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Engineering Principles for Safer Design

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Introduction

The challenge faced on any facility construction project is to create the safest, highest quality structure for the lowest cost. However, rising costs of labor and materials can compel designers and constructors to take risks and cut corners in the area of safety in order to save funds. These short cuts can lead to huge costs when potential disasters are overlooked and unanticipated, potentially causing unmitigated damage to a construction project and its workers.

According to a study published by the International Labour office in Geneva and the European Federation for the Improvement of Living and Working Conditions, approximately 60% of serious, fatal injuries arise from design flaws or insufficient planning. The initial cost of including safety in design is always less than the amount paid after a failure. The costs of recall, retrofit, government intervention, liability, lost bonuses, time penalties, and equipment damage can quickly drain a firm's resources and even lead to bankruptcy. No company can afford to take safety risks that can be avoided with design innovation and construction planning.

Fortunately, construction projects offer three chances for safety success before site work begins. The first chance addresses safety when machines, facilities, and processes are initially designed. The second chance designs safety into the construction planning process. The third chance looks as safety during pre-task planning and pre-task briefing.

The key to each safety opportunity lies in one crucial concept: anticipation. Full scope of hazards must be anticipated to successfully design a preventive safety approach. Two ideas must be mastered in the anticipation department. First, all the potential damage of a hazard must be anticipated and mapped out. Second, factors and conditions that cause hazards must be identified and eliminated. Learning these two skills changes the perception of the entire project. Parameters

of cost and safety become more defined and easier to assess. Potential errors can be foreseen and avoided.

Anticipation of hazards helps change perception in one more vitally important way. Currently, compliance with existing standards is the dominant safety practice of the construction industry. But compliance with existing standards is usually insufficient to fully protect a project from injuries and other damage that can occur during the construction process. Moreover, the compliance process is made unnecessarily difficult when no attempt to identify or eliminate hazards during architecture specs and project pre-planning is made. A few short years from now, the construction industry will be judged not on how well those standards were met, but how effective those standards were in saving lives and property. Anticipation of hazards circumvents the complex compliance process and beelines to the business of saving lives, time and money.

Designing for safety is not a new concept. System safety revolutionized technology in the twentieth century with concepts that made safety a primary function of design before an aircraft or a missile was assembled. This important leap in fail proof design brought the dream of walking on the moon with aerospace technology to reality. In today's world the same concepts can easily be applied to construction projects to save materials, construction costs, and liability fees. Soon it will be considered too costly to build any structure or facility without incorporating safe design features into every aspect of its life cycle and guaranteeing optimum safety it is being erected, operated, and maintained.

Outdated warnings from insurance companies admonishing engineers to stay out of design due to liability concerns and the oft-repeated cautionary phrase, "Safety does not sell", are being swept away by winds of change that bring efficiency, profit, and competition in a global economy. Traditionally, engineers have had few incentives to become involved in the application of technology to achieve safer design, and have been known to express skepticism regarding the reliability of some safety features. As safety professionals, we must collaborate with the engineering professions to encourage their use of tools of inherently safer design and assist them in designing for safety.

Applied technology provides easy solutions to eliminate most hazards during the design phase. Hazard controls implemented during the design and planning phase can eliminate the necessity and cost of compliance adjustments to construction plans while simultaneously eliminating hazardous circumstances that encourage injuries. No one in their right mind would accept a design of an automobile without brakes, regardless of how carefully that automobile was made. So why should any facility project design omit rudimentary lifesaving features?

We live in century of rapid change and rely upon technological advances more than ever before. To stay ahead of the curve, progressive management teams are selecting designers and construction personnel committed to design excellence and maintainability. Engineer input is an increasingly critical part of new designs, especially the incorporation of safety as a function of design and construction planning. The more that industry leaders learn about the benefits of safer design, the more designers, engineers, and constructors are learning to anticipate hazards and integrate hazard control measures into initial design plans. Leaders of similar innovative and cost effective techniques include the Washington Group International, Exxon Mobil, OSHA, NIOSH, the US Department of Energy, and others.

A vital component of a thriving and creative safe design culture is the involvement of engineers who have the vision and expertise to design technological or physical controls to eliminate common hazards at every stage. The most efficient way to embrace this culture of safety is to train engineers how to identify and control hazards with technology. Safety professionals have a vital role as ambassadors to the engineering profession to encourage their role in safety and their use of the tool box to eliminate construction hazards.

