System Safety

Inherently Safer Design

Five principles for improving construction safety

By David V. MacCollum

AS EARLY AS 1985, the International Labor Office reported that approximately 60% of fatal construction accidents arise "upstream" from faulty design or insufficient planning to remove hazards from the worksite before construction begins. Many documents have been published on how to investigate the cause of "accidents" and establish blame. While the exact percentage remains the subject of debate and discussion, a number of this magnitude challenges those who manage the process of design to save lives and money simply by applying improved engineering practices.

Little has been published on a methodology regarding ways to identify hazards and ensure their control at the time of design or in the construction planning stages. A recent study by the Hazard Information Foundation Inc. (HIFI), funded by the Center to Protect Workers' Rights, reveals that for more than 50 years, a great body of knowledge has existed for the system safety analysis of design for failure modes and how they can be avoided by engineering or the use of appliances. This study is an original development of five principles that rely on the author's previous publications and the listed references. The text of the study distills seemingly complex system safety engineering concepts into easily applied steps to hazard identification and prevention, and presents 34 case examples to illustrate the role of safer design, safety planning, safer equipment design and the use of safety appliances achieve an inherently safer construction process.

Design and planning priorities for utility, productivity and immediate return can obscure the vision that many hazards can be removed before construction begins. Technology is available to easily incorporate safety as an overriding priority to protect the consumer, user, operator and construction workers from injuries. However, without the application of this technology, safety is often relegated to a function of the user, operator or consumer.

Nearly a century ago, the founders of ASSE were engineers dedicated to the elimination of hazards by design modification or the use of safety appliances. Their philosophy was founded on the design ethics established some 4,000 years ago in the Code of Hammurabi, an ancient king of Babylon who deemed, "If a builder builds a house for a man and does not make the construction firm and the house collapses to cause the death of the man, the builder will be put to death."

In the 1890s, the Railroad Safety Appliance Act emphasized design safety by requiring the adoption of self-couplers and Westinghouse air brakes on railroad cars in order to save the lives of both railroad workers and passengers. [Note: The term appliance used in the 1890s is a more encompassing term than the similarly applied term safety device. The term appliance relates to enhanced productivity and is defined as a piece that, when used as an addition to a piece of equipment, machine or system, enhances the performance of the system and raises its level of inherent safety. A good example of a safety appliance is an over-pressure relief valve on a pressure vessel (such as a water heater boiler) to prevent rupture.]

After World War II, the U.S. Army Corps of Engineers applied these concepts of design engineering to achieve safe construction, operation and maintenance of large hydroelectric navigation flood control dams. Simultaneously, the aerospace industry and military were developing increasingly sophisticated system safety concepts that were codified in the U.S. Department of Defense military specifications starting with the Air Force in 1963.

Concepts in design engineering have been expanded and modified in small but important safety circles in recent years. For example, in response to the exponential interest in safety sparked by OSHA, National Safety Council promoted the concept of safety by design (Christensen and Manuele; Hecker, et al).

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The five principles assembled in the HIFI study can be applied to every aspect of design engineering, although the study explores the broad subject of designing for construction. This article focuses on key elements of the study in order to develop a methodology for easily identifying and controlling hazards at the time of design:

- Define a broader meaning of the term hazard.
- Establish a standard for safe design.
- Categorize the hazard into groups.
- State a safe design hierarchy of four methods to physically control the hazards through engineering principles.
- Control the hazard by matching it to appropriate design improvements or appliances.

Principle One: Define the Term Hazard

To begin to address inherently safer design principles in construction, one must first understand the actual nature of hazards. A specific definition provides the engineer with a basis to develop a strategy for planning and evaluating the construction process for safety, and ensuring the design of inherently safe construction equipment and other support systems. Such an undertaking leads to inherently safe operation of a completed facility.

To accomplish this, let's start by defining a hazard in practical terms: A hazard is an unsafe physical condition that is always in one of three modes: 1) dormant/latent (unable to cause harm); 2) armed (can cause harm); and 3) active (causing injury, death, and/or damage by releasing unwanted energy, substances, biological agents and/or defective computations from computer software).

