

The objectionable nature of such particulate matter as dust, fumes and mist probably always has been recognized and even the harmful nature of some has been recognized, at least since the time of Pliny (1). However, the extent of the need for furnishing respiratory protection against atmospheric particulate matter has been recognized only since about the beginning of this century. The increased effort to improve working conditions under the present complex industrial developments has led to an increase in knowledge concerning harmful effects of atmospheric particulate matter and has stimulated much interest in respiratory protection against these contaminants.

The filtering efficiency of fibrous materials was not studied appreciably until the world war (8). More recently studies have been made of respirators by such agencies as the United States Bureau of Mines (9, 10) and the Harvard School of Public Health (11).

These studies of mechanical filtration by fibrous materials revealed that filtering efficiency varies with the particle size and the amount of solid particulate matter retained; also that the resistance to air flow varies with the amount of solid particulate matter retained and the rate of air flow. This information has been of value in developing suitable mechanical-filter respirators.

The United States Bureau of Mines' schedule covering respirators for atmospheric particulate matter (12) has been responsible for a marked improvement in filtering efficacy and facepiece fit of mechanical-filter respirators.

The difficulty of properly fitting the half mask facepieces of mechanical-filter respirators to all types of faces has been brought out by the approval work on such respirators. Most of the manufacturers who have submitted respirators for approval have had to modify their respirator facepieces before they would meet the approval requirements. A simple practical test that anyone can run to determine whether a respirator facepiece is making a tight seal, is to wear it in a high concentration of coal dust. The time of the test can be shortened by blowing a stream of air containing a high concentration of coal dust around the edges of the facepiece. Figure 1 shows the results of such a test. Toothpicks were inserted under the edges of the facepieces worn by the persons at left and right to produce leakage. The location and approximate magnitude of the leaks are shown by the streaks of coal dust on the part

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of the face covered by the facepiece. Another test consists of plugging the intakes to the respirator and then attempting to inhale. This type of test could well be supplemented by the coal dust test.

For protection against high concentrations and combinations of gaseous and particulate contaminants

Industrial processes such as pneumatic drilling, abrasive blasting and spray coating have introduced atmospheric conditions for which none of the respirators previously described are particularly suitable. Certain kinds of pneumatic drilling are responsible for dust concentrations so high that they would rapidly overload a dust respirator. The operator of an abrasive blasting outfit must be protected not only against the inhalation of air containing high concentrations of dust but also against impact and abrasion of the head and shoulders by the rebounding abrasive and loosened abraded material. Spray coating is responsible frequently for pollution of the surrounding atmosphere by a combination of particulate matter (mists that are liquid particles or a combination of solid and liquid particles) and harmful vapors resulting from the evaporation of the liquid vehicle of the coating used in the spray gun.



FIG. 1.—Results of test for fit of mechanical-filter respirator facepieces. The results plainly show the location and approximate magnitude of the leaks caused by the tooth picks and that the facepiece worn by the person in the center did not leak.

Since these operations are carried out frequently in isolated places and at different locations at various times, they do not lend themselves always to general control measures.

The apparatus responsible for contaminating the air, in each case, is operated pneumatically. The idea of furnishing the operator of these devices with a respirator designed to be supplied with air from the same source as

that of the air for operating the apparatus must have occurred to someone soon after the introduction of these devices. Such supplied-air respirators are available, but it is questionable whether at present most of them are satisfactory for their intended use. Using air from the ordinary compressed air system found in industry to supply respirators is not to be indiscriminately recommended. These compressed air systems are usually of the high-pressure, internally lubricated, reciprocating-compressor type. The air supplied by these systems is contaminated frequently with malodorous constituents such as vapors, mists and products of decomposition of the compressor lubricant, slugs of water, and rust from the pipe line. All or most of these contaminants can be removed probably by some of the commercial air purifiers sold for this purpose. A pressure-reducing mechanism should be used also in the line to prevent any possibility of sudden accidental blasts of high-pressure air from injuring the lungs of the wearer of the respirator. With a compressor of this type there is always the possibility, however rare it may be in well-kept systems, of the generation of carbon monoxide due to overheating of the compressor lubricant (13). This danger can be minimized or eliminated by the use of temperature controls or carbon monoxide alarms on the compressor which, of course, should be so maintained as to prevent the generation of carbon monoxide.

The trend in supplied-air respirators is to use special low-pressure, externally lubricated, positive-pressure air-supply devices. Most of the objections to the high-pressure reciprocating-type compressor do not apply to an air-supply device of this kind. Since these devices are not common in industry, however, it is usually necessary to purchase a special one for use with the respirator. Since air purifiers, pressure-reducing mechanisms, and special compressor-control or alarm mechanisms are not necessary, the price of this respirator complete with air-supply device should not exceed that of the other type of respirator without the air supply system.

The use of a special air-conditioning unit to regulate the temperature and humidity of the air supplied to the respirator wearer is desirable.

Supplied-air respirators have the following advantages for routine non-emergency use over those of the air-purifying respirators such as gas masks, mechanical-filter respirators and the combination of gas mask with a mechanical filter:

1. No resistance to inhalation.
2. Freedom from inward leakage of contaminated air.
3. Protection against all kinds of contaminants and even against atmospheres deficient in oxygen.

SUGGESTED IMPROVEMENTS AND DEVELOPMENTS

Although respirators have reached a high stage of development there is still considerable room for improvement of present respirators and development of new ones. Some needed developments and improvements are:

1. Safe and suitable supplied-air respirators for use with special air-supply systems free from possible generation of carbon monoxide.

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TABLE 1

Comparison of Characteristic Features of Respiratory Protective Devices

Respirator	General design features	Protection provided	Service life period of protection	Approximate weight carried	Approximate cost
				lbs.	
I. Supplied-Atmosphere Respirators					
A. *Supplied-Air Respirators*					
1. Type A (commonly called hose mask)	Hand-operated blower, large-diameter hose, harness, and facepiece.	Against any atmosphere	Unlimited	5	$150
2. Type B (special hose mask)	Large-diameter hose, harness, and facepiece.	Against any atmosphere, but should not be used in immediately harmful atmospheres.	"	5	$50
3. Type C (airline respirator)	Externally-lubricated low-pressure air-supply system, air-conditioning unit, hose, harness, air-regulating valve, detachable coupling, and suitable face or head covering.	"	"	2	$150
4. Type D (airline respirator)	Attachment for connecting hose to ordinary industrial source of high pressure air, air-conditioning unit, pressure-reducing mechanism, air-regulating valve, detachable coupling, hose, harness, and suitable face or head covering.	"	"	2	$100
5. Types EA, EB, EC, and ED (abrasive-blasting respirator)	Features same as of type of supplied-air respirator indicated by the second type letter with the necessary modifications or additions to make these devices suitable for use in abrasive blasting. Regular supplied-air respirators usually require coverings to protect the head and shoulders of wearer from impact and abrasion by rebounding abrasive and loosened abraded material.	Against inhalation, impact, and abrasion of particulate matter in air during abrasive blasting. Also against any atmosphere, but all types except Type EA should not be used in immediately-harmful atmospheres.	"	3–10	$75–$175
B. *Supplied-Oxygen Respirators* (commonly called oxygen-breathing apparatus)					
1. Type A (½-hour apparatus)	Cylinder of compressed oxygen, pressure gage, pressure-reducing mechanism, reservoir, mouthpiece, nose clip, saliva trap, carbon dioxide absorbent, and cooler. The entire device is carried by the wearer.	Against any atmosphere	The cylinder of oxygen will supply needs of wearer during a 30 minute strenuous work period, or for longer period while doing easier work. Oxygen and carbon dioxide absorbent supply must be renewed at end of this period.	12–21	$150
2. Type B (1-hour apparatus)	"	"	Same as for Type A except for 45-minute protection period.	20–30	$175
3. Type C (1-hour apparatus)	"	"	Same as for Type A except for 1-hour protection period.	30–40	$200
4. Type D (2-hour apparatus)	"	"	Same as for Type A except for 2-hour protection period.	40	$225
II. Air-Purifying Respirators	Filter, chemical or mechanical, for removing contaminant or contaminants from inhaled air; and facepiece attached to filter directly or by means of short length of flexible rubber tubing. Entire device is carried by the wearer.	Against specific contaminants or types of contaminants. No protection against atmospheres containing insufficient oxygen for respiration. In some cases concentrations of contaminants should be known.	Depends upon filtering capacity, increase in resistance to air flow with material retained by filter, concentration of contaminant in air, and rate of breathing.	½–8	$1–$50
A. *Chemical-Filter Respirators* (commonly called gas masks)	Canister containing suitable chemicals, short length of flexible rubber tubing, and full facepiece.	Against gaseous contaminants.		4–8	$15–$50
1. Type A, or acid gases	Canister containing suitable chemicals, short length of flexible rubber tubing, and full facepiece. Canister contains alkaline chemicals, such as soda lime. Color of canister—white.	Against low concentrations (less than about 2%) of acid gases such as chlorine, formic acid, hydrogen chloride, hydrogen sulfide, and the like.	At least 30 minutes against 2% of an acid gas in air, or longer time against lower concentrations.	4–8	$15–$50
2. Type B, or organic vapor	Same as for Type A, except canister contains activated charcoal. Color of canister—black.	Against low concentrations (less than about 2% in air) of organic vapors such as acetone, benzene, carbon tetrachloride, and gasoline.	At least 30 minutes against 2% of an organic vapor in air, or longer time against lower concentrations.	4–8	$15–$50

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TABLE 1—*Concluded*

RESPIRATOR	GENERAL DESIGN FEATURES	PROTECTION PROVIDED	SERVICE LIFE PERIOD OF PROTECTION	APPROXIMATE WEIGHT CARRIED	APPROXIMATE COST
				lbs.	
3. Type C, or ammonia	Same as for Type A, except canister contains silica gel or kupramite (granular material impregnated with copper sulfate). Color of canister—green.	Against low concentrations (less than 3% in air) of ammonia. Even this concentration is very irritating to the unprotected skin.	At least 30 minutes against 3% ammonia in air, or a longer time against lower concentrations.	4–8	$15–$50
4. Type D, or carbon monoxide	Same as for Type A, except canister contains hopcalite (specially-prepared mixture of copper oxide and manganese dioxide) which catalyzes the action of carbon monoxide with oxygen of air to produce carbon dioxide. Color of canister—blue.	Against low concentrations (less than 2% in air) of carbon monoxide. Such respirators protect against higher concentrations but the intense heat generated can not be long endured.	Two to 6 hours according to size of canister, regardless of any or no concentration of carbon monoxide encountered.	4–8	$15–$50
5. Types AB, ABC, ABCD or N, BC, etc.	Same as for Type A, except canister contains suitable combination of chemicals.	Against low concentrations of combinations of preceding gases. The Type N device is really a chemical and mechanical-filter respirator, since it also contains a mechanical filter for removing particulate matter.	Shorter than that of respirators designed for one gas or type of gas, as it contains a smaller amount of each chemical.	4–8	$15–$50
B. *Mechanical-Filter Respirators* (commonly called dust respirators)	Fibrous filter attached to half mask facepiece directly or by means of a short length of flexible rubber tubing.	Against particulate matter such as dusts, fumes and mists.	Determined by amount of retained particulate matter required to cause resistance to inhalation to increase appreciably. Length of period depends upon concentration of particulate matter in air and rate of breathing.	½–1	$1–$15
1. Type A, or dust	"	Against dusts whose probable safe concention does not exceed that of pure quarts or free silica (SiO_2) dust. Filtering efficiency increases with use or amount of particulate matter collected.	At least 1 day at relatively high dust concentrations.	½–1	$1–$15
2. Type B, or fume	"	Against fumes of various metals. Since fumes are probably more difficult to remove by mechanical filtration than other kinds of particulate matter with the possible exception of smokes, this respirator will protect against such particulate matter as dust and mists.	"	½–1	$1–$15
3. Type C, or mist	"	Against mists as produced by spray-coating with paint and vitreous enamels, chromic acid mist as produced in chromium plating, and mists of other materials whose liquid vehicle does not produce harmful gases or vapors.	"	½–1	$1–$15
4. Types AB, AC, BC, etc.	"	Against combinations of preceding kinds of particulate matter.	"	½–1	$1–$15
5. Type for single particulate contaminant	"	Against particular contaminant.	"	½–1	$1–$15
C. *Chemical and Mechanical Filter Respirator*	Chemical and mechanical filter attached to facepiece directly or by means of a short length of flexible rubber tubing.	Against combinations of gaseous and particulate contaminants.	See remarks under chemical-filter and mechanical-filter respirators.	½–8	$2–$50

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2. Safe and suitable supplied-air respirators that can be used with air supplied by the common high pressure, internally lubricated reciprocating compressors.

3. Self-contained, positive-pressure, air-purifying respiratory equipment that can be carried completely by the wearer and that will not interfere unduly with his work.

4. Simple, light-weight, self-contained, inexpensive, supplied-atmosphere respirators to cover the present fields of the oxygen breathing apparatus and gas mask.

5. Better fitting facepieces for mechanical-filter respirators.

6. More compact, simpler and cheaper approved mechanical-filter respirators.

7. Better means of communication for wearers of respirators.

8. Simple arrangements to permit the wearer of respirators to expectorate without removing the facepiece.

9. Investigation of possibilities of application of principles of thermal and electrical precipitation for use in air-purifying respirators for protection against the inhalation of particulate matter.

10. Less dead air space and resistance to inhalation in all respirators of the negative-pressure type or those in which there is a negative pressure under the facepiece at some part of the wearer's inspiratory cycle.

Summary of Information on Respirators

Table 1 contains information on general design features of respirators, kind of atmospheric conditions they protect against, length of time they will furnish protection, weight of the complete respirator or the part carried by the wearer, and approximate cost of the different types.

Selection

The selection of the proper respirator for a particular situation requires a knowledge of the nature of the harmful or objectionable conditions, the kind of work to be done by the exposed persons and the characteristics of available respirators.

Actually or potentially harmful or objectionable atmospheres in a particular establishment are known or deducible usually from information on the materials used in the various processes. When the nature of atmospheric conditions is not known, it is wise to assume that the air contains insufficient oxygen for respiration and to select a supplied-atmosphere respirator.

The features of the exposed person's work that must be considered in selecting a suitable respirator are: The exertion required, the motions involved, distance or area traversed, obstacles in the working area, and length and frequency of exposure.

Information on the essential characteristics of available respirators is given in table 1. From this information and that on the nature of harmful or objectionable atmospheric conditions and on the features of the exposed person's work, one should be able to select a suitable respirator to meet virtually all of the conditions for which respirators are suitable.

Before selecting the particular make of respirator, however, one should be familiar with the approval system of the United States Bureau of Mines (14). The purpose of this approval

system is to furnish to the mineral and allied industries a list of devices that have met the schedule of requirements of that Bureau. By selecting a respirator approved by this Bureau one is assured of obtaining a device that will meet certain minimum requirements pertaining particularly to performance. The inference should not be drawn that none of the unapproved devices will meet these requirements. The submission of respirators for approval is voluntary on the part of the manufacturer. There are now approval schedules for supplied-oxygen respirators (6), for chemical-filter respirators (15), for Type A supplied-air respirators (16), and for mechanical-filter respirators (12). The schedule for Type A supplied-air respirators is being revised to cover the other types of supplied-air equipment. Lists of approved respirators are issued at intervals, and can be obtained from the United States Bureau of Mines.

The following are some general rules which may be helpful in selecting respiratory devices:

1. In general the use of supplied-atmosphere respirators is preferable to that of air-purifying types, since they protect against all types of atmospheric conditions.

2. The use of positive-pressure respirators or those in which there is a positive air pressure under the facepiece at all times during the wearer's inspiratory cycle is usually preferable to that of the negative-pressure respirators such as the Types B and EB supplied-air respirators and all of the air-purifying respirators, since there is no resistance to inhalation and any leakage around the facepiece edges is outward.

Use and Care

The supplied-oxygen respirators are the only ones so complicated that the wearers must be instructed and trained carefully in their use. Because of the value of these devices in mine rescue work, the United States Bureau of Mines has trained, without charge, about 60,000 qualified persons in their use.

Complete instructions for the use and care of the various other respirators are furnished by their manufacturers. The instructions furnished with approved respirators are carefully checked by the Bureau of Mines which also issues articles on the use and care of respirators.

Summary

The history of the development of various available respirators is discussed. These respirators were developed to meet new types of harmful or objectionable atmospheric conditions or common atmospheric conditions that new knowledge showed to be harmful.

Suggestions are made for the improvement of present respirators and for the development of new types of respirators.

Information on the general design features of respirators, kinds of atmospheric conditions they protect against, their service life period of protection, weight of the respirator or the part carried by the wearer, and approximate cost of available respirators is summarized in tabular form.

The selection, use and care of respirators are discussed briefly.

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THE APPLICATION OF AIR CONDITIONING IN NORMAL LIFE*

Philip Drinker

Ventilation consists in supplying or removing air to or from confined spaces. It is a dilution process and requires no pretreatment or purification of the added air. Air conditioning, on the other hand, controls the quality of the air and may necessitate heating, cooling, drying, moistening, or purifying. The Holland vehicular tunnels must be ventilated in order to control the concentration of carbon monoxide from the exhausts of the automobiles but the air thus introduced into the tunnels is not pre-treated in any way. The modern moving picture theatre would be impracticable in either summer or winter unless air conditioned. The heat supplied by the audience, with the resultant odors and general stuffiness make it essential to pre-cool the fresh air which is added and to treat and recirculate a fair portion of the old air. Just what percentage of the total air handled by the fans is recirculated and what is fresh depends upon local conditions.

The objective in the ventilation of any building is the general comfort and health of the occupants. It may be possible to set up an arbitrary measuring stick or to draw up precise specifications, but the layman will judge conditions solely by his own sense of comfort and well being. If the atmosphere is stale or odorous his opinion will not be changed by the fact that the temperature and percentage relative humidity happen to agree with the accepted optima.

The measurable factors are temperature, moisture content, air movement, carbon dioxide concentration, odor intensity, dustiness, gas concentrations and degree of ionization. By means of modern air conditioning it is possible to attain practically any desired combination of the above factors. All of them, except odors, are measurable with precision.

The physiological requirements of the atmosphere are easier to satisfy than are the esthetic or psychological demands. Thus, it is easy to keep the carbon dioxide concentration well below the level which is detectable physiologically and to maintain comfortable temperatures but the atmosphere may still be objectionably odorous.

In estimating the air-conditioning requirements for any building one treats the human occupant exactly as if he were a machine, an electric light bulb, or a gas jet giving off so much heat, moisture and carbon dioxide and using up so much oxygen. The required data are given in full in such hand books as the annual Guide of the

* From the Department of Industrial Hygiene, Harvard School of Public Health, Boston.

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American Society of Heating and Ventilating Engineers which is kept up to date by persons carefully selected to write upon their own specialties.

There is a decided international difference of opinion as to the optimum physiological conditions but the reasons for these differences are perfectly understandable. There is no dispute at all as to the basic thermal requirements, based upon human metabolism, heat transmission, heat conduction, leakage or infiltration, and the like.

The Comfort Chart.—It has long been known that there are various combinations of temperature, percentage relative humidity and air motion which feel substantially the same or produce the same sensation of comfort or warmth. Thus, the presence of excessive moisture renders extreme air temperatures (hot or cold) much more severe than does dryness. There is a broad zone in which no differences in comfort can be claimed although the subject may be perfectly aware that one condition is slightly colder or slightly warmer than another.

Yaglou, (1) with various colleagues, has determined the comfort limits as accepted in the United States and placed them in simple charts (figure 1) and tables. As abscissas the chart gives the dry bulb temperatures measured by the ordinary thermometer while the ordinates are wet bulb temperatures. The percentage relative humidity is given in the upper right hand corner while the air motion is assumed to be from 15 to 25 ft. per minute.

The only manner in which data for such charts can be obtained is by subjecting volunteers to the various conditions and asking their opinions. As these opinions were based upon conditions as found in everyday life, the subjects dressed normally and no restrictions were imposed as to diet. In all of these experiments the rooms used were air conditioned and the equipment was run for a considerable period before the subjects entered the room so that differences in temperature between the walls and the air within were trifling. However, all heat or cooling resulted from the air blown into the room; there was no heating or cooling by radiation. (It might be more accurate to speak of cooling by *negative* radiation.)

The term "effective temperature" is used in the United States to indicate the physiological effects of various combinations of temperature, humidity, and air motion upon man. Thus, a dry bulb temperature of 70°F, a wet bulb of 58° gives an effective temperature of 66°. This same result is obtained from saturated air at 66°F. This scale is purely empirical and is based solely upon sensations of warmth or coolness. It does not imply that subjects are equally comfortable under these different combinations but that they feel equally warm or cool.

The obvious limitations in such a chart are imposed by the convection type of heating used in obtaining the experimental data. In climates like that of England where such extremes as ours are not met, heating by convection is not practiced as much as in the United States. The chart, then, applies only to conditions such as one finds in this country.

