The Ohio State University

SAFETY FIRST: A Fault Tree Expert System for Construction Falls

Volume I: The Knowledge Acquisition

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16. Abstract (Limit: 200 words) The fault tree expert system SAFETY FIRST was developed to identify safety problems that may result in a fall accident and investigate the causes of a fall accident that has already occurred. The first major tasks in the development of the system was to acquire the knowledge which would be needed regarding the causes of construction falls. Experts in the field of construction safety were interviewed and searches were made of all available literature. It was determined that unintentional falls resulted from seven major elevated components: floor edges, floor openings, roofs, wall openings, tops of walls, steel beams, and portable ladders. There were also six major types of scaffoldings identified for analyses: form, tube and coupler, suspended, wood pole, tubular welded, and mobile scaffoldings. The causes of falls from the same level and slips were also determined. The causes of falls were classified into two major groups: basic causes which may directly induce a fall (enabling, triggering, or support related problems), or conditioning causes whose occurrence make a fall more likely to happen, such as safety problems.

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EXECUTIVE SUMMARY
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Construction falls have been identified as the most frequent cause of deaths and injuries of workers during construction operations. These falls can be categorized into falls from higher elevation, from the same elevation, and slips. While the frequency in which the latter two categories occur is higher than that of the first, the consequence of falls from higher elevation is the most severe of all. During construction, falls can occur from any working platforms. However, this study reveals that such accidents frequently occur from floor edges, floor openings, wall openings, tops of walls, steel beams, roofs, ladders, and scaffoldings. These hazardous platforms (components) are the focus of this study.

The study's objectives are to develop a tool to diagnose the causes of falls and to identify potential causes prior to fall occurrences. In addition, such a tool can be used for training purposes. Safety organizations and industry alike have recommended the development of such a tool, particularly one that can mimic the thought process of safety experts in determining the cause(s) of a fall. Very often, experts conclude such a cause heuristically, based on their experiential judgment, rules-of-thumb, educated guesses, and assumptions. For the above reasons an expert system, SAFETY FIRST, was developed.

The first major step in developing SAFETY FIRST was the acquisition of knowledge. Throughout the project period, numerous experts contributed their expertise directly and indirectly to the development of the expert system. Other knowledge was also acquired from literature recommended by experts including fall- and safety-related cases, codes, and regulations. During the knowledge acquisition process, the study revealed that while literature provides some knowledge for building the system, much more had to be gained from domain experts in order for SAFETY FIRST to meet its objectives. Through their extensive practical experience these experts have provided a wealth of detailed knowledge about construction falls that cannot be found in literature.

The next major development step was structuring the acquired knowledge using fault tree models. These models are furnished with numerous branches, each of which represents a path indicating the sequence of events and causes an expert may have gone through when diagnosing a fall case and concluding the basic cause(s) of the fall. Furthermore, these models reveal the causes of the events that contributed to a fall. By themselves, these models can be used as a visual template for training novices to analyze the cause of a fall by the method of deduction. When used to structure the knowledge for SAFETY FIRST these models classify causes of falls into a pattern of enabling, triggering, and support-related events or causes.

Constructing the knowledge base of SAFETY FIRST was the final major step of this study. This step includes the development of the user interface, which calls for a systematic design of screens displaying the queries prompted to the users. These queries are prompted to obtain evidence and information that may verify the cause of a fall. For this purpose, the fault tree models were converted into decision trees arranged in tabular form. While fault trees show the causal relationships among contributing events or causes to a fall, the decision trees were developed following the fault tree pattern to include the evidence and information about conditions which existed during the fall. Once the decision trees were constructed, the knowledge base was implemented by developing frames, production rules, and other properties following the pattern laid out by the decision trees.

Throughout the development of SAFETY FIRST, numerous tests were conducted by the knowledge engineers, experts, and potential users. The knowledge engineers evaluated SAFETY FIRST for its efficiency and logic, while experts validated its accuracy, completeness, applicability, and how well the system solves a problem. Potential users tested the system checking for user convenience and interface with the system. Further, to maintain the objectivity of the knowledge contained in the system, tests were also conducted by independent experts who encountered the system for the first time upon testing it. Both formal and informal evaluations were performed by experts and users alike. The results indicate that the system has a great potential of being a useful training tool for the construction industry.

