What Do Design Engineers Really Know About Safety?

The major problem concerning design safety is providing the engineer with methods to address safety issues. Moreover, design engineers face the problem that many of them receive little or no formal safety training. Those are two findings of a recent study focusing on the current and future state of safety knowledge and design engineering.

Bruce W. Main
President
design safety engineering
Ann Arbor, Mich.
Allen C. Ward
Department of Mechanical Engineering and Applied Mechanics
University of Michigan
Ann Arbor, Mich.

Design engineers are facing increasing pressure to improve the level of safety in their designs. Such pressure often takes the form of product liability, increased costs or inaccessibility of liability insurance, and accident and medical costs. In some industries, such as motorcycle helmet, light aircraft, and ladder manufacturing, these costs have become dominant, exceeding the costs of either design or manufacture. In virtually every industry, the costs are believed to be high and rising [1]. To better understand how engineers incorporate safety in design, a survey was conducted of both current and future design engineers. The results of the survey provide a basis for understanding what engineers actually do in their design efforts regarding safety, and suggest how it might be improved.

Survey Format

The survey was administered to four population samples including: a random sample of practicing engineers (randomly selected from the ASME Design Engineering Division membership), practicing engineers known to the authors (located throughout the country), University of Michigan faculty in the Mechanical Engineering and Applied Mechanics department, and University of Michigan students in senior and graduate design classes. The survey was administered through the mail, with the exception that the student surveys were personally administered.

Certain novel approaches were employed in conducting this survey. To prompt subjects to consider various types of safety training when answering the survey questions, the questions of training were positioned early in the survey, rather than in the demographic section later in the survey. To increase the number of responses, the nonrandom population sample of practicing engineers was asked to solicit additional responses among their associates who participate in the design process. The rating scales, while not traditional, did provide ordinal data. Since no statistical analyses were conducted on the variations within the populations, no substantial detriment was introduced by not employing more formal rating scales. In all cases the responses were kept confidential.

The response rates for the populations are shown in Table 1. The random survey of ASME Design Engineering Division engineers proved an overwhelming success. Of the 311 engineers responding, 15 of the surveys were received too late to be included in the quantitative analysis, but were reviewed for responses to the open-ended questions.

Although the solicitation for additional responses from the engineers

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population sample was unconventional, this methodology proved successful in that each return netted an average 1.94 surveys. Of the 20 faculty responses, one was a written response in place of the survey.

How Important is Safety To Design Engineers

The importance of safety to the design community was queried through two specific closed-form questions and two open-ended questions.

Product Liability in Design. Figure 1 shows the responses to the questions concerning product liability. The skewing toward the right and the relatively high means indicate that product liability is a significant factor in design.

Safety Value in Design. The respondents' evaluation of the contribution of product safety to product value is shown in Figure 2. The skewing of the distributions toward the upper values is relatively consistent across the four populations.

Financial Adjustments Regarding Safety. When asked, "Given the frequent claims of inadequate designs with respect to safety, how can the design process (or designs) be improved?" a majority of subjects who commented recommended that safety should receive greater financial emphasis. A common suggestion was that an adjustment in the financial inputs to design is needed, for example: decreasing sales and administration budgets and increasing engineering and manufacturing investment.

Several respondents said time and cost factors receive greater emphasis than good design. Many respondents indicated that the lack of time is a factor in safety issues not being adequately addressed. Respondents cited problems with managers listening to cost accountants rather than designers. Respondents also expressed concern with the tradeoff between design for cost versus good, safe design. One frustrated respondent even said: "There is never enough money to do it really right."

