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Forensic Engineering Investigation of Workplace Incidents Involving Machinery

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Abstract

On many occasions, a forensic engineer faces numerous questions when investigating workplace incidents involving machinery, such as: Why did this incident happen? Was it the operator who caused the incident? Was the operator properly trained? Was the equipment properly maintained? Was the equipment defectively designed or manufactured?

This paper focuses on potential product defect issues. How can one determine whether the product was defective and unreasonably dangerous? The paper outlines issues related to the investigation of product liability cases, and discusses potential procedures and steps to be taken in order to establish whether the product is defective or unreasonably dangerous.

The author explains the role of industrial regulations and standards from sources such as the Code of Federal Regulations (CFR), Occupational Safety & Health Administration (OSHA), American National Standards Institute (ANSI), International Organization for Standardization (ISO), and other entities in the process of assessing product safety. In addition, the role of the safety triad, technical and economic feasibility, and warnings/ instructions in assessing product safety are examined. The author also discusses another useful approach to safety: implementation of Failure Modes and Effects Analysis (FMEA). Finally, two product cases are presented to illustrate the process of safety analysis and investigation.

Keywords

Forensic engineering, product defect, unreasonably dangerous, standards, safety hierarchy, safety triad

Introduction

Workplace product safety is a combined effort of a designer, manufacturer, user (operator), and employer (if involved). Installers, maintenance providers, and training entities may also play a role in workplace product safety. However, if something goes wrong, the highest price of injury or death is typically paid by the operator. Therefore, it is essential for manufacturers to design equipment/machines to be as safe as practical.

In many cases, in regards to safety, an equipment manufacturer relies heavily on instructions, manuals, warnings, and proper training of potential users. Therefore, the manufacturer has less emphasis on hazard and risk analysis as a method of hazard minimization and ensuring proper guarding. This approach is quite often unsuccessful, and results in serious injury or death. Some reasons for this type of approach stem from lack of knowledge about best practices in safety, concerns about an increase in product cost by implementing more stringent safety procedures, or simple recklessness. In some cases, safety is simply not a sufficient priority for manufacturers. This author has found that instructions and equipment manuals, written by an individual with great knowledge of the equipment, often assume readers have a great deal of technical knowledge of the equipment, when, in fact, they may not. This may leave the normal operator, especially a new operator, with a great deal of doubt as to the proper operation of the equipment.

On the other hand, many employers have limited financial resources, have a poor understanding of safety, provide inadequate training for their employees, or are simply careless. Further, equipment operators may be tired, poorly trained, illiterate, rushed, or sloppy — and some may even misuse the product.

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Any combination of the situations noted above can create a perfect setting for a serious or even deadly incident. Even with proper training and years of experience, machine operators are still getting seriously injured or killed. It may happen because the equipment is simply not safe, or an operator is confused about the safe operation of equipment.

This paper discusses a broad approach to product liability cases, which includes basic terminology, industry standards and practices, and then presents two examples of brief case studies that involve some of the product liability issues addressed in this paper.

Defective and Unreasonably Dangerous Products

In some cases, when serious injury or death occurs, the injured party or his/her estate brings a lawsuit against the designer, manufacturer, distributor, or other entities under the claim of a "defective and unreasonably dangerous product." After analyzing the incident, an expert witness is asked whether a product is defective and whether the defendants or operator contributed to the incident causation.

In simple terms, a product may be defective and unreasonably dangerous if it can cause an injury, the injury can be serious, and it is technologically and economically feasible to design the hazard off the machine or to guard against the hazard. Technologically feasible means that before the product was manufactured, there was a technology available to make the product safer and to eliminate (or guard against) the defect. Economically feasible means that a higher level of product safety was available at a reasonable cost.

In safety engineering, hazards represent the potential of a product or process to cause injury, death, or damages; risk is the probability of injury, death, or damages.

A product can be defective and unreasonably dangerous if it is defectively designed, defectively manufactured, has defective warnings and instructions, or is defectively maintained. It should be noted in most cases, because of workers compensation immunity statutes, the plaintiff cannot bring a case against his or her own employer.