In the last volume of this report, the results of a final and formal evaluation of a representative subsystem of SAFETY FIRST by independent experts and potential users is presented. All evaluation criteria (adequacy of conclusion, clarity of queries, user friendliness, efficiency, ease of use, and usefulness of the system), including the overall performance of the subsystem, have been rated as good or better than good.

Despite a successful effort in completing this study, like any other expert system, SAFETY FIRST does have limitations. First, the often innumerable variables needed in solving a fall case frequently limit the system to producing general conclusions. Hence, more specific conclusions requiring other domains of expertise are needed to refine the system. Second, a more efficient and refined system can be developed as an extension of this study by separating the knowledge base of SAFETY FIRST into diagnostic and prognostic modules. Third, at this stage, SAFETY FIRST is furnished with limited sound and graphic capabilities; further development of the system to include the multi-media components will enhance the user interface of SAFETY FIRST. These limitations could become the focus of an immediate extension of the system. In fact, plans have been set for the principal investigator of this project and his doctoral student to continue developing SAFETY FIRST in a multi-media environment. New results will be reported as research progresses.

ABSTRACT
VOLUME I

Falls are a leading cause of accidental death in the United States, second only to automobile accidents. Fall accidents are also critical in the construction industry where construction falls have been identified by the Occupational Safety and Health Administration (OSHA) as the most frequent cause of construction deaths, making up 33 percent of all construction-related fatalities. To try to curtail this problem, this project proposed the development of SAFETY FIRST, an expert system to identify fall safety problems that may lead to a fall accident (i.e., for prognosis purposes) and investigate the causes of a fall accident that has already occurred (i.e., for diagnosis purposes).

To develop this system, three major tasks were proposed: (1) to acquire knowledge regarding the causes of construction falls, (2) to represent the knowledge acquired in the form of fault tree structures, and (3) to incorporate this knowledge into the expert system. Volume I of this report focuses on the first task.

The knowledge required to determine the causes of construction falls was acquired from experts in the field of construction safety through extensive interviews and from the available literature (e.g., OSHA codes). As a result, the causes of unintentional falls from the following seven major elevated components were established: floor edges, floor openings, roofs, wall openings, tops of a walls, steel beams, and portable ladders. Furthermore, the possible causes of falls from six major types of scaffoldings were analyzed: form, tube and coupler, suspended, wood pole, tubular welded, and mobile scaffoldings. Finally, the causes of falls from the same level and slips were also determined.

These causes of falls were classified into two major groups: basic causes which may directly induce a fall (i.e., enabling, triggering, or support-related problems) or conditioning causes whose occurrence may make a fall more likely to happen (i.e., safety problems). It is expected that by focusing the industry's attention on all of the potential causes of falls, the corresponding safety measures to prevent their occurrence will be taken.

CHAPTER 1
INTRODUCTION

1.1 Background of the Study

The construction industry is one of the largest industries in the United States, making up about 10 % of the country's GNP [Nunnally 1993]. The industry also encompasses one of the largest labor forces in the country, accounting for about 6% of the private-sector work force. Unfortunately, the construction industry also accounts for one of the largest worker accident rates in the United States.

Numerous studies of construction worker accidents have been reported [NIOSH 1988, NIOSH 1989, OBWC 1989a] and the statistics of such accidents have been presented in many reports [BLS 1984a, BLS 1984b, BLS 1986, NSC 1987, OBWC 1989b]. Regulations and codes to avoid these accidents have also been published [AGC 1990, CFR-29 1988, OBWC 1989a].

For example, in 1980, the National Safety Council (NSC) reported that construction worker injuries accounted for nearly 11% of all work injuries and more than 20% of fatalities [NSC 1981]. In the 1990s, inspite of years of efforts by the industry and government regulatory offices to introduce new safety regulations and safety-oriented construction techniques, these high injury and death rates have not decreased. In fact, in 1990, *The Business Roundtable* reported that the worker injury rate in this industry was about 54% higher than the rate of all other industries combined [Business Roundtable 1990]. In addition, the death rate in construction is 71 per 10,000 workers versus an average in all industries of 18 per 10,000. Over 200,000 construction workers suffer disabling injuries each year, and over 2,000 construction workers die as a result of work-related injuries each year [NSC 1991].