Other respondents expressed different views on financial considerations. Some said consumers do not value safety enough to pay the premiums. Others suggested that companies should sell safety features to customers. One said that better financial rewards to developers of safety features are needed. The example offered was in the automotive field: "Eaton Corp. developed

TABLE 1
Response Rates

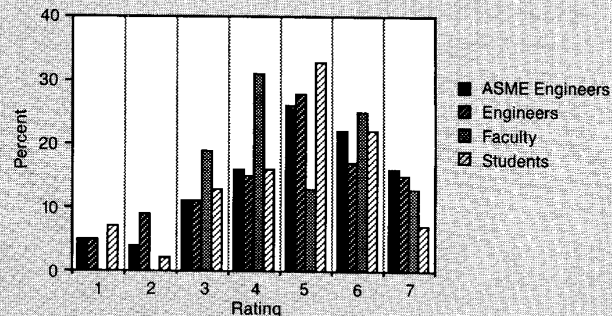
	ASME Engineers	Engineers	Faculty	Students
Number of surveys	500	60	46	not available
Number returned	311	50	20	52
Percent returned	62	83	43	not available
Additional responses		47		
Total number of responses	311	97	20	52

TABLE 2
Safety Training Through Self Study

Specific self instruction or study pertaining to safety?

	ASME Engineers	Engineers	Faculty	Students
Number of respondents	264	88	18	46
Percent No	53	58	61	70
Percent Yes	47	42	39	30

Among the multiple factors influencing your design decisions, how significant a factor is product liability?



Not a factor	Very minor	Minor	Moderate factor	Major	Very major	Extreme factor
1	2	3	4	5	6	7

Summary statistics

	ASME Engineers	Engineers	Faculty	Students
Mean	4.83	4.59	4.93	4.60
Standard deviation	1.62	1.70	1.33	1.53
Number of respondents	278	96	16	45

Figure 1. Significance of product liability in design.

the air bag, but the Japanese will reap the profits."

Motivation Versus Empowerment

These results demonstrate that most engineers recognize the impact of product liability and are motivated to include safety in their designs. Contrasting these findings with statements from the safety community highlights an apparent dichotomy between the design and safety communities.

Aurioles [2] suggests that "The need is to motivate scientists and engineers to include safety in all the steps of research and development work. They have the necessary skills to do it." The results of this survey indicate that motivating engineers is *not* the problem. In fact, the results show that on average, engineers consider safety issues to be quite important.

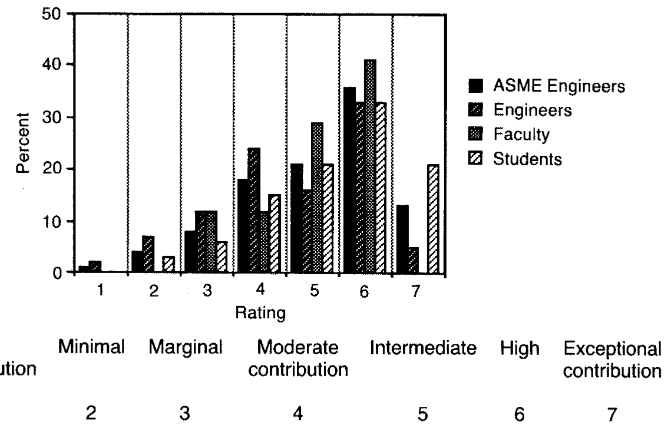
Similarly, in 1981, Colangelo and Thornton said, "We are graduating thousands of engineers annually who have never even heard of the term 'product liability'"[3]. The results of this survey suggest that this is no longer the case. The influence of product liability on design is substantial and equally recognized by the various populations. However, recognizing this influence does not necessarily provide the designer with any direction on how to improve what he or she does. The issue becomes not one of whether engineers *can* easily include safety in their work, but rather do they know *how*?

Inadequacies in Safety Education

Respondents were asked several specific questions about the formal safety training they had received.

As shown in Figure 3, nearly 80 percent of the respondents had not taken a safety course in college. This is true across all four population samples. The figure also indicates that well over 60 percent of the respondents had not taken any safety short courses. Note that 90 percent of the faculty had not taken a safety short course. Further, this figure indicates that 80 percent of the faculty and students had not attended any safety conferences; both engineer populations responded similarly (70 percent) but slightly less. Finally, Figure 3 is notable by the absence of faculty who had attended safety lectures (about 70 percent had not attended safety lectures). In contrast, approximately 60 percent of the other three populations had attended at least one safety lecture. Table 2 shows that self study is a significant source of safety education in that 30 to 47 percent of the respondents had engaged in self instruction or study pertaining to safety.

To what extent does product safety contribute to product value?