The recently published McGraw-Hill book Construction Safety Engineering Principles covers Five Principles of Inherently Safer Design. These principles can be the tool box that teaches safety professionals and team members how to anticipate hazards before they arise on a job site. This tool box is a distillation of the methods learned in aerospace system safety technology. When these tools are understood and utilized by design engineers, safety professionals, project planners, and subcontracting personnel, they can revolutionize the design process, build efficiency, and save money by anticipating hazards and examining design plans for the optimal ways to integrate hazard control measures into the project specs.

The Five Principles can be applied to every aspect of design engineering; however, this presentation explores the broad subject of designing for construction. Excerpts from Part I of the book give an overview of how to develop a methodology for easily identifying and controlling hazards at the time of design:

- Define a more comprehensive meaning of the term hazard
- Establish a standard for safe design
- Categorize the hazard into one of seven easily identified groups
- State a safe design hierarchy of four methods to physically control the hazards with alternate design
- Illustrate the control of the hazard by matching it to appropriate design improvements or appliances on a matrix

Principle One: Definition of a Hazard[1]

To address inherently safer design principles in construction, one must first become familiar with the actual nature of hazards. A broader and more encompassing definition of hazards provides a basis to develop a methodology for planning and evaluating the construction process for safety and ensuring for design of inherently safe construction equipment and other support systems. A thorough definition of a hazard is the first step to hazard anticipation.

To accomplish this, one should first define a hazard in practical terms: A hazard is an unsafe physical condition that is always in one of three modes- *Dormant/Latent* (unable to cause harm), *Armed* (can cause harm), *Active* (causing injury, death, and/or damage by releasing unwanted energy. This can occur in the form of the effects of gravity or other natural forces, corrosive

[1] The following portion of the paper relies heavily upon material previously authored by David V. MacCollum P.E., CSP, including but not limited to the textbook *Construction Safety Engineering Principles* McGraw-Hill (2007), and "Inherently Safe Design: Five Principles for Improving Construction Safety" published in *Professional Safety*, May 2006.

substances, biological agents, and or defective computations from computer software.) Exhibit 1 is a logic chart showing hazards, possible consequences, and preventive steps.