Construction projects involve a wide range of operations and activities, most of which can lead to accidents if proper care is not taken. The most serious construction accidents involve construction equipment operation, trench and embankment failure, falls from elevated positions, collapse of temporary structures and forms, and the failure of structures under construction [Nunnally 1993]. In 1990, the Occupational Safety and Health Administration (OSHA) introduced a classification scheme of construction accidents that kill construction workers, including the following: falls, being struck by a falling or flying object, being caught in between objects, electric shock, and other as shown in Figure I-1.1

Figure I-1.1 Five Types of Construction Accidents [OSHA 1990]

The study, which was based on 3,496 construction fatalities recorded from 1985-1989, clearly shows that falls are the most prevalent cause of accidental deaths in construction, making up 33% of all construction-related fatalities. Falls are defined as the case when "a person loses his or her balance and moves from an erect position to a prone or semi-prone position" [Ellis 1989].

Numerous studies [BLS 1986, 1984a, and 1984b; NIOSH 1989a and 1989b; NSC 1987; Business Roundtable 1988, 1990] have also suggested that falls cause the largest percentage of construction fatalities and injuries. The US Department of Labor reveals that falls are "one of the leading causes of traumatic occupational death, accounting for 8% of all occupational fatalities from trauma in 1986" [BLS 1988]. The National Institute for Safety and Health (NIOSH) National Traumatic Occupational Fatality (NTOF) data base shows that during 1980-1985, falls caused about 10% of all traumatic occupational deaths [NIOSH 1989a and 1989b].

In its *Accident Facts*, the National Safety Council [1987] reveals that by type of accident, falls represent 12% of all deaths in work accidents, making them the next highest type after motor-vehicle accidents. In the same report, a study about work injuries by type of accident in 1983 shows that construction falls were one of the highest types, representing 21.4% of all construction accidents. Furthermore, the statistics from the NSC show that about 1,300 workers died in falls during 1990, while 300,000 others suffered disabling injuries. The former represented around 12% of all fatal accidents in the industry, the latter about 17% of all injuries.

From an international perspective, the Health and Safety Executive (HSE) of the United Kingdom reported that about half of the fatalities in construction operations were attributed to falls from elevations [IC 1994]. In Korea, although the statistics of falls are not available, in a recent study of construction accidents, the Korean Industrial Safety Institution reported that these accidents are on the increase [Ann 1993]. Further, the institution criticized the construction industry for not adequately stressing the importance of preventing their workers from having accidents. In Japan, the Nikkan Kensetsu Kougyou Shinbun [1992] reported that in 1990 alone about 60,000 severe construction accidents had resulted in 1,075 labor deaths, representing nearly 40% of the fatalities of all industries combined. It is no surprise that the Japanese nicknamed their construction industry as the "3K industry," referring to *kiken* (dangerous), *kitanai* (dirty), and *kitsui* (difficult).

1.2 The Costs of Accidents

Today, safety professionals believe that these high injury and death rates are in large part due to the disregard for safety in the construction site. Often safety equipment is not available in construction sites, because both supervisors and workers believe that it will interfere with production. Many construction company managers do not feel that safety is a vital factor in the success of construction projects, especially if money must be spent. However, this attitude shows a lack of foresight and prudence on the part of managers given the costs that the lack of safety on a given construction site can entail.

Among these costs are the insurance premiums related to safety performance. The construction industry has one of the highest premiums for worker compensation. This is not surprising given the high injury and death rates in the industry. According to the NSC, deaths due to falls in the workplace cost employers about seven billion dollars in 1990, while disabling injuries cost them another 950 million dollars [Rademaker 1991]. While these costs represent those of the entire industry, a large portion may go to those caused by construction falls, especially since construction falls represent a large portion of the entire workplace falls (Bureau of Labor Statistics, over 41% of fall accidents occurred in the construction industry in 1982).

