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Engineering Control of Occupational Health Hazards

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Introduction

I have chosen the subject of my Cummings Memorial Lecture for several reasons. For one, it has not been the topic of a Cummings Lecture up to the present and assuredly it is too important an aspect of occupational health to suffer neglect. For another, I would like to share with you some reflections on industrial hygiene engineering derived from the experiences of a number of years devoted to its practice. Lest this lecture seem to be unduly reflective and remote from present-day concerns, I will endeavor to evaluate the current status of engineering for the control of chemical and physical stress in the workplace and to look to the future.

I am certain that industrial hygiene engineers and all industrial hygienists who believe in the primacy of engineering controls for occupational hazards will be appalled by a plan announced by the Occupational Safety and Health Administration (OSHA) in the Federal Register of February 22, 1983(1) to reduce their prior emphasis on engineering controls in favor of greater reliance on personal protective equipment, principally respirators. The Federal Register describes engineering controls as modifications to plant, equipment, processes, or materials to reduce an employee's exposure to toxic materials and harmful physical agents, and lists them as: (1) material substitution (2) process change, including the way the work is performed (3) equipment change (4) local exhaust ventilation (5) general dilution ventilation (6) equipment enclosure and (7) employee enclosure. Administrative controls, the practice of rotating work assignments so as to spread a fixed toxic flux among a sufficiently large number of employees to avoid an overexposure to any single individual, are lumped with engineering controls in the Federal Register; surely an odd couple. We must now ask ourselves whether the OSHA proposal to put greater reliance on respirators and other personal protective equipment in place of engineering controls is a wise decision, or is sufficiently wrong-minded to lead to the same kind of disaster that befell the EPA recently when their newly formulated policies proved to be out-of-step with majority thinking.

It has been a guiding tenet of the profession of industrial hygiene from its very beginning that prevention of occupational illnesses is its goal. As a consequence, we tend to view a need for curative medicine as a defeat for industrial hygiene. During this same period, it has been recognized that prevention of disease should be accomplished by engineering control methods in preference to burdening the worker with personal protective equipment. Even though there are well defined occasions, in practice, when only personal protective equipment will serve, the principle is valid and remains an important goal for most industrial hygiene professionals. The reasons for this preference are clear enough: personal protective equipment cannot achieve its full protective potential without a degree of worker knowledge and cooperation that are seldom achieved in practice. Even when the devices are well used, they are uncomfortable and place a serious additional physical burden on workers that is felt most keenly by those engaged in heavy, hot, stressful occupations. This becomes abundantly clear when industrial hygienists spend a full working day in a steel foundry equipped with OSHA-mandated safety shoes and metatarsal protectors; metal spatter-repelling coveralls, leggings, hood, gauntlets, goggles, hard hat, and a dust and fume respirator. Although I have chosen an extreme example to emphasize my point, the fact remains that most workers must be coerced into using personal protective equipment and seldom use it efficiently. An additional complication is that periodically there are distressing Respirator Information Notices from NIOSH recommending that one or another named respirator is "not to be relied upon".(2) The presence of facial hair is a further complicating problem, and even under the best of circumstances, we are informed, reliance on qualitative fit tests "can create a health hazard for respirator wearers."(3)

Ineffectiveness of personal protective equipment is not confined to respirators. In 1977 and 1981 NIOSH conducted field investigations to determine the amount of noise reduction (attenuation) afforded to industrial workers who use earplugs. Tests of 420 workers at 15 industrial plants indicated that 50% of the workers received less than half the potential protection demonstrated in laboratory tests.(4) Although earplugs can provide adequate protection from noise hazards, workers generally wear earplugs incorrectly, and an identical comment applies to the use of respirators in industry. This is far from fresh news: Sir Thomas Legge, the first Medical Inspector of Factories in Great Britain, who was appointed in 1898, stated the same thoughts in an unequivocal manner. He said, 80 years ago, "Some useful *but not very effective methods* [for protection against dust and fume exposures], depending on the workman's cooperation, are: respirators, goggles, and washing conveniences."(5)

This is so well known to industrial hygienists, that the only reason for restating the obvious is to make a point. Reflecting on OSHA's move to downgrade engineering control of occupational exposures by substituting personal protective equipment, I have come to the conclusion that it probably originates from a conviction on the part of many that engineering controls are too difficult to design and too expensive to install and maintain. This is a serious indictment of industrial hygiene engineers, who are dedicated, as are all engineers, to developing fully effective solutions to practical problems at least cost. I want to examine this thought in more detail.

