ENGINEERING DESIGN FOR THE CONTROL OF WORKPLACE HAZARDS

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Engineering Design for the Control of Workplace Hazards

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Preface

Design of control systems to enhance occupational safety and health is becoming a basic necessity in most industries. The requirements of OSHA, increased employer liability, and heightened worker awareness of the implications of unsafe and unhealthy work environments are all contributing to recognition of this educational need. Although a small cadre of ventilation and safety engineers and industrial hygienists are available to deal with design and control of occupational hazards, their area of application is often limited to large installations or companies. And their contributions are often only belatedly incorporated, after equipment or process design and installation have been completed. The vast majority of engineers concerned with design and operation are not trained to recognize or control existing or potential safety and health hazards. In addition, while many of the principles of engineering control technology are well known, these ordinarily are not collected in one volume convenient for use by the practitioner in the field.

The major thrust of our effort is to reach those engineers who probably will not become specialists in the occupational safety and health field. However, this large group is knowingly or unknowingly often called upon to make significant decisions that will affect the workers' well-being. Our aim is to provide these engineers with guidelines with which to evaluate the problem, and design tools with which to make at least initial estimates of the control technology required. Our text encourages incorporation of control concepts at an early stage of design, and will supply practicing engineers with information to support bid specifications and to ask "the right questions" of contractors and consultants carrying out the actual installations.

We have structured our presentation into four general areas: control rationale, control specification, system design, and control requirements for specific hazards. Chapter 2, "Occupational Injury and Disease," supplies the control rationale, which is ultimately protection of worker health. In this chapter we summarize in some detail injury statistics and the findings of occupational epidemiology in a variety of hazardous industries. We have not attempted to present an exhaustive review, but we have tried to present enough information to give those who are not specialists in epidemiology a reasonable appreciation of the data that do exist.

Under control specification we have included Chapter 3, "Hazard Evaluation and Control," and Chapter 4, "Design Criteria." Chapter 3 is intended as a brief summary of approaches that are used for workplace evaluation. Standard references such as *Patty's Industrial Hygiene and Toxicology* (Clayton and Clayton, Wiley, 1978), NIOSH's *The Industrial Environment* (NIOSH, 1973 and soon to be revised), the National Safety Council's *Fundamentals of Industrial Hygiene* (Olishifski, 1979), and an ever-expanding literature are available for the details of industrial hygiene practice. Likewise, although we have left specific discussion of toxicological testing to more specialized texts, we have presented a variety of relationships based on such testing, which may be used to predict worker exposure. Every design procedure requires a criterion on which to judge success or failure. Appropriate criteria for the workplace, both as performance and specification standards and guidelines, are summarized in Chapter 4, "Design Criteria."

System design includes "Ventilation" (Chapter 5), "Air Cleaning" (Chapter 6), "Process Alteration" (Chapter 7), and "Worker-Machine Interactions" (Chapter 8). Each of these presentations emphasizes procedures to implement the first level of a design solution. The nature of the problems dealt with in these areas is somewhat broader than those summarized under control requirements for specific hazards. "Guarding" (Chapter 9), "Ionizing Radiation" (Chapter 10), "Nonionizing Radiation" (Chapter 11), "Heat" (Chapter 12), and "Noise and Vibration" (Chapter 13) fall under the latter category.

A common format has been used for each design chapter. This includes a description of the particular problems associated with each area (e.g., heat), presentation of the appropriate design equations, and worked-out solutions to realistic design problems. In general, we have included enough data and other reference material so that the reader need not search elsewhere. The choice of design procedures was based on existing practice, with preference given to those methods that have been thoroughly validated in field and laboratory. We have not discussed the theoretical basis for such procedures in depth, nor have we presented approaches that are presently in the speculative stage, although numerous references are cited for the interested practitioner.

A panel of chemical engineers in industry recently advised the AIChE that chemical engineering design classes should present the simplest valid design procedure and the most complex (e.g., numerical integration); and dispense with teaching any of the intermediate "short-cut" approaches of varying complexity, which were formerly so useful before general access to computers became available. We subscribe to this philosophy and have presented the first-level procedures in our text. Although at first glance these may not appear to be "back-of-the-envelope" estimators, all of the calculations can be carried out efficiently with a hand-held calculator.

