SAFETY BRIEF

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Principles of Human Safety*

by Ralph L. Barnett[1] and William G. Switalski[2]

Abstract

This paper describes selected concepts from safety and human factors engineering. Important philosophical tools that affect designs are summarized.

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I. INTRODUCTION

A. DEFINITION OF SAFETY

The dictionary definition of safety is technically acceptable: the condition of being free from injury or loss. Its antonym, danger, is defined as exposure or liability to injury, pain or loss. Safety or danger is characterized by only two concepts; "how badly you are hurt" (severity) and "how often you are hurt" (frequency).

B. THE EXACT THEORY OF SAFETY

Everyone in the field of safety accepts as axiomatic that nothing created by man or nature is completely incapable of inflicting harm. Since we are destined to live with some amount of danger, it is reasonable to attempt its quantification. One popular system for doing this takes the form:

Equation 1: Danger = f(hazard, risk)

The difficulties in applying such a formula to a given machine or system are prodigious, but their contemplation provides important insights into the general problem of safety.

1. Hazard: something that can injure or do damage.

Its magnitude is called severity. No universal measurement exists for severity which has been characterized by economic loss, lost work days and relative ranking on various lists which purport to reflect a hierarchy of human misery beginning with death as the most severe consequence and running down to nymphomania. The subjective nature of severity is illustrated by considering the loss of a hand to a mathematician, a pianist, a person born with only one hand, and a one handed mute person who will no longer be able to sign. Assigning a severity level in such circumstances cannot presently be done within a rational system even though juries do it every day.

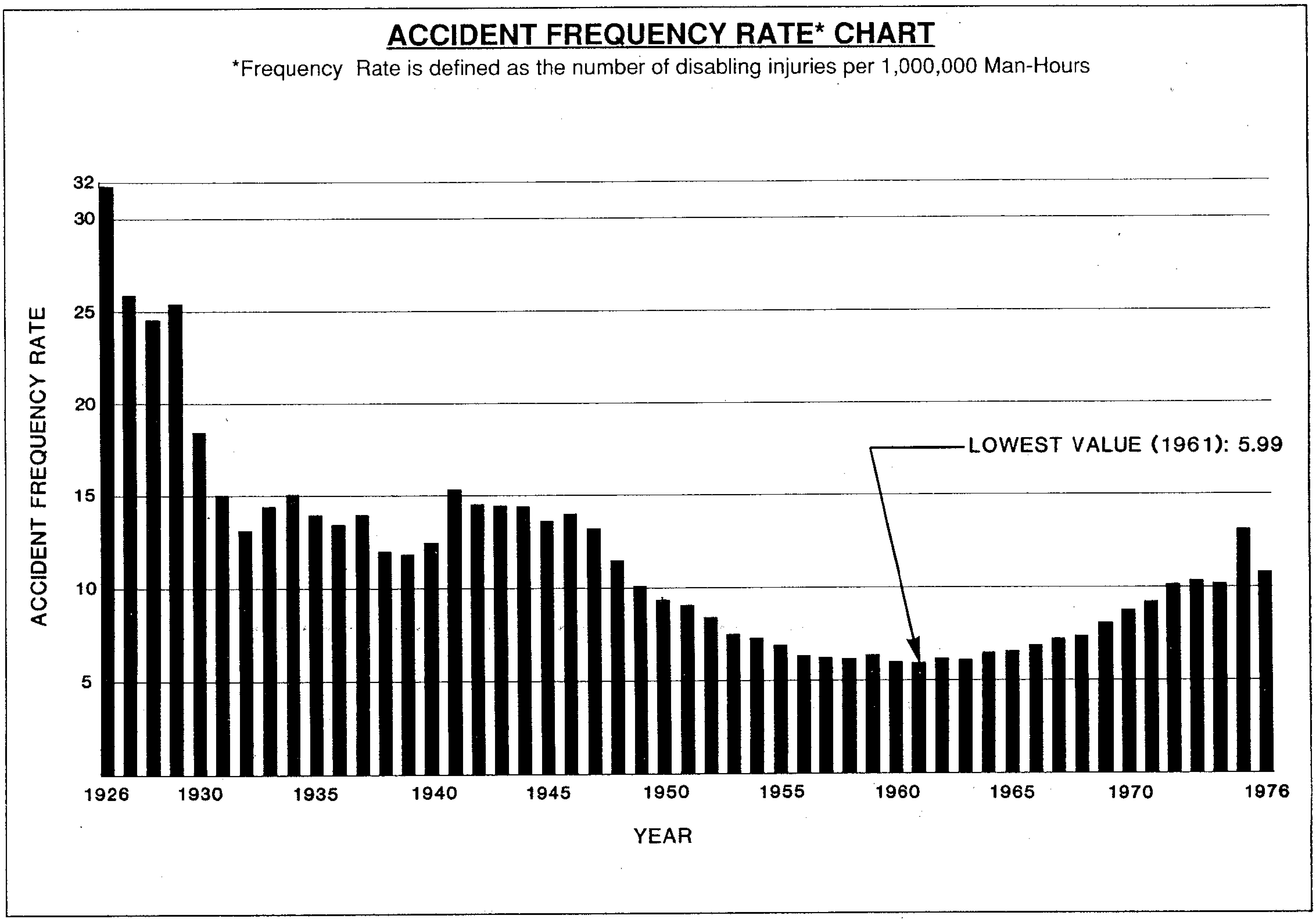
2. Risk: the probability of encountering a hazard and receiving an injury.

It is a measure of frequency and can be defined objectively since it involves counting. Unfortunately, data bases from which frequencies can be estimated are rarely available. Even when the federal government has the information required by design engineers, legal barriers preclude its transfer because such information can compromise the rights of potential litigants (tort-feasors).

In special circumstances where the exact magnitude of the hazard is not an issue, risk statistics provide very valuable safety information; e.g., number of deaths or disabling injuries. Judgements on the relative safety of alternate forms of transportation may be based on statistics such as "deaths per passenger mile."

The most important measure of risk is called the *accident frequency rate* (AFR) [Ref. 1] which is defined as the number of disabling injuries per million man-hours.

The National Safety Council carefully monitored the AFR in dozens of industries from 1926 through 1976. The "all industry average" of these statistics forms a benchmark against which safety professionals may judge their efforts. Specifically, the lowest AFR ever attained, 5.99, was achieved in 1961 (See Fig.1). When a given


ACCIDENT FREQUENCY RATE* CHART

*Frequency Rate is defined as the number of disabling injuries per 1,000,000 Man-Hours

Figure 1. Data is not available after 1976 because the method of compiling accident statistics has changed. However, accident frequency rates have continued to increase.

design has an AFR much lower than 6, it means that the safety strategy is moving in the right direction.

3. The Safety Function

Symbolized by the letter f in Equation 1, the safety function represents a presently unknown function or combination of hazard and risk that would represent an acceptable characterization of danger. An enormous amount of research will be required to establish this "safety function." For the time being, we will postulate merely that danger should increase continuously as hazard (severity) increases and as risk (frequency) increases. Further, danger should be zero if either the severity or the frequency is zero. It should be noted that proposals have been advanced that danger be defined as the product of hazard and risk: no research supports this simplistic thesis.