Viewing occupational health and safety historically, not only is organized prevention of disease and injury a recent phenomenon (as distinguished from earlier times when workers were solely responsible for their own well-being in the workplace), but even newer is the concept of universally applied engineering controls that, in the extreme, free the worker from all personal responsibility for work safety. When we seek the roots of our modern concepts of occupational disease prevention and the unequivocal assignment of responsibility for effective safety and health practices squarely on the shoulders of the employer, we must start with British 19th century legislation that was designed to lessen the harsh working conditions of women and children in mines and factories. Adult male workers benefitted, as well, from the initial concern for the well-being of working women and children.

One of the earliest occupational hazard controls of an engineering nature was the introduction of steam engines to ventilate British mines during the first two decades of the 19th century. Improved ventilation made it possible for miners to extend diggings into hitherto unreachable coal deposits and deep ore veins. However, is not at all clear that the miners' work situation was perceptibly bettered by this engineering innovation inasmuch as the driving force was the exploitation of evermore remote mineral deposits, whereas the miners continued to labor at the outermost reaches of habitability. In other words, at mine, mill, and factory, early mechanization efforts merely expanded the workplace to the limits of human endurance. Often, working conditions were worsened by the characteristic of speedier machines to generate greater quantities of dust and fumes than are possible by unaided human and animal effort. The dire effects of mechanization on workers, many of them women and children, were widely noted, and by 1833, Britain had established an inspectorate for mines and for factories. Similar activities took place in the other industrializing countries at about the same pace. Although early legislation in Europe and the U.S. was concerned with the minimum age of employment, hours of work for children, young persons, and women, and elementary hygienic conditions in mines and mills, once a system of inspection had been established, reports revealed the need for the scope of legislation to be broadened; first, to cover traumatic injury and later, toxic metals and dusts.

Until well into the 20th century, engineering control of occupational health hazards consisted almost exclusively of improving general mine and factory ventilation to dilute and carry off airborne dusts and fumes. Factory lighting, a matter of lesser concern, was addressed by establishing minimum sizes of window openings. In Britain, an 1854 mine safety act directed that there be "adequate ventilation to dilute and render harmless noxious gases" in all mines, and in an 1866 act, there was specific mention of "ventilation for the removal of injurious gases and dusts." Later British Factory Acts called for the application of power for the extraction of injurious dusts, and cited the need to provide a "fan or other mechanical means" to accomplish this. The first attempt to regulate dangerous manufacturing occurred in 1883 and included a provision for the safe venting of stoves and stacks. An 1889 act contained provisions for guarding against excessive heat and humidity in cotton cloth factories by fixing a minimum standard of 600 cu. ft. of outside air per hour per person employed. This brief recital of a growing recognition, during the 19th century, of the critical importance of ventilation engineering for protecting workers from harmful airborne substances arising from their work, describes the beginnings of a profession that can now be identified as industrial hygiene engineering. Although engineering control of occupational exposures embraces many additional skills, ventilation remains central as the most widely applied of the engineering control measures.