The following statistics from the National Safety Council [1981] help to illustrate the cost of work-related accidents. Over 8.5 billion dollars of worker compensation benefits were paid to disabled workers in 1978. This amount consisted of wage compensation costs (5.8 billion dollars) and medical and hospital costs (2.7 billion dollars). If the value of other indirect costs is added to the direct costs of these accidents, the total cost comes to 23 billion dollars. This means that the cost per worker was 242 dollars per year [Marshall 1982].

The indirect costs are any extra costs generated by the occurrence of an accident on the job site. Among these costs are losses of the injured worker's productivity, losses of time and productivity of the crews working in the vicinity of the accident, losses of supervisory and administrative time, losses of working time for accident investigations, the cost of hiring a temporary replacement worker, and damage to equipment and material, among others [Hinze and Applegate 1990]. A study made by Stanford University in 1979-1980 estimated that the average ratio of hidden costs to direct costs could be as much as four to one, or higher [Stanton and Willenbrock 1991]. Another reason why the construction industry should change its attitude toward safety is the increased enforcement of Occupational Safety and Health Administration (OSHA) regulations and fines.

The above studies regarding the significance of the costs of construction accidents (i.e., direct and indirect) have induced some contractors such as Bechtel, Fluor, and Rust to recognize the importance of construction safety, and has led them to provide employee safety training. As a result, they have benefited from an improved and safer performance on job sites [Hislop 1991].

Given the significant human and material costs to construction firms when a construction fall accident occurs, the industry cannot afford to ignore this problem. Many of these accidents could be prevented if we could identify the basic causes of falls and use preventive measures to avoid them. The general objective of this research project is to develop an expert system that can be used to determine the causes or combination of causes contributing to construction falls from several construction platforms. By focusing both the construction companies' and government agencies' attention on these causes, it is expected that the number of fatal construction accidents and injuries will be reduced and that, in this way, construction safety may be improved.

1.3 Objectives of the Study

Many factors, such as the skill of workers, the attitude and health of workers, the condition of the structure component, the weather conditions, the types of construction equipment, the availability and condition of safety equipment, and so on, affect construction safety. A working environment is "provisionally categorized as safe if its risks are deemed known and in the light of that knowledge judged to be acceptable" [King and Hudson 1985]. The identification of the causes of construction fall accidents is mandatory to reduce the risks of such accidents and, subsequently, create a safer construction site.

Therefore, the main objective of this research project is to develop an expert system, SAFETY FIRST, containing knowledge regarding unintentional construction falls in the construction industry, including falls from higher elevation, falls from the same level, and slips (not fall). SAFETY FIRST emphasizes the engineering aspects, and further incorporates other aspects pertinent to the engineering control system (e.g., procedural, behavioral, social, and economic aspects). Specifically, SAFETY FIRST includes a fault tree technique in an expert system environment. The system may be used to investigate and to simulate construction accidents. In this project, we limit the use of SAFETY FIRST to construction falls. When implemented, SAFETY FIRST is expected to accomplish the following:

1. To provide a tool with which to investigate a construction fall that has already occurred. The fault tree models show all possible causes (and any combination of these causes) contributing to the accident. The expert system traces a particular cause and explains how and why the fall has occurred. In addition, it shows users how to avoid this accident in the future.

2. To provide a tool to examine the contributing causes of potential construction falls. The expert system models determine if the fall protection devices used to prevent falls from a given elevated component are adequate (according to OSHA standards). The system also serves as a means to warn users of potential falls and to suggest applicable precautions.

It is expected that the system developed will play an important role in minimizing construction falls, improving safety, and investigating the causes of fall accidents in the field. In addition, we expect that SAFETY FIRST will be used by private companies, such as general contractors, subcontractors, safety consultants, and other safety-related companies as a tool to identify conditions that are potentially hazardous to workers and to understand that safety pays; and by government agencies, such as OSHA and BWC to investigate the causes of construction fall accidents and to train their safety inspectors; and by academic and safety institutions to train construction students so they can appreciate and simulate the often dangerous conditions of construction operations and subsequently suggest pertinent safety measures.