One cannot expect too great uniformity in the opinions of impartial subjects as to conditions of comfort or of warmth. The chart (figure 1) makes it clear that, in summer, it is unlikely that one could satisfy more than 97 per cent of the subjects and in winter 98 per cent. The aim of the air-conditioning engineer is, then, to establish conditions which will bring this degree of satisfaction and he expects criticism of his results from a small percentage no matter what con-

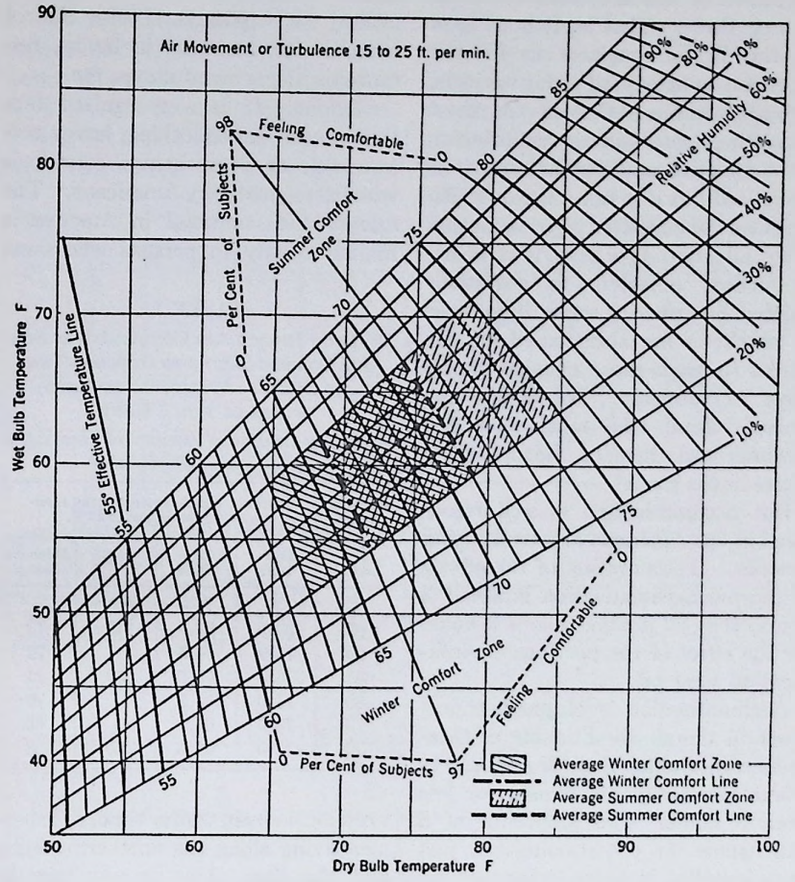


FIG. 1.—The comfort zones plotted on the effective temperatures charts as determined by the American Society of Heating and Ventilating Engineers. Note that this chart applies to air velocities of 15 to 25 feet per minute (still air). These data apply to inhabitants of the United States only. Application of the winter zone is further limited to rooms heated by central station systems of the convection type, and not to rooms heated by radiant methods. Application of summer comfort zone is limited to homes, offices and the like, where the occupants become fully adapted to the artificial air conditions. The zone does not apply to theaters, department stores, and the like where the exposure is less than 3 hours.

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ditions he furnishes. There is general agreement between the British and ourselves on the degree of unanimity of opinion of test subjects on matters such as these. That is, it is as hard for the British engineer as for the American to satisfy all of his subjects.

Acclimatization.—One of the most interesting factors in air conditioning is the effect of acclimatization. It is recognized but it is not a factor which as yet can be measured physiologically.

We all know how easy it is to accommodate ourselves to conditions which are warmer or cooler than those to which we are accustomed but we dislike to have these changes thrust upon us suddenly. We dislike the fresh-air fiend who must open the windows regardless of the desires of others in the room

But acclimatization is well recognized in our American air-conditioning practice. The duration of the effects of diurnal acclimatization is about 3 hours, that is, it takes about 3 hours for the effect of the previous environment to wear off.

Acclimatization is of great importance in the air conditioning of theatres, restaurants, and similar places where the occupants remain for less than 3 hours. The proprietor of a cafe where air conditioning has just been installed in order to increase his patronage during the hot summer days may, in his enthusiasm, show his guests what his new equipment really can do and thus have the air uncomfortably cool. The air-conditioning engineer should have provided him with the schedule given in table 1.

If one compares this table with the chart of figure 1 one can see clearly the effect of acclimatization as the cause of the significant differences between the winter and summer comfort zones. It is recognized that still higher temperatures in summer are needed for exposures shorter than 1 hour, as for instance, in banks, restaurants, department stores, etc.

Clothing.—It is a recognized fact that woolen underclothing, heavy cotton-wool, or even heavy cotton, is worn infrequently by Americans. The sale of such material in America is limited mostly to persons who must work outdoors in winter time, to fishermen living along the northern coasts, and the like. This is not true in Great Britain for Britishers dress far more warmly than do Americans. On the other hand, we Americans unquestionably keep our houses warmer than do the British.

TABLE 1

MINIMUM INDOOR AIR CONDITIONS IN SUMMER CORRESPONDING TO OUTDOOR TEMPERATURES. APPLICABLE TO EXPOSURES OF 1 TO 3 HOURS

(Courtesy American Society of Heating & Ventilating Engineers)

OUTDOOR TEMP.	INDOOR AIR CONDITIONS WITH DEW-POINT CONSTANT AT 57°F.			
Dry-Bulb	Dry-Bulb	Wet-Bulb	R. H.	Effective temp.
°F.	°F.	°F.	*per cent*	
95	80.0	65.0	45	73
90	78.0	64.5		72
85	76.5	64.0	50	71
80	75.0	63.5		70
75	73.5	63.0		69
70	72.0	62.5	60	68

In figure 2 are reproduced graphs showing the proportions in which wool, cotton-wool mixtures and lightweight cotton underclothing are purchased in representative department

stores throughout the United States and the lower part of Canada (2).

Radiant vs. convected heat.—In this country we have to prepare for extremes in temperature. We expect annual differences, in most of our states, of at least 60°F. while differences of more than 100° are common. During the months of January, February, and March, we often experience here in Boston outdoor temperature drops of 40° in the course of 24 hours. It is imperative that our heating plants be able to maintain uniform indoor temperatures in spite of the wide range in heating loads which result. The plant must, therefore, be capable of responding quickly to great changes in conditions.

These requirements mean, generally, that the plant will need too great capacity for average conditions and is then apt to be forced needlessly in mild weather, because the heating capacity is there. Thus, it is common to find American homes heated to temperatures in excess of those desired. This criticism does not apply so forcibly to complete air-conditioning systems for these are under thermostatic control and maintain automatically the proper conditions. Likewise, the modern household heating plant can be equipped with satisfactory thermostatic control.

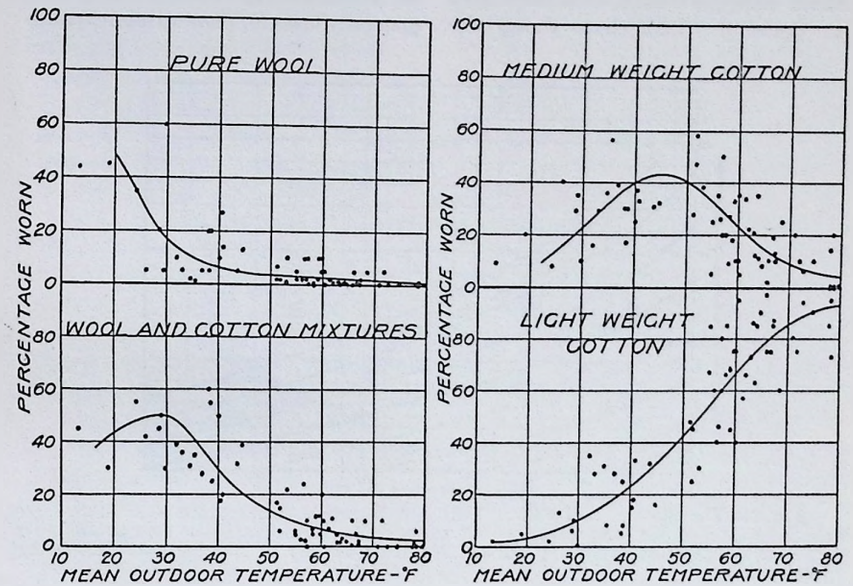


FIG. 2.—Underclothing worn by men in the United States and lower Canada at various outdoor temperatures

We heat our houses by a combination of convected and radiant heat. Of the two the convection method is the more general and is typified by air-conditioning methods and by indirect radiators heated by hot water or by low pressure steam. In England, radiant

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heat is preferred and seems to answer very well where rapid temperature changes such as ours are unusual.

Our American effective temperature scale has been criticized by the British because it disregards the effects of radiant heat. That criticism is partly true but the defect is one of which we are perfectly aware and for which Houghten and McDermott (1) have made some allowance, as is illustrated in figure 3. This chart shows the

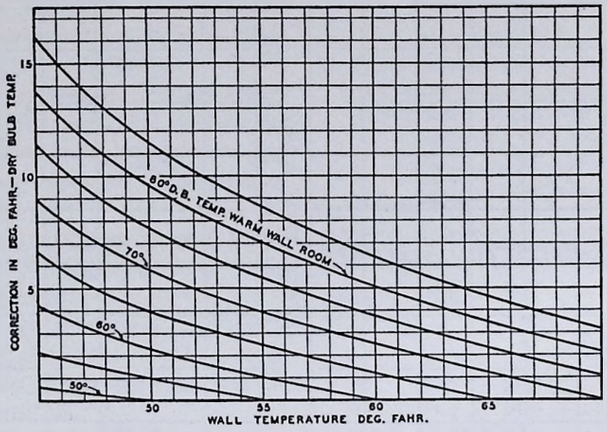


FIG. 3.—The effect of cold walls. Thus, a wall surface temperature of 55°F. on three sides requires an air temperature of 74° to make the room conditions comparable to a uniform temperature of 70°. (Courtesy American Society of Heating and Ventilating Engineers.)

correction which must be made if the walls of the room heated by convection methods are too cold but it does not indicate what drop in air temperature is permissible under the reverse conditions so common in England, namely, a source of radiant heat at a temperature substantially above that of the air in the room. Bedford (3) suggests that the pleasantest conditions probably would be obtained by a judicious combination of air heating and radiant heating.

Dust and bacteria.—In ordinary air conditioning work atmospheric dust is usually not a troublesome item. Dust is removed from the air by filtering it through materials which offer a very low resistance to air flow. It is rarely necessary to remove large amounts of dust such as one demands in the purification of the air of factories or mines with a silicosis hazard. In air conditioning, therefore, the filter generally lasts for days without requiring attention. It then may be cleaned or destroyed and a new one put in its place.

One of the most welcome invasions of air conditioning is in the field of transportation. Compare, for example, a trip in a modern air-conditioned sleeping car with the hot dirty conditions we had to endure a few summers ago. A feature of air conditioned cars is the cleanliness of the air as contrasted with that of the non-conditioned car. This cleanliness is

achieved by filtering the air rather than by washing it.

It is questionable if one has any right to advocate air conditioning or air filtering, in ordinary life, because of the cleaner air one may thus breathe. We know a good deal about harmful dust concentrations when substances like quartz dust are in question but we have no proof at all that the degree of air cleanliness accomplished by a modern first-class air-conditioning installation makes us healthier than we otherwise would be. It should be remembered that industrial dust concentrations of known hygienic significance are vastly heavier than those met in air conditioning.

Both air conditioning and simple air filtration will reduce the concentration of plant pollens in the air to the point where the person susceptible to hay fever can usually obtain relief or even complete freedom from allergic attacks (4). Those who sell air-conditioning equipment have every right to make much of this fact as the medical evidence in its support is conclusive (fig. 4).

The total or partial removal of air-borne bacteria by air conditioning procedures has been claimed by various manufacturers but the justification for these claims is not at all impressive. In fact, in our studies at this School, of commercial filters which were supposed to catch air-borne bacteria, the results were very poor. It seems likely that the application of ultra-violet radiations to the killing of bacteria in recirculated air, as advocated by Wells, may earn a place in air conditioning. One cannot dispute Wells' evidence of the bactericidal effects of such radiations but the conservative person today who is unacquainted with the alleged advantages of sterile or germ-free air may doubt its need. It may be, in the future, that germ-free air will become as necessary as germ-free water or milk and will be gauged by tests somewhat analogous to those now used for water or milk.

Odors.—One of the oldest criteria of ventilation is the presence of disagreeable odors, particularly from the human body. In discussing general building ventilation in 1884 Billings (5) wrote that "the best test for the presence of an undue amount of impurity in the air is the sense of smell. When a person goes from the fresh outdoor air into an inhabited room, and does not perceive any special odor, it is usually safe to assert that that room is well ventilated." Billings believed that concentrations of carbon dioxide could be used as an index of odor intensity, a point of view which is no longer accepted. However, we all agree with his opinion that the control of odors is essential to good ventilation. It is imperative in good air conditioning.

Odors in ordinary air conditioning can be divided into two main classes, (a) those which come from the human body and are relatively water-soluble, (b) those from organic substances such as perfumes which are difficultly soluble. Odorous gases, such as hydrogen sulfide, powerful stenches from slaughter houses, and even excessive odors from kitchens and restaurants are avoided (or isolated) rather than treated in modern air conditioning.

Practically all organic odors are derived from complex substances which are not chemically strong compounds. The strength or concentra-

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tion of odors, as from perfumes, cannot be preserved indefinitely like samples of carbon dioxide gas. All such odors can be destroyed completely, not simply masked, by powerful oxidizing agents such as chlorine, ozone, or by simple combustion of air and are affected by ordinary sunshine. But it is extremely difficult to apply powerful oxidizers in practical air-conditioning work as the curative agent generally must be applied in excess and the neutralization of this excess is not easy. The treatment of the air escaping from fertilizer plants and similar places, by means of chlorine and by ozone is fairly common, but no great success has been attained in the use of ozone in the air of theatres, schools, and the like.

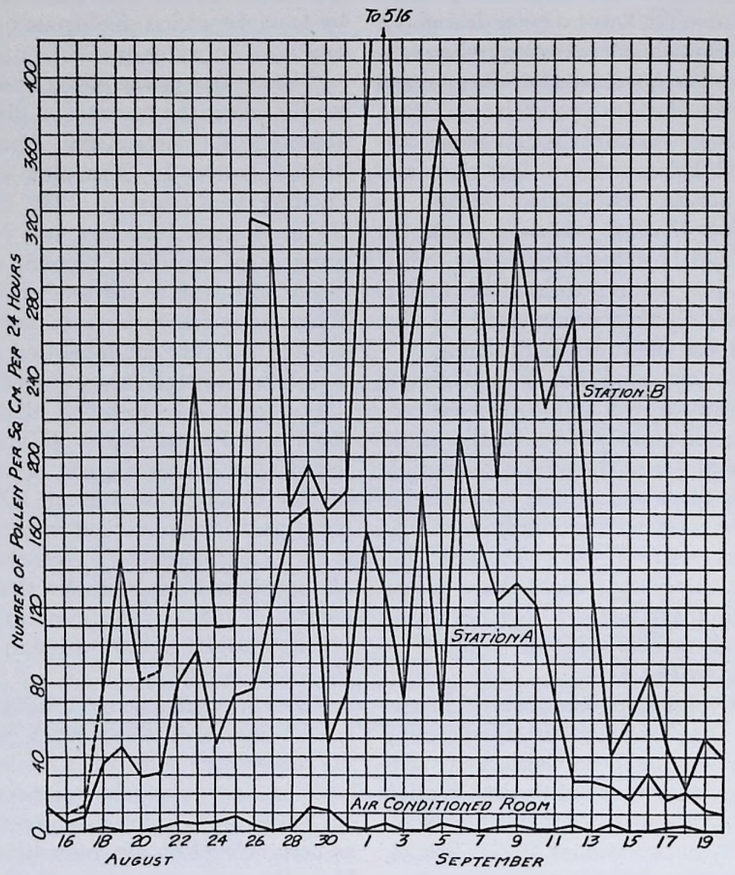


Fig. 4.—The effectiveness of commercial air-conditioning filters for removing plant pollen from air. Station A was on the campus of the University of Kentucky, Louisville, and Station B was at a point about 1½ miles distant. (Courtesy American Society of Heating and Ventilating Engineers.)

Low concentrations of practically all gases and fairly powerful stenches

can be eliminated completely by passage through a bed of activated charcoal such as is used in gas masks. However, the adaptation of this well-known procedure to modern air conditioning has not been accomplished, largely because of the rather high power consumption involved in forcing the air through the charcoal bed.

There has been no progress at all in the control of tobacco smoke in air conditioning. We admit the great success of air conditioning railroad trains but to the non-smoker, at least, the modern air-conditioned smoking car is still objectionably smelly.

Air conditioning is very effective in the control of body odors. Yaglou (6) determined first the amount of fresh air, by simple ventilation, needed to reduce body odors to an acceptable level and then showed that the same result could be attained with less fresh air if a portion of the air of the room was passed through an air-conditioning apparatus as it would be in a theater, for example. One of his charts is shown in figure 5.

The old standards of 30–50 cubic feet per person per minute should probably be changed. It seems reasonable that one should now supply 100–500 cu. ft. of space per person and that the fresh air should vary from 25 to 7 cubic feet per person per minute—that is, crowding increases the demand for ventilation. If air conditioning is applied, then less fresh air is needed. A further allowance can properly be made for temperatures —more air is needed in warm than in cool weather.

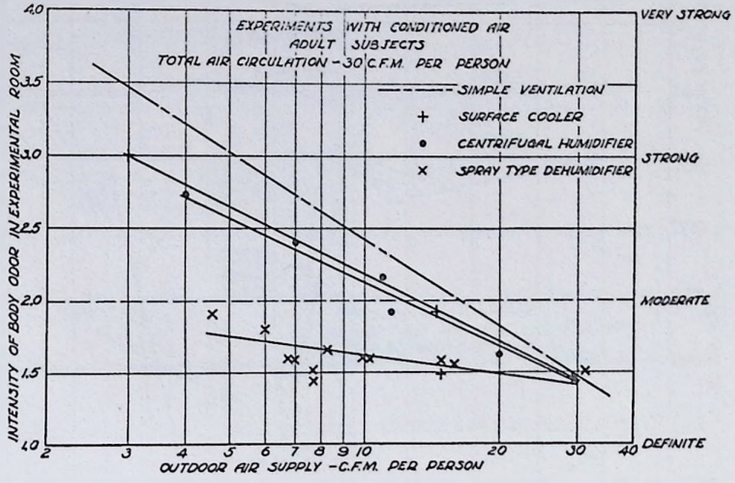


Fig. 5.—The odor-removing capacity of various air-conditioning processes. Net air space per occupant, 200 cubic feet. (Courtesy American Society of Heating and Ventilating Engineers.)

Ionization.—It is well known that air which passes through metal ducts and especially through air washers loses an indescribable property which is present in outdoor air. It is often said that washed air is flat and has lost

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the pleasant brisk and stimulating property which is so welcome in clean country air. A series of studies made at this School (1) showed that there is a decided drop in ionic content of indoor air following human occupancy. In figure 6 are shown data which indicate the influence of human occupants upon the air of a 10,000 cu. ft. room. It is not difficult to reionize

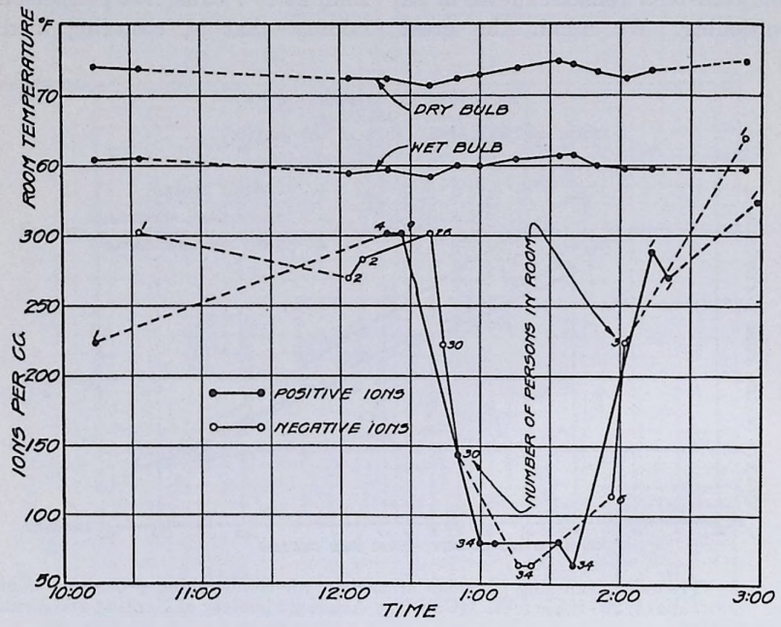


FIG. 6.—Influence of room occupancy on ionic content. The room used was 30 ft. x 33 ft. x 10½ ft. The number of occupants is indicated on the chart. There was good window-gravity ventilation. (Courtesy American Society of Heating and Ventilating Engineers.)

such deionized air or to bring the ion content above that found outdoors but it has not been shown that there is any physiological need or justification for such treatment. At the present time, therefore, artificial ionization is not being used to any important extent in air conditioning.