In greater detail, a dormant/latent hazard is a design defect that is susceptible to a failure mode. Foreseeable misuse should also be considered (e.g., a kitchen chair may be stood on to reach high cabinets and must be sturdy enough to prevent collapse). The armed hazard is created by a change of circumstances and is ready to cause harm (e.g., the chair may have a knot on one leg). The active hazard is an armed hazard triggered into action (e.g., when the chair is stepped on, the knot cannot support the additional load and the chair leg collapses, causing a fall).

The three modes of a hazard can be further explained by this simple analogy: Icebergs in the north Atlantic Ocean present a dormant hazard. The hazard becomes armed as the *Titanic* steams full speed at night into an area where icebergs are common. The hazard becomes active when the ship strikes an iceberg, resulting in massive loss of life.

The initial perception that the captain's conduct was outrageous with regard to the life and safety of passengers and crew is justified. Even assuming that the captain believed the ship was unsinkable, it was still foolish to steam through a sea known to be filled with hazardous icebergs. His actions were caused by the erroneous perception that the 11 watertight bulkheads just below the waterline made the ship unsinkable. Design of battleships of that time included double-compartmented 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 design feature that was not used.

Principle Two: Establish a Standard for Safe Design

To be effective, safety must be converted into a powerful design priority and overriding planning concern. It must rely primarily on the physical elimination of each hazard, rather than on human performance, which is variable and cannot be programmed. Through the evaluation and close scrutiny of each activity, task or phase of the construction process, one can identify possible failure modes and hazardous conditions.

In creating a priority for safety in the design stages, project planners and design engineers assume responsibility for project safety. Many current practices avoid taking a step like this because of the perception of added liability. However, taking an active role in safety planning allows the engineer and project planner to define the parameters of their involvement and designate responsibility to appropriate parties. Responsibility for safety allows for control of the project itself. If an injury from causes outside the realm of the designated hazard control were to occur, the source of the hazard would be easy to pinpoint and only those parties responsible for the injury would become entangled in the repercussions of the occurrence.

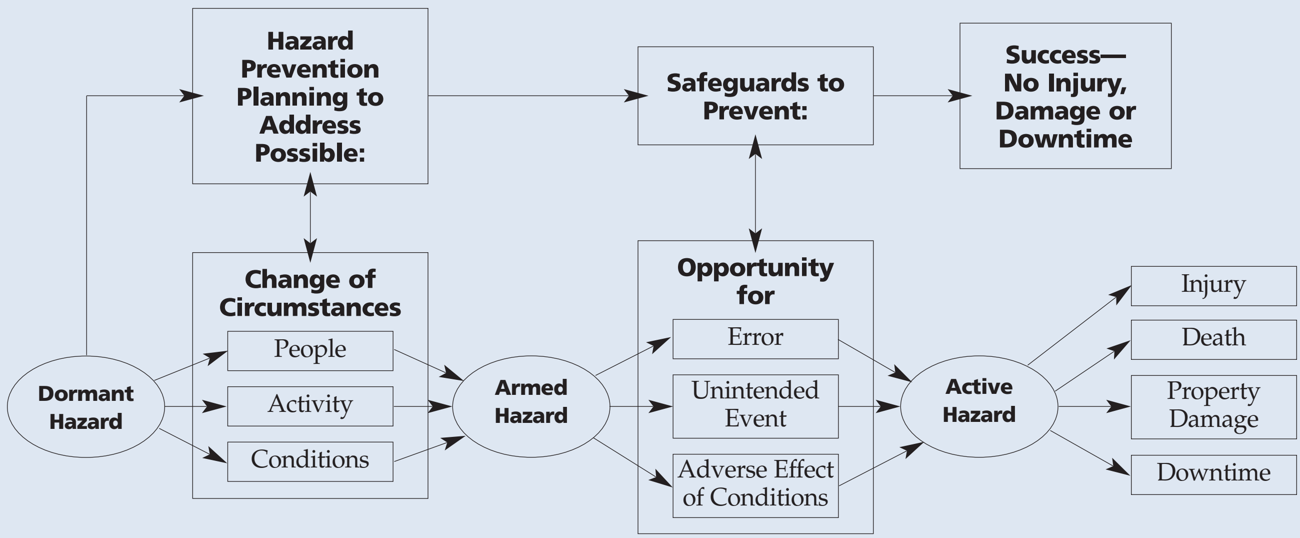
A well-known tenet of safety engineering often presented to the jury in injury litigation is, "Any hazard that has the potential for serious injury or death is always unreasonable and always unacceptable if reasonable design features and/or the use of safety appliances are available to prevent the hazard" (Philo). 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 routine expectation to design out hazards, thus changing an inherently dangerous facility, product or service into an inherently safe one.