1.4 Tasks to Develop SAFETY FIRST

In order to develop this system specific major tasks were proposed and followed. First, specific knowledge was obtained from experts in the construction safety field and from available literature including OSHA codes. Then, common problems or combinations of problems causing falls from hazardous construction platforms were identified. This knowledge was then classified and incorporated into the system. To acquire and compile this knowledge, the knowledge engineers (those who construct the knowledge base) reviewed existing literature, communicated with and interviewed experts, and classified the causes and parameters of falls.

Next, fault tree structures representing the knowledge acquired in the previous tasks were constructed. These trees represent the causes of fall accidents and the procedures an expert follows when investigating a construction fall. The top undesired event--a worker falls from [a structure component]--in the fault tree models was predetermined to establish all possible causes (and any combination of these causes) contributing to the falls. The models show graphically the relationships among these causes. Therefore, the fault tree development involves fault tree logic evaluation, modeling, and analysis.

Finally, the expert system development tasks includes taking the fault tree structures and changing them into decision structures which were then incorporated into the system's knowledge base in the form of IF-THEN rules. This task also includes designing the user interface displays and providing all of the facilities required to make the system as user-friendly as possible. Furthermore, the system was validated to check the logic of its questions and conclusions, and was tested for the user-friendliness of all the provided facilities. More specifically, the following tasks were conducted to complete SAFETY FIRST.

TASK-1: Knowledge Acquisition:

(A) Literature search,

(B) Communication with experts.

TASK-2: Classification of Causes and Parameters:

(A) Classification of causes of accidents, and

(B) Classification of accident parameters.

TASK-3: Fault Tree Development:

(A) Fault tree logic evaluation,

(B) Fault tree modeling, and

(C) Fault tree analysis

TASK-4: Expert System Development:

(A) Development of expert system architecture,

(B) Construction of the knowledge base, and

(C) Development and interface with external programs.

TASK-5: Validation of SAFETY FIRST:

(A) Validation by knowledge engineer,

(B) Validation by participating experts, and

(C) Validation by other experts.

TASK-6: System Refinement:

(A) Refinement of fault trees,

(B) Refinement of knowledge base, and

(C) Enhancement of SAFETY FIRST.

TASK-7: Preparation of Final Product:

(A) Annual report,

(B) Final report, manual, and run-time package.

1.5 Scope and Limitations

Numerous factors determine the causes of a construction fall. These factors vary with the components from which falls originate, the device used to prevent falls, the condition of the workers, and so forth. In this study, we limit our scope to causes of falls directly affecting the worker, such as the enabling (e.g., worker stress, worker drunk) and triggering causes (impact from an equipment). Causes related to the general safety conditions and measures to prevent falls are also incorporated.

Also, in order to study the causes of falls from higher elevations, we had to determine which surfaces or structural components were more significant (i.e., where most of the construction falls had occurred). From preliminary studies and after consulting with experts, we decided on the following components: floor opening, floor edge, top of wall, wall opening, steel beam, roof, and ladder.

The causes of the collapse of a component or structure supporting the worker are discussed but analysis of these causes is beyond the scope of the study. Although, structural collapse may lead to a fall, such a collapse often requires structural analysis. However, we recognize that falls from scaffolding structures are significant. In fact, in 1988, the *Health and Safety Executive* investigated 739 construction fatalities that occurred between 1981 and 1985. Of these, 121 fatalities (32%) occurred due to falls from scaffoldings. Another study shows that around 80% of all scaffolding injuries are related to falls [Potts 1992b]. Therefore, in this project, we also studied the causes of falls from six major types of access scaffoldings: form, tube and coupler, suspended, wood pole, tubular welded, and mobile scaffoldings.

Because of the inherent nature of the analysis of scaffolding structures which often requires structural analysis, for these structures, we limit our scope to only determining the causes of falls and developing the corresponding fault trees. In addition, given the fact that scaffolding-related accidents are due to support-related problems, we focus our attention on showing the relationship among these problems (i.e., worker enabling and triggering causes are discussed but not developed in detail). However, to show the feasibility in constructing the knowledge base of a scaffolding, we incorporated a form scaffolding into the knowledge base of SAFETY FIRST.

In addition, it should be noted that the focus of this study is on falls that occur during the construction of vertical structures like residential houses and commercial buildings. Falls into trenches and falls during bridge construction are beyond the scope of this study.