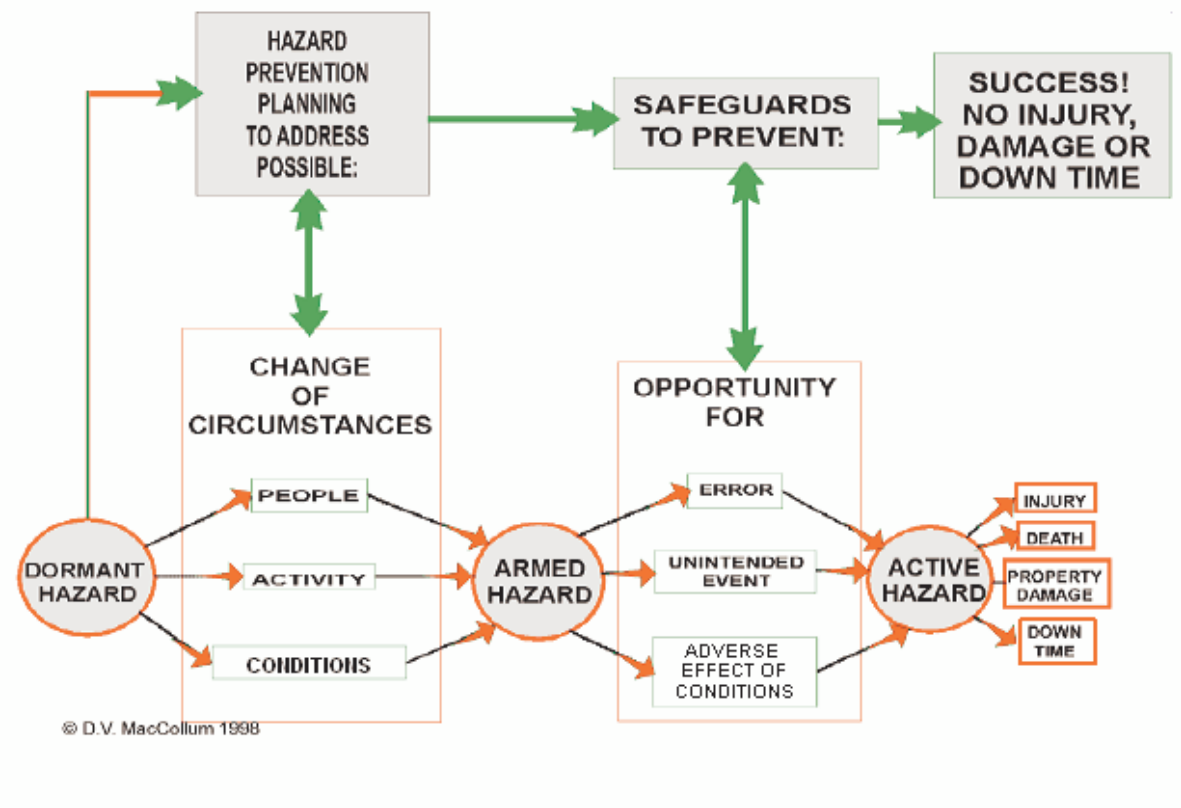

Exhibit 1. The Logic Chart of Hazard Identification shows hazards in three modes.

The three modes of a hazard can be further explained by this simple analogy: Icebergs in the North Atlantic present a dormant hazard. The hazard becomes armed as the *Titanic* steams full speed at night into an area where icebergs congregate. The hazard becomes active when the *Titanic* strikes an iceberg, tearing the hull and causing the ship to slowly sink and resulting in massive loss of life. The initial perception that the conduct of the captain was reprehensible in regard to the life and safety of the passengers and crew is justified. Even assuming that the captain believed the ship had a state of the art, unsinkable ship, it was foolish of him to steam through a sea known to be filled with hazardous icebergs. His actions were due to the erroneous perception that the eleven watertight bulkheads just below the waterline made the ship unsinkable. Design of the battleships of that time included double hulls as damage prevention from torpedoes. This design feature, in addition to the watertight bulkheads above the waterline, would have confined the flooding to outer compartments and the *Titanic* would not have sunk. This is an example of an available safe ship design that was not used. When designing for hazard prevention, the key is, wherever possible, to include two or more redundant safety features into the design to overcome failure mode: anticipated exposure to machines, equipment, or facilities and foreseeable human response.

Principle Two: Establish a Standard of Safe Design

Safety must be converted into a powerful design priority and overriding planning concern to be effective. In essence, it must become part of company culture. The optimum culture change occurs when designers and corporate managers start focus on the physical elimination of each hazard rather than on human performance, which is variable and cannot be programmed. Time set aside for review of each design and evaluation of each activity, task or phase of the construction process helps to identify possible failure modes and design out hazardous conditions, and could save millions of dollars in potential damages.

A well-known safety engineering tenet often considered as a standard of care states: **Any hazard that has the potential for serious injury or death is always unreasonable and always unacceptable if reasonable design features and/or the use of safety appliances are available to prevent the hazard[2].** The key to successful safety engineering is to identify and design out as many hazards as possible. When this tenet is applied as a design standard, it becomes a reasonable expectation to design out hazards.

Principle Three: Categorizing the Hazard

The third step in hazard identification is to establish that hazards can be identified as belonging to one of seven categories and determining which of the following seven categories contains the source of the hazard:

Hazard Source

- Natural Environment
- Structural/Mechanical
- Electrical
- Chemical
- Radiant Energy
- Biological
- Automated Systems/ Artificial Intelligence

Selecting one of seven categories in which the hazard may be identified helps define its nature and determine its control. Almost every conceivable hazard can be placed into one of the seven categories. Following are several examples in each category; they are presented as a starting point in the development of additional lists of failure modes. It is important to note that hazard categories may overlap or fall into more than one group. It is common to encounter a hazard that contains simultaneous natural, mechanical, and chemical properties. In these cases, specific hazards should be broken down into as many individual properties as possible.

Natural Hazards

The first category is the natural environment. The laws of gravity cannot be repealed, nor can the weather be programmed or the ocean drained. The natural environment is the cause of many

[2] Philo, 198

dangerous hazards such as earthquakes, tidal waves, hurricanes, and tornados. Applications of engineering technology can help to reduce these hazards. Following are a few hazard source possibilities that the design engineer must contend with in the natural environment.