4. Danger

Only the technical definition alludes us, and that is defined by Equation 1. What are the units of danger? Are three units of risk equivalent to one unit of hazard?

Assume that we are capable of computing the danger from Equation 1. What danger level is acceptable, i.e., how safe is safe enough? Unfortunately, nothing in technology can answer this question. The proper domain for questions of this type is "value systems." Such systems reflect the viewpoints of our society and as such may be geography and time dependent.

Important value systems which deal with safety questions are:

a. American National Standards Institute - A consensus value system comprised of all parties substantially concerned with the safety of particular machines;

b. Occupational Safety and Health Administration - A governmental regulatory value system;

c. State Building Codes - Legislative value systems;

d. Case Law - The judicial value system.

In summary, the exact theory of safety involves a subjective component (hazard), an objective component for which no general data base exists (risk), a research component involving an unknown functional relationship between severity and frequency and a value system component (danger). No direct use of this exact theory can be forecast in the near future. On the other hand, it has great merit as an indirect safety tool.

It should be noted that another popular form of Equation 1 uses risk as a function of severity and frequency [Ref. 2]. The multiple definitions of risk are disconcerting and counter-productive and are typical of fundamental problems that compromise progress in the field of safety.

C. COMMUNITY OF USERS

Radically different safety strategies apply to various groups of people such as:

1. Workers who build a product;
2. Installers of a product;
3. Operators;
4. Maintenance personnel; and
5. Bystanders.

Important definitions of a "product defect" involve explicit reference to this community of users. (In Section III.C.2, note how the California Supreme Court refers to the community of "Ordinary Consumers.") Most safety research has been directed toward operation. Recent efforts, however, have begun to focus on maintenance.

II. ASPECTS OF DESIGN PHILOSOPHY

Every engineered system represents a trade-off among at least three criteria: cost, safety and function. Indeed, other requirements may have to be met such as esthetics, light weight or liability resistance, but these are not universal whereas cost, safety and function are.

A. CODE OF ETHICS

Every engineering code of ethics requires that: "Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties" [Ref. 3]. Note that welfare includes economic well-being. The code of ethics adds to the normal functional focus of engineering the extra ingredients of cost and safety.

B. SAFETY HIERARCHY

The past four decades have witnessed the emergence of various safety hierarchies which safety practitioners have embraced in their approach to accident prevention. The hierarchies do not arise from a research base; they reflect the experience of safety professionals and safety organizations. An examination of the literature reveals enough similarities among the hierarchies to suggest the existence of a consensus. The safety hierarchy shown in Table I represents the current consensus reflected in the literature [Ref. 4].

The first priority is the elimination of danger. Recall that the word "danger" is taken as a function or combination of hazard and risk. The elimination of a hazard was attempted in the design of lawn mowers by removing the metal blade and substituting a whirling nylon string. An example of risk removal is the use of a central lubricating system. Note that a central lubricating system, which itself is not a safety device, effects the system safety by reducing the number of potentially hazardous locations that need to be accessed during lubrication activities.

The second priority is the application of "safeguarding technology." This includes all safety concepts except warning, training, and personal protection. It includes not only guards and safety devices, but also more abstract notions such as redundancy, structural safety factors and fail-safe design, e.g., the use of shear pins to limit the torque delivered to a power shaft.

The third priority is placement of warning signs and placards on and about machinery. The fourth priority is training and includes verbal and written warnings which appear in instruction manuals and the full range of teaching techniques. The fifth priority is the prescription of personal protec-

TABLE I

SAFETY HEIRARCHY - 1985

FIRST PRIORITY: **ELIMINATE THE HAZARD AND/OR RISK**

SECOND PRIORITY: **APPLY SAFEGUARDING TECHNOLOGY**

THIRD PRIORITY: **USE WARNING SIGNS**

FOURTH PRIORITY: **TRAIN AND INSTRUCT**

FIFTH PRIORITY: **PRESCRIBE PERSONAL PROTECTION**

TABLE II

PRINCIPLES OF PREVENTING WORK-RELATED INJURY*

EXACT SAFETY THEORY	INJURY PREVENTION OBJECTIVE	EXAMPLES	RELEVANT CONTROL PRINCIPLES
ELIMINATE HAZARD	1. To prevent the creation of the hazard.	One-story buildings reducing the need for ladders.	Elimination, Substitution
REDUCE SEVERITY OF HAZARD	2. To reduce the amount of hazard of vehicles.	Reducing speeds.	Process design
	7. To modify relevant basic qualities of the hazard.	Using breakaway roadside poles, Making crib slat spacing too narrow to strangle a child.	Process design
	8. To make what is to be protected more resistant to damage from the hazard.	Making a structure more fire and earthquake resistant.	Process design
ELIMINATE RISK	3. To prevent release of the hazard.	Bolting or timbering mine roofs.	Enclosure
REDUCE FREQUENCY OF EXPOSURE	4. To modify the rate or spatial distribution of release of the hazard.	Brakes, Shutoff valves, Reactor control rods.	Ventilation
	5. To separate in time or space the hazard and that which is to be protected.	Walkways over or around hazards, Evacuation.	Isolation, Administrative controls
	6. To separate the hazard from worker by interposition of a material barrier.	Operator control booths.	Isolation, Personal protective equipment

*The numbers correspond to eight relevant categories described by Haddon; two additional ones are "after accident" strategies.

tive devices, such as eye protection, hearing protection, and environmental garments.

It should be noted that in spite of the fact that the safety hierarchy in Table I constitutes an important tool for improving safety, it does not rise to the level of a mathematical theorem or a scientific law. This safety hierarchy was born out of consensus, not research, and its general validity can be disproved by numerous counterexamples.

C. DANGER REDUCTION-EXACT THEORY OF SAFETY

The safety hierarchy is qualitative and is thereby restrictive in guiding designers. On the other hand, the exact theory of safety provides useful quantitative directions which follow directly from a desire to minimize danger. Certainly, elimination of hazard or risk gives zero danger. Also, when we minimize hazard or risk we minimize danger. Consider, for example, the well known injury prevention strategy proposed by Haddon [Ref. 5], reorganized along the lines of minimizing severity and frequency in Table II. Note how naturally danger reduction schemes suggest themselves when using the exact safety theory.

D. DOWNSIDE EFFECTS

Safety devices may help you, hurt you, or do nothing. Depending on the character of particular safety devices, different philosophies are available to guide designers in device application.

1. Intrinsic Classification of Safeguarding Systems

If one takes every combination of positive, negative or neutral characteristics of a safety device, seven mutually exclusive and jointly exhaustive categories are obtained as shown in Table III [Ref. 6].

2. Philosophical Positions

From a purely safety point of view—ignoring things such as function, practicability and cost—this classification permits a clear delineation of professional responsibility. Dealing with the most obvious problems first, we would focus on categories VI and VII where devices that compromise public safety are placed on a machine and are without any redeeming or offsetting characteristics. The code of ethics of every engineering society would consider the inclusion of such devices unethical and not in concert with the professional's obligation to protect the public.