Summary statistics

	ASME Engineers	Engineers	Faculty	Students
Mean	5.14	4.66	5.19	5.39
Standard deviation	1.35	1.46	1.17	1.32
Number of respondents	264	91	17	33

Figure 2. Safety contribution to product value.

The respondents were asked to rate their knowledge with respect to safety. Figure 4 shows the responses to this question. Of particular note is the contrast between the two response groupings—the faculty and students view themselves as being less knowledgeable than the practicing engineer populations. This contrast is also reflected in Figure 5, where respondents rated the effectiveness of the methods they use. The average means for these groupings are very similar for both questions.

In the open-ended questions about improving the design process, respondents advocated more safety education in several areas. The primary suggestions included more engineering education, namely seminars and workshops, more classes in school, a required college course, greater emphasis in the engineering curriculum, incorporation of safety issues in design and project management courses, and more formal education covering the theory of safety. Although a few respondents suggested that all engineering courses should include safety concerns, most respondents considered this insufficient. A few respondents suggested that engineers should try what they design (become the user either mentally or with the actual end product) or increase the personal investment by designing for their own use.

Safety Education And Training

Most engineers receive little or no formal training in safety. The most significant safety "training" occurs through lectures or self study, and, even here, 70 percent of the faculty and 40 percent of the remaining three population samples had not received such training. These data offer empirical evidence for Hammer's statement that "Because so many subjects and facts must be taught in engineering schools, instruction in safety and accident prevention is generally often omitted"[4].

The education shortfall is especially pronounced in the engineering faculty, who received the least formal safety training in nearly all categories. These results lend some support to statements made by Philo, "Engineering educators know little

of safety engineering and teach less"[5], and by Hammer, "Most engineering school faculty members who instruct students in safety matters have themselves been inadequately educated"[4].

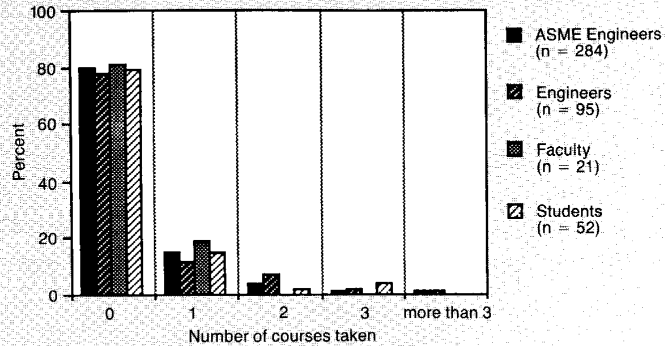
The differential between the faculty and student populations compared with the two engineer populations is notable in two areas. The engineer populations rated both their knowledge and their overall effectiveness higher than the faculty and students rated theirs. This may indicate that the additional safety training engineers receive through safety lectures and self study may have had an impact on their knowledge of safety (as self reported). Without an independent measure of safety knowledge or effectiveness, no absolute conclusions can be drawn regarding the actual benefit or effect of this training.

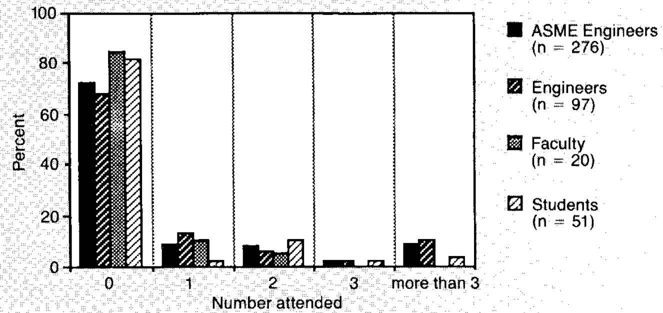
Measuring the Results Against Other Institutions. Three populations of this survey are strongly affected by the two institutions with which both authors have intimate experience (the University of Michigan and MIT). Informal consultations with mechanical engineering faculty at the University of California (Berkeley), Stanford University, and the University of Illinois indicate few differences in the safety instruction methods used in each institution.