The effects upon furnishings.—It is well known that air conditioning, particularly humidity control, is very helpful in preventing the drying out or deterioration of woodwork, tapestries, paintings and the like. It is common, therefore, for architects to recommend that new art museums, natural history museums, and the like, be air conditioned. By the same argument the person with valuable household furnishings of any kind will find that they are better preserved in atmospheres in which our extremes of atmospheric conditions are effectively overcome.

One of the most successful fields for industrial air conditioning has been in the manufacture of textiles of all sorts. In fact it can be claimed, without much fear of contradiction, that the textile industry in the United

States would be impracticable today without air conditioning. New industries are being developed and old industries re-born with air conditioning as a prerequisite to successful industrial enterprise.

A comparatively new invasion of air conditioning is into the preservation of valuable records. A careful study can be seen at the National Archives in Washington, a magnificent building, which is completely air conditioned and in which our national records are to be stored.

Health and resistance to disease.—There have been many attempts to determine whether or not air conditioning has any measurable effect upon

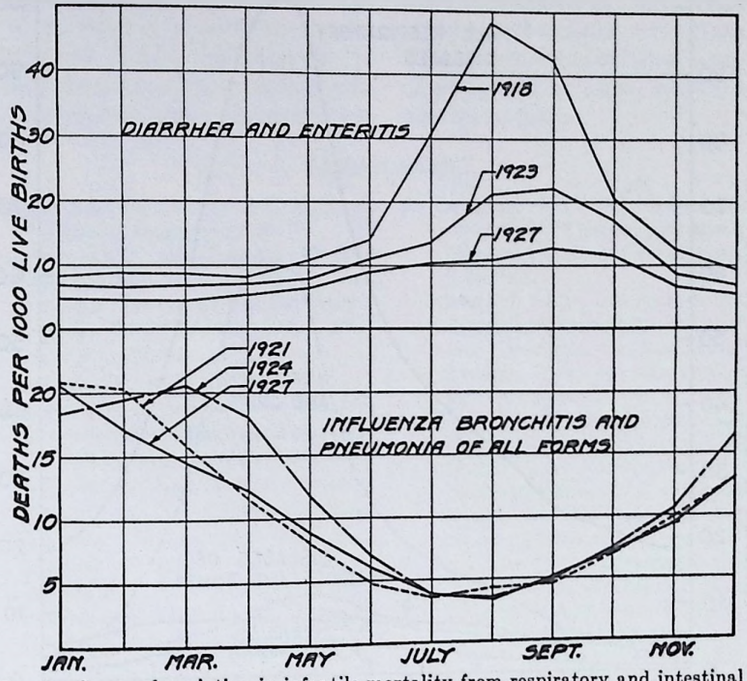


FIG. 7.—Seasonal variation in infantile mortality from respiratory and intestinal diseases in birth registration area of Continental United States. (From report of Committee on Growth and Development, White House Conference on Child Health, 1932.)

was made by Kimberley (7) at the Bureau of Standards on the effects of low concentrations of sulfur dioxide upon book paper, book bindings and the like, and it was found that careful control of the hydrogen-ion concentration of the wash water would eliminate the sulfur dioxide or reduce it to harmless levels. A result of this study the health of normal persons including children. The program of research of the New York State Commission on Ventilation was perhaps the most ambitious on this subject which has been undertaken but after a decade since their reports appeared, one has difficulty in convincing himself that their findings on the relation of ventila-

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tion or air conditioning to respiratory infection are significant.

On the other hand, the seasonal trends of respiratory infections are very well known. Perhaps one of the outstanding achievements in the field of public health and pediatrics is the reduction of infant mortality due in very large measure to the great reduction in intestinal disorders during the hot summer months. A chart which illustrates these trends was prepared by Yaglou (8) for the White House Conference on Child Health in 1931 and is shown in figure 7.

In figure 8 is shown a chart prepared from data collected by Brundage (9) which shows the seasonal incidence of respiratory illness. Year after year such curves can be made, one differing from the other only when epidemics of influenza occur. Even in such years the peak of the curve is likely to come around the end of February although the severity of the epidemic, of course, distorts the curve from its usual shape.

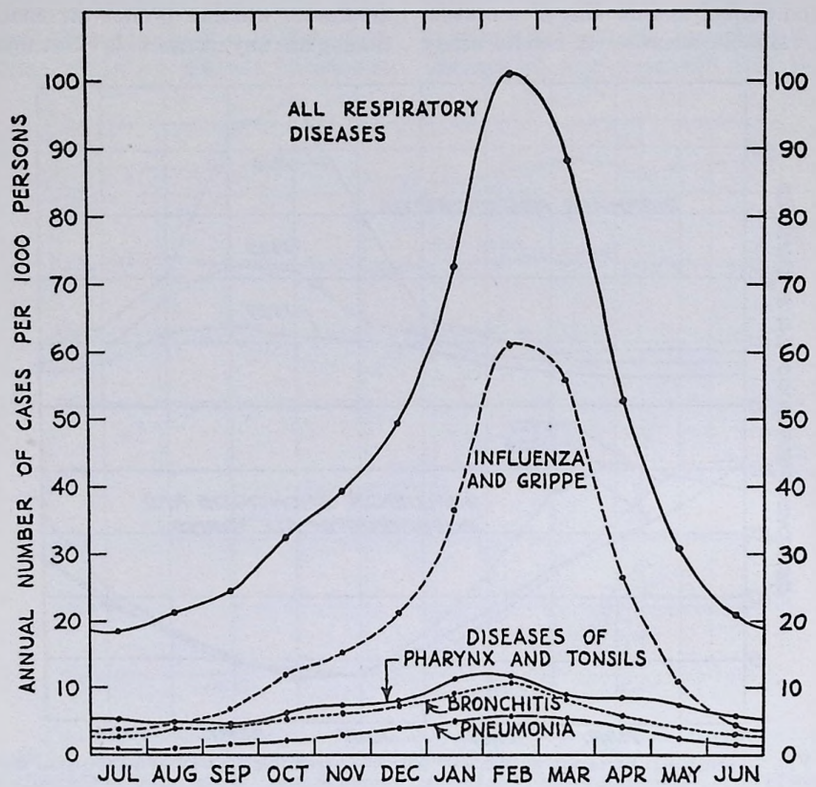


FIG. 8.—Average monthly frequency (1921–1926 inclusive) of specified respiratory diseases causing disability for 8 consecutive days or longer in a group of about 100,000 wage earners in different industries. (Courtesy U. S. Public Health Service.)

A question which constantly arises is: "If careful feeding, adequate refrigeration, and pasteurization of milk have contributed to the reduction in infant mortality, cannot adequate control of atmospheric conditions reduce the likelihood of respiratory infections in winter? Will we adults have less colds if we control the humidity in our houses, if we ionize the air, or if we sterilize it with ultra-violet light?" It would be pleasant to answer these questions positively but, at the present time, there are not enough data to justify affirmative answers.

Air conditioning more than justifies itself in making the atmosphere more comfortable than it otherwise would be. Better work is done in moderate, pleasant atmospheres than under extremes of any sort. The success of many industrial processes depends upon environmental control. In our opinion such reasons are enough and the engineer need not ask of hygienists or physicians for data which cannot now be supplied.

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HOSPITAL AIR CONDITIONING*

C. P. Yaglou

APPLICATION of air conditioning to hospitals is now mainly confined to four or five wards in which partial or complete air conditioning has proved of sufficient value to justify its use. These wards are: (a) nurseries for premature infants, (b) anesthesia and operating rooms, (c) oxygen therapy chambers, (d) heat therapy rooms or cabinets, and (e) allergic wards.

Application to delivery and maternity rooms is at present believed to be a secondary consideration, at least in the North. The most popular use of air conditioning is in operating rooms and nurseries, with a steadily increasing number of installations, particularly in new buildings.

The purpose of the present paper is to discuss the objectives of air conditioning as applied to these five wards, and the special problems arising in each particular case.

Air Conditioning Nurseries for Premature Infants

Of first importance is probably the application to the institutional care of premature and other debilitated infants. In these cases the maintenance of suitable temperatures with a high relative humidity as determined by extensive research, results in a striking reduction of the incidence of respiratory and digestive diseases and a great improvement in the infants' chances for life.

It has been long recognized that one of the most important requirements in the care of premature infants is the stabilization of body temperature. This is necessary because their heat-regulating system is not fully developed; the metabolism is low and the infants generally exhibit marked inability to maintain a normal body temperature by their own efforts. The resistance to infections is low and the mortality rate very high.

Air-conditioning requirements—The optimum air conditions for the growth and development of these infants were determined by extensive research at the Infants' Hospital, Boston (1), using four valid criteria, namely, stability of body temperature, gain in weight, incidence of digestive syndromes, and mortality. Wide variations were found in individual requirements for temperature according to the constitutional state of the infants and body weight, as shown in table 1. The optimum relative humidity was about 65 per cent.

A single nursery conditioned to 77°F. temperature and 65 per cent relative humidity would fulfill the requirements of the majority of premature infants. Additional heat for weak or debilitated infants may be furnished in the cribs, or by means of electric incubators placed inside the conditioned nursery and adjusted according to individual requirements (see table 1). In this way the necessity for multiplicity of chambers and

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TABLE 1

Air Conditioning Requirements of Premature Infants

From Studies at Infants Hospital, Boston, Massachusetts, 1926–1929

Classification of infants	Weight groups	Incubator or room temperatures	Room relative humidity	Air motion	Suggested method of treatment using a single conditioned nursery
	lbs.	*°F.*	*per cent*	*ft./min.*	
Congenitally diseased and malformed infants	1.5–2.9	100*–84*	65	10–20	Infants requiring a temperature higher than 77° may be placed in heated beds with tops open, and heat gradually adjusted according to individual requirements. In this way infants breath cool room air of about 77° temperature, and 65 per cent relative humidity
	3.0–4.4	90*–78	65	10–20	
	4.5 and over	85*–76	65	10–20	
Normal premature infants	1.5–2.9	88*–78	65	10–20	
	3.0–4.4	86*–75	65	10–20	
	4.5 and over	85*–72†	65		With exception of definite cases of hypothermia infants may be discharged to general wards

* Incubator temperature between basket and metal wall.

† Approximate temperature in general wards in wintertime.

TABLE 2

Fluctuation of Body Temperature in Unconditioned and in Conditioned Nurseries

Infants Hospital, Boston, Massachusetts

(Courtesy Am. J. Dis. Children)

Body weight at beginning of each week	Unconditioned nursery (1923–1925) natural humidity					Conditioned nurseries (1926–1929) relative humidity (50–75 per cent)				
	Number of observations	Mean weekly body temperature			Mean maximum fluctuation	Number of observations	Mean weekly body temperature			Mean maximum fluctuation
		Minimum	Average	Maximum			Minimum	Average	Maximum	
lbs.		*°F.*	*°F.*	*°F.*	*°F.*		*°F.*	*°F.*	*°F.*	*°F.*
1.5–1.9	0					1	96.7	98.0	99.7	3.0
2.0–2.4	2	96.0	98.7	102.3	6.3	9	96.1	98.0	99.7	3.6
2.5–2.9	11	97.1	98.8	101.4	4.3	23	96.4	98.2	99.9	3.5
3.0–3.4	26	97.4	99.1	101.6	4.2	48	96.9	98.3	99.8	2.9
3.5–3.9	44	97.3	98.8	100.9	3.6	84	97.2	98.4	99.7	2.5
4.0–4.4	49	97.3	99.0	100.8	3.5	103	97.5	98.5	99.6	2.1
4.5–4.9	55	97.6	99.1	100.9	3.3	103	97.6	98.7	99.9	2.3
5.0–5.4	51	97.6	98.7	100.3	2.7	63	97.7	98.7	99.9	2.2
5.5–5.9	39	97.5	98.7	100.4	2.9	31	97.7	98.6	99.9	2.2
6.0 and over	33	97.6	98.7	100.2	2.6	15	97.9	98.7	99.8	1.9

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of air-conditioning apparatus is obviated; the infants in the heated beds derive the benefit of breathing cool humid air, and the nurses and doctors need not expose themselves to extreme conditions.

Stabilization of body temperature.—Comparative data on stabilization of body temperature in the unconditioned and air-conditioned nurseries of the Infants Hospital are shown in table 2, including all infants treated in the old and new nurseries except those who died of acute infections and congenital anomalies incompatible with life. The improvement in the conditioned nurseries apparently resulted from a better control of temperature, superior ventilation methods, suitable provisions for cooling the room in warm weather, and the comparatively high humidity which prevailed.

Although external heat is an important factor in the maintenance of normal body temperature, humidity appears to be of equal or greater importance. The studies at the Infants Hospital showed that when low relative humidities between 25 and 50 per cent prevailed for 2 weeks or longer, the body temperature became unstable, gains in weight diminished, the incidence of gastro-intestinal disturbances increased and the mortality rose. On the other hand, continuous exposure to air conditions with 55 to 65 per cent relative humidity gave satisfactory results over a period of years.

*Initial loss of body weight.**—In table 3 is given the initial physiologic loss of body weight among premature infants treated in unconditioned and in air-conditioned nurseries with low and high humidities. The loss appears to vary inversely with the humidity. In the old nurseries with natural humidity the average weight loss for all infants was 12.4 per cent of the birth weight; in the conditioned nurseries it was 8.9 per cent with 25–49 per cent relative humidity, and 6.0 per cent with 50–75 per cent relative humidity.

TABLE 3

"Initial Loss" in Body Weight of Premature Infants and Days to Regain Birth Weight under Various Air Conditions

Infants Hospital, Boston, Massachusetts
(Courtesy Am. J. Dis. Children)

Approximate birth weight	Old unconditioned nursery (1923–1925)—natural humidity	Conditioned nurseries (1926–1929)	
		Low relative humidity (25–49 per cent)	High relative humidity (50–75 per cent)
"Initial loss" in percentages of birth weight			
lbs.			
Under 3		10.2	9.3
3 to 4	12.7	8.8	6.1
Over 4	11.5	5.4	4.7
All weights	12.4	8.9	6.0
Days to regain birth weight			
Under 3		20.7	28.5
3 to 4	19.5	18.3	14.1
Over 4	33.5	18.3	13.0
All weights	26.5	19.5	15.1

*Loss occurring within first four days of life.

The number of days required to regain the birth weight was correspondingly maximum in the old nursery, minimum in the conditioned nurseries under high relative humidity and intermediate in the conditioned nursery with low relative humidity (see table 3).

Gain in body weight.—Maximum gain in body weight after the first week of life occurred in the conditioned nurseries under high humidity in infants weighing less than 5 lbs. The gain was less under low humidity and in the old nursery, and least after discharge to the general wards (table 4). The calorific food intake during the period, 1926–1929, was uniformly regulated according to age, weight, and condition of the infant, and it was on an average about 6 calories less than in the old nursery per pound of body weight.

TABLE 4

Average Weekly Gain in Weight of Premature Infants under Various Air Conditions

Infants Hospital, Boston, Massachusetts
(Courtesy Am. J. Dis. Children)

Weight at beginning of week	Unconditioned nurseries (1923–1925)—natural humidity	Conditioned nurseries (1926–1929)—relative humidity		After discharge to general wards (1926–1929)—natural humidity
		25–49 per cent	50–75 per cent	
lbs.	*oz.*	*oz.*	*oz.*	*oz.*
Under 2.5	(−7.0)	1.6	2.5	
2.5–3.9	2.8	2.6	3.8	
4.0–5.4	4.7	3.9	5.0	3.9

Digestive disturbances.—The incidence and severity of digestive syndromes, with diarrhea, persistent vomiting, diminishing gains or loss of body weight, and other untoward symptoms, were generally twice as high under low than under high humidity (table 5). In a comparable group of 63 infants who lived under both high and low humidity during periods in which the humidity was altered weekly or biweekly between high and low, the incidence under low humidity was about three times higher than under

TABLE 5

Weekly Relative Incidence and Severity* of Digestive Syndromes in Premature Infants

Infants Hospital, Boston, Massachusetts
(Courtesy Am. J. Dis. Children)

	Incidence	Severity
All premature infants		
	per cent	*per cent*
Unconditioned nursery, 1923–1925		
Natural relative humidity	21.1	17.7
Conditioned nurseries, 1926, 1929		
Relative humidity 25–49 per cent	22.9	18.3
Relative humidity 50–75 per cent	11.6	8.4
A comparable group of 63 infants exposed to alternating humidity conditions (1926–1929)		
Relative humidity 25–49 per cent	30.2	20.3
Relative humidity 50–75 per cent	11.1	5.4

*Evaluated by the duration of syndrome in weeks. Percentage severity is the number of infant-weeks of the syndrome expressed in percentage of the total number of infant-weeks under observation.

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high humidity and the severity was about four times higher, as shown in the lower part of table 5.

Mortality.—Finally, the mortality of premature infants was found to be greatly affected by humidity. In table 6 is given the net mortality according to the humidity in which the derangement of body function began. Acute and chronic infections were the principal contributory cause of death. In the old nurseries the death rate from this cause was 26.5 per cent, as compared with 9.7 per cent in the contioned nurseries under low humidity and 0 per cent under high humidity.

Summarizing the conclusions of these studies: the best chances for life in premature infants are created by maintaining a relative humidity of 65 per cent or more in the nursery and

TABLE 6

NET* MORTALITY OF PREMATURE INFANTS ACCORDING TO HUMIDITY

Infants Hospital, Boston, Massachusetts
(Courtesy Am. J. Dis. Children)

CAUSE OF DEATH	UNCONDITIONED NURSERIES (1923–1925)—NATURAL HUMIDITY	CONDITIONED NURSERIES (1926–1929)—RELATIVE HUMIDITY	
		25–40 per cent	50–75 per cent
	per cent	*per cent*	*per cent*
Acute and chronic infections	26.5	9.7	0.0
Congenital deformities	1.2	0.0	0.7
Unclassified	1.2	4.8	0.0
All causes	28.9	14.5	0.7

* Excluding cases with multiple congenital anomalies incompatible with life, and also deaths occurring within 48 hours after admission to the hospital.

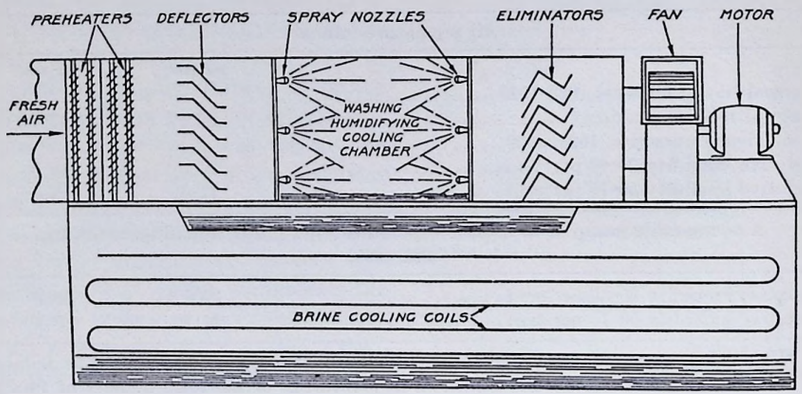


FIG. 1.—Diagrammatic sketch of central air-conditioning apparatus. (Courtesy Am. J. Dis. Children.)

by providing a uniform external temperature just sufficiently high to keep the body temperature within normal limits. Medical and nursing care are, of course, factors of equal and sometimes of greater importance.

A humidity of 65 per cent cannot be obtained without resorting to mechanical equipment. As a matter of fact, even the lowest humidity used in these studies (25–30 per cent) was considerably higher than that which prevailed in the unconditioned nurseries during the cold season of the year.

Air conditioning equipment for premature nurseries.—The air conditioning system of the Infants Hospital has been fully described in another paper (2). Briefly it consists of a central station plant in the basement of the building, including a spray type dehumidifier (see figs. 1 and 2), a Baudelot brine cooler, aerofin preheaters and reheaters, and a separate supply and

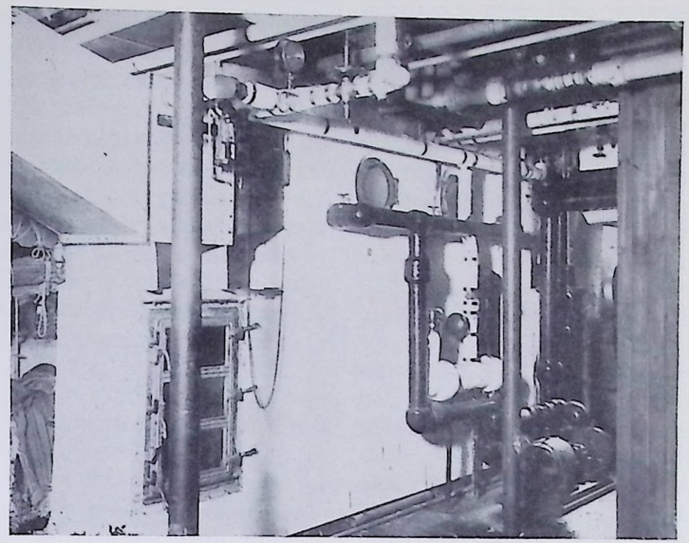


FIG. 2.—Central air-conditioning apparatus in basement directly under nurseries. (Courtesy Am. J. Dis. Children.)