1.6 Organization

This report is made up of three volumes each of which contains the results of the research tasks proposed for this study. Volume I discusses the knowledge concerning construction falls acquired from experts and literature. Volume II includes an introduction to fault tree analysis, a description of its application in this study, and all of fault tree models developed for this study, along with the corresponding explanation. In Volume III, a general discussion about expert systems, a description of the development of SAFETY FIRST knowledge-based expert system, and the validation results are provided.

Please also note that Task-1 (Knowledge Acquisition) and Task-2 (Classification of Causes and Parameters of Falls) were completed and described in Volume I of this report. Task-3 (Fault Tree Development) was performed and explained in Volume II. Task-4 (Expert System Development), Task-5 (Validation of the System), and Task-6 (System Refinement) have been conducted and elaborated in Volume III of this report.

In the first report (Volume I), Chapter 1 includes the motivation, objectives, tasks, and limitations of the research. Chapter 2 contains a discussion of preliminary studies regarding construction safety, construction falls, and fault tree and expert system models previously developed by the first author. Chapter 3 gives an introduction about the knowledge acquisition process, and describes how this process was applied to this study. Chapter 4 includes a description of all the causes of falls from higher elevations, from the same level, and slips. Chapter 5 summarizes and concludes the first stage of this study.

Finally, the authors realize the often complex, unique, and unprecedented characteristics of construction operations. The authors are also aware of the continuous changes in the material and design of safety devices, and the new safety regulations that were recently established. In achieving a safe yet economical construction operations, these characteristics and changes promote numerous complex parameters and variables for use in determining the potential and possible causes (and their combination) of falls. While these causes are not exhaustive, we believe that those explored in this report represent the most frequently encountered causes that may directly or indirectly result in falls. In addition, although at the time we started this study, the new OSHA standards were not mentioned, SAFETY FIRST includes both the old and new regulations.

CHAPTER 2
PRELIMINARY STUDIES

2.1 Introduction

As alluded to in the previous chapter, the knowledge required to develop SAFETY FIRST came from two sources. The first and foremost is information from experts, which is the basis of the system. A detailed process of acquiring knowledge from experts is discussed in Chapter 3 of this volume. The second source is information obtained from reviewing the literature on various topics related to this research. The objective of this chapter is to present a summary of studies conducted by researchers regarding construction accidents and, more specifically, construction falls, and preliminary studies performed by the authors of this report. In addition to those cited in Chapter 1 of this volume, knowledge from studies presented next has partially or substantially contributed to the development of SAFETY FIRST.

2.2 Other Studies of Construction Accidents and Falls

In 1959, Heinrich investigated the conditions and circumstances that cause industrial accidents. The accident sequence in this approach is represented as a series of dominos, as shown in Figure I-2.1.

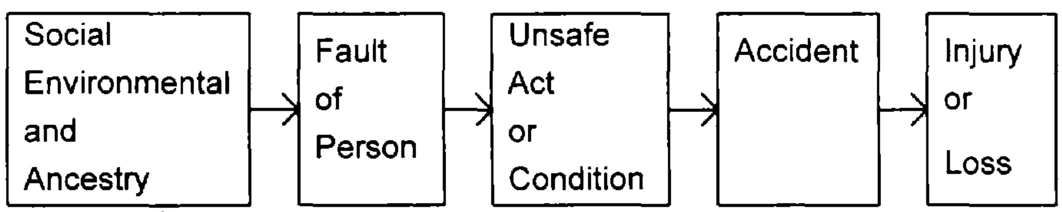

Figure I-2.1 Heinrich's Domino Theory

This approach concentrates on an unsafe act or condition, the removal of which interrupts the sequence of dominos. Therefore, the accident and its possible consequences of injury or loss of life can be prevented [Stanton and Willenbrock 1990]. However, the question of "what percentage of all accidents is caused by unsafe acts and what percentage is caused by unsafe conditions?" arises. The answer is hard to determine. According to Marshall, it is very obvious that to prevent accidents, one needs to understand both how people behave in a work environment and how tools, equipment, and the environment itself can be designed and controlled. Therefore, he says "the safety engineer must study human capabilities and limitations, as well as the range of variations in human behavior, and constantly be aware of them." It is important that the safety engineer considers all the intrinsic aspects of human beings - physical, mental, emotional, and psychological - in order for him or her to be successful in helping to prevent accidents [Marshall 1982].