Hazard identification is the basic building block to ensure an inherently safe construction project. To many, it is like Lewis Carroll's *Through the Looking Glass,* when Alice remarked, "I can't remember things before they happen," and the Queen described the advantage of living backwards, "Your memory can work both ways!"

Most construction managers would agree with Alice's observation because many do not anticipate accidents. They have few clues to predict failure modes that can arise, as construction injuries/deaths are widely separated by geography, time and trade. Without professional safety assistance in the event of injury or death, engineers are confronted with costly OSHA fines and sometimes liability claims. Engineer involvement in inherently safer design is critical, as this is their best option to avoid foreseeable accidents.

Figure 1

Logic Chart for Identifying Hazards



Often, the same hazard that has been causing injury, damage or downtime surfaces uncontrolled on multiple occasions. For example, falling loads due to two-blocking (which occurs when the lifting hook on the hoist line strikes the cable sheave on the boom tip with force sufficient to break the cable, causing the hook/load to fall) were recurring hazards on construction sites for many years. This trend stopped when anti-two-blocking devices were installed by manufacturers on all new cranes and retrofitted onto most cranes in the field. By relying on past experiences, "remembering backwards" is not all that difficult to begin to control hazards. Figure 1 presents a logic chart to help those involved look for changes of circumstances that can arise and how they affect people, activities and conditions.

Principle Three: Categorize the Hazard

The third step in hazard identification is to determine which of the following seven categories contains the source of the hazard: 1) natural environment; 2) structural/mechanical; 3) electrical; 4) chemical; 5) radiant energy; 6) biological; or 7) automated systems/artificial intelligence.

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 Environment 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 dangerous hazards such as earthquakes, tidal waves, hurricanes and tornadoes. Applications of engineering technology can help to mitigate 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.
- **Slopes:** upset; rollover; sliding; unstable surfaces.
- **Water:** floating; sinking; drowning; ocean tides.
- **Atmosphere:** change in altitude; humidity; wind; visibility (e.g., fog); dust; temperature.
- **Limitations on human performance:** People are not perfect. Errors due to unreliability in human performance must be factored into any work environment.

Mechanical Hazards

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

- **Unstable surfaces:** lack of traction; protruding obstacles; incline (steps, ladders).
- **Lever**
- **Rotation:** wheels; gears; pulley; screw; auger; cams; pinch points.
- **Reciprocation**
- **Compression:** shearing; puncture; structural failure.
- **Causes of vibration**
- **Metal failure**
- **Bending/hinge**

- **Tension/spring**
- **Hydraulic forces**
- **Pneumatic**
- **Vacuum**
- **Entanglement:** noose; snagging; entrapment.
- **Impact**
- **Velocity**
- **Airborne**
- **Blind zone**

Electrical Hazards

The third category is electrical hazards. Electricity is a power source that is silently conveyed and can cause great harm.

- **Voltage, amperage:** causing shock, burn, heart fibrillation.
- **Alternating current**
- **Direct current**
- **Spark/arcs**
- **Electrostatic**

Chemical Hazards

Chemical hazards are the fourth category. Many substances pose potential dangers in several forms. To begin this analysis, the following are a good starting point.

- **Combustion (fire)**
- **Corrosive**
- **Toxic substance:** liquids; fumes/vapors; dust.
- **Degradation**
- **Exothermic** (hot)
- **Endothermic** (cold)
- **Decomposition**
- **Hydrogen embrittlement**

Radiant Energy Hazards

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

- **Sound**
- **Heat**
- **Light**
- **Radiofrequency**
- **X-ray**
- **Nuclear**

Biological Hazards

Biological hazards are the sixth category. Again, these are broad groups intended to aid in identifying possible hazards.