TABLE III

INTRINSIC CLASSIFICATION OF SAFEGUARDING SYSTEMS

Type I -	**Devices that always improve safety.** Generally, U-joint shields and PTO guards are of this type.
Type II -	**Devices that sometimes improve safety and at other times leave the system unaffected.** An example may be an awareness barrier which defines the safe (outside) from the unsafe (inside) region on a piece of farm equipment.
Type III -	**Devices that always leave the system unaffected.** Adding redundancy to a fail-safe system provides an example of this type.
Type IV -	**Devices that sometimes improve the safety and sometimes increase the danger of the protected system.** The interlocked guard is usually of this type.
Type V -	**Devices that sometimes improve the safety, sometimes increase the danger and sometimes leave the system unaffected.** The seat belt is a classic example in this category.
Type VI -	**Devices that sometimes increase the danger of the protected system and sometimes leave it unaffected.** An example would be an emergency stop control mounted on a tractor drawn cornpicker which invites an operator into an area where he should never be while the machine is running (see Fig. 2).
Type VII -	**Devices that always increase the danger of the system to be protected.** A "Man Cage" for a mobile crane is an example of a system which legitimizes an unsafe use historically admonished by every crane manufacturer.

Clearly, Type I and II devices, which increase safety without collateral disadvantages, cannot be excluded from engineering systems on the basis of safety alone. Indeed, there are compelling humanitarian, ethical and legal reasons to incorporate such devices when they are feasible, compatible and economically practicable.

Type III safety devices, devices which do nothing, must be rejected. One of the most important objectives of engineering is to minimize cost. It follows that non-functional devices should be excluded from all engineering works. Furthermore, it is unethical to mislead the public and increase cost when no value is delivered.

Certainly, the most provocative devices fall into categories IV and V. Here, the devices themselves create danger. Has an engineer or a manufacturer in our society the right to foreseeably cause harm to individuals for any reason not dictated by the society's value system? For example, can an engineer unilaterally force drivers to wear seat belts in order to save 100,000 lives, knowing that 10,000 people, who would otherwise be unharmed, will be killed by drowning, fire and lower abdominal injuries because they were wearing their seat belts? One cannot find an answer to this question in technology. We must look to the society's value system for guidance.

Perhaps the most unequivocal position taken in the safety literature is the admonition against the use of guards which offer accident hazards of their own. Typical excerpts from this literature, which date from 1916, provide some insight into this philosophy [Ref. 7]:

1980: *Concepts and Techniques of Machine Guarding* (OSHA 3067). Washington, DC, OSHA, 1980.

"What must a safeguard do to protect workers against mechanical hazards? Safeguards must meet these minimum general requirements:.... Create no new hazards. A safeguard defeats its own purpose if it creates a hazard of its own, such as a shear point, a jagged edge, or an unfinished surface which can cause a laceration." pp. 7-8.

1975: *Handbook of Occupational Safety and Health,* Chicago, IL, National Safety Council, 1975.

"It is a cardinal rule that safeguarding one hazard should not create an additional hazard." p. 138.

1948: *American Standard Safety Code for Power Presses and Foot and Hand Presses*, ANSI B11.1-1948. New York, American National Standards Institute, 1948.

"5.2 General Requirements for Point of Operation Guarding. 5.2.1 Every such device shall be simple and reliable in construction, application, and adjustment. It shall be permanently attached to the press or the die. It shall not offer any accident hazard of itself." pp. 9-10.

The admonition not to adopt safety devices that have a downside applies to individual designers and manufacturers. Such devices, however, are often required (shall) or approved (should) by safety standards and codes. Here, the respective safety organizations represent value systems that balance the upside and downside effects of particular safeguarding systems. If they find the upside sufficiently compelling, permission is granted to use the Type IV or V devices.

E. ZERO MECHANICAL STATE (ZMS)

ZMS [Ref. 8] is a philosophy which applies mainly to maintenance personnel. The act of shutting off and locking out the electrical power disconnect is not sufficient to minimize hazards during maintenance. Other potential sources of energy that may produce a mechanical hazard must also be minimized. For example, evacuating compressed air, lowering suspended loads, relaxing the stored energy of springs and isolating pressurized hydraulic fluids are also necessary procedures for achieving ZMS.

1. Responsibility

In 1975, the ZMS system was introduced into the American National Standard, Z241.1, Safety Requirements for Sand Preparation, Molding and Coremaking in the Sand Foundry Industry [Ref. 9]. In this standard, portions of the responsibility for achieving ZMS lie with the manufacturer, employer and employee. The manufacturer must provide as part of its maintenance instructions a description of the procedure for ZMS. The employer must provide maintenance personnel who have the technical background necessary to understand the information in the maintenance manual and must develop a standard ZMS procedure. The employee must ultimately carry out the ZMS procedures before placing any part of his body into the path of a machine member which normally has the ability to move. When possible, the ZMS should be verified, e.g., by depressing the start button after the electrical power has been locked out to make sure the equipment will not start.

2. Activities Other Than Troubleshooting Maintenance

Persons performing installation, cleaning, adjustment, setup, repair and lubrication must be trained in and observe the ZMS concept of not placing a part of their body into the path of possible moving machine members and not entering a machine until ZMS procedures are satisfied.

3. Troubleshooting

The ZMS concept recognizes the necessity to troubleshoot machinery (problem diagnosis) with the power on, guards removed and protective devices bypassed. However, prior to removing guards or placing a part of the body into the path of a machine element, the equipment must be put into ZMS. Afterwards, the equipment may be observed while under power. Sometimes it is necessary to adjust a machine during powered operation (training conveyor belts); here, special training and background is usually required. Prior to placing the equipment back into production, the original mechanical problem must be repaired and the safety devices replaced.

III. ASPECTS OF ERGONOMICS

Ergonomics, or human factors, is an applied science concerned with the design of facilities, equipment, tools and tasks that are compatible with the anatomical, physiological, biomechanical, perceptual and behavioral characteristics of human beings. Overlapping areas in safety engineering and ergonomics deal with the reduction of personal injuries.