Safety Practices

In safety engineering, it is commonly understood today that a risk analysis is required by the designer to identify and eliminate or guard against serious hazards. When hazards with significant risks of serious injury or death are identified with a product, safety methodologies should be used to mitigate the risks associated with the product. The methodology to mitigate the risks has been referred to as an engineering hierarchy, design order of precedence, or engineering triad. Methodologies for proper product design and safety engineering principles have been published in many texts on safe product design[1,2,3,4] and have also been recognized in engineering standards[5,6,7]. In essence, hazards are to be eliminated according to the following hierarchy of steps:

- The first priority in safety engineering is to eliminate the hazard through design.
- If the hazard cannot be eliminated due to practical or functional reasons, the hazard must be guarded against.
- If the hazard cannot be guarded against, then warnings should be used.

The safety hierarchy can also be expanded to the following:

- Design so there is no hazard.
- Eliminate hazards through redesign.
- Provide guards/barriers against hazard.
- Provide automatic and manual warning systems (visual, audible).
- Provide warning signs and labels.
- Provide warnings in manuals, written instructions, and training.
- User must wear protective gear, since hazard is unavoidable.

It should be clearly understood that guards or safety devices should only be used if the hazard cannot be eliminated by design. Warnings are a last resort <u>to be used only</u> if the hazard cannot be eliminated by design or guarding. Warnings are a <u>minimum</u> requirement of safety engineering. The hierarchy has been graphically represented as **Figure 1**.

The safety triad principle is important because it requires the manufacturer to be proactive and deal directly with the hazard, rather than simply expecting the operator to comply with what may be very complicated instructions, warnings, or manuals.

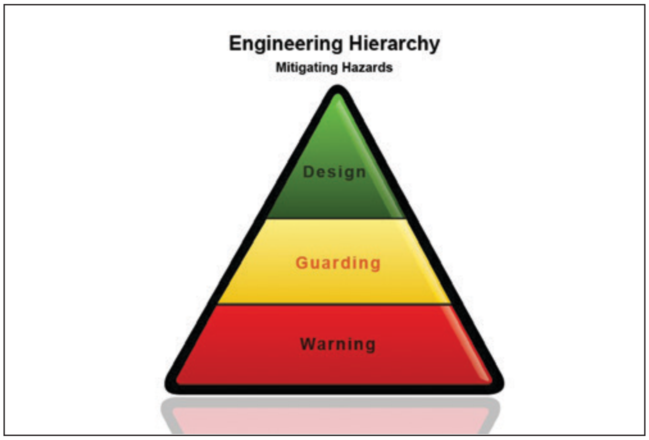

Figure 1
Engineering safety hierarchy of hazard mitigation.

Another important safety design practice is to design a product not only for foreseeable use but also for foreseeable misuse by the potential operator. The term "reasonably foreseeable misuse" is defined in ANSI/AMT B11.0 2008: *Safety of Machinery – General Requirements and Risk Assessment* as: "The use of a machine in a way not intended by the supplier or user, but which may result from readily predictable human behavior."

Role of Standards

There are many standards available to assist in safety assessment of a given product. These range from mandatory to voluntary to industry guidelines/recommendations to industry "verbal" practices. When conducting investigation of product liability cases, a forensic engineer should be familiar with applicable industry standards and practices. He or she should use them in reaching opinions, including whether the product is defective and unreasonably dangerous. Examples of important standards and regulations are listed below:

A. **Code of Federal Regulations (CFR)** consists of thousands of regulations (and referenced standards) that are related to many different industries, such as:

- Transportation (Title 49), including:
  - Federal Motor Carrier Safety Administration (FMCSA) - 49CFR300-399
  - Federal Motor Vehicle Safety Standards (FMVSS) - 49CFR571
- Labor: Occupational Safety and Health Administration (Title 29), including:
  - General Industry - 29CFR1910
  - Construction - 29CFR1926

B. **American National Standards Institute (ANSI)** is an accreditor of voluntary consensus Standards Development Organizations (SDOs), which, in turn, publish safety standards for products, including cranes (ANSI/ASME B30.17), forklifts (ANSI/ITSDF B56.1 and B56.6), wood chippers (ANSI/ISA Z133.1), and many more.