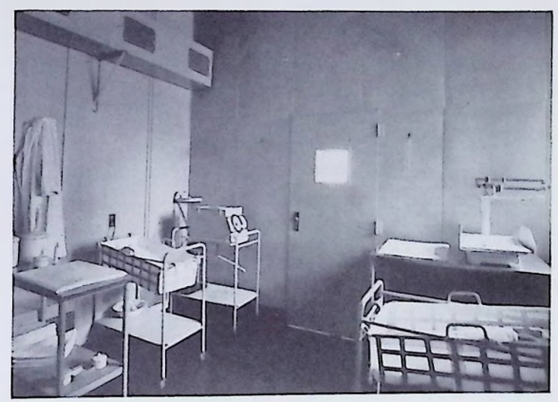


FIG. 3.—Interior view of one of the nurseries at Infants Hospital, Boston, showing location of supply (top) and exhaust (bottom) registers.

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exhaust system (see fig. 3) in each of the three nurseries.

Compact unit air conditioners are now available at reasonable cost for installation inside the nursery or in an adjoining small space, more often taking the place of radiators under windows in the nursery. These units perform all the essential functions of the central system and when properly designed and operated, give fairly satisfactory results.

Air Conditioning Operating Rooms

Air conditioning in operating rooms is mainly concerned with the welfare of the patient, the comfort and efficiency of the surgeon and his personnel, and with the safety of the whole procedure.

Explosion of anesthetic gases.—The recent introduction of ethylene in modern anesthesia, and the increasing use of oxygen in combination with ether or with ether-nitrous oxide mixtures has increased the possibility of explosion from static sparks which might result from accumulation of frictional charges on the rubber surfaces of the anesthesia apparatus, on woolen blankets, and on the bodies of the operators as they walk on insulated floors, when the humidity is quite low. Ethylene or ether in themselves are not explosive but they become explosive when mixed with oxygen or air in certain concentrations. The approximate limits of inflammability of ether and ethylene are given in table 7. The lower limits are fairly definite, but the upper limits are subject to great variability depending upon a number of factors (3).

The upper limits shown in table 7 represent approximately the highest values recorded by Coward (3), but the data are incomplete. Most violent explosions occur in mixtures containing about 30 per cent ethylene or ether and 70 per cent oxygen (4, 5, 6). Actually the risk of serious explosion with ether is not so great as with ethylene because the concentrations of ether used for full anesthesia are below the violent explosive range.

During the course of ethylene anesthesia the mixture (usually 80 per cent ethylene and 20 per cent oxygen) is so rich that the danger of explosion is slight and is confined to an area in the immediate vicinity of the face mask, where leakage of ethylene into the air may accumulate to the lower explosion concentration (7). With good ventilation this rarely occurs.

TABLE 7

Approximate Limits of Inflammability of Ethylene and Ether
(Coward (3))

Mixed with	Ethylene		Ether	
	Lower limit	Upper limit	Lower limit	Upper limit
	per cent	*per cent*	*per cent*	*per cent*
Air	3.0	30±	1.7	50−
Oxygen	3.0	80−	1.7	40±
Nitrous oxide			3.8	26±

The most dangerous period is at the end of the operation when the patient's lungs and the apparatus are customarily "washed out" with oxygen, with or without the addition of carbon dioxide. Even when this procedure is omitted it is impossible in practice to avoid dilution of the anesthetic gas with air during the normal course of breathing following the administration of anesthesia. In either case the mixture would pass through the explosion range and extraordinary precaution is necessary for the safety of the patient and operating personnel.

The danger from the use of cautery and sparking electrical apparatus during or after the administration of explosive anesthetics is now well recognized, and proper precautions are being taken to preclude further accidents from this cause. Static electrification, the most important cause of accidents is of a more fortuitous character and cannot be effectively controlled in a dry atmosphere by grounding the various parts of the anesthesia apparatus, so long as rubber remains in use in the conventional equipment (8, 9). Grounding affects but a small section of the rubber, while a section an inch or two away may still remain charged as shown by Herb (9) by means of an electroscope.

To prevent accumulation of static charges within the apparatus or on persons coming near to it, the measures proposed by the committee on anesthesia accidents of the American Medical Association (4, 8) are humidification of air to between 55 and 60 per cent relative humidity, grounding the apparatus and operating table, and using conducting floors and shoes so that the operating staff and attendants will always be grounded as they move about.

The significant factor is the absolute humidity, rather than the relative humidity, because upon it depends the electrical conductivity of the air. There is complete unanimity among all workers in the effectiveness of high humidity, not only in operating rooms but in many industrial plants where similar situations arise, provided, however, that mechanical humidification methods can be depended upon to maintain the humidity.

In Cuba, with its warm and moist climate, explosions from static sparks are unknown despite the fact that the apparatus is seldom grounded (10). The only precaution taken there is to avoid the use of cautery and sparking apparatus in the presence of explosive mixtures.

The chief drawback to artificial humidification is the need of constant supervision, as a drop of humidity due to failure of the humidistat or humidifier might prove disastrous. To overcome this objection a piece of sheet metal is sometimes applied to the floor, large enough to accommodate the operating table, anesthesia apparatus, and personnel, which are kept grounded at all times by contact with the earthed metal sheet. In new buildings, terrazo floors with grounded brass strips are often installed.

Artificial humidification in operating rooms during the winter months may also prove beneficial in reducing evaporation from exposed cavities and from the wet skin of the patient, and by allowing a lower room temperature.

Operating room temperatures.—The problem of operating room temperature is a difficult one and not much is known concerning the optimum air conditions necessary to maintain a normal body temperature under the influence of anesthesia and in the immediate post-operative period.

All anesthetics are known to be vasodilators to some extent. The dilatation of the cutaneous vessels is accompanied by much sweating, particularly in the case of ether anes-

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thesia, irrespective of environmental temperature (11, 12), and may lead to a serious concentration of the blood. The loss of body heat is increased considerably, while the general metabolism may be depressed. The organism loses ability to regulate its own body temperature and becomes unusually sensitive to chilling and post-operative complications. The dangers and necessary precautions have been stressed by many and recently by Eliason and McLaughlin (13) and Brown (14). One of the advantages of ethylene over ether is that it does not cause so much sweating. This conserves fluids and guards against chilling of the body with its serious complications (15).

Barbour and Bourne (11) demonstrated that normal dogs under ether anesthesia are so lacking in power to regulate their body temperature that an air temperature as high as 88°F. (31°C.) is required to maintain normal body temperature in either dry or moist atmospheres. Below 88°F. the body temperature fell and the blood solids increased, while above 88° there was a slight increase in body temperature. Administration of water or hypotonic solution in sufficient amounts completely to offset the concentration of blood induced by ether lowered the body temperature and an air temperature of about 91.5°F. was necessary to keep normal body temperature and fluidity of blood.

Such high temperatures are obviously unbearable for the surgeon and his team and in order to alleviate the condition the room temperature is usually kept between 72 and 80° in cold weather with the patient carefully clothed and surrounded with blankets and hot water bottles during and for sometime after the operation.

Post-operative heat stroke.—It would seem that surgeons have learned to fear so much the occurrence of post-operative pneumonia and shock that even in hot summer weather patients are sometimes needlessly "bundled up", with detrimental consequences.

In 1916 Moschcowitz (16) reported several deaths from heat stroke following surgical operations, and a number of cases suffering from a mild isolation. He wondered how often cases of post-operative heat prostration were recognized as post-operative reaction or shock with a history and course that were characteristic of heat prostration. He concluded with the warning that all operating room activities should cease during summer heat waves with the exception of urgent operations, when every effort should be made to keep the patient cool and comfortable.

In cases of exopthalmic goitre, Walton (17) warns most emphatically against the performance of operations in extremely warm weather, for under such conditions the risk in spite of all precautions (prior to the introduction of summer cooling in operating rooms) is too great. An analysis of his cases over a 10-year period shows a striking rise of post-operative deaths in June, July, and August, resulting unexpectedly from extreme post-operative reaction passing onto acute hypoerthyroidism.

More recently Martin (18) reported four cases of post operative heat stroke admitted 24 hours preceding operation and sheltered from direct sun rays. All four were not ill and apparently good risks. There occurred, however, at the time of operation and for several days preceding it a heat wave, with a moderately high temperature, a high relative humidity, and no wind. In addition to warm weather, excessive loss of body fluids is believed to have been a factor in the production of heat stroke in these four cases.

Aside from the possibility of post-operative heat stroke in warm and sultry weather, the surgeon is also concerned with the lowered recuperative power of the patients, and with his own discomfort and that of his team which impairs the efficiency of the technic, to the disadvantage of the patient.

In view of this experience it is customary to defer major operations as much as possible until the passing of heat waves in hospitals not equipped with cooling facilities. But there are exceptional cases, like acute appendicitis for instance, which sometimes comes in epidemic waves paralleling summer heat waves (19), a highly fatal condition unless promptly operated upon.

Complete air conditioning of operating rooms would, therefore, seem to be a necessity for the protection of the patient and operating personnel against summer heat as well as for minimizing the possibility of explosion of anesthetics in dry winter atmospheres.

Satisfactory air conditions.—Although the comfortable air conditions for the operatives are not identical with those of the patient, a compromise is as a rule not difficult. With a relative humidity of 55 to 60 per cent, a temperature of 80° in warm weather, and between 72 and 75° in cold weather will probably prove satisfactory. Additional heat may be furnished to the patient locally or by suitable covering according to body temperature in individual cases.

Comments from surgeons and superintendents of hospitals with conditioned operating rooms are uniformly favorable except in a few instances in which the air conditioning engineer failed to appreciate the special requirements of this important application.

Air conditioning equipment.—Central station air conditioning plants and individual unit air conditioners proved satisfactory in operating rooms producing between 8 and 15 air changes per hour of filtered and properly humidified air, with full provision for summer cooling and dehumidification but no recirculation during the course of anesthesia. A separate exhaust fan system is as a rule necessary in order to confine and remove the gases and odors. Double windows are desirable and often necessary to prevent condensation and frosting on the glass in cold weather and to minimize drafts. The high air flow of 8 to 15 air changes in operating rooms is desirable for three reasons: (a) to reduce the concentration of the anesthetic to well below the physiologic threshold in the vicinity of the operating team, (b) to remove excessive amounts of heat and sometimes moisture from sterilizing equipment if inside the operating room, from the powerful surgical lights, solar heat, and from the bodies of the operatives, and (c) to provide extra capacity for quickly preparing the room for emergency operations.

Much can be gained by careful insulation of sterilizing equipment and

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by thorough exhaust ventilation of sterilizing rooms adjoining the operating rooms.

It is generally believed that in addition to operating rooms, an adjoining small ward should also be conditioned as the prostration often occurs after removal of the patient from the operating room. Such a post-operative ward would also prove valuable in treating patients with heat stroke, fever, summer diarrhea and other cases affected by high temperature.

Air Conditioning in Oxygen Therapy

Oxygen therapy is the principal measure employed for preventing and relieving the destressing symptoms of anoxemia,* and its serious consequences. Excellent reviews of the underlying physiological principles of oxygen therapy and its value in various diseases have been made by Haldane (20), Barcroft (21, 22), Lundsgaard and Van Slyke (23), Meakins and Davis (24), and more recently by Peters and Van Slyke (25), Boothby (26) and Potts (27).

Some of the more important conditions in which oxygen treatment has proved beneficial are pneumonias, anemia, heart affections, post-operative pulmonary disturbances, certain mental disturbances, asphyxia, asthma, and atelectasis in new-born infants.

Recently, Evans (28) and Barach (29) made interesting statistical evaluations of oxygen therapy in pneumonia and other respiratory diseases on the basis of symptoms and mortality in various groups of patients treated with and without oxygen. The general conclusion is that oxygen therapy is beneficial in the treatment of many cases and life-saving in a substantial number of cases. The efficacy in the treatment of pneumonia appears to be practically in direct proportion to the day of the disease on which the oxygen treatment is started (28).

* Deficiency in the oxygen content of the blood.

Methods of Administering Oxygen

Nasal catheter.—The most common methods used for administration of oxygen to patients are the nasal catheter, the oxygen tent and the oxygen chamber. The nasal catheter is the routine method of oxygen administration in all hospitals under ordinary conditions. With it, concentrations between 35 and 38 per cent may be obtained in the inspired air using an oxygen flow rate of 4 to 5 liters per minute. The method is simple and inexpensive, but it may cause considerable discomfort to the patient and it is not at all satisfactory for continuous administration and in restless or delirious states.

Oxygen tents.—For oxygen concentrations higher than 40 per cent, a suitably-cooled oxygen tent or an air-conditioned oxygen chamber must be employed. The conception of a tent-like arrangement is credited to Thomas Beddoes (30), pioneer in inhalation therapy. The first practical tent, as used by Leonard Hill (31), consisted simply of a rubberized fabric fixed about the bed of the patient. Modern oxygen tents consist of a round or square hood of at least 10 cu. ft. capacity, made of rubberized fabric with transparent cellulose acetate windows, as shown in fig. 4.

Oxygen tents are usually equipped with an ice-cooling system for controlling the temperature and to some extent the humidity inside the tent (fig. 4). The air is circulated by means of a small motor blower which sends the air over soda lime to remove carbon dioxide and then over ice to remove excess heat and moisture. The concentration of oxygen in the tent is regulated by means of a pressure-reducing valve and flowmeter. It is very important that the concentration be tested routinely to guard against leaks and to see that it conforms with the physician's prescription.

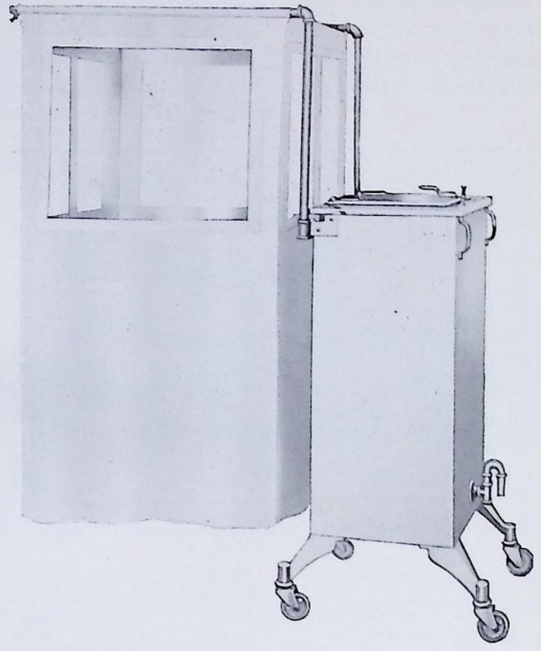


Fig. 4.—A modern oxygen tent with ice chest for cooling. (Courtesy Warren E. Collins, Inc.)

The usual requirements for air conditions inside the tent in the treatment of pneumonia are a temperature of about 65°, relative humidity under 50 per cent, oxygen ± 50 per cent, carbon dioxide less than 1 per cent, with more or less odorless air (32). Higher temperatures up to 75° may prove suitable in the aged and feeble, or in patients with little or no fever. The oxygen flow rate is between 5 and 10 liters per minute, or higher in old, leaky equipment.

In an inadequately cooled oxygen tent, high temperatures and humidities are inevitable (33) increasing the discomfort of the patient and imposing an added strain on an already overburdened heart. Oxygen therapy under such conditions may do more harm than good. It is estimated that an ice-melting rate of about 10 lbs. per

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hour gives satisfactory results in patients with fever (34).

The oxygen tent is somewhat confining to the patient; the restless type of person is difficult to control, and the delirious, impossible to control (34). Nursing and medical care is complicated, as the tent must be opened or removed with attendant loss of oxygen. Oxygen concentrations of 50 per cent or more are difficult to maintain, and it is difficult to keep the temperature and humidity low enough to meet the requirements under certain conditions.

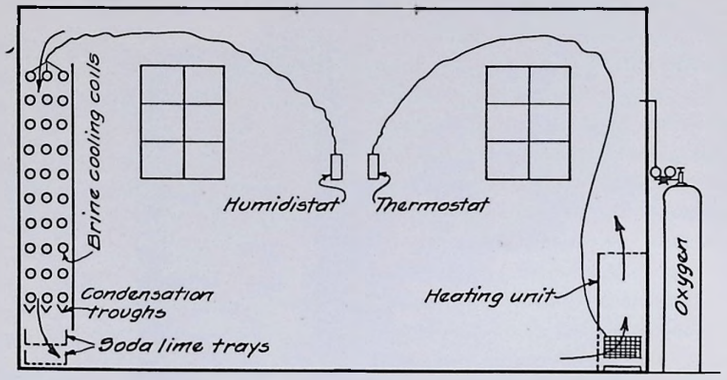


FIG. 5.—Diagrammatic sketch of a conventional oxygen chamber with gravity air circulation.

The advantages are portability, which in emergencies is an important factor, and low initial and operating costs compared with the oxygen chamber. With proper care the tent was found to fulfill most clinical requirements of oxygen therapy in many hospitals at a reasonable cost.

Oxygen chambers.—Oxygen chambers were introduced by Barcroft, Hunt and Dufton in England (35) and by Stadie (36) and Binger (37) in America. The conventional chamber is an air-tight sheet metal enclosure of fire proof construction, large enough to accommodate one or two patients. Trap doors or curtains are provided for the personnel, food, and service, to avoid loss of oxygen; glass windows in the ceiling and side walls admit light from electric fixtures outside the chamber.

The air-conditioning system may be of the gravity type used first by Barach (38), or the fan type using mechanical refrigeration or silica gel for drying the air. The gravity system includes a bank of brine coils which cool and dehumidify the air (see fig. 5). The cool air then passes over trays containing soda lime to remove the carbon dioxide given off by the occupant. A heater at the base of the opposite wall warms the air to the desired temperature and is regulated by means of a thermostat controlling the amount of steam flowing through the heater. The humidity is controlled by means of a humidistat regulating the flow of brine through the cooling coils which in turn controls the rate of condensation of moisture on the coil surfaces. A spray dehumidifier is not suitable for this purpose because it is often desired to cool the air below 32°F. in order to obtain low relative humidities. The only change of air in the chamber is that taking place by leakage through trap doors.

Ordinary industrial oxygen is introduced from storage tanks outside the chamber. The concentration is tested at frequent intervals and regulated according to the prescription of the physician.

The chief objections to the gravity circulation system are stratification of cold air near the floor, and accumulation of odors, which may require the use of activated charcoal or an excess of oxygen for deliberate aeration.

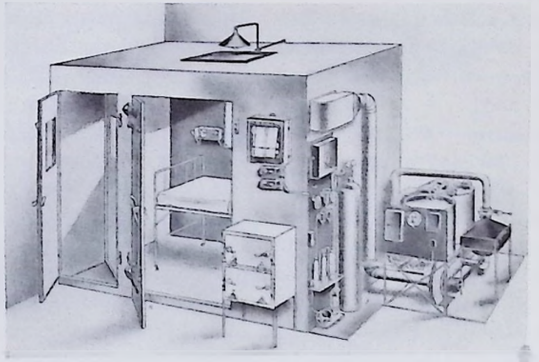


FIG. 6.—A one-patient oxygen chamber of the fan-circulation type, using silica gel for dehumidification of air. (Courtesy Silica Gel Corporation.)

The fan circulation systems include compact cooling coils (extended surface coolers), heaters, and sometimes silica gel beds, installed outside the chamber, as shown in fig. 6.

Silica gel is used for the absorption of moisture but it also removes a little carbon dioxide and some odoriferous matter. For the treatment of certain respiratory conditions, relative humidities well below 30 per cent can easily be maintained by the use of silica gel.

There is also a portable oxygen chamber (39) consisting of rubberized fabric attached to a metal frame. This type of chamber requires no soda lime, as the leakage through the fabric is sufficient to prevent accumulation of carbon dioxide.

Oxygen chambers are unquestionably more comfortable than oxygen tents. The patient receives unhampered medical and nursing care, and the oxygen concentration, the temperature, and humidity can be adequately controlled at any desired level. The chief disadvantage is high initial and operating costs in comparison with simpler methods. The conventional metal chamber costs $2500–$4000 to build and is about twice as expensive to operate as an oxygen tent. The chamber method is of value in large hospitals and for research and experimental purposes, but for routine oxygen therapy alone it may prove a liability rather than an asset in small hospitals.

There is no reason why an ordinary

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room or ward cannot be suitably equipped for the treatment of most diseases affected by heat, cold, humidity, or chemical constitution of the air, including oxygen therapy. Instead of the expensive metal chamber construction, the walls and windows of a room can be specially treated to make them fireproof and reasonably air tight as has already been done (40, 41), while at the same time preserving the general appearance of the room which means so much to certain psychic patients. Pneumonias, respiratory and heart affections, fevers, vascular disorders, summer diarrhea, allergic conditions, etc., can all be taken care of in one or two such rooms without serious difficulties in the engineering of the apparatus. When not needed for any special purpose the rooms can be used as ordinary wards with or without air conditioning.