During the latter half of the 19th century and first half of the 20th, widespread prosperity, comparative political stability, and reductions in rapid population expansion in the industrialized nations, made it the norm for women to assume the role of full time homemakers and child rearers, and for children to undergo schooling, at least until late teens, rather than experience early induction into the industrial workforce. After women and children had largely withdrawn from the industrial workforce, (except for a few traditional womens' occupations, such as the needle trades), adult male occupational health became the principal concern, except for brief interruptions during the two great wars. As everyone is well aware, women have re-entered the workforce in enormous numbers during the past decade or so, and not just in white collar occupations. Government figures show that women represented 43% of the U.S. labor force in 1980, and the upward trend continues. Their presence in industry has become manifest in numerous ways. One was an emphasis during the 1977 OSHA lead standard hearings on the need for a lower permissible value for lead in air than had initially been proposed by OSHA in order to cope with the greater susceptibility of females and their unborn children to the detrimental effects of lead absorption. There was discussion about the detrimental effects of lead absorption on male reproduction as well, and even though male reproductive damage from lead is far less well known, there appeared to be a critical need to establish enhanced male susceptibility to lead to avoid a conclusion that women in the child-bearing ages should be prohibited from employment in all lead-using industries. Concern for the greater susceptibility of women to many occupational toxic exposures and stresses, and the special detrimental effects of occupation on the outcome of reproduction, have received a great deal of attention in recent years. To a remarkable degree, we have come full circle in a little more than a century, with respect to the health of women becoming the primary driving force for legislation pertaining to the safety and health of all workers. Once again, male workers benefit.

In addition to the special concern we have for avoiding reproductive harm in females, their large presence in the workforce creates serious engineering control difficulties associated with their significantly different physical proportions than those of men. This means that engineered safety systems must adapt easily and effectively to a very wide range of statures and body proportions, a difficult enough requirement when only males have to be considered. The difficulties engendered by differences in morphology between women and men become especially prominent when we consider items of personal protective equipment that must fit the body contours exactly. Good respirator fit has been recognized as an especially difficult problem for women.

The enormous strides we are witnessing in all aspects of cell biology, and most especially in knowledge concerning genetic structure, have increased our ability to identify individuals with general susceptibility to chemicals and metals, as well as those having special sensitivity to specific toxicants. Although the technology is not yet well developed or generally accepted as adequate for the task, it is reasonable to expect that rapid progress will be made here, as in all other areas of cell biology, and that it will soon become possible to identify with reasonable assurance the genetically more susceptible fraction of the population that is seeking employment. We must now ask ourselves whether there is a real danger that the two concepts — revolutionary biological technology and an OSHA-sponsored reversion to placing full responsibility for occupational safety on individual workers by re-emphasizing personal protective clothing and devices — will be combined some time in the future to justify elimination of engineered safety systems — the same engineered safety systems we have relied upon to protect the entire workforce without preselection with respect to gender, genes, or generation potential.

Returning once again to the topic of engineering control technology, it is worth noting that although many engineers enter the field of occupational health, relatively few practice industrial hygiene engineering as a specialty. In 1980, the American Board of Industrial Hygiene (ABIH) listed 71 industrial hygienists certified in the specialty of engineering, with 11 of them retired. Therefore, out of 1,500 certified industrial hygienists, only 60 represented the fully-identifiable, active, professional pool of practicing industrial hygiene engineers in the U.S. Many certified by ABIH in the comprehensive practice of industrial hygiene are engineers. Doubtless, some continue to practice industrial hygiene engineering as a part of their total duties but the number so engaged, part-time, is presently indeterminate. It may be large, but the points being stressed are (1) these people do not specifically identify their professional practice with engineering and (2) even when part-time engineers are included, the pool of industrial hygiene engineering practitioners remains small. This has several unfavorable consequences: (1) there are not enough skilled engineers in this specialty to go around, reinforcing the notion among potential users that engineering controls for occupational hazards may be difficult to design and, therefore, overly costly to construct; (2) the small number of people that are easily identifiable as professional industrial hygiene engineers present an exceptionally low profile among the entire engineering profession. Therefore, those in need of their services are unaware of their availability, or even existence, and, instead, seek assistance from professional engineers practicing other specialties. It is a fact that engineers in specialties other than industrial hygiene and who, therefore, lack special knowledge or experience in industrial hygiene engineering, design most of the control systems that possess any significant degree of complexity. Regrettably, they are responsible for the installation of many poorly functioning or inefficient engineering control systems; (3) the third unfavorable consequence is that most local exhaust ventilation systems are installed by sheet metal contractors without benefit of any engineering input whatsoever. It is a firmly held belief among industrial hygiene engineers that all such systems function poorly and are grossly inefficient. I do not know of any reliable survey evidence that supports this belief, but it has not been contradicted by my personal experience. The inescapable conclusions are that there are insufficient numbers of industrial hygiene engineers to do the entire job, other engineering specialties are unable to perform the required industrial hygiene services well, and non-engineers are simply incompetent.