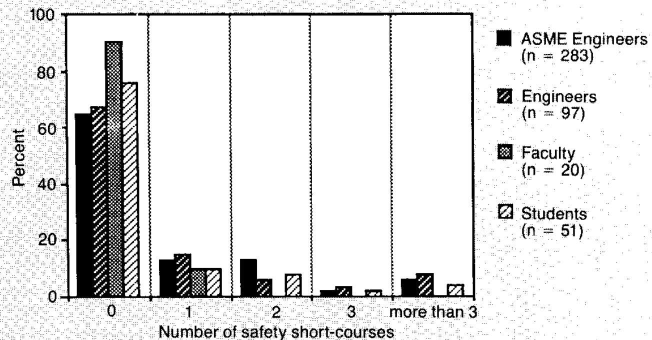
Two Approaches To Safety in Design

Safety is addressed by the design and safety communities in substantially different ways. In the safety community, improving safety centers around eliminating and controlling hazards. The design community employs a much narrower approach.

The relative youth of safety engineering is partially evidenced by the lack of safety engineering methods and tools in "classic" design texts; see Shigley and Mitchell [6] and *Mark's Handbook* [7]. Much of the discussion of safety in these texts is devoted to why safety should be included in design. The few techniques discussed in these types of texts offer little guidance on how to actually include safety in design or how safety efforts fit into the framework of hazard elimination or control. As an example, Shigley and Mitchell state that "The best approaches to the prevention of product liability are good engineering in both analysis and design, quality control, and comprehensive testing procedures" [6]. Although few engineers would disagree with this state-







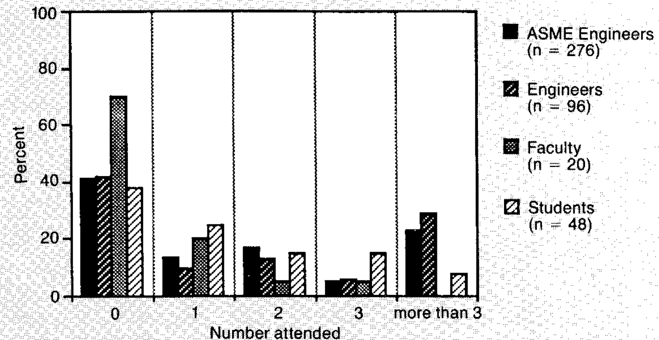


Figure 3. Respondents' safety education and training.

ment, it does not prompt the engineer to take advantage of the more rigorous methods available to analyze safety issues.

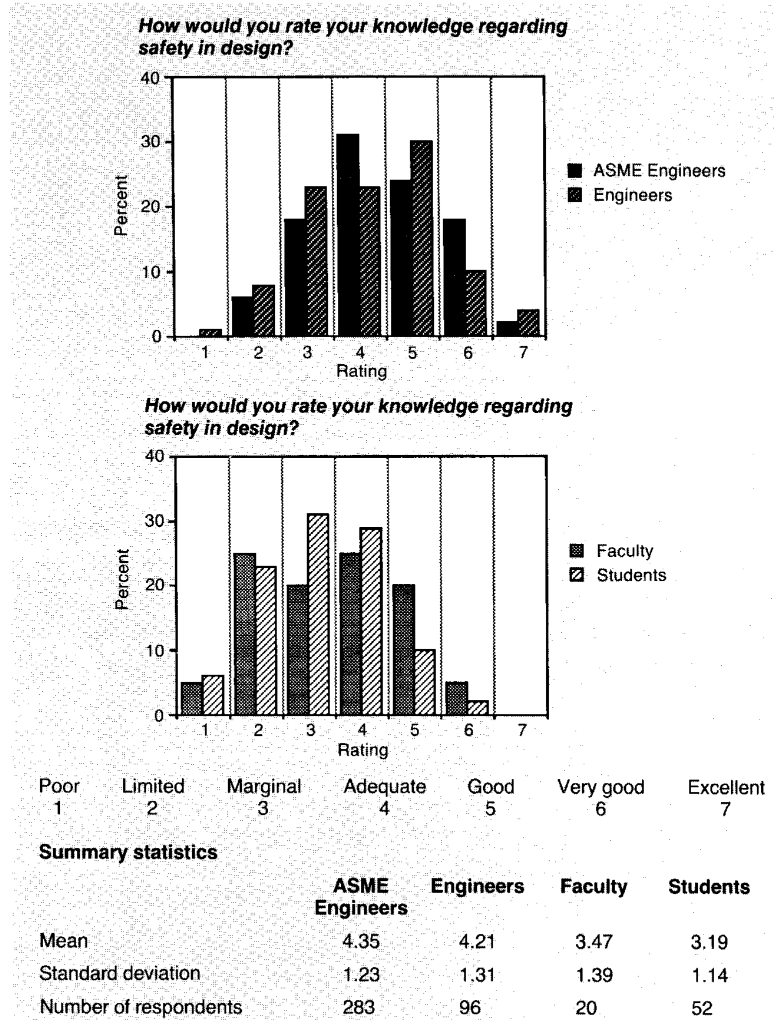
The most prominent techniques to address safety issues found in the literature of the design engineering community include safety factors, safety checklists, and standards or codes. Recent publications within the design community have begun to include some safety engineering techniques (see Dieter [8], Jones [9], and Middendorf [10] as examples), but lack the theoretical basis of hazard elimination and control required to address safety in a comprehensive manner.