The temperature and humidity requirements in oxygen therapy depend primarily upon the physical condition of the patient and secondarily upon the type of disease. In pneumonias, the range of satisfactory temperatures and humidity is placed between 60 and 75°, with 20 to 50 per cent relative humidity. The concensus seems to favor a low humidity, as low as is consistent with economy.

Air Conditioning in Fever Therapy

Underlying Principle

While empirical use of heat in the treatment of disease dates back to the Chinese more than 4000 years ago, it was not until the introduction of malaria therapy by Wagner v. Jauregg in 1918 that the practice of true fever therapy began along scientific lines.

Artificial production of fever in man is an imitation of nature's way of overcoming invading pathogenic organisms. The action may be direct and specific by obliteration or destruction of the invading organism within the safe limit of human fever temperature; or an indirect one in case of heat resistant organisms, through general mobilization of the defensive mechanisms of the body, by means of which the activity of pathogenic bacteria and their toxins may be retarded or neutralized.

The limits of induced systemic fever are usually between 104 and 107°F. (rectal), and the duration from 3 to 6 hours at a time. The total period of fever treatment varies with the type of the organism involved from a few hours to 50 hours or more.

Among the recent articles on the physiologic action of heat in fever therapy are those of Doan and Hargraves (42), Bierman (43) and Cohen and Warren (44). A most thorough review of the general literature on the effects of heat upon the normal organism was written by Bazett (45) in 1927.

The diseases reported (46, 47) to respond favorably to artificial fever therapy are: gonorrhea, neurosyphilis, chorea, asthma, peripheral vascular diseases, occular gonorrhea and syphilis; there are a number of other conditions in which the usefulness of artificial fever is not yet settled. The most striking results are seen in gonorrhea in which the various strains of organism can be killed by artificial fever within the limit of tolerance of man (48, 49).

Air Conditioning in the Production of Systemic Fever

Various means have been tried for producing artificial fever, including injections of vaccines, crystalloid or colloid substances; a number of physical methods such as hot baths, radiant heat, diathermy, radiothermy and, in the last few years, an air conditioned chamber known as the "Kettering Hypertherm."

The relative advantages and disadvantages of these various methods were discussed in a recent paper by Desjardins, Stuhler, and Popp (49), and Doub (50). Although comparable clinical results are possible with most of these methods, the air conditioned cabinet proved to be the safest and most effective method from all points of view.

This type of cabinet was fully described by Simpson (51) and Desjardins *et al.* (49). Briefly, it consists in an insulated cabinet approximately 6 ft. long, 3 ft. wide, and 2½ ft. high, containing in a small rear compartment electric air heaters, an electrically heated water pan for humidification, a centrifugal fan for circulating the air in the front compartment and a thermostat and a humidistat for controlling the temperature and humidity automatically. The nude patient lies on an air mattress inside the front compartment with his head protruding outside the front end through a rubber collar.

Hot air at 130–150°F. temperature and 30–50 per cent relative humidity is blown upon the body of the patient, and the rectal temperature rises to 105°F. usually in from 40 to 60 minutes. The loss of water and chlorides are replaced by mouth during the treatment. Any degree of fever can be attained quickly or slowly, as desired, and maintained for as long as the physician may prescribe according to individual requirements.

In the writer's opinion saturated or nearly saturated air of comparatively low temperature would probably prove more suitable for the production and maintenance of fever than hot dry air as now employed in the Kettering Hypertherm. The cutaneous water and chloride losses would probably be appreciably less (52); skin burns would be entirely eliminated and the room in which the hypertherm is located would not be overheated as much as with drier air of higher temperatures.

The average rate of rise of body temperature in a group of normal male subjects exposed to various environmental temperatures, humidities and air velocities is shown in figure 7 which was constructed from experimental data of McConnell and Yaglou (53). It can be seen that with a relative humidity of 30 per cent it would take much too long to raise the body temperature 6°F. (from 99 to 105) without resorting to excessively high air temperatures. With 60 per cent relative humidity and an air movement of 400 feet per minute over the body, a temperature of about 120°F. is required to raise the body temperature 6°F. in 1 hour, whereas with saturated air the required temperature is between 106 and 107°F. The values would, of course, vary in different individuals and different diseases.

Few data are available on the combinations of temperature, humidity, and air movement required to maintain the body at various fever tem-

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peratures after initial heating. In practice the heat is turned low and adjusted so as to maintain the desired body temperature in each individual case.

Under certain conditions a combination of systemic fever and additional local heating by diathermy or other means is claimed to yield better results than systemic fever alone (54), by reducing considerably the killing time of the organisms and rendering the treatment less trying to both patient and attendants.

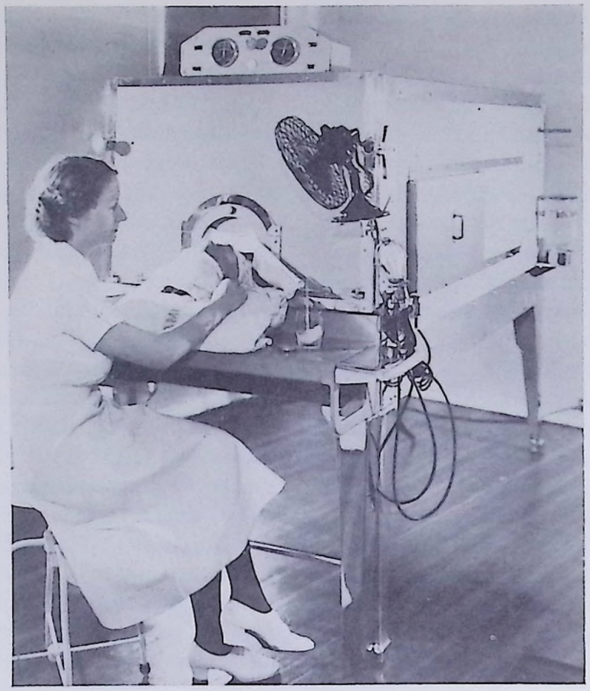


Fig. 7.—The Kettering hypertherm. (Courtesy Walter M. Simpson, M.D., Miami Valley Hospital, Dayton, Ohio.)

The introduction of practical air conditioning methods in fever therapy, accompanied with judicious selection of patients and a skillful technic is believed to have removed practically all danger of serious complications (49). Conditioned air, according to Walker (55), offers a safer method of producing artificial fever than diathermy. Heating rats to 111.4°F. by means of conditioned air seemed to be less harmful than heating them to the same temperature by the use of high frequency currents.

Extensive research is now in progress to determine the usefulness and limitations of fever therapy on a wide variety of pathologic conditions. While this form of therapy is rapidly gaining wide recognition, its application, according to the American Medical Association, "should be strictly a hospital procedure surrounded with the safeguards commonly employed in a major operation and under the direction of skilled physicians".

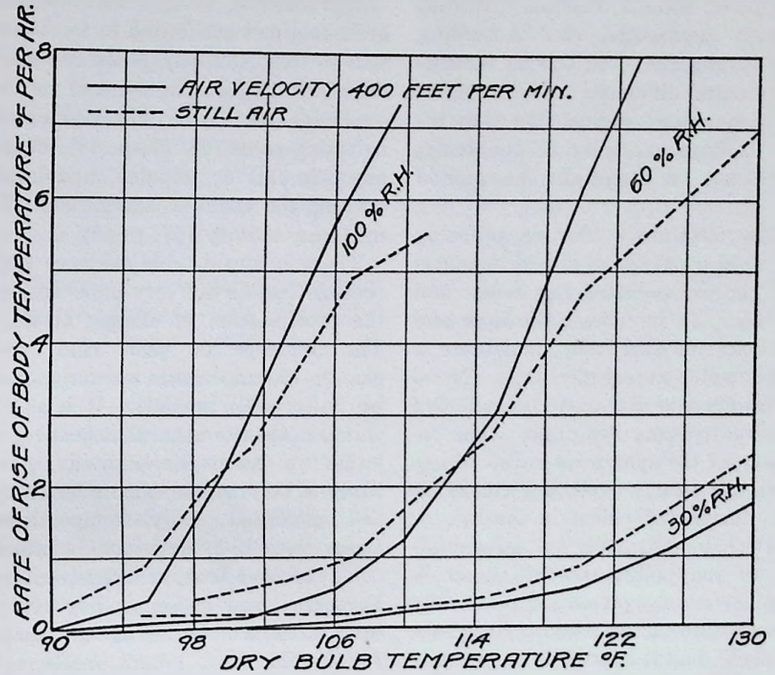


Fig. 8.—Average rate of rise of body temperature (rectal) in a group of normal male subjects exposed to various temperatures, humidities, and air velocities in an air-conditioned room. (Courtesy Am. Soc. Heating and Ventilating Engineers.)

Air Conditioning in the Control of Allergic Conditions

In the treatment of allergic conditions medical methods have gained a high degree of success in a great majority of cases, but a small number of patients (usually between 10 and 25 per cent) have not been sufficiently benefited even in the hands of the best authorities.

Since 1920 considerable effort has been directed toward the elimination of the principal cause of allergy from the air by filtration or other air conditioning processes capable of removing pollens, in the hope of providing relief to individuals who failed to respond to medical treatment.

Cause and Symptoms of Hay Fever and Asthma

A number of excellent reviews have recently appeared on the general subject of allergy, among them being those of Van Leeuwen (56), Vaughan (57), Feinberg (58) and Bray (59).

Although there has been some division of opinion over the ultimate cause of allergy, the prevailing belief is that it is due to an inherited or acquired hypersensitiveness to foreign

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or pollen proteins in certain individuals who react to the offending substance. The reaction may be induced by inhalation, ingestion, or absorption of the allergenes through the skin. The clinical manifestations are hay fever, asthma, eczema, urticaria, contact dermatitis, etc. According to Feinberg (58) and others, there is no essential difference between any of these symptoms except that they affect different portions of the body; the causes are essentially the same in all.

The respiratory tract is probably the most usual site of allergic manifestations, the so-called hay fevers and asthma. In hay fever the nose and eyes are red and itchy, and there is considerable watery discharge. Nasal obstruction is the most common and most distressing symptom. The severity of the symptoms varies widely from day to day depending chiefly on the number of pollen in the air.

Durham (60) made extensive studies of the pollen content of air in seventy cities representing practically every State in the union. By means of these data it is possible to evaluate the various hay fever pollens of regional and general importance during the Summer and Fall.

Seasonal asthma comes in attacks. The most popular theory concerning the mechanism of action is that the offending substance irritates the nerve endings in mucous membranes of the respiratory tract causing spasmodic contraction of the small bronchioles of the lungs, which interfere with breathing, particularly with expiration. The attack may also be induced when the offending protein enters the stomach in food. There is considerable suffering during periods of attack, and despite the old saying that "asthma never kills," all studies by insurance companies (61) show a mortality for asthma cases well above the normal for standard risks.

Non-seasonal allergic disturbances are sometimes attributed to sensitization to fungi (62, 63), house or street dust including one or more of its ingredients (64, 65, 66, 67), odors and irritating gases (68, 57, p. 45), or to any stimulus or impulse capable of exciting the vagus of allergic individuals into activity (57, p. 45).

There is considerable evidence that thermal factors are very important in the precipitation of allergic attacks. The influence of heat, cold, and changes of temperature was recognized by Salter (69) in 1864. It is often stated in the literature that heat regulation in asthmatic individuals is likely to be unstable, with a tendency to subnormal body temperature. Cases have been described in which cold, excessive heat, or intensive light have produced sneezing, hay fever, hives, asthma and other allergic symptoms. The most potent factor appears to be a sudden temperature change. Many allergic cases who are apparently well, develop their attacks when cold weather appears, or upon changing from warm to cool outdoor air (58, p. 55). Although exposure of patients to gradually increasing temperature contrasts has often proved beneficial, the patient must protect himself as much as possible from extreme degrees of exposure (57, p. 248).

Duke (70, 71) propounded the theory of pure physical allergy as a specific clinical entity which can be, though need not necessarily be, associated with an underlying allergic sensitiveness. The mechanism of action of such physical stimuli has not as yet been settled. Although the possibility of pure physical allergy is not denied, physical agents are generally held to be secondary factors operative only in the presence of an underlying allergic cause (58, p. 87).

Humidity also influences the asthmatic, benefiting a few but aggravating the condition in the majority of patients (58, p. 55). The beneficial effects of dry climates were discussed at some length by Van Leeuwen (72).

Usefulness and Limitations of Air Conditioning Methods in the Control of Allergic Disorders

In the care and treatment of hay fevers and asthma, two methods are now in common use: (a) desensitization, or immunization, and (b) pollen filtration with or without air cooling.

According to Vaughan (57, p. 294) desensitization treatment gives satisfactory relief in from 75 to 90 per cent of the pollen sensitive patients, as shown by results of physicians over the entire country. In hay fever and asthma this conservative estimate of cases obtaining satisfactory relief is between 70 and 75 per cent.

With filtration or air conditioning, data are somewhat limited; the available results appear to be comparable to those obtained by sensitization treatment so long as the patients remain in a pollen free atmosphere (72, 73, 74, 75, 76, 77, 78). But while specific desensitization is preventive and in a few instances curative for all practical purposes, filtration or air conditioning methods give only temporary relief. With rare exceptions, the symptoms recur on exposure to pollen laden air. Moreover the usefulness of air conditioning methods is limited because all cases are not caused by air borne substances. Sometimes the symptoms are actually aggravated by air conditioning.

Cases of bacterial asthma do not respond at all to the treatment with filtered air.

Despite these limitations, air-conditioning methods possess definite advantages in the simplicity of treatment, convenience, and under certain conditions almost immediate relief. Hay fever cases are usually relieved of most of their symptoms within an hour or so after exposure to properly filtered air (73, 75, 76, 78). In pollen asthma cases relief comes slower, usually after an exposure of from 1 to 12 days depending upon the severity of asthma (72, 73, 74, 75, 77); the more severe the symptoms the longer the time required for complete relief.

A pollen-free atmosphere is especially valuable for patients in whom desensitization has given little or no relief, and in instances in which desensitization is not advisable owing to intercurrent illness.

Kahn and Grothaus (79) after some 10 years' experience came to the conclusion that an antigen-free room offers an excellent means for diagnosing the real clinical sensitivity of refractory skin cases and many pollen asthma cases, and for the subsequent institution of proper specific dosages. Van Leeuwen (56), the pioneer of filtration treatment, arrived substantially at the same conclusion in 1925. In overtreated pollen cases of the severe chronic intractable type, a

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pollen-free room is considered absolutely indispensable (79).

On the whole, air-conditioning methods are considered to be a valuable adjunct in medical diagnosis and treatment of allergic disorders.

Air Conditioning Requirements in Allergen-Free Rooms

The chief remedial factor in the treatment by conditioned air appears to be the filtration of pollen. Paper and cloth filters proved quite satisfactory in removing all but traces of pollen. Allergens may also be removed by passing the air through a water spray, or over cooling coils kept at a temperature low enough to cause condensation of atmospheric moisture on the surface of the coils. Electrostatic precipitation of pollen (78) also proved effectual in removing the offending substance from the air.

Special filter units are now available for home or office use, with or without air cooling. In the simplest type, which fits in the window like an extension screen, outdoor air is drawn in by means of a small fan and passed into the room through a fine cloth filter which removes most of the pollen. For best results some method of cooling and dehumidification must be provided.

A comfortable temperature between 75 and 82°F. in warm weather according to prevailing outdoor temperature, and a relative humidity well below 50 per cent appear to be quite beneficial and desirable. In the experience of Rappaport, Nelson and Welker (77) the rapidity of relief of symptoms in pollen asthmatic individuals residing in pollen free air is greater under controlled conditions of temperature (76–82°F.) with a low relative humidity (15–40 per cent), than when the temperature and humidity are not controlled. Direct drafts, overcooling or overheating are apt to initiate or aggravate the symptoms (57, p. 248, 58, p. 87, 70, 71).

Nelson and his colleagues (73, 74, 77) believe that there are other atmospheric factors, possibly changes in barometric pressure or ionization, capable of inducing attacks of asthma in pollen sensitive individuals. They noted that even in symptom-free patients confined in a suitably filtered and conditioned atmosphere attacks of asthma developed from 6 to 8 hours following the occurrence of rain and thunderstorms. In pollen free rooms with uncontrolled temperature and humidity, the relapse occurred much sooner, within about an hour after the storm. The symptoms were most severe in patients not confined to pollen free atmospheres and least severe in those exposed to filtered and conditioned air. The rapidity of disappearance of symptoms was likewise greatest under the controlled air conditions.

The possible influence of ozone, due to lightning, in the precipitation of asthmatic attacks was eliminated by running special experiments with artificially ozonized air (77).

Although thunderstorms are known to be associated with high ionization of the atmosphere (80, 81, 82), the effect of such high ion concentration on bronchial asthma cases is not yet settled. Landsman (83) in a recent article reviewed whatever literature there is on the subject and contributed new data of his own. Of a total of 79 cases of asthma treated by him, mostly with large negative ions, excellent results were obtained in 41.5 per cent of the cases; satisfactory results in 16 per cent, slight improvement in 24 per cent, and no change in 16 per cent of the cases. In two cases (2.5 per cent) of cardiac-asthma, artificial ionization aggravated the condition.

Landsman's experience with positive ions is limited, but whatever evidence he presents would seem to indicate an aggravation of symptoms with positively ionized air. This does not offer a clear-cut explanation for the relapse of asthmatic attacks observed by Nelson and his colleagues following severe thunderstorms, as the abnormal increase in the number of positive ions during thunderstorms is as a rule accompanied with an equal or even greater increase in the number of negative ions (81, 84). With thunderclouds and lightning preceding rain, Yaglou and Benjamin (84) observed sometimes but not always a high preponderance of positive ions, shifting to negative immediately after heavy rains set in. Similar observations were recorded by Dessauer (85) before thunderstorms.

General Hospital Air Conditioning

For the general hospital wards the problem is one of ventilation rather than conditioning. The requirements differ from those in a theater or a school where the floor area allowed per occupant is limited to between 5 and 25 sq. ft. Hospital wards are so designed that each patient is usually allotted between 50 and 150 sq. ft. of floor area and 400 to 1500 cu. ft. of air space. Body heat is therefore not an important problem, and except in tropical climates or for a few warm summer days in the North, satisfactory air conditions can be obtained in most wards by natural or semi-mechanical methods without resorting to elaborate and expensive systems.

A hospital in a clean and quiet district requires nothing better for its general and private wards during the cool seasons of the year than natural ventilation through windows with gravity or mechanical exhaust. Excessive outside noise and dust may require the use of suitable silencers and air filters fitting on the window sill. Insulation against heat and sound is much more important than humidification in winter time which in many instances is more bother than it is worth. Insulated walls will help a great deal in keeping the building warm in winter and cool in summer.

The preferred method of heating is by hot water with forced circulation to reduce the size of radiators and pipes. The radiators are placed at the windows or in a recess in the wall and they extend the entire length of the window.

The preferred exhaust system in large buildings uses one or more fans located in the attic or in a penthouse on the roof. Two or more vertical air ducts run up from the ground floor ceiling to the exhaust fan chambers in the attic or roof, connecting, on the way up, with horizontal branches at the ceiling of each corridor. Small ducts connect these horizontal branches with registers in individual rooms or wards. Each room is usually provided with at least two registers, one near the floor, and one near the

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ceiling, for winter and summer use respectively.

Cooling in warm weather can be economically accomplished by means of a few portable room coolers which can be wheeled from ward to ward when needed. In the North, cooling is desirable on but a few days during summer while in the South "stationary" cooling units can be used to advantage from May to October, and in tropical climates almost continuously throughout the year. In private rooms which are too small to accommodate such a unit without serious interference, it is possible to employ a portable cooler of suitable design fitting under the bed.

There is a wide variety of portable coolers designed to filter, cool, and dehumidify the air in a room without requiring changes in plumbing or electric wiring. The unit is placed under or near a window and connected to the outside by means of a telescopic duct, through a partly opened window, for the removal of heat and moisture taken from the air of the room. Objectionable noise of the apparatus, an important drawback to hospital applications, is gradually being minimized by improvements in design.

In the use of multiple stationary cooling units, one or more central compressors in the basement furnish the refrigerant to each individual unit by means of small pipes. This considerably reduces the noise in the patients' rooms and the cost of installation per unit is much less than of the "self-contained" units.

A more thorough description of air conditioning apparatus for hospitals, including initial and operating costs, is given in a Report of the American Hospital Association (86).

Summary

Air conditioning has important applications in certain hospital wards in which partial or complete conditioning of the air has proved of sufficient value to justify the expense. These wards are: nurseries for premature infants, anesthesia and operating rooms, oxygen therapy chambers, heat therapy rooms or cabinets, and allergic wards.

The objectives of air conditioning as applied to these five wards, and the special problems arising in each particular case, are discussed at some length in the light of recent literature on the subject.

For the general hospital wards, the problem is held to be one of simple ventilation, rather than air conditioning, with some provision for cooling over-heated wards on unusually warm summer days by means of room coolers.

Complete air conditioning of the whole hospital involves a large capital investment, depreciation, and running expense which are not justified on any evidence that we have.