- Gravity
  - Falls same level
  - Falls from elevation
  - Falling objects
  - Impact
  - Acceleration
    - Sloshing of liquids
    - Inadvertent motion
    - Movement of loose objects
- Slopes
  - Upset
  - Rollover
  - Sliding
  - Unstable surfaces
    - Earthquakes
    - Avalanche
- Water
  - Floating
  - Sinking (drowning)
  - Tides
  - Floods
  - Oceanic disturbances
- Atmosphere
  - Change in Altitude
  - Temperature
  - Humidity
    - Excessive moisture
    - Excessive dryness
    - Condensation
  - Wind
    - Wind chill
    - Structural pressure
  - Visibility
    - Daylight
    - Darkness
    - Glare
    - Dusty
  - Dust
  - Temperature
- Limitations on human performance
  - Fatigue

- Error
- Distraction
- Anthropometric
- Ergonomic

Structural/Mechanical Hazards

The second category delineates structural/mechanical hazards. Engineers must consider both the advantages of mechanical systems and their potential hazards. Again, this list serves as a starting point for the identification of hazards in a new design and/or during the development of a construction planning schedule.

- Surfaces
  - Lack of traction
  - Instability
  - Protruding obstacles
  - Incline
    - Steps
    - Ladders
- Lever
- Rotation
  - Wheels
  - Gears
  - Pulley
  - Screw
  - Auger
  - Cams
  - Pinch Point
  - Friction
- Reciprocation
- Compression
  - Shearing
  - Puncture
  - Structural failure
  - Ejected Fragments
- Causes of Vibration
  - Noise
  - Dislocation
  - Parts Failure
- Pneumatic (Pressure) Hazards
  - Compressed gasses
  - Unintentional release of gasses
  - Vacuum/ negative pressure effects
  - Blown objects
  - Suction
  - Rupture of container (pipe, hose or vessel)

    - Dangerous overpressure
- Metal Fatigue
- Bending/Hinge
- Tension/Spring
- Hydraulic (Pressure)
    - Water/liquid hammer
    - Vacuum/negative pressure effects
    - Rupture of container (pipe, hose or vessel)
    - Dangerous overpressure
- Entanglement
    - Noose
    - Snagging
    - Entrapment
- Impact
- Velocity
- Blind Zone
- Confined Space
- Waste Disposal
- Access
    - Lack of access
    - Unguarded/ elevated location
    - Low overhead
    - Exposure to adjacent/ proximity hazards

Electrical Hazards

The third category lists electrical hazards. For all its advantages, electricity is a power source that is silently conveyed and can cause harm.

- Voltage/Amperage (causing shock, burn, fibrillation of the heart)
- Alternating Current
- Direct Current
- Spark/Arcs
- Electrostatic
- Source of dangerous heat
- Ground
- Capacitance
- Sneak Circuits

Chemical Hazards

The fourth category lists **chemical hazards**. Many substances pose potential dangers in several forms. To begin this analysis the following are a good starting point.

- Combustion, Fire
- Corrosion
- Toxic Substances

- Liquids
- Fumes/Vapors
- Dust
- Degradation
- Exothermic (hot)
- Endothermic (cold)
- Decomposition
- Hydrogen Embrittlement
- Disassociation
- Combination
- Replacement

Radiant Energy Hazards

The fifth category contains **radiant energy hazards**. Radiant energy can create many perils if improperly used.

- Sound
- Heat
- Light
- Radio Frequency
- X-Ray
- Nuclear

Biological Hazards

The sixth category contains a starter list of **biological hazards**. Though the given list is short, it contains hazards possessing a wide variety of properties, making it tricky to accurately identify. A rule of thumb for this category is to ask the question as to whether the substance *or condition* in question can cause acute or chronic physical or mental harm to someone exposed to it.

- Allergens
  - Mold/ Pollen
- Carcinogens
- Infectious Agents
  - Germs
  - Virus
- Venom
- Conditions that product sustained mental or physical stress in humans

Automated Systems Hazards

The seventh category covers automated systems hazards caused by faulty computer software. While the advantages of computers are infinite, they are capable of disastrous error. Uses include computer programs for load moment devices on cranes (designed to prevent overload and crane upset) to Global Positioning Systems and many automated computer-assisted designs.