Safety Factors. Safety factors are commonly used to account for variations or uncertainties in items such as materials, parts, and loadings, over which the manufacturer and designer have no control (see Shigley and Mitchell [6] for a more extensive discussion). Methods for selecting an appropriate safety factor fall on a continuum between two extremes. Johnson [11] provides an extensive discussion on a quantitative, probabilistic approach to determining an appropriate safety factor. However, Johnson also points out that "although the necessity of its usage is well realized by practicing engineers, the basis for (safety factor) selection is often nebulous"[11].

Although commonly accepted as a design method to eliminate a hazard, a safety factor can also be characterized as merely a guard against uncertainty (discussed in more detail shortly). If the assumptions upon which the design or safety factor are based prove erroneous (for example undetected material impurities in a structural member, reasonably foreseeable use, or abuse beyond what the designer anticipated), the safety factor is void, leaving the hazard exposed. This is not to suggest that safety factors be abandoned, only that the guarding aspect be considered by the designer when using safety factors.

Safety Checklists. Safety checklists are suggested as one method to address safety issues in both the safety and design communities; see Bass [12], Malasky [13]. Safety checklists are useful because creating a safety checklist requires that a safety analysis be conducted. The resulting safety checklist is tailored to the particular design. This same checklist can also be very useful for subsequent designs (or operations or procedures) if strong similarities exist between the designs.

However, checklists are not a panacea for safety issues. Using a safety checklist for a new design instead of a safety analysis is much like applying a finite element analysis result from one design to a different one. If the designs differ, the checklist could obscure serious hazards. Kolb and Ross note that "Most experts polled were wary of using checklists of hazards. They do have their place, but tend to be leaned upon too heavily" [14].



Summary statistics

	ASME Engineers	Engineers	Faculty	Students
Mean	4.35	4.21	3.47	3.19
Standard deviation	1.23	1.31	1.39	1.14
Number of respondents	283	96	20	52

Figure 4. Self rating of safety knowledge.

Standards. Industry and government standards provide technical information, promote consistency, ensure a minimum level of safety, and "provide an excellent source of information on hazards and methods for their elimination or control" [4]. Consensus standards establish the minimum state of the art in industry which must be met with respect to safety and performance.

However, meeting the minimum standards may not be sufficient. Gallagher states that "OSHA and ANSI standards are by their nature less than 'due care'" [15]. Hammer suggests that "too often designers or safety engineers blindly follow cited criteria without analyzing (the requirements)" [4]. In some cases safety improvements, such as hazard elimination via new design, may render moot a guard specified in a standard. In others, the minimum standard may not be adequate for a particular product or design.

A substantial number of survey respondents appear to rely on specifications within industry or government standards as a means to address safety. Standards and codes received high marks as a resource that respondents use. However, the responses to the open-ended questions provide an indication that in some cases safety analyses are being omitted in lieu of the standard. For example, several engineers expressed their satisfaction that safety concerns were adequately met because the de-

sign met the standard.