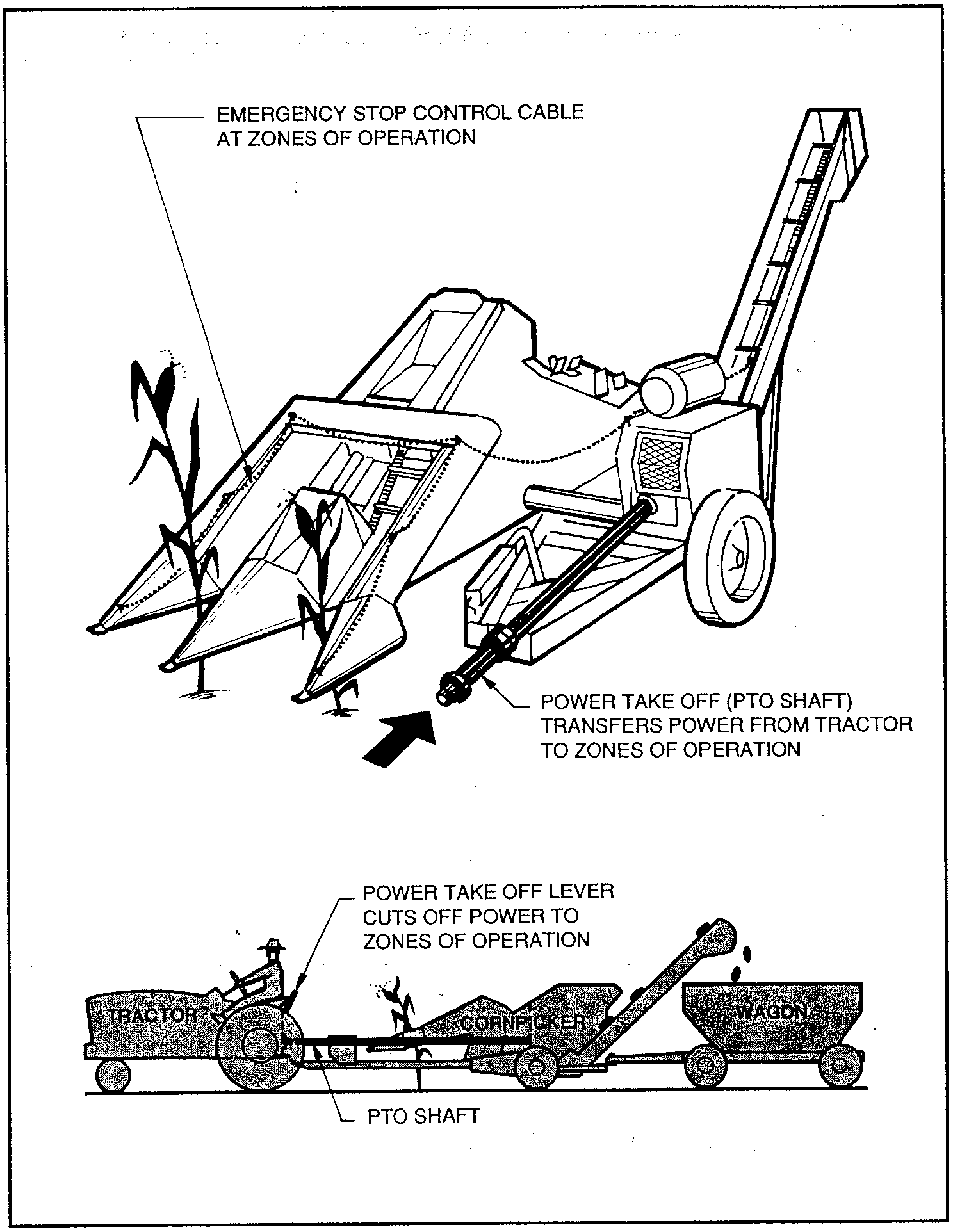


Figure 2.
Tractor-drawn corn picker with controversial Type IV Device, Emergency Stop Control Cable

A. FUNCTIONAL HIERARCHY OF SAFEGUARDING SYSTEMS

In section II.D.1, an intrinsic classification was described which focused on characteristics of individual safeguarding devices or concepts. Here, we are concerned with the relationships among the various safeguarding systems. The initial approach to this relationship classification problem was to establish a sort of pecking order which would allow safeguarding devices to be ranked according to the type of protection offered; Table IV. Application of our initial scheme showed it to be both useful and internally consistent; however, important safety problems seemed to fall outside of its scope. For example, it did not explain why a knife is not unreasonably dangerous or why all but the very young keep their hands out of a Great Dane's mouth. Moreover, the scheme did not account for the very low injury frequency rate associated with the press brake compared to the mechanical punch press.

It became apparent that proper account of a system's safety profile required the introduction of a category which would deal with those safety characteristics inherent in a system. These characteristics, which include simplicity, obviousness, slow motion and widespread user training are ranked under Zero Order Safeguarding Systems in Table IV. All of the Zero Order concepts fall within the discipline of ergonomics.

From the designers viewpoint, zero order systems involve four major man/machine interactions relative to safety: danger recognition, danger control, motivation and human error.

1. Danger Recognition (Perception)

Natural selection, in the Darwinian sense, has produced a community of machine users that recognize immediately certain hazards that are described in the legal literature as "open and obvious" or "patent." Fast moving vehicles, open flames, the in-running nip of a clothes wringer and the reciprocating action of a punch press ram all present hazards that are instantly perceived without training. Neither animals nor aborigines would place their bodies between the closing doors of an elevator.The importance of hazard recognition in safety is brought home when systems are observed in which hazards are hidden, or latent. Young children playing with matches, ingesting tasty and colorful chemicals, touching a "third rail" or darting out into traffic all account for a tragic toll in life and limb. All are examples of man/machine interactions where the community of users does not have the training, experience, or cunning to recognize the hazards. In addition to hazard recognition, personal vigilance also involves risk recognition. For example, the operating status of a machine is normally communicated by visual, auditory or tactile means. Often, electrical shorts provide olfactile cues; contamination of foods is usually revealed by taste.

2. Danger Control

The safety of a machine is greatly enhanced if the user can cope with the dangers presented. This can be accomplished if the user can control either the hazards or the risks.

One of the common ways of dealing safely with hazards is to temporarily suspend them by stopping a machine before placing oneself in jeopardy. This may be achieved using the stop buttons, power-take-off levers or hydraulic valves conventionally incorporated into a machine's control system.

There are man/machine interactions that enable operators to control risks by avoiding hazards or minimizing the probability of encountering them. Speed and directional controls are used by licensed drivers to circumvent accidents, fallen trees and potholes. Construction workers can easily avoid being run over by cranes, concrete spreaders, and asphalt rollers because these vehicles all travel at one-third of walking speed. Knives are considered safe because people can handle them safely thanks to extensive training as children followed by a lifetime of continuous practice.

3. Safety Motivation

Not all people capable of recognizing danger choose to avoid it. In fact, there are people who regularly court or ignore danger: mountain climbers, sky divers, ski jumpers and workers who engage in horseplay or disregard established safety procedures. Legal doctrines such as "assumption of risk" and "contributory negligence" have been used to deny recompense to plaintiffs who were the authors of their own misfortune because they acted in a manner that their community regards as reckless. The ability to recognize danger and the ability to control danger are necessary, but not sufficient conditions to minimize the number of injuries and/or their severity. The desire or motivation to use these two safety tools has a very significant influence on a system's injury frequency rate. Consider, for example, four possible approaches to operating a machine:

a. Maximum Output Method
This is often associated with piecework or bonus compensation. Workers are compensated for the amount they produce which often leads them to stress production over safety.

TABLE IV
FUNCTIONAL HIERARCHY OF SAFEGUARDING SYSTEMS

ZERO ORDER SAFETY SYSTEMS:

Safety properties of a machine or system that derive strictly from man/machine interactions, independent of any safeguarding devices that may be present.

Examples would be the open and obvious danger of the knife, the slow speed of the press brake ram relative to human reaction time, and the simplicity of tin snips.

FIRST ORDER SAFETY SYSTEMS:

Safety devices or concepts that eliminate or minimize a hazard or the exposure to a hazard.