As with any book of this size, many persons contributed to its evolution. In order to implement the intended scope of design, the need soon became evident for insightful contributions from others knowledgeable in the field. It has been our good fortune to be able to call on just such a competent group at the University of Illinois in Chicago who generously made their expertise available. Five of six authors are engineers (chemical, civil, environmental, industrial), four are certified industrial hygienists, and three have professional engineering registration. Dr. Edward Hermann, School of Public Health, University of Illinois, wrote Chapters 12 and 13, "Heat" and "Noise and Vibration"; Dr. Robert Allen of the same school contributed Chapter 5, "Ventilation," and collaborated with us on Chapter 6, "Air Cleaning"; Dr. John Franke, formerly of the University of Illinois and now with Peterson Associates, contributed to Chapters 3 and 4, "Hazard Evaluation" and "Design Criteria," and just as importantly, critiqued the whole book from the vantage point of his extensive experience as a practicing industrial hygienist. Dr. Floyd Miller of the Mechanical Engineering Department of the University co-authored Chapter 9, "Guarding."

John Talty of the National Institute for Occupational Safety and Health (NIOSH) and William Martin, Consulting Environmental Engineer and formerly with NIOSH, were most helpful in supplying information, documents, and review comments. Our thanks also go to Barbara Bates for developing the tables in Chapter 2; Dr. Chung Fung-Li and Thomas Galassi for reference checking; Dr. Daniel Hryhorczuk for his review of Chapter 2; Ms. Dianne Martia Salaty for the original artwork; and the students who participated in our courses in engineering control for occupational safety and health at the Illinois Institute of Technology (ENVE 532) and the University of Illinois at Chicago (CEMM 393). We also offer our greatest appreciation to Frederica Davis, Denise Umstead, and Rosita Plaza for all the typing that was required. Most particularly, we would like to thank Mrs. Davis, who labored full-time for almost seven months through a bewildering morass of scrawled drafts, always with the greatest equanimity.

The choice and presentation of materials represents the authors' pooled academic and workplace experience, and the editor's judgments. Our coverage has been of necessity selective, although we hope that most topics will be useful. We, of course, stand responsible for all errors, omissions, and oversights.

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Contents

Chapter

1

Workplace Hazard Control

R. A. Wadden

The underlying rationale for workplace control is protection of worker and community health. The actual response to a control need may be stimulated by the presence of a regulation or guideline, the desire to maintain good employer-employee relationships, an interest in obtaining reasonable insurance rates, or the threat or implementation of a law suit. Regulations, such as the Occupational Safety and Health Administration's *General Industry Standards* (OSHA, 1983), and guidelines, such as the American Conference of Governmental Industrial Hygienists' *TLV's, Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment* (ACGIH, 1985), provide specifications for developing appropriate design solutions. These are often in the form of numerical goals related to worker exposure. For instance, the OSHA noise regulation specifies 90 dBA as an acceptable 8-hr exposure; and the TLV of 0.05 mg/m^3 of air for chromic acid (expressed as Cr) is suggested as an appropriate average 8-hr air exposure that ordinarily is not expected to cause adverse health effects. Other types of specification detail the actual design configuration that must be used to protect workers from illness and injury, e.g., point of operation guarding for a mechanical power press.

Less easily formulated into design specifications, but just as important a stimulus for control in our present society, is the possibility of legal action. Probably the most notable hazard in this regard, at least up to the present, has been asbestos production and use. Table 1.1 indicates the number of lawsuits that have been filed against several U.S. companies engaged in asbestos work. It has been estimated that asbestos-caused diseases could cost the industry and its insurers $200 billion or more by the end of the century (*Economist,* 1982). Manville Corporation, the largest U.S. asbestos producer, requested relief from asbestos litigation by filing for reorganization under federal bankruptcy laws (NYT, 1982); and additionally sued several of its insurers for $5 billion, alleging that they had wrongfully refused to pay appropriate claims (Brody, 1982).

When numerical guidelines exist for worker exposure, it is usually necessary to determine existing levels for comparison purposes. Careful workplace monitoring of noise and vibration, chemicals in air, temperature (heat exposure), and ionizing and nonionizing radiation will indicate: (1) whether an acceptable level is being met; (2) which machines or processes are responsible for acceptable levels not being met; and (3) what reduction in exposure and discharge is required to reach and maintain acceptable levels. Some approaches to interpretation of monitoring data in order to answer these questions are given in Chapter 3.