Before turning to a consideration of remedial measures, it is important to say a few words about industrial hygienists who are not professional engineers but who, nonetheless perform important engineering functions of an occupational safety and health nature. Practitioners of this variety of industrial hygiene engineering hold graduate degrees in industrial hygiene and have had instruction in industrial hygiene engineering courses but do not hold engineering degrees. This has come about because of the changing nature of the student body in graduate programs leading to degrees in industrial hygiene. Until recently, students with engineering degrees predominated, but now there are few engineers and the majority of students come with baccalaureate degrees in biology, chemistry, and other non-engineering disciplines. There is no reason to believe that these people are not excellent industrial hygienists, but one must ask whether they are capable of performing the engineering design functions we associate with industrial hygiene engineering. Based on recent experience, the answer is a tentative "yes", but they will not be allowed to do so in situations where a registered professional engineer's seal must, by law, be placed on plans and specifications. At present, most industrial hygienists receive their graduate professional education at schools of public health that do not grant engineering degrees, whereas most engineers are educated at schools that lack programs in industrial hygiene engineering. This is an entirely unsatisfactory situation insofar as increasing the pool of fully functional industrial hygiene engineers is concerned and will be referred to again, later.

Industrial exhaust ventilation has been the workhorse method for controlling gases, vapors, and fine particle aerosols since Joseph Dalle Valle published the basic principles

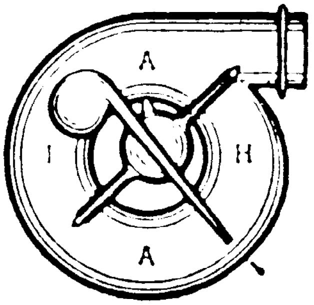

Figure 1.

of local exhaust ventilation in his 1930 doctoral thesis.[6] To the best of my knowledge this was the first doctoral degree ever awarded to anyone in the world in the special field of industrial hygiene engineering, and it has had a profound effect on our profession up to the present. A manifestation of the importance of ventilation in industrial hygiene is the original logo of the AIHA that displayed a retort and an X-ray tube superimposed on a centrifugal fan, the latter to symbolize the engineering component of the Association's membership (figure 1). Although general ventilation for dispersal of workroom contaminants was widely practiced long before Dalle Valle's time, as already noted, and continues to be practiced to a minor degree up to the present, local exhaust ventilation predominates because it gives much more effective control of worker exposures and greater economy of operation. This latter point has come increasingly to the industrial hygiene engineer's attention over the past few years and a great deal of effort has been expended on developing safe and effective ways to recycle industrial exhaust air to reduce energy costs.

An additional motivating factor for reducing exhaust air volumes to the lowest possible level is a need to minimize the costs of cleaning exhaust air prior to discharge for air pollution control purposes. As the cost of effluent air cleaning for air pollution control purposes is closely correlated with the volume of air to be processed (and is scarcely related at all to the concentration of contaminants in the gas stream) it will be clear that this is another powerful incentive to reduce local exhaust volumes at the source. Already, we perceive in the most recent edition of the highly regarded Industrial Ventilation Manual[7] the beginnings of a strong push to reduce control velocities in local exhaust ventilation systems to the least possible values as an energy conservation measure. The danger here is the loss of traditional good practice standards that have stood the test of time by failure to include safety factors that take into account worker misapplication and the inevitable deterioration of equipment through usage.