C. **International Organization for Standardization (ISO)** covers multiple industries and product safety issues.

In the international arena, a company's engineering design procedures are guided by the 2003 ISO 12100-1 *Safety of Machinery – Basic Concepts, General Principles for Design* standard, which defines that the basic concepts for safety of machinery include general principles for design. This ISO standard outlines the mechanical hazards associated with machinery and presents six general provisions for risk reduction. The first two state:

a. "It is assumed that, when present on machinery, a hazard will sooner or later lead to harm if no protective measures are taken."

b. "Protective measures are a combination of measures taken by the designer and the user. Measures that can be incorporated at the design stage are preferable to and generally more effective than those which are implemented by the user."

The ISO 12100 standard, which provides a process for hazard identification and risk assessment, states:

"When carrying out a risk assessment, the risk from the most likely severity of the harm is likely to occur from each identified hazard shall be considered, but the highest foreseeable severity shall be taken into account, even if the probability of such an occurrence is not high." In section 5.4, entitled elimination of hazards or reduction of risk by protective measures, it states:

"This objective may be met by removing the hazards by reducing, separately or simultaneously, each of the two elements that determine the risk: (i) severity of harm from the hazard under consideration; (ii) probability of occurrence of that harm."

The ISO 12100 standard also provides a sequence of steps to achieve a reduction of risk:

"All protective measures intended to reach this objective shall be applied according to the following sequence referred to as the '3-step method,'" which is shown in **Figure 1** and summarized as follows (also see ISO 14121 *Safety of Machinery — Risk Assessment — Part 1: Principles*):

a. *"Inherently safe design measures (Note: this stage is the only one at which hazards can be eliminated, thus avoiding the need for additional protective measures such as safeguarding or complementary protective measures.)"*

b. *"Safeguarding and possibly complementary protective measures."*

c. *"Information for the user about the residual risk. (Note: Information for the user shall not be a substitute for correct application of inherently safe design measures of safeguarding or complementary protective measures.)"*

OSHA regulations require all machines to be guarded. Some courts will not allow mention of OSHA rules and regulations during a products case. The forensic engineer must determine prior to rendering his or her opinions if the courts will allow relying on the OSHA rules and regulations. The retaining attorney should be able to provide this information. The general requirement for machine guarding can be found at 29 CFR 1910.212(a)(1). The regulation states:

"One or more methods of machine guarding shall be provided to protect the operator and other employees in the machine area from hazards such as those created by point of operation, ingoing nip points, rotating parts, flying chips and sparks. Examples of guarding methods are barrier guards, two-hand tripping devices, electronic safety devices, etc."

In many cases, there is a dispute whether equipment was defectively designed, was poorly maintained, if the operator was poorly trained or did not follow instructions, if the operator did not follow lockout/tagout procedures (described below), or the lockout/tagout procedures were defectively written. OSHA specifically regulates lockout/tagout procedures.

OSHA, Title 29 Section 1910.147 *The Control of Hazardous Energy (lockout/tagout)* section (a)(2) states: *"Application. This standard applies to the control of energy during servicing and/or maintenance of machines and equipment."*

The regulation defines "*servicing and/or maintenance"* as *"Workplace activities such as constructing, installing, setting up, adjusting, inspecting, modifying, and maintaining and/or servicing machines or equipment. These activities include lubrication, cleaning or unjamming of machines or equipment and making adjustments or tool changes, where the employee may be exposed to the unexpected energization or startup of the equipment or release of hazardous energy."*

It should be noted that a given product can meet all voluntary and even mandatory standards and still can be found defective and unreasonably dangerous. Examples of such cases include where a motor vehicle meets all Federal Motor Vehicle Safety Standards but nevertheless has problems with crashworthiness or defects in seatbelts, air bags, seats, etc. Recently, General Motors recalled millions of vehicles with a defective ignition switch that affected the safe operation of airbags, brakes, and steering systems. In 2014 alone, General Motors recalled more than 29 million cars worldwide (25 million in the United States) for a variety of different defects[8].

Failure Modes and Effects Analysis

Another useful approach to safety analysis is Failure Modes and Effects Analysis (FMEA), which was originally created in the 1940s by the U.S. military and was further developed by the aerospace and automotive industries.

FMEA is an analytical methodology and a step-by-step approach for identifying both potential reliability issues and potential safety hazards in a design, manufacturing process, product, or service. Failures are prioritized according to how serious their consequences are, how frequently they may occur, and how easily they can be detected. The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones.

FMEA includes review of the following:

- Failure opportunities (What could go wrong?)