All of the classical punch press safeguarding devices fall into this category: barrier guards, pullback devices and two-hand controls. Note that the first order systems enhance the effectiveness of the zero order systems.

SECOND ORDER SAFETY SYSTEMS:

Devices or concepts used only to enhance the effectiveness of first order systems.

An interlock used as a reminder to keep a guard in place is an example in this category.

THIRD ORDER SAFETY SYSTEMS:

Devices or concepts used to enhance the effectiveness of second order systems.

An instruction plate describing how to test and maintain an interlock is an example in this category.

FOURTH ORDER SAFETY SYSTEMS:

Devices or concepts used to enhance the effectiveness of third order systems.

A part reorder number on the third order instruction plate falls into this category.

HIGHER ORDER SAFETY SYSTEMS:

The extension to higher order systems is self-evident.

b. Least Work Method
Operators who wish to conserve their energy sometimes do things the "easy way" rather than the "safe way."

c. Work Standard Method
Industrial engineers give operators a prescription for achieving a specified output. Sometimes these instructions fly in the face of proper safety practices.

d. Maximum Safety Method
These work schemes minimize danger. It is desirable that a work method simultaneously produce maximum safety and output with the least demand on the operator. This goal can rarely be achieved in the real world and often it is safety that is compromised. An extensive literature exists dealing with risk taking [Ref. 10, 11, 12] and with motivation [Ref. 13, 14, 15].

4. Human Error

On a personal level, a human error is an act which is counter-productive with respect to the person's private or subjective intentions or goals. From the safety engineer's viewpoint, human error is defined as any human action revealing a deviation from the action that would have averted a dangerous event or reduced its seriousness. The science of human error makes a useful distinction between slips and mistakes. Slips occur when a person's actions are not in accordance with the actions actually intended, whereas mistakes are actions performed as intended but with effects which turn out, immediately or at a later stage, not to be in accordance with the person's intended goal. The nature, level and factors associated with human errors in the workplace that may be influenced by designers are described in Table V.

TABLE V

ENGINEERING CHARACTERISTICS OF HUMAN ERROR

Nature of Errors
Omission
Inappropriate action
Transposition
Actions performed too late
Actions performed too soon

Level of Task When Error Occurred
Sensing, perception, detection
Information processing, interpretation
Action, control execution

Error Factors
Task characteristics
Workstation characteristics
Work time
Work organization
Training
Procedure format
Individual factors

Ergonomic sources provide many of the tools required to minimize the adverse consequences of human error in the workplace. Ergonomists usually subdivide the field into information ergonomics and physical ergonomics. Information ergonomics is concerned with the collection, display, sensing, and processing of information. Physical ergonomics is concerned with worker size, strength, capabilities for motion, and working posture.

Ergonomists use a number of techniques that include the evaluation of the transmission of information between the machine and the worker (link analysis), discovery and evaluation of system failures (critical incidence analysis), detailed examination of the sequence of actions taken by workers (task analysis) and analysis of situations that may arise from unprogrammed events or human errors (contingency analysis). Ergonomists also make extensive use of anthropometric data concerning the physical dimensions and capabilities of the human population. In addition, the techniques of biomechanical analysis are used to measure expected physical stresses encountered by parts of the body while performing work tasks [Ref. 16].

B. THE DEPENDENCY HYPOTHESIS

Safeguarding systems may be introduced to perform specific safety tasks, to comply with some code or standard, to liability-proof a machine or as a by-product of a functional device.

When safety systems are imposed on a device, alterations in the man/machine interface occur that may go well beyond the intended effects. The Dependency Hypothesis provides a unifying thesis under which observations of safety system effects can be made in an organized manner. Our ultimate concern is that the side effects of safeguards do not compromise the overall system safety.

1. Statement of The Dependency Hypothesis:

Every safety system gives rise to a statistically significant pattern of user dependence.

This may also be stated in legal jargon: "User dependence on safety systems is foreseeable."

The Dependency Hypothesis does not speak to the issue of whether or not reliance on safety systems is good or bad; it suggests only that secondary effects exist as a consequence of behavior modification in the presence of such systems. The evaluation of safety systems must include consideration of these secondary effects which sometimes compromise the entire safety program. From the designer's viewpoint, the Dependency Hypothesis manifests itself in two cogent areas; introduction of misuse and substitution to lower safety profiles.

Some people misuse safety devices by performing tasks that differ from the designer's intent. Examples include misuses as controls, misuses in kind, and misuses in magnitude. There are three reasons why these misuses intrude on the design process:

a. Sellers/Manufacturers have a duty in most states not only to design products for normal use but also for reasonably foreseeable misuses;

b. New hazards may be introduced through the misuse of safety devices; and

c. Compromising secondary effects may outweigh the benefits of the safety devices.

The most provocative behavioral characteristic associated with the normal use of safety systems is substitution. It appears in three areas:

a. The substitution of safety systems for personal vigilance;

b. The substitution of one safety system for another; and

c. The substitution of authoritative direction for personal wisdom and experience.

There is nothing intrinsically wrong with these substitutions, but they must be examined in the light of their potential for mischief. New systems must not be inferior to the originals. Furthermore, substitutions which introduce new hazards must be measured against the prevailing philosophy relative to dangerous safeguarding devices or against operable value systems such as consensus standards, regulations, or the judicial value system.

2. Misuse

User dependence on safety systems commonly results in three forms of system misuse: misuse as control systems, misuse in kind, and misuse in magnitude.

a. Misuses as Control Systems
Many safeguarding systems protect by overriding normal machine operation. They may, for example, freeze motion, prevent start-up, return members to home base, or temporarily remove hazards. As users become familiar with the characteristics of these safety systems, a certain percentage of them will use the safeguards to control the machines.

i. Elevator Door Problem
Almost the entire community of elevator users knows that conventional elevators

have a safety device in the leading edges of the doors which will stop and/or reverse the closing door when the door edge contacts a passenger. It has become a pervasive misuse of the "safety edge" to employ it as a control device for manually interrupting the closing door to accomodate passengers arriving late.

ii. Light Curtains:
A Standardization Dilemma

An extension of the classical "electric eye," a light curtain acts as a sentinel in front of a point-of-operation. Penetration of the curtain signals the machine to stop so that no harm will befall the operator. The light curtain is routinely misused to interrupt the cycle to reposition parts, clean off debris or perform routine maintenance.The light curtain gives rise to a special type of misadventure involving standardization. The misuse of the curtain as an emergency stop control becomes habitual. When operators are transferred to machines not equipped with light curtains, their automatic emergency response is to reach into the machine! This is analogous to the habit of using one's foot to catch small parts that have dropped. This useful predilection fails decisively when the foot automatically catches a heavy die or crankshaft.

b. Misuses in Kind

Designers are variously shocked, amused, bewildered and relieved at the alternative and additional uses which are suffered by safety devices. For example, the defensive characteristics of the modern football helmet are often turned into offensive weapons. The use of helmets for spearing was not originally anticipated by the helmet designers and will cause wearers neck injuries culminating in paraplegia and quadroplegia.

c. Misuses in Magnitude

To provide structural integrity, engineers incorporate "safety factors" or "factors of ignorance" into their designs to account for uncertainties in the assumed loading, shortcomings in workmanship, approximations in their design methodology, variability in material properties and the effects of time, wear and alterations. The use of safety factors almost always leads to designs which are stronger than required by the functional specifications of the problem. Safety factors invariably increase the cost of the final design and very often increase the size and weight. These effects are endured and demanded by society as a guarantee that the final design will perform at least as well as expected. Unfortunately, users come to depend on the extra capacity built into products and compromise their reliability by pushing them beyond their rated performance levels. Some classic examples follow.

i. The Hoisting Problem

A one-ton crane hook is proportioned to achieve a five ton ultimate capacity. This corresponds to a safety factor of five (5). As they use the hooks, many users will divine their excess capacity and take advantage of it. When such misuse results in tragedy, the adversary legal system will suggest that the misuse was reasonably foreseeable and that the safety factor of five (5) is too low in spite of the fact that it meets professional safety code specifications for crane hooks. Such arguments, when abetted by the natural compassion of juries, will frequently lead to verdicts against hook manufacturers.