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A LABORATORY OF INDUSTRIAL TOXICOLOGY*

W. F. von Oettingen

INDUSTRIAL medicine, like the control of contagious diseases, forms part of the large field of preventive medicine. The impressive success gained in the field of the prevention of infectious diseases which resulted in the control of such diseases as cholera, typhoid, typhus, plague and diphtheria were only possible after their cause had been discovered and the mechanism of their action had been elucidated. Industrial medicine is still hampered by a considerable lack of information regarding the causes of industrial poisoning and especially with regard to the mechanism of action of numerous chemical compounds. This handicap becomes more serious in view of the steadily increasing number of chemicals of the most diversified nature being produced constantly by chemical industries all over the world. In order to give the industrial physician all information necessary for the prevention, early detection and the treatment of poisoning, it is not sufficient to determine the toxicity of chemical compounds and to elucidate the toxicological symptoms which may be observed under different conditions; it is more essential to establish the pathologic changes in different organs and to study the effect of such substances on the metabolism and their fate in the organism because it is frequently not the compound proper but its oxidation or split products which produces the deleterious effect. For these reasons a laboratory of industrial toxicology has to comprise three departments—toxicology, pathology and biochemistry, which work together in close collaboration.

In planning a building for a laboratory of industrial toxicology it is essential that the departments of toxicology and pathology be close together because it appears important that the pathologist be thoroughly familiar with the toxicologic picture, since it is only this familiarity which enables him to give the correct interpretation to his findings. The problems of the biochemical division are not so closely linked to the experimental work of the toxicologist and besides, their study requires a number of special provisions and laboratories so that this department forms a more isolated unit and may be located without harm in a more distant section of the building. It need not be mentioned that the animal quarters should form a separate unit and that they should be isolated to a certain extent from the laboratories. It appears convenient that the surgical room, the isolation room, and laboratories for continued exposure be easily accessible to the animal quarters and for this reason they should all be located on one floor.

* From the Haskell Laboratory of Industrial Toxicology, Wilmington, Delaware.

Arrangement of Haskell Laboratory

In the following the grouping of different departments as arranged in the Haskell Laboratory of Industrial Toxicology will be discussed.

The department of toxicology which shares the same floor with pathology consists of four units,—the toxicological laboratory proper, the animal observation room, the toxicologist's office and a small laboratory for organ analysis.

In the toxicologic laboratory are studied mainly the acute toxicity of materials, their toxic symptoms and the mechanism of their action. The laboratory is equipped with cabinets for instruments, laboratory tables, movable tables, experimental benches, sinks and hoods. The cabinets are built in units of two sections. In one type the lower section contains drawers of various size; in the other it contains locker space for larger instruments. In both types the upper sections which serve for the storage of glassware and small instruments have doors with glass panes. This arrangement is very flexible and by proper combination, space for every need can be provided. The standard laboratory table provides more locker than drawer space because in our experience the latter is of limited value in storing equipment. All tables are equipped with outlet for gas, electricity, vacuum, air and water and have a small sink with an overhanging faucet for suction pumps. The tops are made of wood coated with an acid and alkali proof paint. It is advisable to have a groove made along the lower side of the top to prevent the draining of spilled liquids from the table into the drawers. The appliances for water, gas, electricity, vacuum and air are mounted on a shelf behind the table, so that the pipelines are easily accessible after pulling the table away. Over these tables are shelves for reagents; these shelves vary in shape and height in different laboratories. Beside these tables the laboratory contains a number of small tables, the legs of which consist of two iron pipes connected by a screw which allows the top to be raised to different levels. These tables are very useful in setting up more complicated arrangements especially in connection with the experimental benches. These are tables of the same type but fixed to the floor and the different appliances, such as gas, electricity, vacuum, air, water and sewer lines protrude from the floor, so that the table top is entirely free for the experimental set-up. Special attention was paid to the hoods which are built from albarene stone and provided with vents at table level and at the top to secure prompt removal of heavy and light vapors and gases. The faucets for gas, electricity, air and vacuum are at the rear but can be regulated and turned off from the front, so that during or at the end of an experiment the operator does not have to reach into the hood. Each series of hoods is ventilated by an electric fan through a separate flue and the ventilation of different hoods in one series can be regulated by valves. By means of catches at different levels the windows of these hoods can be arrested in order

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to prevent accidents in case the cables become corroded. At the end of the hoods is a chimney for the smoking of kymograph papers. The sink, also of albarene stone, is provided with a draining board on each side and insert draining tube which permits use of the sink as receptacle for soapsuds and water.

Since it is not advisable to keep the experimental animals that are under observation continuously in the general laboratory on account of the exposure to other contaminants and the activities going on, the toxicological laboratory is joined by an *animal observation room* which contains glass hoods on one side of construction similar to those described before and which are provided with special ventilation. These are used for keeping animals being treated with compounds of strong odor or very toxic substances, the dispersion of which may cause a serious inconvenience in the general laboratory. The other side of the room contains wooden racks, provided with casters, for the storing of small animal cages. The animal observation room is joined by the *toxicologist's office* which contains desk space, book shelves, glass cabinets and one laboratory table which in case of emergency may be used for experimental work.

A small *chemical laboratory* equipped with laboratory table, glass cabinet, hoods and sink completes the toxicological department. It is separated from the other rooms in order to exclude their pollution with acid and other vapors. It is planned for organ analysis and for the study of analytical questions in connection with the toxicological problems.

The pathological department consists of two *pathological laboratories* in which the tissues are prepared for histological slides. They are furnished with laboratory tables, cabinets for the storage of glassware and reagents, incubators, refrigerator, paraffin oven and microtomes. The sinks are of albarene stone, have a drainboard on each side and are equipped with a series of six water faucets so that several specimens may be washed at a time. These laboratories contain also a larger table in the center of the room and smaller tables for microscopical work.

The pathological laboratories are joined by a small *serological laboratory* which contains glass hoods and a modified laboratory table, one section of which has no lockers, so that one may sit comfortably close to the table. This laboratory was included since we feel that the investigation of allergic conditions and the study of the possibility of compounds causing allergic reactions is a very essential part of industrial toxicology.

The serological laboratory leads to the *pathologist's office* which is equipped like the toxicologist's and which may also be used for experimental purposes in case of emergency.

The *biochemical laboratory* forms a more independent unit. It consists of a general laboratory, the biochemist's office and the metabolic laboratory. The *general laboratory* is equipped with standard laboratory tables, hoods and all accessory apparatus used for biochemical work. The *biochemist's office* is equipped like the other offices, i.e., it is arranged so that it may be used as an emergency laboratory. This is followed by the *metabolic laboratory* which is air conditioned and equipped with standard laboratory tables, hoods, sinks and special apparatus for studying the metabolism of small and large animals.

Special Apparatus

For small animals we have accepted the arrangement of Lewis and Luck (1).

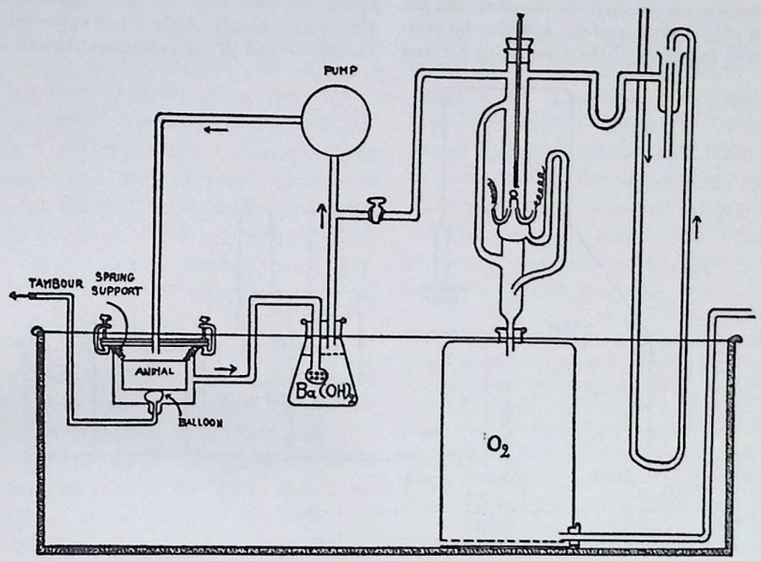


Fig. 1.—Metabolism apparatus for small animals
(After Lewis and Luck)

In this arrangement the air is caused to circulate at a constant rate by means of a pump. It passes through the animal chamber and bubbles through an absorption cell which removes the carbon dioxide. On leaving the absorption cell it passes a side tube through which fresh oxygen enters the system and completes the round by reentering the pump. The animal chamber contains a cage which is suspended by springs from hooks soldered to the inside of the chamber wall. It rests on a rubber balloon, over which all its vibrations may be recorded on a kymograph. In the oxygen supply system a constant pressure is maintained by a constant head of water fixed by the position of an overflow tube. As pressure within the system tends to be lowered by the oxygen consumption by the animal and the absorption of carbon dioxide by the cell, water from the side arm flows into the oxygen unit. The water collects in the trap until its level rises to the level of the siphon by means of which it flows into the reservoir beneath. Within the trap a ball of very light balsa wood, carrying a bridge of platinum wire, is set so that the platinum wires dip into mercury cups which extend to the outside and which are connected with an electric recorder. A lifting of the ball breaks the contacts and the current ceases to flow through the recorder. A bumper placed above the ball prevents its rising far enough to displace the wires from the cups containing the mercury. After the water has been discharged through the siphon, the ball drops in its original position, the contacts through the mercury cups are made and the marker returns to its original posi-

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tion. At the end of the experiment all the water collected in the reservoir is weighed, its volume calculated and the oxygen volume is calculated after the siphon records on the kymograph are counted.

For the larger animals we use the chamber developed by Benedict and Carpenter (2).

This consists essentially of four parts, the animal chamber itself, a pump which circulates air through the chamber and the rest of the whole system, a device for continued sampling of the circulating air and it carries the desired volume of air through the chamber, and is connected to the outlet tube of the chamber.

The air leaving the pump passes through a small tube, the flow being regulated by a valve to maintain any desired pressure. From this pipe two tubes with capillary valves and cocks lead to two counterbalanced spirometers of from 3 to 4 liters, capacity, so that the air pressure in the common line forces a continuous stream of air through the capillaries into the spirometers. In this way air is sampled continuously throughout the whole experiment and at the end of the experiment the air in

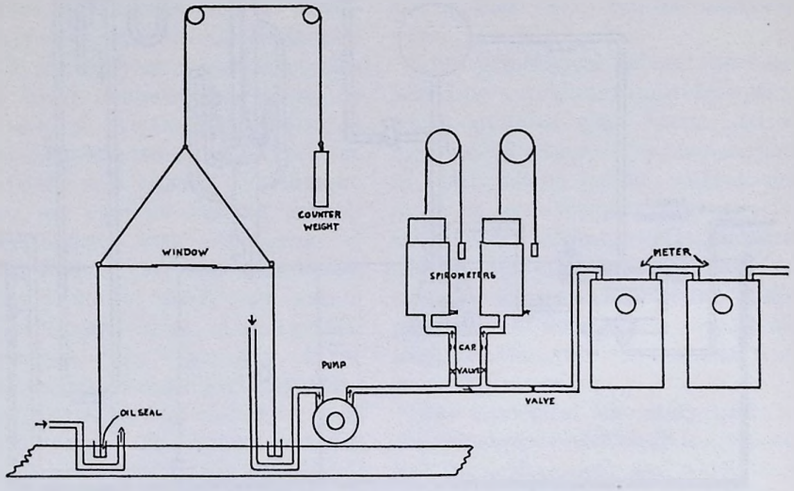


FIG. 2.—Metabolism apparatus for large animals
(After Benedict and Carpenter)

meters for recording the air flow through the chamber during the experimental period.

The animal chamber consists of an airtight container which has a window for observation on the top and which rests in an oil seal. Outside air is drawn through the chamber at a sufficient rate to keep the carbon dioxide content of the outgoing air at 0.3–0.5 per cent. It is advisable to agitate the air in the chamber by means of a fan. Because outside air is used it is not necessary to determine the oxygen and carbon dioxide content of the incoming current since it remains constant.

The pump is adjusted in such a way that the spirometers reflects exactly the composition of the total air in the animal chamber during the experiment.

The air not disposed of in this way passes through dry gas meters which record the total air flow. It is advantageous to place a hygrometer in the circuit leading to the meters, which allows the periodic reading of the moisture of the air and correction of the final volume.

At the end of the experiment air samples are removed from the spirometers and analyzed for oxygen and carbon dioxide and the total amount of carbon dioxide produced and oxygen consumed is obtained by multiplication of these values with the total amount of air recorded by the gas meters.

In the direct neighborhood of the biochemical laboratory is the *photographic laboratory*, the *photographic darkroom* and the *darkroom laboratory* which houses the microphotographic camera, the spectrophotometer and the quartz spectrograph. The last two instruments are essential for studying blood pigments and colorimetric determinations as well as excretion of substances especially in the urine. A *constant temperature room* for potentiometric measurements, blood gas analysis and gasometric determinations completes this unit; the rest of this floor is occupied by the apparatus room, storage room, laboratory, chemical storage room and a small workshop.

The second floor houses the *animal quarters* for rabbits, dogs, cats, monkeys and rodents. In the last two rooms the temperature is maintained uniformly at 75°F. The ventilation is arranged so that the total volume of each room is renewed 20 times per hour; this was found to be sufficient to prevent any marked odor and at the same time is not rapid enough to cause the sensation of draught. Between the two dog quarters is the *dogyard*, in which the animals may be exercised a few hours a day. This contains also a gassing chamber in which diseased animals may be killed by carbon monoxide (illuminating gas). Next follows the *sterilizing room* for cages, on the other side of which is an *isolation room* in which new animals, especially dogs, are kept while they are dewormed and carefully observed for infectious diseases. The animals, when not kept in large pens, are housed individually in smaller wire cages placed on metal shelves suspended from the ceiling from which they are separated by means of cups containing insecticides to prevent the spread of vermin. On the other side of the second floor is the *kitchen* and the *storage room* for food and other supplies. These are followed by a small *surgical room* for aspetic operations which is accessible through a *preparation room* in which the animals are prepared for operation. Adjoining this is a special *laboratory for continued exposure experiments*, followed by a laboratory for experiments with toxic gases and vapors and by one for the inhalation of dust. The former contains a gas chamber similar to that described by Heubner (3).

This consists of an anteroom and a gas chamber of 10 cubic meters capacity, both covered with white glazed tile. This can be used for experiments with stationary air mixtures and also for experimentation with moving air. In the anteroom is the control mechanism for the experimental air current consisting of a rotameter which controls the flow automatically, the switchboard for the different electric devices, a sink and a small laboratory table with outlets for gas, air, vacuum, and electricity. Under the table is a trap in which the animals are placed so that they can be released into the gas chamber at a given time without the experimenter being exposed to toxic vapors. The anteroom is ventilated both from the floor and the top and in addition the special outlet for pure air allows attachment of an open air mask. This and an electric alarm bell offer adequate protection for the experimenter. The walls of the gas chamber are crossed by a number of capped pipes at different locations which allow the introduction and withdrawal of gas-air mixtures over a wide range. The ventilation of the gas chamber is arranged in such a way that it can be completely ventilated within 30 seconds.

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Two fresh air inlets automatically controlled and two outlets connected with a powerful exhaust fan are provided for this purpose. For experiments with gas-air currents sent into the chamber the exhaust through these vents can be so regulated that as much is removed as is introduced. The chamber is provided with a sufficient number of bullet-proof windows to allow observation of animals during exposure. Proper circulation in the chamber during the experiment is secured by a fan attached to a water motor which allows the number of revolutions to be adjusted readily to different needs.

For inhalation experiments with vapors of uniform compounds on a smaller scale, the arrangement described by von Oettingen, Hueper, Deichmann-Gruebler and Wiley (4) may be used.

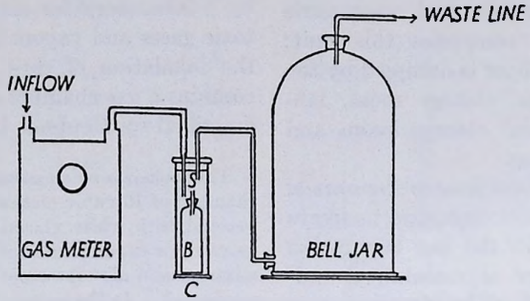


FIG. 3.—Apparatus for inhalation of vapor-air mixtures
(After von Oettingen, Hueper, Deichmann-Gruebler and Wiley)

In this the air flow is measured by a gas meter, passed through a cylinder which contains the test material in a weighing bottle, and enters the gas chamber, a glass jar of 8 liters' capacity, at the bottom and leaves it at the top. The concentration is calculated from the loss of weight of the test material and is controlled by the diameter of the opening of the weighing bottle which can be standardized empirically for different concentrations and materials.

For the study of the toxicity of vapors from mixtures of several volatile compounds the arrangement of Gross and Kuss (5) appears to be very useful. It consists of three units for regulation of the air flow and dosage and volatilization of the test material. This arrangement allows continued experimentation over longer periods of time.

The two cylinders, 1 and 2, are filled with acetylene tetrabromide and serve as valves for control of the incoming air current which is washed and moistened at 3 in order to secure a uniform humidity of the final mixture. 4 is a mercury manometer; it is necessary to refer the quantities of air passing through the gauges D_1-D_6 to certain barometric pressures in order to secure exact results. By means of these gauges the volume of the air current can be adjusted to the desired rate which is read on the flowmeter attached to the inlet and outlet of these tubes.

The arrangement for the dosages (II) consists of two pear shaped containers, 5 and 6, a communicating vessel, 7, and a burette, 8, which leads from the container 7 to the evaporator 14, provisions being made that the pressure in the whole dosage system is uniform. The burette can be replaced by others of different bore, so that they may discharge the desired quantity (by weight) of the material to be tested.

The evaporator (III) consists of a long glass coil which passes through the evaporation chamber, 14, and which is in connection with the heat jacket. The outlet of the

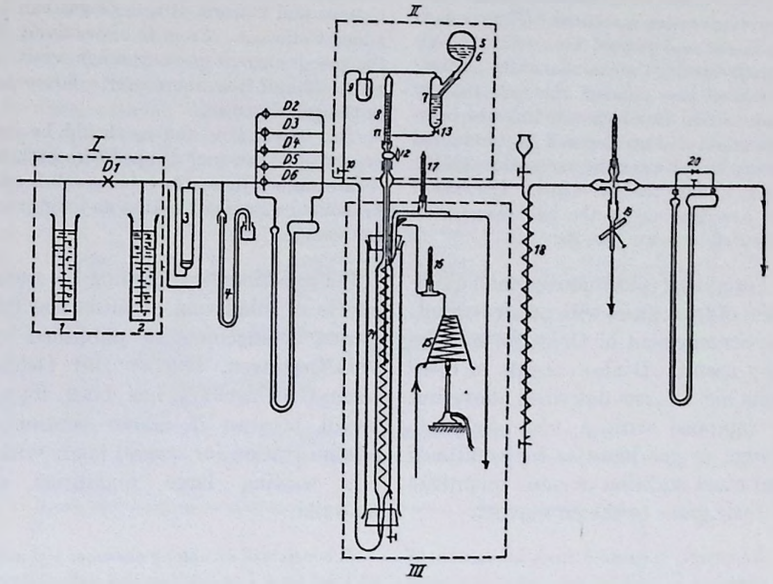


FIG. 4.—Apparatus for continuous inhalation of vapor-air mixtures
(After Gross and Kuss)

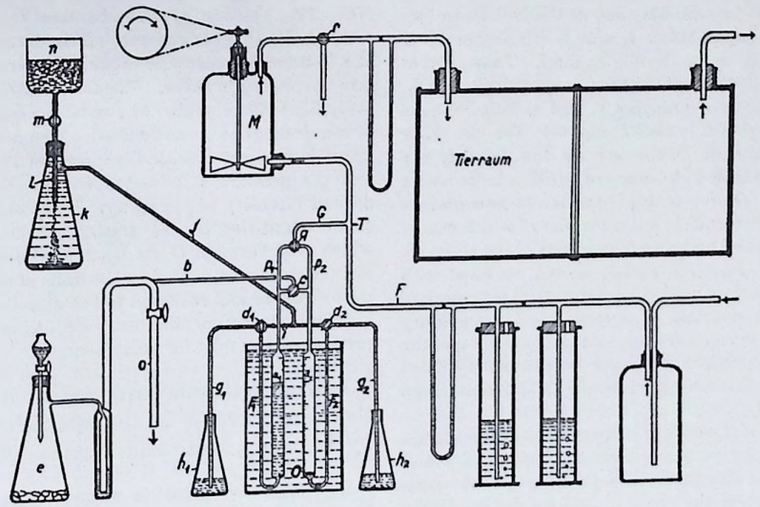


FIG. 5.—Apparatus for continuous inhalation of very dilute gas-air mixtures
(After Gross)

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burette, 8, leads over this coil, so that complete evaporation is secured. These vapors are mixed and carried away with the air current entering the chamber at the bottom; they then pass through the coil, 18, any condensation in which will indicate oversaturation, and are reduced to the desired volume by releasing the excess through the valve, 19, into the waste line. The rate of the flow leading to the gas chamber is measured by flowmeter, 20.