Given an acceptable level to design to, it is then necessary to choose an appropriate mode of control. This may be through engineering design, which includes local and area ventilation; process and equipment modification; substitution of less hazardous materials; pollutant removal, isolation, and shielding; use of devices for personal protection; and administrative controls. As an illustration of each, let us consider

TABLE 1.1 Asbestos-Related Lawsuits

Company	Suits outstanding
Manville	16,500
Amatex	9,300
GAF	10,000
Celotex	11,000
Owens-Illinois	"Substantial number"
Eagle-Picher	11,500
Pittsburgh Corning	8,000
Raymark	10,443
Rock Wool Mfg.	3,000–7,000
Bairnes	11,000
H. K. Porter	Not available
UNR Industries	17,000

SOURCE: *Economist,* 1982.

the options available for minimizing noise exposure in the engine room of a large ocean-going merchant ship, *The Hawaiian Queen* (Jensen et al., 1978). Measurements in the engine room indicated average levels of 120 dBA over 8 hrs, well above the applicable OSHA standard of 90 dBA. In addition, the primary stage of a nested-type double-reduction gear unit of the 9000-hp steam turbine was identified as the major noise source. Requiring protective earmuffs for all engine room workers is one possible approach (although not a complete solution, since earmuffs alone would probably not reduce exposures by 30 dBA). Administrative solutions might be to minimize worker entry into the engine room; or to specify (possibly illegally) that only those sailors who already have significant hearing impairment be employed at this worksite. An engineering solution, which was actually implemented, was to enclose the gear train casing with modular acoustic panels. A split commercial silencer was also installed at the point of propeller shaft penetration into the enclosure to attenuate sounds that would otherwise escape around the shaft. These steps reduced the noise to engine room ambient levels. Before and after sound pressure levels are given in Figure 1.1. However, the ambient noise level is 91 dBA, which is still above the OSHA standard. Consequently, further control is required. Monitoring of personal exposures would still be advisable to determine whether hearing protection is required, since workers will spend different amounts of time near the equipment and elsewhere in the engine room.

The thrust of this book is toward engineering design to solve such problems. We have attempted to explain and demonstrate ways to control workplace hazards at their source. We have suggested methods of control, tested by ourselves and others, which are generally agreed upon in the environmental and occupational field. Procedures to predict

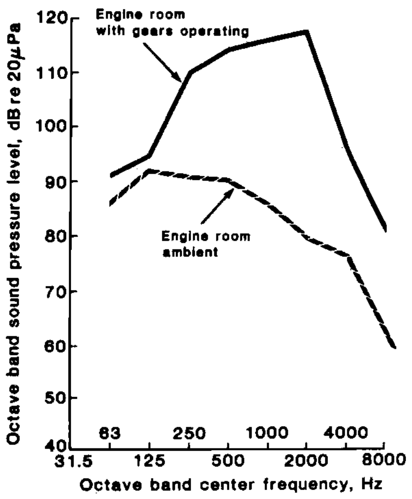

Figure 1.1 Engine room sound pressure levels (*Jensen et al., 1978*).

control efficacy are recommended whenever appropriate. The goal of these calculations is to make a reasonable first estimate of the important design parameters for a particular problem. For example, the appropriate thickness and material for shielding from a neutron source are determined in Chapter 10; the acoustical treatment required for an enclosure to control a 500-Hz noise source is specified in Chapter 13; the design requirements for ventilating an open-surface dip tank are developed in Chapter 5. These estimates can subsequently be used by the practitioner for planning purposes, initial cost estimates, and control equipment and process specification and evaluation. They also serve as a basis for informed discussion and consultation with design specialists and contractors, and provide a format for field evaluation of the effectiveness of the ultimate design solution.

The suggested design methods will often not supply a final answer to a workplace problem. This will ordinarily require a more intensive investigation of the technical and economic feasibility of various available alternatives, followed by a specific design in more depth at the nuts-and-bolts level. The details of final design solutions for such diverse problems as shielding of ruby lasers, local ventilation of a chromic acid electroplating bath for bicycle parts, or reduction in the vibrational energy of a metal grinder probably will come from specialists in these areas.

Nor are our recommended procedures meant to be all-inclusive or to produce an "instant expert." Most design solutions require several rounds of "cut-and-try." However, the following chapters do supply an approach to problem definition leading to an initial evaluation of control alternatives. Application of the design methods will allow the practitioner to intelligently and systematically initiate and participate in the design process.