- Failure causes (Why would the hazard happen?)
- Failure effects (What would be the consequences of each failure?)

Important FMEA-related standards include:

1. Commission Electrotechnique Internationale: IEC 60812 Edition 2.0 (also known as British Standard: BS EN 60812:2006).
2. Society of Automotive Engineers: SAE-J1739
3. Automotive Industry Action Group: FMEA-4

All the above provide users with information on how to identify the potential for system elements to fail and how to assess and analyze the hazard. By using an FMEA standard, the designer may be able to eliminate the hazard during the design stage, or mitigate the hazard effects to avoid undesirable safety consequences on the existing hazard.

1. **IEC 60812 Edition 2.0** from 2006, *Analysis Techniques for System Reliability – Procedure for Failure Mode and Effects Analysis (FMEA),*[9] (also known as BS EN 60812 2006) describes failure mode and effects analysis (FMEA) and failure mode, effects and criticality analysis (FMECA), and gives guidance as to how these techniques may be applied to achieve various reliability program objectives by:
   - Identifying appropriate terms, assumptions, failure modes, and criticality measures.
   - Providing the procedural steps necessary to perform an analysis.
   - Providing examples of the typical forms used.

2. **SAE J1739**, *Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA)*[10]. This SAE-recommended practice was jointly developed by Chrysler, Ford, and General Motors under the sponsorship of the United States Council for Automotive Research (USCAR). It is geared toward the ground vehicle community and assists users in the identification and mitigation of risk by providing appropriate terms, requirements, ranking charts, and worksheets. As a standard, this document contains requirements and recommendations to guide the user through the FMEA process.

3. **AIAG FMEA-4,** *Potential Failure Mode & Effects Analysis – 4th Edition*,[11] is a reference manual to be used by suppliers to Chrysler, Ford, and General Motors as a guide to assist them in the development of both design and process FMEAs. The manual does not define requirements; it is intended to clarify questions concerning the technical development of FMEAs.

Wood Chipper Fatality Incident

This is a case study of a fatal incident involving the operator of a commercial wood chipper. The operator was a 20-plus-year veteran of the tree trimming industry, was well trained, and was a supervisor of his two-man crew. One man would trim the tree, and the other would feed the chipper. A witness saw the tree trimming truck and the chipper pull up to the incident location. He observed the branches being cut, saw the operator picking up loads of branches (with both hands and arms) from behind the area of the chipper, and then watched him carry each load of branches to the rear of the chipper where the branches were fed. He saw the operator doing this same process numerous times over an approximate 30-minute period before the incident happened. There were no eye witnesses to the actual incident.

Based on the witnesses' statements and biomechanical evaluation of the operator injury pattern, as the operator was feeding branches into the chipper, his right hand or arm apparently became caught or entangled, which pulled him into the infeed chute, the feed wheel, and then the cutting drum containing the blades. The victim died in this very gruesome incident (see **Figure 2** and **Figure 3**).

The wood chipper (as designed) has a quick-stop and reverse control bar that allows the operator to feed the material in, stop, or reverse the material out. The

Figure 2
Wood chipper with the towing truck.

Figure 3
Still frame from an animation of the incident.

wood chipper manual stated that the machine complied with the ANSI/ISA Z133.1 *Standard for Arboricultural Operations – Safety Requirements*. The ANSI Z133.1 is a minimum voluntary standard. It states:

"The activating mechanism for the quick-stop and reversing device shall be located across the top, along each side, and close to the feed end of the infeed hopper within easy reach of the worker."

In certain conditions, the operator's glove or clothing can be entangled with wood branches, and the operator's body can be pulled into the wood chipper. Under an emergency condition, the operator has to reach and activate the "quick-stop." Because the *"activating mechanism,"* as designed, was too far for the operator to reach under an emergency situation, the operator was unable to reach the quick-stop and was fed into the wood chipper. **Figure 3** shows the operator when feeding the wood chipper with the branches in relationship to the control bar.

Although the wood chipper apparently complied with this ANSI standard by providing "quick-stop and reversing device," it did not comply with the standard by making this reversing device "within easy reach of the worker." While in danger, the worker could not reach the reversing device, and the fatal incident still took place[12].