For mixing continuously small quantities of toxic gases with an air current, the arrangement of Gross (6) may be very useful. It also consists of three units like the one described above but is equipped with a very elaborate system of gas burettes for continued and exact addition of small quantities of toxic gases to the air current.

An exactly measured fresh air current F is mixed at T with the current of the toxic gas coming from G. The latter is produced as follows: Two graduated burettes a_1 and a_2 of 50 cc. capacity are filled from the gas generator e through b and three-way cock c. The two burettes end at the bottom in two S-shaped tubes f_1 and f_2 which are filled with some levelling fluid. These tubes branch out at the three-way cocks d_1 and d_2. The open branches g_1 and g_2 immerse into two wash bottles h_1 and h_2. The two other branches, connected by the tube i, are connected by means of j with a large bottle k. On top of this bottle is a large container which ends in a fine capillary l which can be opened and closed by means of the stopcock m. k_1, j_1, f_1 and f_2 should be filled with levelling fluid at least up to the zero mark of the burettes. The vessel n and the capillary l contain mercury. At the beginning of the experiment k should be completely filled with levelling fluid and should contain no air.

If the cock m is opened a very fine stream of mercury displaces the fluid in bottle k and also replaces, depending upon the position of the cocks d_1 and d_2, the gas in the burettes a_1 and a_2. The burettes are connected over the tubes p_1 and p_2 and the three-way cock q with G. By using alternatingly the two burettes a_1 and a_2 a continuous and uniform stream of gas can be added to the air. From G, respectively T, the gas air current passes through a mixing vessel M and from there over a flowmeter in the gas chamber.

The burettes a_1 and a_2 should be immersed in a constant temperature bath to secure uniform dosage and the vessels h_1 and h_2 should be arranged so that no toxic gases can escape.

For experiments regarding the acute effects of inhalation of mists the following arrangement as published by von Oettingen, Hueper and Deichmann-Gruebler (7) has been found useful because it allows continued administration for several hours without wasting large quantities of material.

It consists of an oblong chamber MC with an inlet tube I on the top and a drain tube D at the bottom, which has a bulb B at the free end, in which an atomizer A is inserted in such a way that its opening just protrudes through a stopper into the mist chamber MC. The opening of the chamber O is connected with an animal mask M by means of a T-tube, the open end of which extends into an exhalation valve. The test material is filled into the chamber at I until the bulb of the drain tube is nearly filled. The atomizer is connected with the pressure line and the pressure is adjusted to give the desired intensity of the spray. Since only small quantities of the testing material which pass through O are used up, the remainder being condensed on the walls of the mist chamber and returned to the atomizer bulb, this arrangement allows the continued production of a mist for many hours.

A more elaborate arrangement for the same purpose is that published by Lehmann, Saito and Mayima (8).

The main air current is sucked through the exposure chamber AB and measured with the gas meter C. This current is mixed at F with the mist carrying the material dispersed in E. The larger droplets are precipitated in H and F and returned to the container E. The quantitative determination of the mixture is made at two positions. A measured current is taken from B through the cotton filter J and the wash bottle K. The main air current passes also through a wash bottle and cotton filter. This usually gives lower analytical value than the side current because some of the material is condensed on the walls of the chamber.

For the study of the effects of air colloids, such as lead- and zinc oxide and others, the arrangement described by Froboese and Brückner (9) may be useful.

It consists essentially of four parts: (1) the exactly adjustable air currents I, II and III; (2) the air colloid generator G; (3) the diluting chambers MR-1 and MR-2 which allow the proper dilution of the colloids produced in G, the excess of which is carried away through V over the filters GE and F_1; and (4) the animal room TR with the exhaust lines leading through filter F_2 into the hood. The air current D, which should have a constant pressure as indicated by the mercury manometer Mo, is divided at I, II and III and regulated by means of the cocks R_1, R_2 and R_3 after passing over the flowmeter St_1, St_2 and St_3 and the mercury manometer M_1, M_2 and M_3. Current I passes through the colloid generator G and current II directly into the diluting cham-

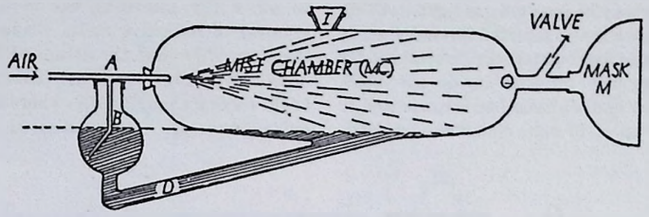


FIG. 6.—Apparatus for short inhalation of mists
(After von Oettingen, Hueper, and Deichmann-Gruebler)

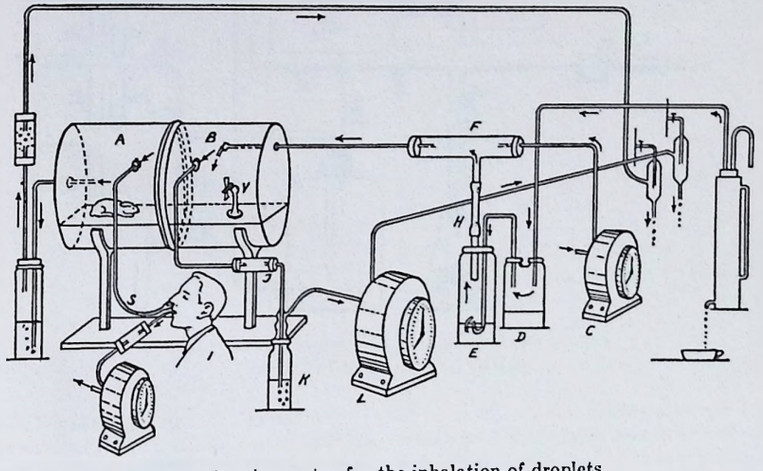


FIG. 7.—Apparatus for the inhalation of droplets
(After Lehmann, Saito and Mayima)

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ber *MR-1*, whereas current *III* goes to the diluting chamber *MR-2*.

The air colloid generator *G* consists of a glass bulb of 1.5 l. capacity containing two side tubes of 40–50 mm. diameter on opposite sides. The longer, upper tube has a side tube *a*. A metal cap *b* is connected to the lower tube. It carries a fitting *c* through which an arc carbon *d* of 20 mm. diameter may be inserted gas tight. A thin metal tube *e* is also inserted through the cap *b* to which a manometer may be attached for measuring the pressure inside the bulb. The upper end of the carbon is excavated to form a cup of 10 mm. diameter and depth

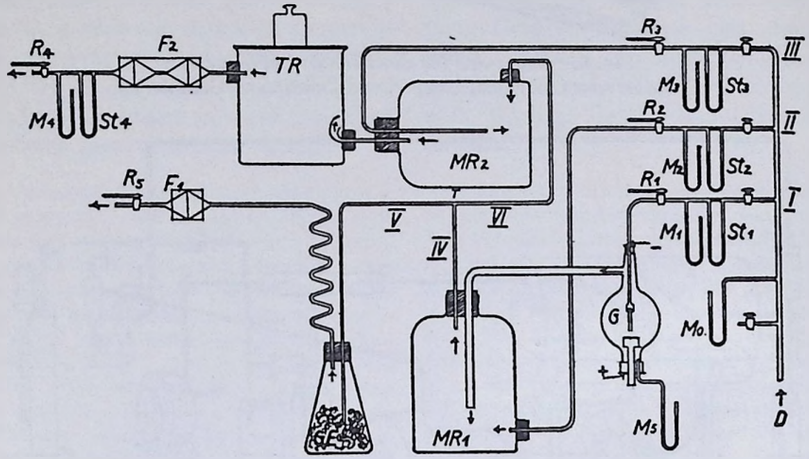


Fig. 8.—Apparatus for inhalation of "metal fumes" (After Froboese and Brückner)

and carries a carbon cup *f* of 25 mm. diameter and 30 mm. depth made from a piece of arc carbon of 35 mm. diameter which is inserted into the cup of 10 mm. diameter by means of a protruding stem. The material to be studied is placed into this cup *f*. The upper glass tube carries also a cap *g* with fittings *h* through which passes a metal tube *l* which has on one side a notched metal strip, so that by means of the notched wheel *i*, which is insulated by the fiber ring *h*, it can be moved up and down. The metal tube *l* ends in a thinner, bent down copper tube *m*, through which the air is carried into the bulb and on the lower end is a carbon *n* of 180 mm. length and 10 mm. diameter. This has a 3 mm. bore, so that the air passes right into the carbon beaker. The metal caps *b* and *g* are furnished with clamps for the electric current.

From the generator the "metal fumes" are carried to the sedimentation and diluting chamber MR_1 and MR_2 through the tube *IV* and *VI* between which a T-piece is placed to allow (by adjusting the cock R_5) the removal of excessive metal oxide through the filters *EG* and *F*, the details of which are described by Froboese (10). Tube *VI* leads to the mixing chamber MR_2 where the metal oxide fumes are further diluted with air coming through *III* and finally the oxide-air mixture passes into the animal chamber *TR*. Here the opening of the inlet tube is widened so that the velocity of the flow is reduced and at the same time it is directed toward the wall so that it does not blow directly on the experimental animal. Before being released into the hood the air from the animal chamber passes again through a filter in order to reduce the toxicity of the waste.

For the study of the effect of toxic dusts the arrangement of Jötten-Arnoldi-Kortmann (11, 12) is distinguished by its comparative simplicity. It consists of three parts, the compressor for the production of an intermittent air current, the dusting arrangement and the dust inhalation tower.

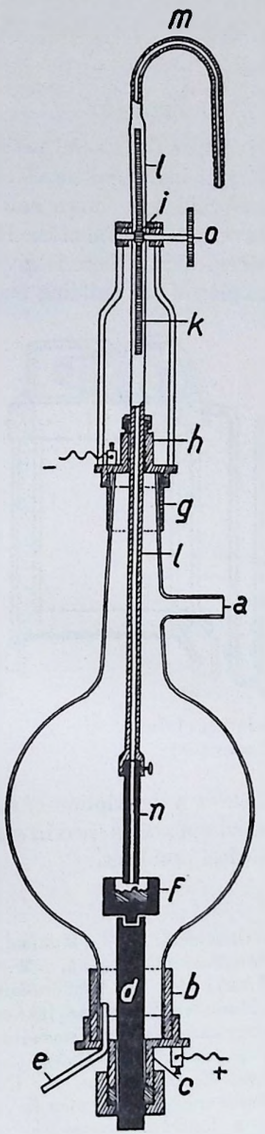


Fig. 9.—Generator for "metal fumes" (After Froboese and Brückner)

Instead of the Silten electro-compressor used by Jötten a simplified arrangement may be used which consists in rhythmic compression of a wide rubber tubing through which the air current passes into the dusting arrangement. This consists of three vertical glass tubes of 40 mm. diameter and 80 cm. length. The first tube contains a measured quantity of dust. The air current enters this tube on the lower end through a side tube and leaves it through another side tube 5 cm. below the top, the main opening being closed by means of a rubber stopper. In this way the dust passes through the two following tubes which secures a fairly uniform distribution of the fine dust particles. From here the dust cloud passes into the dust inhalation tower. This consists of a cylindrical container of 90 cm. height and 27 cm. diameter with two rows of screen covered windows in front of which the animal cages can be attached, so that the lower series is intermittent with the upper row. Each of the cages has on the top an outlet for air which can be plugged with cotton and another opening on the funnel shaped floor for the collection of urine. The tower is closed on top with a cover containing a glass window and a tubulated opening for removal of samples for analysis, and at the bottom by a funnel through the center of which the air cloud enters the whole system.

These are only a few of the arrangements which were developed for use in industrial toxicology. It need not be pointed out that they may find adaptations for different problems but it would be too time-consuming to go into further detail on this subject.

The foregoing discussion shows that the complexity of problems of industrial toxicology requires their study from different angles by men who have

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had special training in their lines. For this reason it does not appear advisable to set up small units for the study of such questions because these would necessarily suffer from lack of facilities and of the necessary diversified staff. It appears to be more reasonable that smaller concerns of similar interest collaborate in establishing and maintaining such a laboratory, which would result in a more complete and more detailed knowledge of the toxicological properties of chemical compounds and their potential dangers. Without such knowledge industrial medicine will be hampered in its progress and only after these foundations have been laid by the collaboration of those concerned with these problems, may it achieve such impressive results as those obtained in the field of infectious diseases control.

Summary

In this paper the special needs of a laboratory of industrial toxicology are considered and it is shown how these needs have been fulfilled at the Haskell Laboratory. First there is given the physical plan of the building and then there follows a description of some of the special apparatus used in studying toxicological problems.

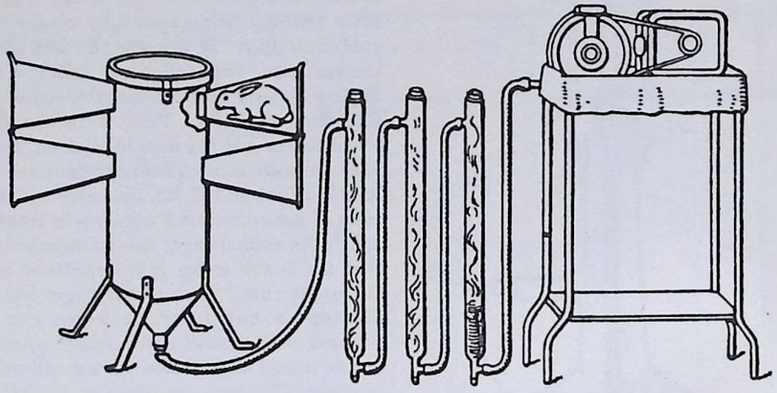


Fig. 10.—Apparatus for the inhalation of dust
(After Jötten, Arnoldi and Kortmann)

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THE INDUSTRIAL HYGIENE LABORATORY*

WARREN A. COOK

THE necessity of measuring the extent of exposure to injurious materials in industrial environments as an essential factor in the control of occupational diseases has resulted in the development of the industrial hygiene laboratory. Such a laboratory must be specially designed and equipped to determine the concentration of the great variety of contaminants found in industrial atmospheres. These contaminants are present often in exceedingly minute amounts and frequently offer special problems for their collection and determination.

The nature of the problems undertaken in the industrial hygiene laboratory gives it a distinct character from that of other types of laboratories. Even where analysis of the very same material is to be made in the industrial hygiene laboratory and in the general chemical laboratory, the methods utilized for its determination may greatly differ. In the analysis of carbon monoxide, for example, the general laboratory employs apparatus which gives negative results for less than 0.1 per cent. From the industrial hygiene point-of-view, such results would seldom be of any value. The desired information is whether the concentration of the material is within safe limits—in this case, 0.01 per cent of carbon monoxide in air. A well-equipped industrial hygiene laboratory would be provided with apparatus having a sensitivity of 0.005 per cent, or preferably, 0.001 per cent. This instrument gives a continuous indication of the carbon monoxide concentration in the air on a dial reading directly in parts per million of carbon monoxide; its use is not confined to laboratory determinations, as it is easily portable. Equipment of this type is required for meeting the demands placed upon the industrial hygiene laboratory.

Realization that the industrial hygiene laboratory is vital to the control of occupational diseases is resulting in the establishment of such laboratories in units charged with the control of this public health problem. At the present time industrial hygiene laboratories are being operated by federal, state and municipal departments engaged in the control of industrial health hazards, by insurance companies extending industrial group and compensation coverage, by universities, and by private consultants in industrial hygiene and industrial concerns interested in the control of their own occupational hazards. The utilization of such laboratories by all of these groups is permitting a more

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intelligent and effective attack on the occupational disease problem and is essential to the solution of this problem.

It is the purpose of this paper to present a picture of the industrial hygiene laboratory, to discuss its functions and to describe the type of equipment necessary for accomplishment of these functions. The laboratory entity considered is limited to the determination of injurious materials and does not include provision for animal experimentation or toxicological research. Its field is essentially the practical application of standards of permissible exposures formulated by such agencies as the United States Public Health Service, U. S. Bureau of Mines, universities and toxicological laboratories. Lists of necessary or desirable equipment are not included as they have been prepared by a number of bureaus operating industrial hygiene laboratories (1, 2) and by laboratory equipment houses especially interested in serving this field.

PHYSICAL LAY-OUT OF LABORATORY

The design and the equipment of the industrial hygiene laboratory depend upon the field which it is to serve. Three types of laboratories are generally considered: the completely equipped, central laboratory for all types of industrial hygiene determinations, the branch and the plant industrial hygiene laboratories to cover limited fields or to be partially dependent upon a central laboratory, and a portable laboratory which may be mounted in a small truck or on a trailer.

Complete Central Laboratory

The laboratory of the Bureau of Occupational Diseases of the Connecticut Department of Health may be taken as an example of a central laboratory designed to conduct the entire range of industrial hygiene determinations. The great diversity of industries in Connecticut results in a wide field of problems which this industrial hygiene laboratory is called upon to solve.

As shown in the floor plan (fig. 1), the Connecticut industrial hygiene laboratory occupies a room 27 ft. by 30 ft. with a 10-ft. ceiling. A 12 or even 14 ft. ceiling is preferable to allow height for the hoods and exhaust ducts above them. The laboratory is well lighted by windows extending along the 30-ft. south side. The furniture is of standard steel units with stone tops. The center of this room is occupied by a flat-top table, 11 ft. by 4 ft. 6 in., and by a chemical table, 10 ft. by 4 ft. 6 in., the latter with a deep sink at one end and the balance table at the other. Both of these tables are provided with gas, water, electricity and drains. Provision is made also for pressure and vacuum.

Space limitations do not permit segregation in one room of the chemical table with acids and other corrosive materials, although such segregation is desirable.

Along the east wall adjacent to the chemical bench are located the four hoods. These are provided with sliding wire-glass doors. An electric muffle furnace occupies one of the hoods, a gas hot-plate another and

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two electrically heated water-baths, with six holes each, part of a third hood. This last one, together with the fourth hood, are provided with gas, water and electrical connections and drain-bowl. The temperature control for the furnace is also located along this wall.

A bench extends along the entire 30-ft. south side of the laboratory under the windows. Along the north wall, are located cabinets for glassware. The west wall adjacent to the flat-top table is occupied by a cabinet, bench-space and sink. A third sink, placed at the southeast corner, provides an excellent distribution of washing facilities which has proved to be most advantageous for expeditious work. A desk and letter file are provided and also open shelving for books, journals and special references.

All tables and benches are placed at standing height, 37 in. above the floor, excepting the bench along the windows and the balance table which are 31 in. above the floor. Cupboards are located beneath all benches and tables, excepting where knee-room is provided at convenient intervals along the bench at the south side of the laboratory. Glass tubing and rodding are kept in long drawers extending longitudinally under the center of the flat-top table and accessible from the end. Gas and electric outlets are provided at convenient points along the benches.

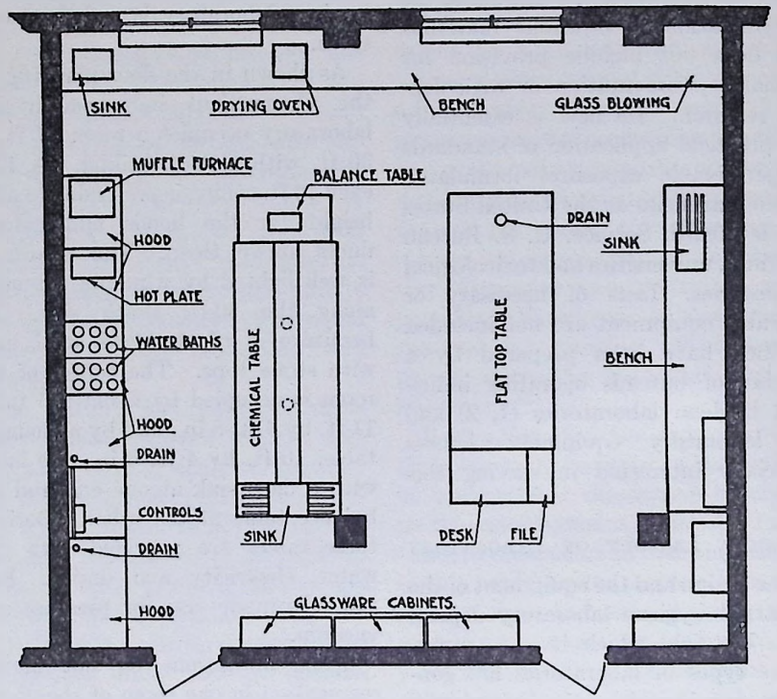


FIG. 1.—Floor plan of laboratory. Bureau of Occupational Diseases, Connecticut State Department of Health.

The western end of the bench along the windows is reserved for glass-blowing. A double gas outlet is placed at the front of the bench to permit easy access to the gas-cocks and to obviate the necessity of extending the rubber tubing for the blast-lamp across the bench. Since compressed air is not yet available, a small electric blower is connected to an air reservoir under the bench for operating the blast-lamp. Oxygen is also available for the blast-lamp.