Safety Methods Used. Respondents were asked several questions about how they include safety issues in their designs, and what "safety resources" they use in their design activities. The data suggest that some safety resources are underutilized by design engineers. Most notably, accident data and consultations with safety specialists received low ratings. Also remarkable is that hazard identification techniques remain largely unknown or unused by the people primarily responsible for creating a design. Finally, although engineers recognize the low utility of using an "implicit method," the respondents use this method more frequently than either quantitative or qualitative risk assessments, both of which received substantially higher utility ratings.

The System Safety Approach

In the safety community, improving safety in a design centers around systematically identifying, eliminating, and controlling hazards. Hoys and Zimolong suggest that "The effective control hazards must always be anticipatory. They must contain actions which forestall the appearance of danger and which keep hazards from developing into accidents" [16]. Roland and Moriarty outline the overall approach to considering hazards in designs shown in Table 3 [17].

Hazard Control Hierarchy. The safety community has developed a preferred approach to controlling and eliminating hazards; see Hammer [18], Roland and Moriarty [17], Malasky [13] among others. This hierarchy is preferred due to the increased likelihood that an accident could occur as the hazard controlling method selected progresses down the hierarchy. Understanding the "hazard control hierarchy" is necessary to fully appreciate the trade-offs involved in design decisions regarding safety. The preferred hierarchy of eliminating or controlling hazards, in descending order, is: to eliminate hazards through the design; to protect or guard against the hazard; to warn the user(s) about the hazard; and to train the user(s) to avoid the hazard. De Ville includes a fifth point where he emphasizes that the designer "accept the remaining residual hazards and risks" [19].

Eliminating hazards through design produces "inherently safe" designs. The term "inherently safe" refers to designs in which hazards have been completely eliminated or reduced to levels of little consequence. Gallagher said that "Prudent designers *never* use warning, training, and personal-protection equipment as a substitute for safe design, guards, or safety devices."

Protecting or guarding is a less preferred approach than design because, as Hoyos and Zimolong suggest, "The protection approach has only limited value, because isolation of hazards can be undone by unsafe behavior" [16]. Unsafe behavior can be overt, as in intentionally defeating or not using a safety device such as a saw blade guard, or inadvertent, as in a guard that won't function because of improper maintenance, adjustment, or neglect.

Hazard control by using warnings exhibits several difficulties. Warnings as a science represent a relatively new field; see Lehto and Miller [20]. "Warning" in this context includes product information beyond the commonly perceived on-product labels (instruction manuals, product fliers, and others). How, why, and if warnings are effective is a topic of current research (and litigation). A major difficulty in designing effective product information is that the designer must explicitly rely on the behavior of the human user. The human user introduces complexities of eliciting attention, comprehending, educating, persuading, and informing. Further, variations in users (such as skill in literacy and languages) increases the difficulty of the information design task. The complexities of these issues have led to much research and modeling; see Rhoades [21]. Developing effective product information has become a design effort in itself.

Although many designers can appreciate the difficulty of creating designs without hazards or with effective guards, few designers have a basis (or the expertise) to understand the complexities of designing a warning. The warning or product information design process is similar to (and ideally concurrent with) the actual product design in that prototypes and revisions must be tested with appropriate population samples; see Miller [22]. A casual approach to warning against a hazard ("put a warning on it") is equivalent to a casual approach to eliminating a hazard through design. As an example of a casual approach, Shigley and Mitchell state that "glowing promises in the warranties and sales literature... should be reviewed carefully by the engineering staff to eliminate excessive promises and *to insert adequate warnings and instructions for use*" [6]. This approach implicitly assumes that engineers know what information is needed and know how to effectively convey that information to the users. This approach to developing product information runs strongly contrary to current warnings and instructions research.

Training, the least preferred method of controlling hazards, expressly relies on each user to avoid the hazard. Since the hazard exists for all users, this approach to hazard control requires that every user, including temporary or stand-in users, receive training. Additionally, training provides small tolerance for operator error. Issues of unintended

TABLE 3
Hazard Resolution Process

Define the system
Define the physical and functional characteristics and understand and evaluate the people, procedures, facilities, equipment, and the environment

Identify hazards
- Identify hazards and undesired events
- Determine the causes of hazards

Assess hazards
- Determine severity
- Determine probability
- Decide to accept risk or eliminate/control

Resolve hazards
- Assume risk or
- Implement corrective action
  - Eliminate
  - Control

Follow-up
- Monitor for effectiveness
- Monitor for unexpected hazards

From Roland and Moriarty, "System Safety Engineering and Management" (1990)

users and training costs decrease the desirability of this hazard control method.