- Program Error
- Software/Hardware Failure

The seven categories of hazards as described above have been listed to spur the engineer, safety professional, or anyone else to fully understand the nature of hazards as being easily segregated into seven logical categories. Once the hazards are isolated it becomes easier to begin a systematic evaluation of possible controls.

Principle Four: The Safe Design Hierarchy to Physically Control Hazards

The following engineering hierarchy of controlling hazards has become the accepted sequence of evaluating with and controlling recognized hazards:

1. Eliminate the hazard or substitute a safe alternative.
2. Guard to prevent the hazard from causing harm.
3. Include safety factors[3] to minimize the hazard.
4. Use redundancy[4] for a group of parallel safeguards; this requires that they all be breached before a harm-causing failure mode occurs.

As construction projects become more complex, safety must be addressed with the same scrutiny as is applied to achieving the desired utility the projects themselves. The project construction schedule should be highlighted at those points where hazards have been identified in order to identify and control potential problem areas. For the hazards to be eliminated, the entire construction process needs to be examined in this fashion. Listing hazards in the critical path forces the planner to consider itemized alternatives. This fact leads to the need to apply a systems safety approach, the same approach that has become the backbone of aerospace and nuclear energy design. System safety relies heavily upon the additional provision for *safety factors* and

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[3] "*Safety factors"* can be easily explained by the example of a bridge with a ten-ton load limit that is designed to sustain 30 tons, thus allowing for foreseeable misuse. Closer to the safety of construction equipment is an example of a questionable safety factor. Cranes are generally rated at a capability that is 85% of the tipping load at any radius. By industrial standards, this is a rather thin margin. In some cranes, rated capacity is only 85% of the structural design of the telescoping boom, which is far less than the tipping load. In such a circumstance, the consequences of an overload would not be a crane upset but a structural collapse of the boom.

[4] *"Redundancy"* is more than one safeguard, each of which must fail before the system experiences actual failure mode. A good example is the fuel system on a military helicopter, which has several fuel tanks and a number of fuel lines. In the event of enemy machine gun bullets piercing the fuel tank, it is self-sealing to stop leaks. If a fuel line is broken, both ends have automatic shut-off, as fuel has several other routes through different lines to keep the engine running. This same principle is achieved in construction equipment with the combined use of ROPS for tractors and other heavy equipment and the use of seat belts to hold the operator in place in the event of an upset. Both measures work together to prevent the operator from being crushed or ejected from an incident of overturn. In facility design, fire prevention and protection is always a system of redundant safeguards. In many cases, walls of the facility are constructed with flame-retardant materials. Staircases and elevators are built to provide alternate exits in an emergency. Smoke detectors are rigged to fire alarms, which are probably rigged to sprinkler systems. Fire doors and hand-held extinguishers provide an extra measure of protection. These redundant safeguards ensure the best possible protection from fire for property and personnel. The effective protection achieved by measures of *redundancy* should make it a requirement in the design of civilian products and machines.

redundancy in addition to hazard elimination and guarding. Zero injuries through error-free worker performance is not an achievable goal.

Each control in the hierarchy briefly addresses various design choices to achieve an inherently safe design with an expectation of near-zero harm-causing failure mode. This hierarchy reflects the hazard prevention methods developed by system safety pioneers. It creates a scale of efficiency to help designers choose the most effective method of hazard control. Users may expand the listing in each of the four headings to accommodate a specific circumstance.

Eliminate the Hazard[5]

Hazard elimination can be achieved many ways. The four listed below are the methods most often used.

- Designing out the hazard by developing an alternate safer design or using safety appliances on equipment
- Substitution of safer construction machinery.
- Relocation of dangerous facilities (such as powerlines or other utilities) from the construction site.
- Provision of design criteria to suppliers of structural components to ensure for safe assembly at the construction site.

Guard Against the Hazard

This category includes safety appliances to overcome foreseeable operator/user error. Examples of these include anti-two-blocking devices and load measuring indicators, which are designed to intercede, safe space clearance devices, and insulated links for cranes.

- Establish barricades around any danger zones to eliminate hazardous conflict between equipment and/or existing facilities.
- Provide automatic interlocks that will disarm the hazard for service and maintenance functions.
- Provide detection systems that audibly and visually warn of a changing circumstance and will intercede before the hazard becomes active and produces a harm-causing failure mode.
- Control unwanted energy sources. An insulated link on a crane hoist line will prevent the passage of high voltage to the worker guiding the load in the event that the boom or hoist line comes into contact with a powerline.