Describing the principles of engineering control of occupational hazards is reasonably simple and straightforward; applying them is complex because of the very large number and diversity of occupations. The Bureau of Labor Statistics' Dictionary of Occupational Titles[8] contains more than 20,000 job descriptions, and the list continues to grow at a fairly steady rate. The latest edition of the NIOSH Registry of Toxic Effects of Chemical Substances[9] contains toxic dose information on close to 25,000 different chemicals and there may be another 25-30,000 industrial chemicals awaiting listing. Add to this the hazards of physical agents in the workplace, such as noise, vibration, and pressure, plus a full spectrum of non-ionizing and ionizing radiations, and it will be clear that the number of combinations and permutations of combinations that one may reasonably expect to encounter in the workplace borders on the infinite. Perhaps as a direct result, we note with considerable awe the information explosion in the field of occupational health. Patty's 1962, two volume, second edition of Industriald Hygiene and Toxicology[10] contained 2,300 pages, whereas the five volume, third edition, 20 years later,[11] contains well over 7,000 pages, more than a 3-fold increase during a rather brief period. This phenomenon may be characteristic of the entire field of environmental health as Stern's 1962 two volume, first edition of Air Pollution[12] contained 1,170 pages, whereas the five volume, third edition, sixteen years later,[13] contains almost 4,000 pages, a 3.2-fold expansion. This is not intended as a negative comment on these two very valuable reference tests, but it is instructive to contrast their growth with that of the familiar Handbook of Chemistry and Physics that went from 2,950, 5×7 in. pages in 1952[14] to 2,432, 7×10 in. pages in 1982,[15] an expansion less than double in 30 years. More noteworthy in this respect is the Chemical Engineers' Handbook that went from 1,942 pages in the 1950 edition[16] to 1954 pages in the 1973 edition,[17] an increase of only two pages in nearly a quarter of a century.

The point I wish to make by contrasting the growth of these familiar reference texts is that general scientific and engineering knowledge seems to have increased at a much slower rate than has the information about industrial hygiene over the past few decades. An additional factor leading to increasing complexity is industrial hygiene's technical dependence on a number of well established basic scientific and engineering disciplines that are, themselves, prolific generators of new and useful information. In a very real sense, industrial hygienists are avid consumers of the most recent fundamental discoveries generated by chemists, toxicologists, physicists, and chemical engineers, just to mention a few of the important wellsprings of our scientific support structure. We must, therefore, look for ways in which the bewildering array of jobs, chemicals, and physical stresses can be reduced to a few basic models that will transform chaos into order and make it possible for an industrial hygiene engineer to function well when new challenges arise. The first thing that must be recognized is that effective problem-solvers do not rush in to apply a formula or an equation. Instead, they try first, to understand the problem and then to consider the interrelations of the variables. Only after they are satisfied that they understand the situation in a qualitative way do they start to apply quantification. The essence of problem solving, therefore, is to look for meaning, regularity, and order in the absence of complete information.

Therefore, I consider it regrettable and wrong minded for experienced industrial hygiene engineers to continue to advocate a careful, stepwise, empirical, trial-and-error approach to industrial hygiene engineering design whereas other engineering specialties have progressed to quantitative design procedures firmly based on theoretical considerations and first principles. Just as one no longer designs bridges and airplanes by trial-and-error methods, so should we abandon our empirical approach to the design of controls for occupational health exposures.

As this is not the place to develop this thesis to the point where it encompasses 20,000 occupations and 25,000 chemicals, it will suffice to cite a single operation to define the methodology. If one takes a very broad interpretation of the term, *evaporation*, it is possible to list many familiar operations, of widespread application, that can be covered under this single rubric. A few are: fabric coating, welding, paper coating, brazing, galvanizing, soldering, steel melting and solvent degreasing. For control purposes, all of these processes look very much alike. In each case there is a pool of evaporating liquid that may be at any temperature from ambient for degreasing to 2800° F for steel melting. The vapor evolves by molecular diffusion but is immediately entrained by air currents bringing in the concept of eddy diffusion. When the objective is to conserve the liquid pool, or prevent oxidation, as in a steel furnace, the process must be enclosed and exhaust ventilated to draw off only whatever air enters the enclosure. When vapors are explosive, attention must be paid to maintaining the vapor-air mixture safely below the lower explosive limit. If, however, one is interested in having the liquid evaporate rapidly, (*e.g.*, drying paper coatings), there will be no need to enclose the process completely and, in fact, plenty of airflow will be useful for carrying the vapors away. The penalty for maintaining an open process is a need to generate much higher control velocities to overcome the effects of convectively generated turbulence. The higher the temperature, the more vigorous the turbulence currents become and the greater will be the in-flow needed to prevent escape of contaminated vapors to the workroom.