Of necessity, many of the problems faced by plant engineers are due to existing situations. Processes may be unsafe because of poor original design, or they may have become so because of change in function. Sometimes the health implications of unsolved or unrecognized safety hazards may not be realized for long periods, even years. It is hoped that this text will be helpful in responding to such immediate concerns. But the underlying motive of our approach is to encourage consideration and inclusion of safe design at the early, conceptual stages of project planning. Making hazard control an integral part of the design process provides a powerful method of attaining a safe workplace.

A case in point is a recent report called *Computerized Manufacturing Automation* (OTA, 1984). Although it discusses the economic implications of robotics in terms of both projected lost jobs and increased plant investment, and also the potential development of a "dehumanizing" work environment, there is only one mention of the possible workplace hazards associated with such devices. Unfortunately, an equally current NIOSH report (NIOSH, 1984) details the death of a trained, experienced die-cast worker after being pinned between the back end of an industrial robot and a steel safety pole. The hydraulic robot had been installed to remove and transfer die-cast parts from a die-cast machine. The worker entered the robot's work envelope to clean up scrap metal accumulated on the floor. To do so, he evaded the safety rail interlock system and evidently did not recognize the hazards associated with the movement of parts of the robotic assembly other than the active arm. The need for more thorough worker training and supervision, adequate clearance for robot operation, and the incorporation of motion sensors or light curtains to inactivate the robot when a person crosses the work envelope boundaries are among the recommendations for future robot designs.

Retrofit controls are by their nature often expensive, and frequently are considered as incremental "extra" production and investment costs due to the necessity to fulfill recently recognized regulatory or legal requirements. However, many times good engineering design for hazard control at the planning stage, and even retroactively, will result in economically attractive solutions. An example is given in Chapter 7 of an oxychlorination process in which a process change increased yield as well as reducing pollutant production and discharge. The control of leaks in chemical plants and petroleum refineries (discussed in Chapters 3 and 7) is also a procedure that has the potential for yielding financial dividends.

Better employee morale is another likely outcome. The finishing of stereo cabinets in one spray-painting plant offers an example (O'Brien and Hurley, 1981). In this process the wooden cabinets are finished with a base coat, a glaze, and a clear lacquer in a multistep, conveyorized operation. At one of the steps a robot was installed to apply a heavy coat of glaze to cabinet exteriors and lid undersides because of high employee turnover in this messy operation. Besides eliminating the operator from an unpleasant function, using the robot reduced waste from overspray and increased material utilization by 15%, and the company expects a 5-year payout.

In another example, from a corrugated box factory, slit side trim was blown through a conveyor duct to collection bins (Jensen et al., 1978). The 12-in. duct was suspended 10 ft from the floor, extended across the 40-ft work room, and contained blower fans with heavy blades, which chopped up and conveyed the trim. The trim hitting the walls caused ear-level sound levels of 93 dBA (Figure 1.2). Noise-level control was sought to improve worker communication as well as to meet the OSHA 90-dBA requirement. The solution was to wrap the problem duct locations (mainly at the bends) with 2 in. of mineral-wool building

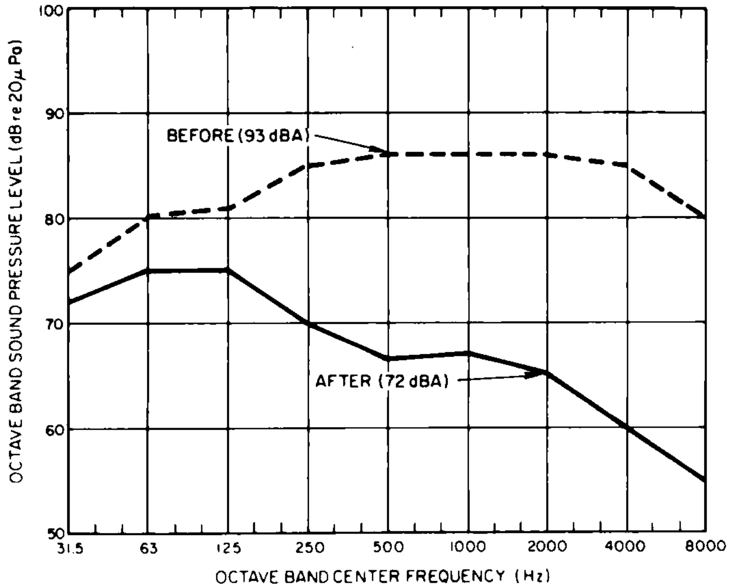

Figure 1.2 Noise levels in scrap duct for corrugated box industry, before and after covering (*Jensen et al., 1978*).

insulation to furnish an absorbing and resilient layer. Two impervious layers of heavy tar paper, spirally wrapped with 50% overlay (to prevent noise leakage) were placed over the insulation. The resulting noise level was 72 dBA (Figure 1.2). This reduction was more than enough to meet the OSHA standards, and the conveyor noise could hardly be heard above the ambient noise in the building. Plant safety and employee morale improved because speech interference was greatly reduced.