Repeated punishment by the courts will eventually compel manufacturers to make their products "liability-proof" by adopting higher and higher safety factors. Thus, a one-ton hook may achieve an ultimate capacity of ten (10) tons, i.e., a safety factor of ten (10). Unfortunately, users will continue to depend on the ever increasing excess capacity of the hooks, accidents will result, suits will be filed and the process will continue without end.

ii. The Grinding Wheel Problem

Most grinding wheels are proof-tested by overspeeding them by 50 percent at the time of manufacture.This safety system removes all the weak members from the statistical population of wheels and assures that the survivors have a strength level at least 50 percent greater than the wheel rating.

In use, the faster the grinding wheel, the faster material is removed. This motivates users to overspeed the wheels in spite of maximum speed instructions marked on them. These users depend on the built-in 50 percent overspeed capability.

3. Expected Use

Engineers and lawyers do not always have the same definition of "expected use" of a safety system. To an engineer, "the expected use" is the use(s) he intended for the safety system. To a lawyer, the "expected use" is the use(s) expected by the community of users - what a "reasonable person" would do with it under like or similar circumstances. The lawyer's definition incorporates what people really do rather than merely what they're supposed to do. Note that the two definitions are not mutually exclusive. The engineer's intended use is probably one of the uses of a "reasonable person."

There is nothing cerebral in the supposition that users will depend on safeguarding systems to perform in a normal manner. On the other hand, it is provocative to contemplate the possible harm such dependence can lead to in the face of unreliability, ineffectiveness, and sabotage. The behavioral changes resulting from such dependence are discussed in the following paragraphs.

a. Decreased Vigilance

Without safeguarding systems, users of machinery protect themselves by diligently applying their natural abilities to recognize and control danger. The safety literature has recognized the transference of such personal vigilance to dependence on safety devices. For example, increased production is claimed to result from elimination of an operator's fear of the machine in the presence of safety devices [Ref. 17].

b. Obedience

Safety information is communicated in various forms that are regarded as authoritative. Accordingly, significant numbers of people will rely on written, audible, and graphic warnings, instructions, codes, standards, manuals, and safety publications. Verbal admonitions from supervisors or instructors are often very compelling methcds for modifying or reinforcing safety behavior.

Misadventures stemming from obedience to safety misinformation are particularly insidious since they arise from conscientious behavior. The following communication shortcomings highlight the problem:

i. Incomplete Information

The Occupational Safety and Health Administration requires that skylights have the "capability of supporting the weight of a 200 lb. man." One manufacturer meticulously satisfied the language of this requirement by applying 200 lbs. of sand uniformly distributed over the surface of their 4 ft. by 4 ft. skylight. Unfortunately, the skylight collapsed when a roofer stepped onto it.

ii. "A Little Bit of Knowledge"

Consumer power table saws are the most dangerous of woodworking machines. In an attempt to "liability-proof" their machines, some manufacturers have incorporated a safety instruction plate containing a half dozen or so admonitions. This carries with it the implicit suggestion that strict adherence to the safety instructions qualifies one to operate the table saw safely.

When the safety plate is compared to the safety training program administered by typical high school woodworking shops, the plate's inadequacy is immediately apparent and frightening.

iii. False Information

One of the classic cases of misdirection arises from the use of safety status lights that indicate a danger when lit. When the bulb burns out, a safe condition is falsely indicated.

iv. Dangerous Instructions

OSHA provides written instructions for testing the upper hoist limit switch on overhead and gantry cranes. Their written procedures are dangerous:

29 CFR 1910 179(k)(1)(ii): *"The trip setting of hoist limit switches shall be determined by tests with an empty hook traveling in increasing speeds up to the maximum speed. The actuating mechanism of the limit switch shall be located so that it will trip the switch, under all conditions, in sufficient time to prevent contact of the hook or hook block with any part of the trolley."*

29 CFR 1910 179(n)(4)(i): *"At the beginning of each operator's shift, the upper limit switch of each hoist shall be tried out under no load. Extreme care shall be exercised; the block shall be 'inched' into the limit or run in at slow speed. If the switch does not operate properly, the appointed person shall be immediately notified."*

Note that the tester and bystanders are in jeopardy when the procedure reveals a defective limit switch by dropping a hoist block on them.

c. Change in Safety Philosophy

The imposition of safety devices into a system may radically alter the prevailing safety strategy. Consider, for example, the introduction of Emergency Stop Controls (ESC's) on a corn picker (See Fig. 2).

Since corn pickers are completely automatic, only maintenance functions such as cleaning, unclogging, and lubrication require "hands on" work. Such work can safely proceed using ZMS (Zero Mechanical State) concepts (Section II.E). These provide the most modern and advanced safety maintenance philosophy.

Before starting to maintain the corn picker, the farmer disengages the Power-Take-Off (PTO) lever isolating the motion of the entire corn picker. He then disembarks from the tractor and may work in safety. The PTO lever is one of the most popular and most reliable controls on the tractor and provides almost continuous check-out and training.

Accidents have occurred when farmers have neglected to disengage the PTO before performing maintenance and it has been proposed that Emergency Stop Controls (ESC's) such as pull cords be provided at the maintenance points. There are three types of user expectations engendered by emergency stop controls (ESC's):

i. Prevention - They will prevent injuries.

ii. Mitigation - If any injury occurs, the ESC will lessen the severity of the injury.

iii. Invitation - The area near the ESC will be safe when the machine is running. (There are controls there; controls are meant to be activated by people; therefore the control areas must be safe areas.)

The heart of the ZMS approach is to prevent accidents. This may be contrasted with the proposed use of ESC's which cannot eliminate injuries which occur faster than human reaction time. This is particularly devastating in view of the fact that a significant number of farmers will accept the invitation of the ESC. They will be lured into the zones of operation to perform tasks with the corn picker running and with no possibility that the ESC can fulfill the promise of preventing injury.