In conducting the investigation, this engineer also analyzed the presence and effectiveness of warning labels and instructions. There were warning labels attached to the wood chipper warning the user against potential hazards as follows:

- Never reach inside infeed chute.
- Never operate this machine when wearing loose clothing, scarves, gauntlet-style gloves, or gloves with large cuffs or holes.
- Never operate this machine alone. Make certain there are at least two people with this machine at all times.
- Never operate this machine without thoroughly reading the operator's manual.

However, the warnings were not clear, did not include graphical representations, and were written in small letters. Some of the warning labels were worn and not readable. Therefore, this engineer concluded that warnings and/or instructions would not have prevented this incident.

Because of the ineffectiveness of the control bar and warnings and instructions in preventing this incident, this engineer evaluated other safety devices that could have prevented this incident. One effective safety device is a "knee bar" depicted in **Figure 4**. A knee bar is a passive safety device, located across the horizontal opening of the infeed chute/tray and is activated by a caught or entangled operator whose knees come in contact with the bar. The bar, pushed passively by the knees, activates the infeed reverse motion and prevents the operator from being pulled into the infeed chute.

Had a knee bar been present on the subject machine, as it should have been to provide safety protection to operators, the operator's body (particularly his upper leg and knee) would have activated the knee bar before any part of his body came in contact with the feed wheel (**Figure 4**).

Figure 4
Wood chipper with knee bar and surrogate testing.

Research shows the knee bar was available on the market from one manufacturer when the wood chipper in question was manufactured (2002). Such a "knee bar" and its design was technologically and economically feasible for many years before the wood chipper in question was designed and manufactured. Furthermore, there were many patents describing knee bar design and technology – years before the wood chipper in question was manufactured.

In this engineer's opinion, it was unreasonable for the manufacturer not to implement a knee bar design as standard equipment simply because the existing standards (including ANSI Z133.1) did not require such a device. The knee bar is an effective safety feature, had been economically and technologically feasible for many years, and would prevent many serious or fatal incidents. It took several years before all major wood chipper manufacturers decided to equip their wood chippers with a safety knee bar.

Since 2012, most manufacturers offer knee bars with their commercial wood chippers, even when the ANSI standard does not have such a requirement.

When processing wood branches in the wood chipper, the branches are fed into the wood chipper at a speed of 2 feet per second. Many operators do not comprehend how quickly an operator, if entangled with branches, can be pulled into the wood chipper — a situation that can result in a fatal incident. In many cases there is not even time for an operator to activate the control bar and rescue himself. Simply relying on operator training, safety labels, and warnings or instructions is not reasonable and can lead to many serious and deadly incidents[13].

The wood chipper case study shows that the wood chipper (as designed) did not meet the ANSI/ISA Z133.1 *Standard for Arboricultural Operations – Safety Requirements*; there was no evidence that OSHA regulations were violated. At the time the wood chipper was manufactured, only one manufacturer offered a knee bar as safety equipment. Today, all major wood chipper manufacturers not only provide a knee bar for their wood chippers as a standard equipment but they also provide retrofit of knee bars to any commercial wood chipper equipped with a control bar.

The forensic engineer should be prepared to answer the following questions:

1. ***What was the probable cause of the incident?*** *The probable cause of the incident was the operator being caught and entangled with the wood branches during the feeding process and his inability to free himself. In addition, he did not have enough time to reach the control bar because it was located too far for him to reach and activate it.*

2. ***Is this product defective and unreasonably dangerous?*** *The wood chipper was defective and unreasonably dangerous as designed due to lack of a passive safety device to prevent an operator, in certain emergency conditions, being fed into the wood chipper.*

3. ***Could this incident be prevented by a safer design?*** *Yes it could, by providing a knee bar. Operator training, warnings, and instructions will not prevent this incident.*

Forklift Double Fatality Incident

This incident occurred at a plastic pipe manufacturing plant in a loading area. The forklift operator had just finished loading a semi-trailer with a pipe load. After the operator finished loading the semi, the operator parked the forklift on a slight incline near the semi. The operator then set the subject forklift's transmission to neutral, turned the forklift's engine off, and applied the forklift's parking brake. After applying the parking brake, the operator got off the forklift and walked toward the semi driver, who was located near the right front of the semi's trailer.