The hazard control hierarchy developed by the safety community presents a systematic approach to addressing safety issues. Several specific methods and tools have been developed within the safety community to implement hazard elimination and control. One such method, the hazard analysis, will be discussed in detail because it forms the basis of the framework proposed herein.

Preliminary Hazard Analysis. A primary method for identifying hazards is the Preliminary Hazard Analysis (PHA), also known as hazard analysis or system hazard analysis. This analysis is used to identify potential hazards associated with designs or work places.

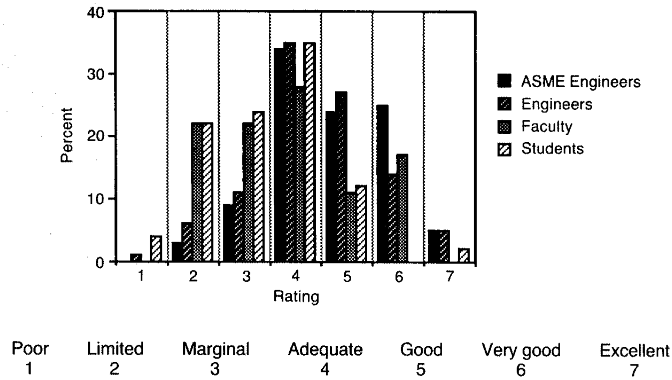
The PHA is essentially a hazard discovery analysis. Conducting a hazard analysis requires that the designer list the hazards associated with the use and expected misuse of the design in all the environments in which the design will be used. The designer attempts to anticipate how an accident or injury might occur by drawing on design and safety data and experience. The result of the analysis is a list of hazards which need to be addressed during the design efforts.

Usually a PHA is conducted very early in a design. Hammer [18] states that a "PHA is generally the first analysis made of a new product design or a product to be modified" (Kolb and Ross [14] concur). In fact, Aurioles [2] argues that engineers should include exhaustive hazard identification in research and development efforts. Hoyos and Zimolong report that the Seattle-based Boeing Corp. has used the results of PHA in both the design and system safety engineering departments as early as 1968.

A PHA can be used for a qualitative evaluation of potential hazards (see Hammer [18]; Hoyos and Zimolong [16]; and others) or a quantitative analysis of hazards; see Ozog [23]. Often the results of the PHA are used as a basis for subsequent analyses of hazards using other safety methodologies, such as failure mode and effects analysis and fault tree analysis.

In summary, a PHA and other hazard identification techniques offer potential for the design engineer as well as the safety practitioner. Kavianian et al. suggest that "Hazard evaluation procedures, when integrated with engineering design, provide the design engineer with the necessary tools to identify and modify those components of the system which have the potential for causing an accident" [24].

How would you rate the overall effectiveness of the methods you use to incorporate safety in your designs?



Summary statistics

	ASME Engineers	Engineers	Faculty	Students
Mean	4.75	4.43	3.79	3.37
Standard deviation	1.19	1.25	1.43	1.20
Number of respondents	278	96	18	49

Figure 5. Effectiveness of methods used to address safety.

The safety community has developed a systematic approach to addressing safety concerns. This "system safety" approach is defined in Roland and Moriarty [17] as "the application of special technical and managerial skills to the systematic... control of hazards throughout the life cycle of a project." Drawing on the methodologies developed by the safety community can be beneficial to designers concerned with improving the level of safety in their designs.

Dichotomy of Knowledge

This investigation of the literature in the safety and design communities has shown an apparent dichotomy: safety experts have methodologies to address safety issues in a comprehensive manner, but do not normally develop the actual design; and design engineers, responsible for developing designs, lack the tools and safety theory developed in the safety profession. This dichotomy is also supported by the survey results and reflected in the safety resources that design engineers use.