C. THE COMPATIBILITY HYPOTHESIS

Safeguarding systems may be missing from a machine for a variety of reasons that are dominated by human factors considerations:

1. Removed to increase production
2. Left off for ease of maintenance
3. Were uncomfortable
4. Were worn out or damaged
5. Left off for esthetic reasons
6. Not reinstalled on machine after maintenance
7. Machismo
8. Horseplay
9. Not shipped originally
10. Lost during use
11. Cannibalized to repair other machines
12. Had undesirable side effects (Types IV & V; see Table III)
13. Removed to improve safety (Types VI & VII; see Table III)
14. Were incompatible with other safety systems
15. Sabotage

Note that some of the reasons for removing or circumventing the safeguards are related to utility (Examples 1, 2, 3, 5, 11) and some are concerned with safety (Examples 12, 13, 14). In these cases, the following hypothesis provides guidance to the designer in dealing with this important safety problem:

1. Statement of The Compatibility Hypothesis:

The larger the perceived improvement in utility compared to the perceived increase in risk, the greater will be the motivation to circumvent a machine's safeguarding system.

Note that risk is taken as the probability of encountering a hazard already present on the machine.

2. Barker v. Lull Engineering Co.

A risk/utility criterion for judging the safety of a machine was introduced in 1978 in a product liability decision:

Barker v Lull Engineering Co. 573 P.2d 454 (1978). In this case, the Supreme Court of California stated that, "a product may be found defective in design, so as to subject a manufacturer to strict liability for resulting injuries, under either of two alternative tests...

a. A product may be found defective in design if the plaintiff establishes that the product failed to perform as safely as an ordinary consumer would expect when used in an intended or reasonably forseeable manner.

b. A product may alternatively be found defective in design, if the plaintiff demonstrates that the product's design proximately caused his injury and the defendant fails to establish, in light of relevant factors, that, on balance, the benefits of the challenged design outweigh the risk of danger inherent in such design."

Among the "relevant factors" the jury may consider when weighing the benefits of the design against the risks, in the second test, are:

"(i) the gravity of the danger posed by the challenged design;

(ii) the likelihood that such danger would occur;

(iii) the mechanical feasibility of a safer alternative design;

(iv) the financial cost of an improved design;

(v) the adverse consequences to the product and to the consumer that would result from an alternative design."

Since the Barker case, many other states have adopted the risk/utility criterion in their products law and in each state it is assumed that the judges and juries possess the ability to compare alternative designs on the basis of risk and utility. The compatibility hypothesis implies that operating personnel, who possess greater familiarity with their machines, exercise the same type of judgement requested of jurors.

3. Design Consideration

To illustrate how designers may benefit from the compatibility hypothesis, consider the following:

a. Multifunction Guards

If guards are designed with many functions, their removal may lead to a very small or negative increase in utility. For example, a power transmission guard that also serves as an oil bath for gears cannot be left off the machine since the machine cannot function without lubrication.

b. Redundancy

An operator may not perceive an increase in risk when a backup safeguard is removed. Meat grinders, for example, have two First Order safeguards; the stomper and spider (barrier) guard. Large increases in the feed throat capacity are achieved by removing the spider guard; concomitant increases in risk are not perceived by operators who always use the stomper. Here, manufacturers have embraced a number of antisabotage techniques to minimize guard removal.

c. False Impressions
The compatibility hypothesis operates on the basis of perception; not fact. If operators harbor a false impression that may compromise their safety, the designer may decrease circumvention by communicating correct information. For example, operators ignore admonitions not to wear jewelry because they don't understand the severity or frequency of the danger warned against.

D. "K.I.S.S."

"Keep It Simple, Stupid" - This is an old admonition that requires designers to adopt simplicity as a design goal. Almost all of the traditional engineering attributes seem to benefit from simplicity, e.g., cost, function, maintainability, weight, operator training, safety, reliability, etc. Unfortunately, "Simplicity is the most deceitful mistress that ever betrayed man" [Ref. 18]. Furthermore, achieving simplicity is anything but simple.

Indeed, the notion of simplicity appears throughout the literature of ergonomics. Task difficulty is a common reason for conducting a task analysis to determine the level and type of skills and knowledge required for performance. When too many tasks comprise an activity or when too little time is allotted which unduly paces production, the term "task overloading" is often applied. Task overload appears regularly in scheduling, load stress, message display and human error analysis. Simplification is often its cure.

E. DECOUPLING

The notion of decoupling is that a designer should not require an operator or maintenance person to place his well-being in the hands of another person. It is difficult enough for the right hand to consistently know what the left hand is doing, let alone know and track what another actor is up to. The graphic arts industry has successfully addressed the problem of multiple operators working simultaneously on large machines. Each workstation on a printing press incorporates an Inch/Stop/Safe control which precludes all motion of the press when set to the "safe" position. There are three lights at each workstation. A green light indicates that someone has set the machine on "Safe". An amber light glows only at those workstations that are set in the "Safe" mode. A red light at each station signals that the press is in "running condition". Furthermore, when the press is started up in either the jog or run modes, a time delay is encountered during which interval an audible alarm is given. Complete standardization has been the rule for several decades [Ref. 19].

F. WARNINGS

The goal of warning signs is to enhance safety by modifying human behavior in order to reduce the severity and frequency of injuries. Most warnings have little or no effect on safety; some compromise it [Ref. 20]. The success of the media and the advertising industry in influencing behavior does not have its counterpart in safety signs. Communication theory has not addressed warnings and almost no research has been directed toward this challenging concept. On the other hand, a vast literature on warning signs has arisen from the law and consensus which is filled with misinformation and misdirection.

A few results that may prove useful in guiding designers are briefly discussed:

1. Warning Signs - The Safety Hierarchy

Recall that the third priority of the safety hierarchy is to use warning signs. It is regarded as more important to try to eliminate the danger or safeguard it.

2. The Rule of Seven, Plus or Minus Two

On complicated machines such as automobiles and aircraft, there are hundreds of hazards that cannot be eliminated or technically safeguarded. Even if it is possible to invoke the third priority and produce suitable warnings for these individual hazards, the sheer number of warnings destroys their effectiveness. The majority of the population can recall only five to nine written items in a series. In communication theory this is called the "Rule of Seven, Plus or Minus Two" [Ref. 21]. Where large quantities of safety information must be communicated, warning signs cannot be used and one must resort to training.

3. Colors and Human Factors

Ergonomic research has determined the most desirable colors and color combinations [Ref. 22]:

a. Visibility of opaque colors under similar light conditions:

1. Yellow is the most luminous and visible.
2. Orange and red-orange hold maximum attention value.
3. Blue is likely to be hazy and indistinct.

b. Most legible color combinations are listed in order:

1. Black on white (most legible)
2. Black on yellow (most attention gained)
3. Green on white
4. Red on white
5. White on blue
6. Combinations of pure red and green or red and blue are not satisfactory.

Note that red is not prominent. About 8% of the male population and 0.05% of the female population has difficulty in discriminating certain colors; red is a problem color. The popularity of red as a safety color is entirely due to its association with danger (fire, blood).

4. Warning Label Shapes

Riley, Cochran and Ballard [Ref. 23] studied 19 different geometric shapes of warning labels. Their results show the triangle on its vertex is the preferred warning indicator. Furthermore, shapes that appear unstable tend to be preferred as warnings. It should be noted that the triangle on its base, not its vertex, is rapidly becoming the international safety symbol. In the United States, it's used for slow moving vehicles and as a general safety alert. Especially note that the triangle on its base and containing an exclamation mark is the safety alert symbol for agricultural equipment [Ref. 24].