- **Allergens** (e.g., mold)
- **Carcinogens**
- **Infection**
- **Agents known to cause disease in humans**
- **Virus**
- **Venom**
- **Conditions that produce sustained mental or physical stress in humans**

Automated Systems Hazards

The seventh category covers automated systems hazards caused by faulty computer software. This can include computer programs for load moment devices on cranes (designed to prevent overload and crane upset) to global positioning systems and computer-assisted designs.

- **Program error**
- **Technical malfunction**

These seven categories of hazards are offered to spur key project stakeholders 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.

The same hazard that causes injury, damage or downtime often surfaces uncontrolled on multiple occasions.

Principle Four: Use the Safe Design Hierarchy to Physically Control Hazards

The following hierarchy of controls is an accepted sequence of evaluating and controlling recognized hazards:

1) Eliminate the hazard.

2) Guard to prevent the hazard from causing harm.

3) Include safety factors to minimize the hazard.

4) Use redundancy 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 and sophisticated, safety must be addressed with the same attention to technical detail as is applied to the engineering of these projects themselves. The project critical path should be highlighted at those points where hazards have been identified in order to highlight potential problem areas.

For hazards to be eliminated, the entire construction process must be examined in this manner. Listing hazards in the critical path forces the planner to consider itemized alternatives. This leads to the need to apply a system safety approach—the same approach that has become the backbone of aerospace and nuclear energy design.

System safety relies heavily on the provision of safety factors and redundancy in addition to hazard elimination and guarding. Zero injuries through error-free worker performance is not an achievable goal. The age-old adage of human factors psychologists, "To err is human, to forgive design," has proved time and again to be a sound philosophy supporting the concept that the elimination of error-provocative circumstances is the basic reason for system safety.

"Safety factors" can be easily explained by the example of a bridge with a 10-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 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 circumstances, the consequences of an overload would not be a crane upset, but a structural collapse of the boom.

"Redundancy" is more than one safeguard, each of which must fail before the system experiences actual failure mode. A good example is the fuel sys-

Figure 2

Hazard Identification/Prevention Matrix

	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								
Artificial Intelligence								

tem on a military helicopter, which has several fuel tanks and fuel lines. Should bullets pierce the fuel tank, it is self-sealing to stop leaks. If a fuel line is broken, both ends have automatic shut-offs, 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 rollover protective structures for tractors and other heavy equipment, and the use of seatbelts to hold the operator in place in the event of an upset. Both measures work in concert to prevent the operator from being crushed or ejected.

In facility design, fire prevention and protection involves a system of redundant safeguards. In many cases, facility walls 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 often rigged to sprinkler systems. Fire doors and handheld 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. The fact that several alternate safeguards are not required to prevent or control the hazard of powerline contact is one reason injuries and deaths from boomed equipment contact with powerlines continue to occur.

Each control in the hierarchy briefly addresses various design choices in order 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 select the most effective method of hazard control. The engineer is encouraged to expand the listing in each of the four areas to accommodate a specific circumstance.

Eliminate the Hazard

Hazard elimination can be achieved in many ways. The following methods are used most often.

•Design out the hazard by developing an alternate safer design or using safety appliances on equipment.

•Substitute safer construction machinery.

•Relocate dangerous facilities (such as powerlines or other utilities) away from the construction site.

•Provide design criteria to suppliers of structural components to ensure for safe assembly at the construction site.

Guard the Hazard

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

•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 should the boom or hoist line come into contact with a powerline.

Safety Factors

•Raise the structural strengths above the foreseeable misuse and wear limits in order 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. For example, a bridge should be able to withstand foreseeable excessive-weight vehicles, even those with posted weight limits for autos, and the likely exposure to heavy trucks, cement and ready mix.

•Ensure that the cable tension loading is sufficient to overcome any foreseeable wear and that the sheave diameters will not accelerate wear.

•Ensure that the established limits for toxic radiation, gas, vapors and dust are well below the levels known to produce health effects.

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 can achieve an effective hazard control network. For example, an insulated link of a crane's hoist will protect the individual guiding or touching the 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 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 worksite.