If one looks for solutions to this rather straightforward engineering problem in the Industrial Ventilation Handbook(7) one finds empirical factors for each separate operation that reflect several decades of practical, trial-and-error experience. Most of the time (but not always) the empirical solutions do work, but there will be no firm grasp of the basic mechanisms involved or of the efficiency of the system, either for capture or for energy conservation, that is, efficiency of the system, either for capture or for energy conservation. That is to say, we don't know if the recommended airflow rate is excessive or just barely adequate to do a minimum job of control, with no allowance for deterioration. However, by starting from first principles, it becomes possible not only to understand the process in a more intimate way, but to acquire methods adequate to measure practical performance against an ideal standard.

To those with some acquaintance with chemical engineering, the procedure described will be reminiscent of the unit operations approach that has been a stock-in-trade of chemical engineers since Arthur D. Little presented this concept in 1915. This is not accidental. The unit operations concept has proven enormously useful to the chemical engineering profession for teaching, for research, and for engineering practice. It stands as a model that can provide useful ideas and inspiration to the industrial hygiene engineering profession for the future. I venture to state that the ability of the Chemical Engineers' Handbook to reflect the essence of their profession in the same number of pages over a 25 year span reflects an extraordinary ability to organize their body of essential knowledge under a relatively few basic categories, rather than professional stasis.

The point being made is that the education of industrial hygiene engineers needs to be improved for the benefit of the health and growth of the industrial hygiene profession because the profession is still living off Dalle Valle's 1930 doctoral thesis and Silverman's 1942 doctoral thesis(18) for its entire body of local exhaust ventilation theory. All ventilation work since then has been in the nature of refinement and commentary. We are desperately in need of a new infusion of science and engineering into industrial hygiene control engineering to match the enormous changes that have occurred in work practices. We are still applying control technology developed 40 and 50 years ago to 1983 work situations, and this includes the design of respiratory and other personal protective equipment. We are painfully aware of the plight of the U.S. auto industry trying to use 1973 manufacturing technology for 1983 production needs — and that is only ten years out of date. Industrial hygiene engineering must go back to basic principles to transform an empirical control art into a science of advanced control engineering or we too will end up buying our technology from the Japanese. In short, we need to start a new trend in education and research for producing and sustaining industrial hygiene engineers.

I am pleased to report that there have been some encouraging stirrings recently in the direction I am advocating. I will mention just two. Brief and his colleagues have been developing the seminal concept of a near-field dispersion model, designed to predict personnel exposures to airborne substances in the workplace by applying classical thermo- and aerodynamics to manufacturing descriptions and the physical and chemical characteristics of the materials in process.(19) There is a reasonable expectation that this approach will ultimately be capable of guiding engineering control activities on a rational basis. The other is Burgess' recent publication entitled, "Recognition of Health Hazards in Industry".(20) It makes a good start on the important task of developing an integrative approach to occupational health protection.

When I say that I believe very firmly that industrial hygiene engineers should be expected to have a good working knowledge of basic chemistry, mathematics, and physics as well as physiology, anatomy, and toxicology, in addition to their own special engineering discipline, to prepare them to perform their work in the most effective manner, it is entirely appropriate to inquire how this can be accomplished in the face of the information explosion to which I have already referred. The answer, I think, revolves around the fundamental difference between information acquisition and education. I am of the opinion that we need to return to a type of education, starting from the earliest years and continuing through graduate school, that concentrates on the basic principles of science and engineering, rather than a long list of vocational courses. It is basic understanding that makes it possible to focus on important problems that span traditional disciplines and to arrive ultimately at an effective synthesis, often with the active assitance of those who are specialists in the separate disciplines involved. Without the integrative force of interdisciplinary knowledge, it is not possible to cope with the myriad of seemingly special cases that confront the industrial hygiene engineer as a daily experience. I can foresee no other solution to a mastery of the enormous and growing body of industrial hygiene information, and of the similar expansion of knowledge in the disciplines on which industrial hygiene depends heavily, than to reorient our educational and professional development programs in the direction of enhancing basic understanding of the underlying facts so that we can transform our profession from one of empiricism to one of science.

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