A number of additional facilities should be provided for a complete industrial hygiene laboratory. A workshop is a most desirable adjunct since much of the field equipment can best be designed and constructed by those who are to use it. If necessary, the workshop may be limited to a small carpenter's bench and a few hand tools, but any elaboration of such workshop equipment will be of real value in the construction of special field and laboratory apparatus.

Photographs are of much assistance in presenting the results of industrial hygiene studies. Where much photographic work is to be done, a dark room should be provided for developing and printing. Photographs of dust samples for purposes of record or for inclusion in reports of studies, photographs of the dust itself in connection with certain of the dust determination methods, and photographs of manufacturing operations all find a definite use in an industrial hygiene program. Dark rooms are also necessary where x-ray diffraction methods and spectrographic methods are to be used.

A dust-chamber has a place in the industrial hygiene laboratory. It serves a number of purposes. Where more than one dust determination method is being employed, the various instruments can be compared by sampling dust from the dust-chamber. Where new workers are to be trained, the dust-chamber is of value in developing dust counting technic. Checking dust counting technic is also desirable where two or more workers may be making determinations independently. As new developments are suggested in dust determination methods and instruments, the dust-chamber affords a means of testing their efficacy.

It has been suggested (3) that a dust-chamber of about 500 cu. ft. would be sufficient for general purposes of an industrial hygiene laboratory. Its height should be at least 8 ft. to provide opportunity for settling of the dust. A dust-chamber recently constructed under Brandt's direction, measuring 8 ft. 4 in. by 8 ft. 4 in. by 15 ft., giving a volume of about 1,000 cu. ft., is of all-steel construction, welded to make it dust tight; it cost approximately $450. The dust-chamber of the U. S. Bureau of Mines Experiment Station at Pittsburgh is two stories in height, the upper story providing for introduction of dust and for ventilation, whereas the lower chamber is used for sampling.

General Equipment for Central Laboratory

In addition to equipment for making special determinations as mentioned later in this paper, the industrial hygiene laboratory should be well equipped for general qualitative and quantitative analytical work, and be stocked with the requisite miscellany

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of chemical reagents, laboratory glassware and incidental equipment.

The analytical balance should preferably be of the chainomatic type, since this is especially desirable in weighing activated charcoal tubes in connection with the determination of solvent vapors.

A distilled water apparatus of a capacity of 1 gallon per hour with a 10-gallon storage tank is adequate for the average laboratory.

Since colorimetric methods are constantly coming into wider usage, a Duboscq colorimeter should be included as general equipment. Nessler tubes can be used, but when a considerable number of determinations are to be made, the colorimeter permits a saving in time and, in addition, permits greater accuracy in making determinations. Among the injurious materials found in industry which can be determined by the colorimetric method, the following may be mentioned:

Chromium compounds
Lead
Benzene and many other solvents
Chlorine
Mercury
Arsenic
Aniline
Cyanide
Hexamethylenetetramine
Hydrogen sulfide
Hydrochloric acid
Manganese
Phenol
Silica

A spirometer is of value for calibration of gauges and rate-of-flow equipment in general. If a spirometer is not included in the laboratory equipment, wet and dry gas meters can be used for calibration purposes. The wet gas meter is more accurate for low rates of flow and may be used for flows up to about 12 litres per minute. The dry gas meter most adaptable for industrial hygiene laboratory purposes is the five-light type with a large dial indicating 1 cu. ft. to a revolution of the pointer. This meter can be used for air velocities as high as 4 cu. ft. per minute. It should be re-calibrated from time to time.

If physical examinations and x-rays are contemplated, the necessary standard equipment should be included.

A camera is necessary both for laboratory and field purposes. Standard attachments are available for certain types of cameras so that they can be used for taking microphotographs. A camera for use in manufacturing plants should be provided with a good lens since many such interiors are poorly illuminated. Photoflood lamps may be used in some cases but there are several reasons why such auxiliary equipment may be inadvisable. With some cameras, many exposures may be taken on 35 mm. film at a low cost and only those which are required need be enlarged. Furthermore, the 35 mm. film may be projected directly onto a screen. Although photographs of manufacturing operations should, of course, be taken only on approval of the management, a small camera is advantageous since it more easily permits photographing normal working conditions instead of the posed picture often obtained if a larger camera must be set up.

Since most of the information on methods of determination of atmospheric contaminants found in industrial environments is found in the current literature, it is of especial importance to maintain at the laboratory a card reference of methods of determination. Reprints of the more promising methods should be included in the reference library kept at the laboratory. A nucleus for a card reference system of methods of determination may be obtained from a list given in the 1935 report of the American Public Health Association Committee on Ventilation and Atmospheric Pollution (4).

Branch and Plant Laboratories

Where an industrial hygiene organization serves a large territory in which there may be several industrial areas somewhat distant from the central laboratory, it may be expedient to install branch laboratories. The layout and equipment of such a laboratory should be in accordance with the principal problems to be undertaken in the local area. Equipment should be provided for conducting determinations which are to be made regularly, and which involve collection of samples which could not be readily transported to the central laboratory.

The number of companies conducting industrial hygiene studies of their own working conditions is constantly increasing. The industrial hygiene laboratory operated by such concerns is naturally limited to the determination of injurious materials present in the plant of that concern. Frequently, the state industrial hygiene organization can be of much value in supplementing the industrial unit. Where the expense factor must be carefully considered, a laboratory can be started in a small way and built up as its value is demonstrated.

Portable Laboratory

The problem of covering an extensive territory may also be met by the use of a portable laboratory. One industrial concern with widely distributed plants (5) employs a commercial sedan for transporting its special laboratory equipment from plant to plant. A trailer was originally used, but this was found less satisfactory than the use of the commercial sedan or light delivery truck. A workbench is being planned which will serve both as a laboratory table and also for storage of the special equipment during transportation. Only that special equipment is transported which is not available at the research and control laboratories of the individual plants where the work is to be done.

General Field Equipment

When the industrial hygienist is making determinations or collecting samples in manufacturing plants, it is of great importance that he be provided with equipment which will permit him to conduct his operations with dispatch and with as little interference as possible to the normal operations of the workers. When a chemistry instructor is conducting lecture experiments, his technic must not only produce the desired results, it must display a practiced and faultless, yet unobtrusive finesse. When the industrial hygienist is at work in the industrial plant, he is under no less critical and observant an audience. The plant engineer and chemist, the workers themselves and probably the manager of the concern will have an interest in the proceedings which may be more discerning than is apparent

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on the surface. The credence which is accorded the findings is unquestionably influenced by the impression which these plant men receive of the capabilities of the hygienist and the adequacy of the equipment. A complicated apparatus of fragile and intricate design brought into the midst of a bustling factory bespeaks more of thaumaturgy than of sound scientific procedure, whereas sturdy, compact equipment carries with it an impression of practical common sense, a valuable aid in gaining the confidence of the man in the plant in the authenticity of the results obtained.

There are a number of fundamental requirements which should be met by equipment which is to be used in the field. It should be readily portable and for this reason the weight of apparatus should be kept at a minimum. For example, an aluminum base-plate should be used for a motor-vacuum pump assembly rather than a cast-iron base. The equipment should be durable. Where glassware must be used, provision should be made in the design of the field equipment for its protection. Sampling equipment should be devised so that the collection of the sample can be conducted rapidly if this is found to be desirable.

It is often advantageous to provide one type of equipment which permits the collection of a sample continuously over any required period of time, and another type of equipment which will permit the collection of a "grab sample". The former type of equipment gives the best indication of the average exposure of the worker to an injurious material, whereas the latter type of equipment gives information concerning just what part of an operation presents the major hazard or introduces the greatest amount of the injurious material into the workroom air.

Sampling equipment should include provision for collection of two or more samples simultaneously. By the collection of multiple samples it is possible to gain valuable information which cannot be obtained by taking several successive samples. As an illustration, one sample may be taken of the exposure of workers conducting a dust-producing operation and a simultaneous sample of the general workroom atmosphere to show how much the operation is contributing to the dust content of the workroom. Collection of simultaneous samples also assists in gaining information on the efficacy of various dust control measures of a particular process in a plant during its normal operation.

Apparatus which will show the results of the determination without recourse to the laboratory are, of course, desirable wherever they can be used. Equipment has been devised which will give results immediately, in some cases a direct reading on a dial, as is mentioned elsewhere in this paper. It is to be hoped that there may be further development of such equipment.

Collection of Samples

Equipment to be used for collection of the air sample depends not only upon the material to be collected, but also upon its probable concentration and the conditions under which it is found. The sampling device for some gases can consist simply of a bottle of water. When it is desired to collect a sample of the room air, the water is poured from the bottle at the desired point, the stopper is replaced and the sample thus obtained. Since minute quantities of many of the injurious materials may affect health and so require determination of exceedingly small concentrations, the more usual method of obtaining the sample is to draw the air through an appropriate medium which retains the injurious material. In this manner, the lead from 100 cu. ft. of air can be transported to the laboratory for analysis in an 8-oz. bottle.

Various methods may be utilized to draw air through the sampling apparatus. That in most common and most satisfactory use depends upon the ejector principle. Compressed air, readily available in most manufacturing plants, is connected to the ejector to obtain the necessary suction. The ejector has the advantages of small size, durability, large capacity and simplicity of operation.

The ejector is used extensively as a means of obtaining suction in the collection of dust samples (6). Instead of providing this device with only one suction nozzle, as described by Hatch, a T-fitting can be placed at the suction end of the ejector and two suction nozzles each with its own orifice plate attached. By this means, the one ejector equipment will permit collection of either one or two samples. This ejector apparatus can be used for other purposes than the collection of dust samples and is convenient wherever it is desired to draw air through a system. For small rates of air sampling, a water-type ejector such as is in common laboratory use may be employed.

Where compressed air is not available, it may be necessary to utilize an electric motor connected to an air pump. The capacity of such an equipment, as described by Greenburg and Bloomfield (7), is sufficient for the operation of two impingers. By a slight modification of the apparatus described, simultaneous samples may be collected. Instead of using a flowmeter as suggested in the paper cited above, a calibrated vacuum gauge can be employed. If a vacuum gauge is used, it is desirable to introduce an orifice plate beyond the gauge, so that the pointer will indicate at least 5 in. of vacuum. Where the vacuum gauge is used, the orifice plate need not be drilled with the precision required when it is employed in the equipment described by Hatch (6); its aperture need merely be such as to increase the resistance in the line sufficiently to give a reading on the vacuum gauge.

Where neither compressed air nor electricity are available, a hand-pump can be used (7), although drawing 1 cu. ft. of air through an impinger by means of such a hand-pump is an exceedingly laborious and fatiguing operation.

Another means of drawing air through collection apparatus where no power is available is by use of aspirator bottles. The equipment consists of two bottles, one above the other. The upper bottle is filled with water which is allowed to flow into the lower one. The air which displaces the water is drawn through the sampling apparatus. Such a system is adaptable to small air volumes and low rates of sampling.

A number of methods are available for measuring the rates of flow of air through the sampling apparatus. The flowmeter and vacuum gauge, to-

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gether with the method of calibration, are described by Greenburg and Bloomfield (7). Wherever a vacuum gauge can be used, it has a number of advantages over the flowmeter. It is more durable and not subject to disruption in case of sudden changes in the air-flow. The flowmeter may be provided with a trap on the low pressure side of the U-tube to prevent loss of the liquid, but usually the air-flow must be stopped momentarily to permit the liquid to drain back into the U-tube.

The vacuum gauge (and also the simple manometer) cannot be used where the resistance in the line changes. Consequently, a flowmeter rather than a vacuum gauge must be used with such apparatus as activated charcoal tubes where the resistance increases as sampling progresses. Such apparatus as fritted glass bubblers where the air must pass through minute orifices also increases its resistance during sampling due to the presence of dust in the air.

Another device which has the advantages of the flowmeter without its disadvantages is the "Rotameter" (8). This device consists essentially of a vertical tube having a tapered bore (with a small end at the bottom) and a top-shaped rotor placed inside the tube and held in suspension by the upward flow of liquid or gas. The rate of flow is read directly from the scale etched on the tube.

For the timing of sampling periods, two types of stop watches are desirable. The watch-type permits recording the time of day during which the sample is collected and will time as long a period as the sample may run. Where intermittent operations are to be timed, the stop-and-go type of stop watch is of value. The two stop watches can be used in conjunction when it is desired to know how great a proportion of the total elapsed time is actually taken up by some intermittent operation, or by intermittent exposures.

Where laboratory glassware must be used in the field, a method under development at the Massachusetts Bureau of Occupational Hygiene (9) may well be adopted. The glass apparatus for a given determination is attached to an aluminum plate which can be inserted into a fiber carrying case. Set-ups are prepared, each on its individual aluminum plate for determination of various atmospheric contaminants found in industrial environments. A description of such equipment is to be published by Bowditch and Elkins.

Ventilation instruments for checking industrial ventilation systems should include a 4-in. anemometer, Boyle velometer, pitot-tube with inclined manometer, glass U-gauge, revolution counter, sling psychrometer and the heated thermometer anemometer (Yaglou).

Equipment for Specific Determinations

Dust Determinations

A completely equipped laboratory should preferably have two types of dust collection equipment: the impinger apparatus where a continuous sample is to be collected, and one of the grab sample dust collection devices.

The impinger apparatus and also some of the grab sample devices are discussed by Bloomfield in the 1935 Report of the American Public Health Association Committee on Ventilation and Atmospheric Pollution (10).

Other devices which are available for determination of dust concentrations over a continuous period are the electrical precipitator (11), the atmospheric dust recorder (12), and the hot wire thermal precipitator (13). Of these, the impinger is by far the most widely used in this country and should be standard equipment of all industrial hygiene laboratories conducting dust control work.

The konimeter and Owens dust counters, both described by Bloomfield (10), have undergone a number of modifications. The konimeter manufactured by Zeiss is equipped with a microscope which permits counting the sample without recourse to a laboratory set-up. This konimeter is also equipped with stops which permit the collection of samples either of 5 cc. or of 2.5 cc. By collecting the smaller sample, the range of the instrument may be increased from about 17 million particles per cubic foot of air to about 34 million particles per cubic foot. The konimeter constructed by Devers, of South Africa, has been modified by us so that samples of 1, 2, 3, 4 or 5 cc. may be collected. By collecting a sample of but 1 cc., the range of the instrument is increased to about 85 million particles per cubic foot of air. We have used this instrument extensively in industrial plants and plan to publish details of our modifications together with its application in industrial dust studies.

The Owens dust counter has been modified by Bausch and Lomb as a result of suggestions by Beyer and other members of the Liberty Mutual Engineering Staff so that a number of dust samples may be collected on a circular plate similar to that used in the konimeter and examined under a built-in microscope. The dust concentration in millions of particles per cubic foot of air can be obtained directly from the dark field count by merely inserting a decimal point.

Other dust determination devices which collect grab samples are the electrostatic dust count sampler developed by Barnes (14); the photographic dust counter, developed by Ficklen and Ott (15); and a Tyndallmeter constructed by Leitz and described by Matthiass and Landwehr (16).

There is a definite need for dust determination equipment which will permit the engineer at the plant to obtain an indication of the dust concentration without the necessity of extensive training and technic, utilization of complicated equipment, or laborious procedure. It is possible that some of the methods cited, or a modification of them, may fulfill the requirements of a rapid, facile means of determining the dust concentration, and it is hoped that either these methods or methods not yet conceived may be developed to fill this need.

Analysis of Dust for Free Silica

In view of the fact that free silica is of outstanding importance in the extent of the hazard presented by a dust, it is desirable to have equipment for making this determination. For certain dusts, petrographic methods may be preferable; for other dusts, chemical methods seem more satisfactory; but for most of these determinations a combination of both methods is required. The essential

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equipment for petrographic methods is a petrographic microscope with the necessary attachments. General laboratory equipment is usually adequate for conduct of the chemical methods.

A method employing x-ray diffraction has been described by Clark and Reynolds (17). It is stated that duplicability of results is within 5 per cent of the amount of the substance sought in the case of quartz; this is sufficiently sensitive for the purposes of the industrial hygienist. The equipment is expensive, a factor which will tend to limit its use.

Determination of Metals and Metalloids

Equipment for collection and analysis of metals and metalloids is generally included in the usual laboratory set-up. The impinger is of value for collection of such materials as lead and lead compounds. Special equipment may, however, be used for certain of these materials.

The spectroscope has been used advantageously for the determination of mercury by Armstrong (18). As many as twenty mercury determinations could be made in a day with the spectroscopic method. The spectroscope can also be used for other determinations, though a certain amount of development work is usually necessary before it is applied to any specific industrial hygiene problem. The amount of the element to be determined is estimated by measuring with a microphotometer the intensity of one of its spectrum lines, and on the same plate the intensity of another line in the same spectrum due to another constituent added in constant amount to all the samples. The ratio of these two intensities is referred to standards for evaluation. The expense of spectrographic equipment is a deterrent to its general use, but where a considerable number of determinations is to be made, it may be shown to be the most economical procedure. Spectrographic methods are generally so sensitive that the samples to be determined can be much smaller than those required when chemical determinations are to be conducted. The sensitivity of spectrographic methods also permits determination of mercury and other materials in such biological fluids as blood where the sample must necessarily be small.

A convenient method for the determination of mercury vapor is the Nordlander apparatus constructed by the General Electric Company (19). A less expensive mercury vapor detector has been developed by the same company, but this is hardly a precision method. It also depends upon the selenium sulfide reaction discussed by Nordlander (19).

The determination of radioactive materials in the workroom atmosphere and in the bodies of the workers themselves requires electroscopic measurements of both gamma and beta-rays. The equipment for such determinations is described in some detail by Bloomfield and Knowles (20) and by Ives, Knowles and Britten (21). Such equipment need be included in the industrial hygiene laboratory only where there is exposure to radioactive materials in the territory served by the laboratory.

Organic Solvent Vapors

Equipment for several methods of determination of organic solvent vapors is discussed by Cook and Coleman (22). This paper includes a brief discussion of the interferometer, the refractive index and the thermal conductivity equipment, together with a detailed description of an activated charcoal apparatus.

In the determination of specific organic solvent vapors by chemical methods, the equipment for collection and analysis of the sample is often specially designed for use with the particular method that is being employed. Where it is desirable to make specific determinations of an individual organic solvent vapor, it is suggested that reference be made to the literature and any special equipment necessary for determination constructed as required.

Spectrographic methods are also available for certain of the organic vapors. These methods have the advantage of sensitivity, but the cost of the equipment cannot be overlooked.

An inflammable vapor detector is of value for certain types of determinations. Where workers may be cleaning a gasoline storage tank, it is desirable to obtain immediate information concerning the concentration of hydrocarbon vapor to which they are exposed. An inflammable vapor indicator which will show as little as 10 per cent of the lower explosive limit of the vapor is sensitive to about 0.2 per cent of gasoline vapor in air.

Gases

In addition to the use of such general apparatus as gas collection tubes and bubblers for sampling gases, a number of specific instruments have been developed for their determination.

The M-S-A Continuous Carbon Monoxide Indicator, made by Mine Safety Appliances Company, needs merely to be connected to a 6-volt electric current and the carbon monoxide concentration may be read direct on the dial in terms of parts per million, the lowest division showing 10 parts per million; the highest, 1,000 parts per million. Since this instrument weighs about 17 pounds, it is easily portable. Because carbon monoxide is a potential health hazard in such a great variety of industries, an indicator of this type is desirable equipment for the industrial hygiene laboratory.

Where it is desired to determine whether sufficient carbon monoxide is present to cause loss of consciousness of a worker who is to remain in the area for only a brief period, the Hoolamite detector is of value. The range of this instrument is from 0.07 to 1 per cent. The air is drawn through this detector by means of a rubber bulb, the readings being made by comparing the depth of purple color of the indicator with a standard color scale attached to the instrument.

An instrument similar to the latter has been developed for the determination of hydrogen sulfide in air based on a method described by Littlefield, Yant and Berger (23). The limit of sensitivity of this instrument is 25 parts per million. It may be used as a control instrument or where a quick method is needed. Other methods should be employed where smaller concentrations are to be quantitatively obtained. These last two pieces of apparatus are also made by Mine Safety Appliances Company.

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Illumination Equipment

In making determinations of the adequacy of illumination, an illuminometer operating on the photoelectric cell principle is the most desirable type. The reading is given directly on the dial in foot candles, no batteries or auxiliary equipment being required.

Conclusion

The design and equipment of a laboratory of industrial hygiene must be well adapted to the function it is to serve in occupational disease control. The purpose of the laboratory cannot be fulfilled, no matter how complete the physical appointments may be, unless it is manned by a staff trained in making the necessary determinations, in conducting field studies and in interpreting the results. Qualifications for such personnel are briefly discussed by Gray (24) in a paper which also presents the place occupied by the laboratory in relation to the entire occupational disease control organization. An extensive experience in coping with occupational disease problems has conclusively demonstrated the vital importance of a well designed and well equipped industrial hygiene laboratory.

Summary

The essentials in the design of an industrial hygiene laboratory have been presented together with a description of the laboratory from which this paper is contributed. General types of equipment for the industrial hygiene laboratory are discussed, both for field and laboratory operations. Equipment for specific determinations of dust, metals and metalloids, organic solvents, vapors, gases and illumination are briefly described.

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