Safety Factors

- Raise the structural strengths above the foreseeable misuse and wear limits to reduce failure mode occurrences.
- Reduce exposure to toxic materials.
- Ensure that the structural design is well above the rated capacity in the event of an unintended overload. (Bridge design should be able to withstand foreseeable excessive weight vehicles, even those with posted weight limits for autos, and the likely exposure to heavy trucks.)

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[5] Some safety appliances, such as an overpressure relief valve on a pressure vessel or an air compressor, can entirely eliminate the hazard, as long as they work.

- Ensure that cable tension loading is sufficient to overcome foreseeable wear and that the sheave diameters will not accelerate wear.
- Ensure that toxic limits for toxic radiation, gas, vapors, and dust are well below health hazards.

Redundancy

Installing design barriers in parallel so that each one must fail sequentially before the hazard can cause a harm-producing failure mode is the most effective method of hazard prevention and control.

- A combination of safeguards is able to achieve an effective hazard control network. An insulated link of a crane's hoist will protect the individual guiding or touching a load (such as a steel beam), but will not protect the individual touching the crane's outrigger. A proximity warning device can audibly warn of an adjacent powerline and alert the crane operator to stop boom movement and avoid touching the powerline. Workers should be trained to avoid touching the load or crane upon hearing the alarm. The proximity alarm becomes a redundant safeguard. The combination of the proximity alarm, insulated link, and a defined boom space control monitor provide reasonable reliability of avoiding unintentional crane powerline contact.
- Ensure that each barrier in concert with the other barriers covers the entire spectrum of failure modes inherent to the specific equipment, structural and/or construction method used at the work site.

Principle Five: Control the Hazard with the Appropriate Design Improvement or Appliance

The concepts developed by the chemical industry for production processes and system safety innovations for aerospace are remarkably similar to the current principles of inherently safe design. When applied to the construction industry, these same values can create inherent safe design. Safe design improves constructability. In the construction process, the contractor's role starts when the project is advertised for bid. At that time a rudimentary construction plan is developed primarily to determine costs; however, the assessment of the inherent hazards must be performed and figured into the costs. For instance, a major and oft overlooked source of hazards is the design of construction equipment and machines. Once the successful bidder is selected, site-specific construction planning affords the opportunity to screen the use of such construction equipment to ensure that it is safe for its intended use. This two-phase approach includes:

- Safety in the construction sequence plan:
  - Outline specific phases of the project
  - List for each all possible hazards and corresponding ways to prevent them
- Repeat this step, specifically for construction equipment, by listing anticipated hazards for all construction equipment used on the site and corresponding ways to prevent them.

Completion of a Hazard Identification and Prevention Matrix" (See Ill. 2) can be a useful approach to a design guide. This matrix is an innovative tool that allows engineers to quickly chart each hazard, define the necessary safety engineering steps.

The horizontal dimension provides space to list specific hazards and prevention measures in the appropriate boxes of the seven categories in the vertical dimension. This matrix allows the design engineer and/or construction manager to graphically identify the hazard and focus on the necessary design features or appliances that prevent the hazard from becoming armed or active.

	Eliminate the Hazard		Guard the Hazard		Provide a Safety Factor		Provide Redundancy	
	Hazard	Safety	Hazard	Safety	Hazard	Safety	Hazard	Safety
Natural								
Structural/ Mechanical								
Electrical								
Chemical								
Radiant Energy								
Biological								
Automated Systems								

Exhibit 2: The Hazard Identification/Prevention Matrix visually maps hazards and their controls.

Warning labels, operator instructions, and work practices cannot be considered a substitute for inherently safer design. The most valid and authoritative proof of acceptable inherently safe design is a record of injury-free performance. Once a new design feature of the use of a safety appliance is adopted it is necessary to develop a record of performance. The easiest system is to record the injuries in the *number of units times the years of injury-free use.* When such data has been accumulated, it can be used as evidence of the efficacy of inherently safer design. The cost-saving idea of inherent safety will become a culture, then a tradition of saving lives and averting disasters. Together, engineers and safety professionals who embrace this methodology can change construction history.

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