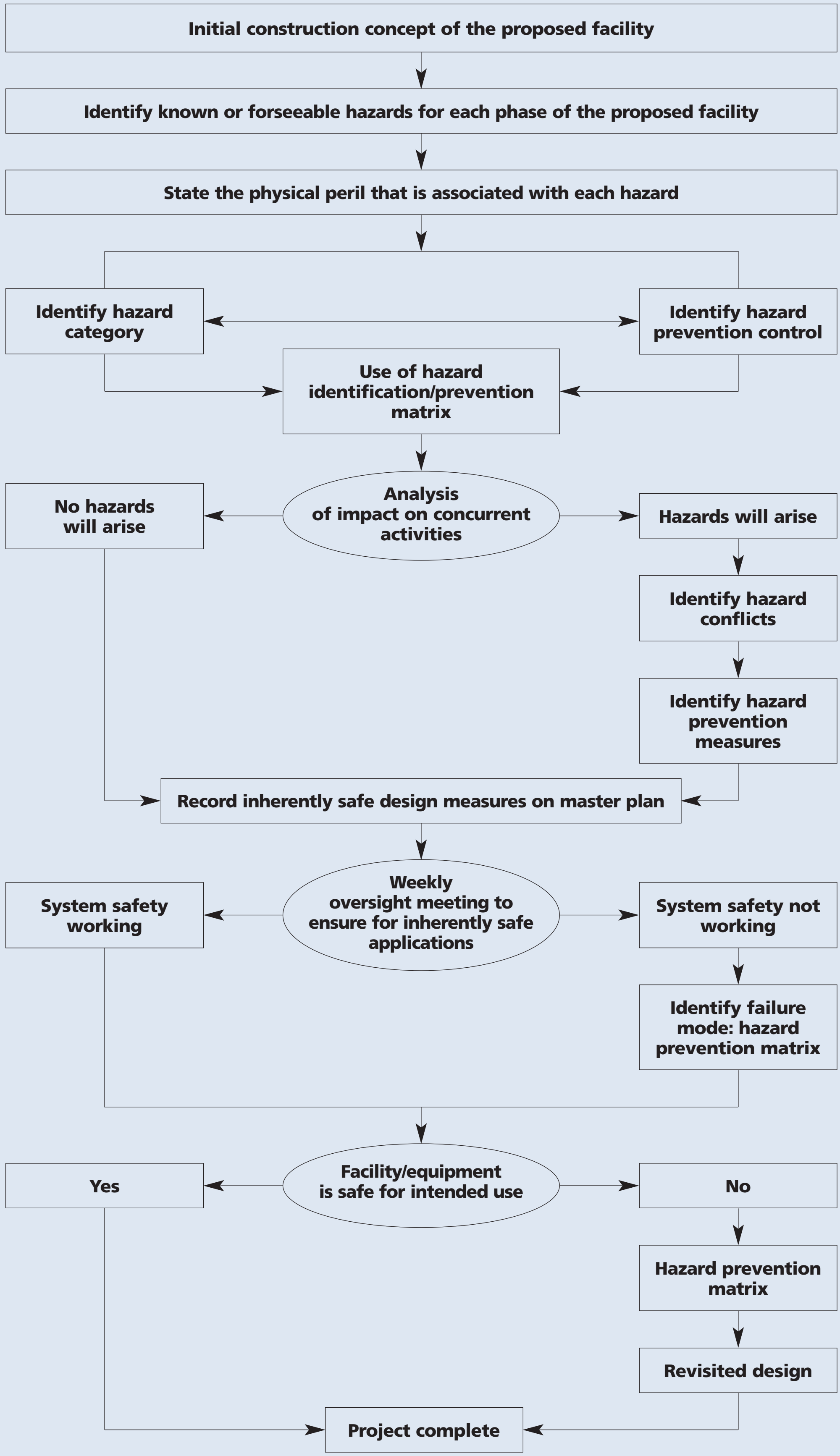
Widespread Application Needed

The application of system safety principles has been largely limited to the aerospace and electronics community. These principles need to be adopted by forward-thinking design and build contractors.