Every design that is implemented to control workplace hazards, whether retroactive or original, needs to be followed up with field measurement to check the efficacy of control. There is no substitute for this step. Of the unsuccessful design solutions we have observed, most occurred because the designer and client assumed that specification and installation were equivalent to effective operation. Prediction methods will not be 100% accurate, and actual operation of a plant may differ considerably from design specifications. Maintenance of ventilation and control systems is as important as initial design.

Figure 1.3 shows the effect of engineering controls on vinyl chloride monomer (VCM) air concentrations at a number of sites in a polyvinylchloride (PVC) dispersion polymerization process (Enviro, 1978). The controls, instituted in 1975, included improved seal-leak detection, maintenance, and venting; individual permanent local exhaust systems for batch mix tanks, orifices, pumps and compressors, reactors, blend tanks, filter enclosure, and PVC cake breaker; and enclosed

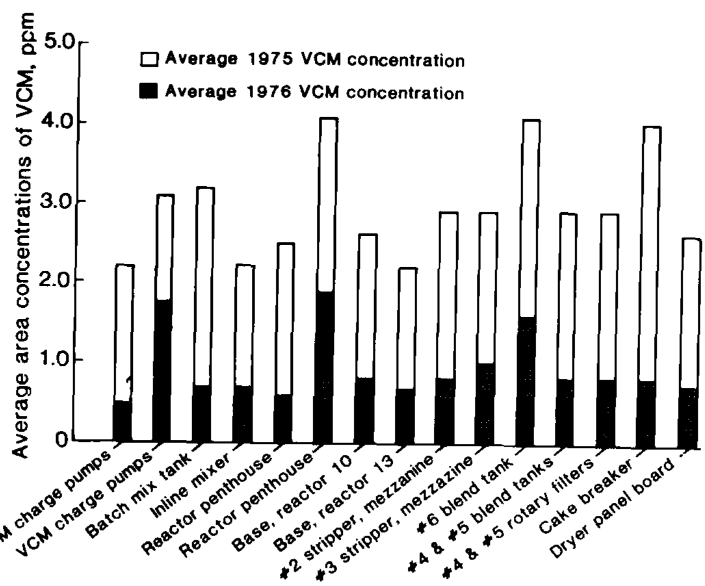

Figure 1.3 Average area VCM concentration at work stations (*Enviro, 1978*). (*Note:* VCM charge pumps and blend tanks were in areas that do not require regular operator attendance; and the reactor penthouse was posted to require personal protective devices.)

waste-treating facilities for process liquids. Although improvement is still necessary [the OSHA permissible exposure limit for VCM is 1 ppm (OSHA, 1983), and the material is a recognized human carcinogen (ACGIH, 1985)], the impact of engineering controls is evident.

The noise control design of a 70,000 bbl/day catalytic hydrosulfurizing facility (CHD) also illustrates such design follow-up (Jensen et al., 1978). The design objective was 85 dBA at normal work stations and 87 dBA maximum in passageways and normal maintenance areas. Figure 1.4 shows the noise contours at the plant site generated from vendor-guaranteed noise emissions for 78 pieces of as-purchased equipment, and simplified assumptions about source location and noise propagation. The problem areas are clearly delineated. Figure 1.5 shows the predicted noise levels that would result from optimum placement of equipment and off-the-shelf noise controls. After the plant was actually built to these specifications, a field test resulted in the contours of Figure 1.6. The general pattern was the same as predicted, particularly close to the plant boundary, but significant levels still occurred at several locations. These were traced to an unexpectedly noisy stripper bottoms pump, two improperly insulated valves, and an unpredicted noisy coupling. The solutions to these problems were relatively straightforward.

This project pointed up the difficulty of gathering good source-noise emission data, and this lack is a problem for other types of emissions