5. Warning Sign Clutter and Seriousness

Because of liability-proofing, it is rare that a modern machine does not contain a plethora of warning and caution signs. These rarely deal with hidden dangers; mostly they warn against hazards that are open and obvious and serve only to liability-proof the machine. On the other hand, from a safety point of view, they frequently compromise the machine. For example, too many warning signs produce clutter and increase the probability that none of the signs will be read, including the really important ones. Furthermore, it is difficult to encourage people to take safety signs seriously when most of them are silly — Expect the Unexpected, A Clean Machine is a Safe Machine, Obey all Signs and Don't Place Hands Under Blade.

These may be contrasted with warnings dealing with hidden dangers - Danger-20,000 Volts, Machine May Start Unexpectedly in Automatic Mode, Press May Stroke After Motor is Shut Off, Wait Until Flywheel Has Stopped Before Servicing and Beware of Guard Dog.

A rule of thumb for detecting silly warning signs is to examine the opposite warning, e.g., "Keep Machine Dirty and Obstructed". If the opposite of the intended warning sounds ridiculous, then the sign is probably unnecessary because common sense dictates the intended admonition.

6. Guidelines

Gomer [Ref. 25] has compiled a listing of current guidelines recommended by consensus standards, federal regulations, in-

TABLE VI

1986 GUIDELINES FOR WARNINGS

I. Does the warning command attention:
  A. Is the warning conspicuous?
    1. Is the warning clearly visible?
    2. Have attention-directing symbols and pictographs been used?
    3. Has the appropriate signal word been used?
    4. Has appropriate color coding been used?
    5. Is the size of the warning scaled to the dimensions of the product?
    6. Has a border been used to isolate the warning?

II. Does the text of the warning:
  A. Identify the hazard?
  B. Indicate the degree of risk and the consequences of exposure?
  C. List conditions under which the product is likely to be a hazard?
  D. List precautions and means of avoiding the hazard?
  E. Identify actions to be taken if exposure to the hazard occurs?
  F. Employ clearly understandable, familiar language?
  G. Provide a message that:
    1. Is accurate?
    2. Uses active voice?
    3. Is affirmative and avoids "fudge" words?
    4. Creates the appropriate concern for safety and perception of the risk by incorporating an urgency that is commensurate with the danger?
    5. Is concise?
  H. Take into account the persons to whom the warning is addressed?
  I. Conform to common standards, regulations, and practices?

III. Is the warning placed in reasonable proximity to the hazard?

IV. Is the text readable?
  A. Has a foreseeability analysis considered reading distance, illumination levels, and other factors?
  B. Have label life and degradation been considered?
  C. Have typographic features been considered?

dustry handbooks, government recommendations, textbooks and journals (Table VI).

This guideline list can be compared to the scope of the Draft January, 1987 ANSI Z535.4, Product Safety Signs and Labels:

"A product safety sign or label should alert persons to a specific hazard, the degree or level of hazard seriousness, the consequences of involvement with the hazard, and how the hazard can be avoided."

It is noteworthy that ANSI and most modern safety authors use "Signal Words" to designate "danger" or the degree of hazard seriousness. The signal words for product safety signs are Danger, Warning and Caution. They are characterized as follows:

a." DANGER" indicates an imminently hazardous situation which, if not avoided, will result in death or serious injury. The signal word is to be limited to the most extreme situations.

b."WARNING" indicates a potentially hazardous situation which, if not avoided, could result in death or serious injury.

c. "CAUTION" indicates a potentially hazardous situation which, if not avoided, may result in minor or moderate injury. It may also be used to alert against unsafe practices.

To contrast the results of consensus and research, the work of Leonard, Matthews, and Karnes [Ref. 26] suggests that the signal words had no effect on the perception of risk:

"The experiment concerns the problem of responding appropriately to warnings. Some organizations, such as the military and the American National Standards Institute have adopted particular meanings for certain signal words. The population at large is not trained in these respects. Therefore, it is not known how they interpret different signal words. In keeping with the assumption that the stronger the warning, the more likely it will be heeded, an effort was made to determine how the population in general differentiates levels of warnings. The study examined population stereotypes for various signal words. Contrary to some studies (of Karnes and Leonard, 1986), no differences were found in ratings of perception of risk to different signal words. Further, size of the signal word and color of the signal word had no effect on perception of risk. Statements of consequences of disregarding the warnings and type of risk situation did affect rated perception of risk" [Ref. 27].

Another study by Ursic [Ref. 28] reached the same conclusion - size, color and signal words are not effective safety parameters:

"This study using 91 undergraduates attempts to alleviate this void through an experiment in which the design and presence of a safety warning are systematically varied. The presence of a warning is found to have a positive impact on an individual's perception of the effectiveness and safety of a brand. The use of a pictogram, the strength of a signal word and the use of capital letters in a safety warning are found to have little effect on perception of a brand or on memory of safety information."

Perhaps the safety profession can learn something from automotive designers who indicate the fullness of the fuel tank by several schemes that require no words. A thermometer is used by many fund raising organizations to indicate relative closeness to their goals. Such methods could indicate relative danger (death to no injury) without training or standardization. Furthermore, such schemes are infinitely variable as opposed to settling for three signal words.

7. Warning Sign Philosophy

The 1941, ASA Z35.1, Specifications for Industrial Accident Prevention Signs, stated their scope as:

"These specifications apply to design, application and use of warning signs or symbols intended to indicate and, in so far as possible, to define specific hazards of a nature such that failure to so designate them may lead to accidental injury to workers or the public, or both or property damage."

Note that all hazards are not addressed; only the hidden hazards. This scope uses the ability of workers to recognize hazards and in so doing minimizes the number of required warnings. With time, the safety profession expanded their scope to the status indicated in the preceding section. It is obvious that too much information is being required especially in multiple hazard situations.

A simple and effective philosophy can be formulated by combining ideas contained in the various ANSI scope statements. To aid in "attention arresting", signal words or more advanced notions can be used to indicate the relative danger magnitude. It is important to characterize the hazard so that it may be avoided and, also, to communicate the level of harm to make the sign more persuasive. To do this, we must identify the hazard and give some notion of its magnitude which can best be done by describing the consequence of contacting the hazard. Here, we would state that a designer should:

a. Identify the hazards where failure to do so will lead to injuries.

b. Describe the consequences associated with the hazard where failure to do so will lead to injuries.

As an example, it is not necessary for adults to be told the consequences of touching a busbar with a potential of 20,000 volts. On the other hand, informing workers that continued exposure to chemicals produces accumulated long term effects may persuade them to seek proper ventilation.

As a final goal, a warning sign should provide danger control which may include both avoidance techniques and remedies after exposure. This may be stated as follows:

c. Describe methods for avoiding or controlling the hazard where failure to do so will lead to injuries.

d. Describe remedies if failure to do so will exacerbate the injury.

In situations where the activities in (a), (b), (c) and (d) are not required, a warning sign should not be used. Most warning signs will not require all four components.

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