In more than 4 decades of experience, the aerospace industry has shown that qualifying risk as a peril stated in terms of reliability has made it easier

Figure 3

Master Critical Path Safety Plan



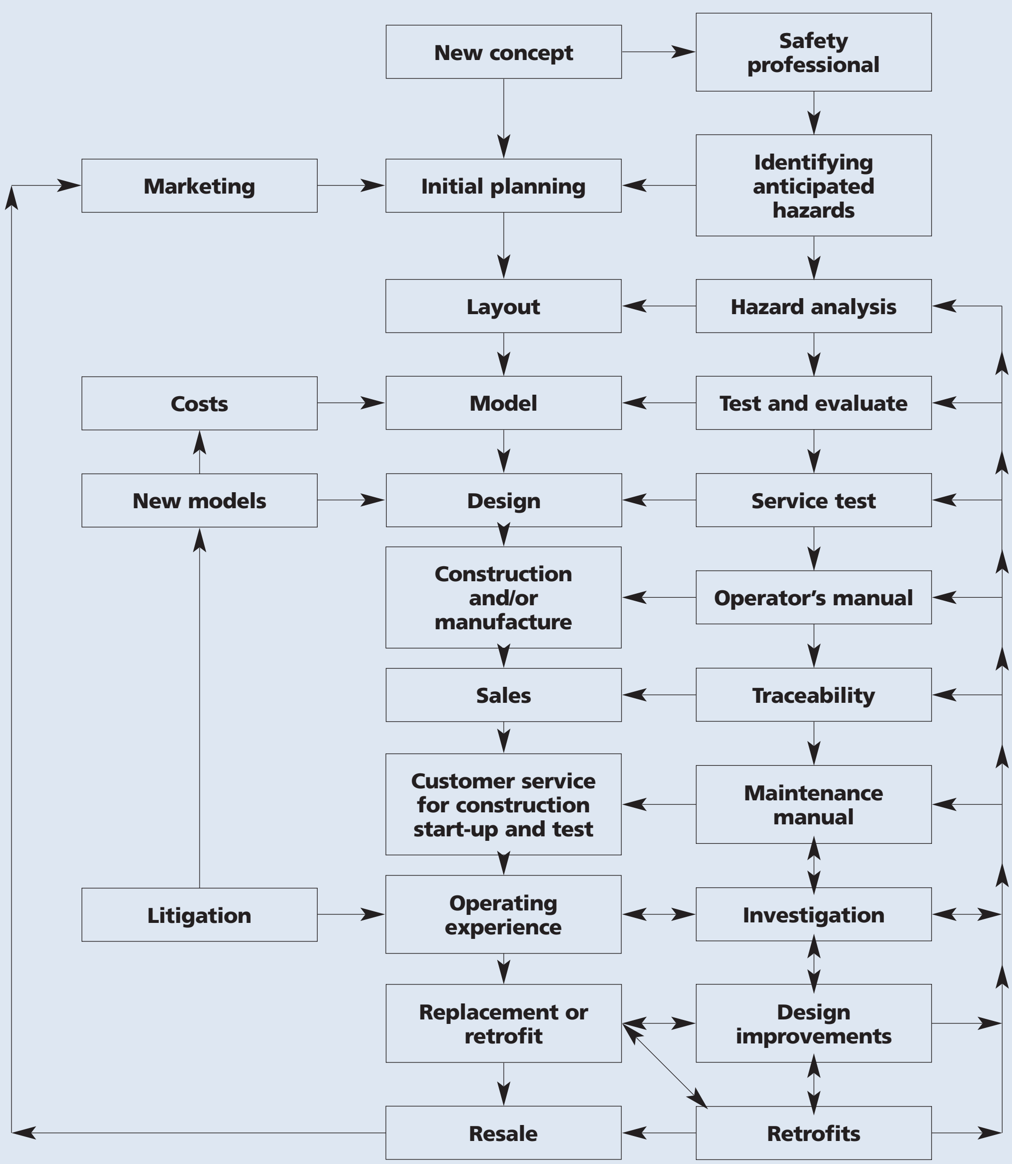
for management to provide funds for design improvements. Previously, when dealing with unknowns, management has been reluctant to authorize money for safety modifications during the design stage because some or all of the potential modifications have not been proven to work. The system safety analysis approach has shown that hazards can be effectively identified, controlled and measured without the need of costly accidents to identify and highlight potential hazards.

The language used in this hazard identification process is paramount. In many cases, the actual peril is confused with the term risk. It is important that the actual peril be defined as the type of injury, death or damage that may occur when the hazard becomes active. In these discussions, the term "risk" must be replaced with a sound byte of hazards that are likely to occur.