Concurrent engineering offers one approach to bridging this dichotomy because safety specialists can be included in the design development from the conceptual design. Concurrent engineering, while unknown to some respondents, was advocated by others as a method to improve design safety.

The safety community tends to recommend multiple design reviews as an alternative method to improving design safety. How the individual designer in a smaller company can practically execute this approach without the resources of safety specialists found in larger firms remains a research question.

A different and perhaps more functional approach to bridging the dichotomy is to educate designers to be better at "doing safety." Kolb and Ross [14] suggest that there is a consensus among experts that safety must be considered at the very beginning of product development, and that "the design engineer is the prime mover of safety concerns." Although design safety should not be left solely to one individual, design

safety would improve if design engineers knew more about hazard identification, elimination, and control (an intuitive rather than empirical argument). This approach is the basis for the proposed framework to improve design safety.

A Framework for Improving Product Safety

We suggest "empowering" design engineers with the fundamentals of safety theory and hazard identification techniques as an approach to improving product safety. Specifically, engineering education and training should include the basics of conducting safety analyses.

The proposed approach focuses on the hazard identification task of the hazard resolution process (see Table 3). Under the proposed approach, a designer would explicitly identify and document the hazards as well as he or she can. As the design evolves, so too will the understanding of the hazards involved. The underlying hypothesis of this proposed approach is that the fundamental safety methods (specifically hazard identification techniques) can be learned and applied by designers. This approach is an adaptation of the more formalized approach within safety engineering. Kolb and Ross [14] have proposed a similar approach for design engineering staffs.

The results of this survey indicate that motivating the design engineer is not a problem; engineers do not try to create unsafe designs. Therefore, if the hazard identification task is explicit or formalized within the design process, the subsequent hazard evaluation and control would likely follow. Engineering judgment would dictate how far the hazard analyses should be carried. Designs with complex or difficult hazards may require a quantitative hazard evaluation or other more sophisticated techniques available through safety specialists. A documented hazard identification list also can be extended to serve as a design-specific safety checklist; see Hammer [18] for further discussion.

This framework is supported by several comments from survey respondents. Several respondents suggested that an increased emphasis on safety *analysis* would improve design safety. Such methods would include "considering misuse and the effects of failure" and "greater failure and safety analysis and not conclusions by 'managers' who have lost touch with engineering design." The efforts would, according to the respondents, include input from insurance companies, direct end-user feedback, and more engineering analysis prior to prototypes.

Advocating that a safety analysis be performed on designs is not without costs. Conducting such an analysis requires time and financial support. Certain low-risk designs may be detrimentally affected by any delays. Although the fundamental safety analysis techniques lie within the reach of designers, system complexity is driving safety engineers beyond the fundamental hazard-analysis methods. In particular, Hoyos and Zimolong [16] suggest that because today's systems have "hidden hazards which cannot be directly and intuitively perceived makes it necessary to use new methods—not only the classical hazard analyses—to determine which hazards and dangers exist." Finally, since students of design rarely produce anything while in college, such an analysis may or may not be pertinent to academic design projects.

The primary problem concerning safety in design is not motivating design engineers, but empowering the design engineer with methods to address safety issues. Likewise, the issue is not whether engineers can easily include safety in their work, but rather do they know how? Specifically, most engineers recognize the impact of product liability and are motivated to include safety in their designs. This is a predictable consequence of what is typically taught to design engineers about safety.

Most engineers (especially faculty) receive little or no formal safety training. This is a predictable consequence of what design engineers are *not* taught about safety because faculty members have themselves received inadequate safety training and because the design literature omits formalized safety theory.

A review of methods in both the safety and design communities suggests that a dichotomy exists in how safety is included in design. The design community literature largely omits many applicable techniques developed by the safety community to address safety issues. In particular, methods developed by the safety community to identify and evaluate hazards appear to remain largely unknown in the mechanical design community.

Safety education and training in the design community should be changed to include safety analyses and emphasize hazard identification, elimination, and control early in the design process. We suggest that the PHA is a fundamental method which should be a part of an engineer's education and training. However, which particular safety method or analysis technique is used may not be as critical as the fact that a safety analysis be conducted. ■

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