Witnesses' statements, inspection of the incident site, inspection and testing of the forklift, and PC

Crash[14] simulation of the forklift motion (with known initial and final rest position, slope at the incident site and rolling resistance of the forklift) indicate that the subject forklift started rolling forward slowly as soon as the operator took his foot off of the forklift's service brake pedal. PC Crash simulation was used for camera match animation of the incident, and **Figure 5** and **Figure 6** are still frames from the animation.

Figure 5
Still frame from the animation depicting the incident.

Figure 6
Still frame from the animation depicting the incident from another camera view.

When the operator got off the forklift, the machine began traveling at such a low velocity that it apparently remained undetected by the operator. After the operator got off the forklift, he began to walk much faster than the forklift's velocity at that time. Approximately 15 seconds after the operator got off the forklift, the forklift struck both the operator and the semi driver at an approximate speed of 2 to 3 mph and pinned them against the trailer (**Figure 5** and **Figure 6**). Both the operator and the semi driver died as the result of the incident.

After the incident, the Occupational Safety and Health Administration (OSHA) performed an investigation of the subject forklift. OSHA issued a citation to the employer for failing to chock the wheels of a powered industrial truck while parked on an incline (see **Figure 7**).

After the incident, this engineer inspected the braking system and found a lot of caked-on dirt and debris on the outside of the caliper housing and linkage system (**Figure 8**), indicating that the parking brake system components had not been serviced in a long time — possibly years. In addition, the operator's manual preventive maintenance schedule stated that the parking brake pads must be checked and replaced, as necessary, every 300 hours. However, the heavy wear on the movable parking brake pad and the employer's maintenance records indicated that the subject forklift's brake pads had never been replaced in its five-year history and approximately 6,900 hours of service. Therefore, the employer failed to follow the manufacturer operator's manual preventive maintenance schedule regarding checking and replacing the parking brake pad every 300 hours, as necessary.

Figure 7
Subject forklift showing parking brake lever.

Figure 8
Caked dirt located over parking brake linkage components.

In addition, the parking brake was tested by this engineer on the incident site (1.2 percent slope), and it was found that with the parking brake engaged, the forklift began to roll down the incline. Furthermore, review of the ANSI/ASME B56.6 *Safety Standards for Rough Terrain Forklift Trucks* was conducted to determine if the subject forklift's parking brake was defective. Section 8.8.1 of the standard states:

> *"The parking brake system shall be capable of holding the rough terrain forklift stationary on a 15% dry swept grade under all conditions of loading in both forward and reverse directions"*[15].

The subject forklift's parking brake was not able to hold on an incline of no more than 1.2 percent, which was substantially lower than the holding requirement of 15 percent outlined in ANSI B56.6. Therefore, this engineer determined that the parking brake was defective at the time of the inspection.

The operating manual discussed a very simple six-step method that provides forklift operators the ability to adjust the parking brake from within the forklift's operating compartment without the need of any tools or specialized maintenance personnel.

This engineer also conducted testing of braking performance of the forklift and determined that after the parking brake was adjusted per the instructions in the operator's manual, the forklift's parking brake functioned properly. Therefore, had the employer followed the parking brake adjustment procedure described in the forklift's operational manual prior to the incident, the parking brake would have been in proper working condition, and the incident would not have occurred.

The forensic engineer should be prepared to answer the following questions:

1. *What was the probable cause of the incident?*
2. *Is this product defective and unreasonably dangerous?*
3. *Could this incident be prevented and how?*

Incident analysis shows there was nothing wrong with the forklift design or manufacturing. The forklift was simply in an out-of-service mechanical condition caused by lack of proper maintenance and adjusting of the braking system, perhaps for many years. Although the forklift was properly designed and manufactured, it was kept in a defective und unreasonably dangerous condition due to improper maintenance, resulting in a double fatality incident.

Conclusions

This paper shows examples of paths for a forensic engineer to investigate certain types of "product liability" cases. It discusses the basic techniques and procedures to investigate such cases. Furthermore, the paper shows how industry standards, product manuals, product testing and examination, market research, and literature research are used to determine whether a product is defective and unreasonably dangerous.

Furthermore, this engineer shows that relying on instructions and warnings may not be an effective method in preventing certain types of incidents. This paper demonstrates that the equipment can be defective and unreasonably dangerous not only by design but also solely by defective maintenance. As shown in this paper, if something goes wrong, the operator/user typically pays the highest price.

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