To effectively communicate the gravity of a hazard, strong language is often needed to gain the attention that will result in immediate corrective action. For example, a lifting hook without a latch to physically restrain the load straps should be defined as a "killer hook" since the loss of the load may fall and kill someone underneath [MacCollum(b)]. Hazards are too often described in a passive manner that does not address the seriousness of harm in terms of human injury. Vague language obscures the actual peril and destroys the incentive to ensure inherently safe engineering. Such language does not convey the actual danger that an active hazard can cause.

Figure 4

10 System Safety Steps to Ensure Hazard Prevention in Design through Life Cycle



Principle Five: Control the Hazard with the Appropriate Design Improvement/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 concepts can create safe design for construction processes specific to that field.

The contractor's role begins when the project is opened for bid. At that time, a rudimentary construction plan is developed primarily to determine costs; however, inherent hazards must be assessed and factored into the costs. Once the successful bidder is selected, site-specific construction planning affords the opportunity to screen the use of construction equipment to ensure that it is safe for its intended use. This approach includes two phases:

1) Integrate safety into the construction sequence plan:
- Outline specific phases of the project.
- List all possible hazards and ways to prevent them.

2) Ensure that the construction equipment used on the site is safe for its intended use by listing for each piece of equip-

ment a) anticipated hazards and b) ways design or use of appliances can be achieved to ensure an inherently safe construction site.

A critical path and other master construction schedules provide a visible vehicle through which to highlight the presence of potential hazards which will arise and ensure that everyone on the project receives notice and begins to consider the safety measures necessary to achieve inherently safe construction. One must examine closely the hierarchy of design in conjunction with the identified hazards. The most efficient way to accomplish this is to marry the hazard to the appropriate engineering control.

To this end, a simple worksheet matrix (Figure 2, pg. 30) has been developed as a design guide. This matrix can help an engineer quickly chart each hazard, define the necessary safety engineering and arrive at a reliability evaluation. The horizontal dimension provides space to list specific hazards and prevention measures and the seven hazard categories on the vertical dimension. This matrix allows the design engineer and/or construction manager to visually identify hazards and focus on necessary design features or appliances that prevent the hazards from becoming armed or active. This methodology gives management a comprehensive safety appraisal of new products, facilities and systems as well.

The question now is how can we make this transition? The answer is clear: by expanding the knowledge of all SH&E professionals in system safety and of fault tree and failure mode analysis so they can develop system studies for complex construction sites and the machines used in construction.

One way to approach this complex task is to seek the assistance of a system safety engineer. Most engineers' talents are directed toward designing a high-performance system. Their safety knowledge is often limited to a specific subsystem and perhaps a safe interface to adjoining parts. Because of such specialization, the engineer's safety overview is often limited, particularly when many engineering disciplines are involved in the entire system. Therefore, the design engineer needs the help of a special type of SH&E professional—one with thorough knowledge of system safety, who can participate as a member of the design team and can systematically analyze the system for unsafe conditions.

The most valid and authoritative proof of what is accepted as inherently safe design is a record of injury-free performance. Once a new design feature or the use of a safety appliance is adopted, a record of its performance must be developed. The easiest strategy is to record the injuries in the number of units times the years of use. From there, a more refined analysis can be performed regarding how the exposure to a hazard can be overcome by design rather than by reliance on human performance. Facility design and construction is really a system of many engineering disciplines that work cohesively to design multiple components and assemble the resources to erect the facility.

Figure 3 (pg. 31) depicts a critical path overview. It presents a system safety flowchart for examining a master construction safety plan that is integrated with the construction management schedule (often known as the critical path) and offers the opportunity to address each hazard that will arise during the phases of the construction process.

Figure 4 shows how a piece of equipment can also be evaluated at the time of design/manufacture to identify hazardous conditions. Many pieces of equipment brought onto a worksite have never been evaluated for hazards (HIFI). When selecting equipment for construction planning, each piece of equipment needs to be evaluated for hazards to ensure that only inherently safe equipment is brought onto the project.

The five principles outlined here give SH&E professionals the basic tools they need to help architects, equipment designers and engineers who are construction managers to eliminate the hazards before they ever reach the worksite. ■

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