However, so many variables affect human behavior that it is very difficult to predict what motivates a worker. Douglas McGregor developed theories of human behavior that have been widely utilized by management in the industry. He presented two theories regarding human motivation. The first one is that workers are motivated both by remuneration and other rewards and by the fear of disciplinary action. Therefore, if management wants the worker to perform in a safe manner, it must provide some tangible reward for doing so and some punishment for failing to do so. His second theory is that workers are motivated by job satisfaction. Therefore, management should find ways to make the job satisfying to the workers. In other words, management has a very important role in controlling the workers' attitude toward safety in the job site. Nothing is more important than the workers' attitude toward their work in determining their behavior and performance in the workplace.

In addition to controlling worker motivation towards the job, management also controls the job site working conditions. With this in mind, modern safety professionals have modified Heinrich's domino theory (Figure I-2.2). They have asserted that Heinrich's theory does not take into account the importance of supervisory and management aspects of accident causation and prevention. They have maintained that unsafe acts and conditions are not the causes of accidents, but only the symptoms. Therefore, to prevent accidents, the causes of an accident must be addressed, and they are often related to the management system in the work the place.

Figure I-2.2 shows the modified domino theory introduced by Winder in 1973. This modification allows safety engineers to seek causes and take corrective actions in the management system. The Basic Cause(s) domino in Figure I-2.2 refers to personal factors, such as a lack of motivation to work safely, and/or environmental factors, such as uncorrected hazards. Both types of factors can be controlled by company management.

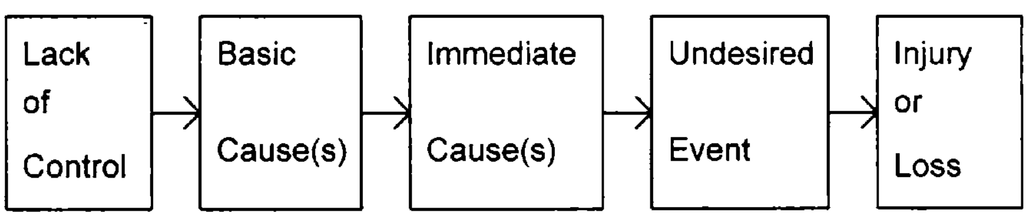

Fig. I-2.2 Updated Domino Theory

According to the theory, of the five domino positions, the greatest potential for accident prevention lies in the first domino. Therefore, management control is the most important factor in the accident sequence [Stanton and Willenbrock 1990]. Please note that as readers of this report reach Volume II (Development of Fault Tree Models), some similarities may appear between these domino theories and our fault tree models. While the domino theory starts with the basic causes to reach the top event (injury or loss), a fault tree begins with the top event (worker falls) and ends with the basic causes.

Lately, the responsibility for safety on the job site has been discussed in several articles and there seems to be a tendency to place the burden of safety on the contracting or subcontracting company's management or the project's owner. An example of this is the criminal prosecution of contractors whose companies fail to comply with OSHA standards or increasing the fines paid by these contractors in case of violations. Arden [1992a] suggests that the owner and general contractors should take responsibility and examine the safety record of subcontractors before taking their bids. According to Arden, hiring a subcontractor with the lowest bid, but a bad safety record, may be costlier in the long run. Loulakis and Cregger [1991] discuss the liability of contractors in case of a fall accident. They consider the 1991 Florida case of *Wenzel v. Boyles Galvanizing Co.* in which the construction manager (CM) was found liable for negligence when two workers fell from a work platform and were seriously injured. The CM's contract with the owner specified that he would be responsible for controlling the work conditions on the site. Other parties including the subcontractor and the general contractor were also sued by the workers; however, they settled out of court.

A good safety program can prevent many accidents in a construction site. According to Hislop [1991], management should recognize the importance of implementing sound safety programs and providing employee safety training. The cost of an effective construction safety program, according to the *Business Roundtable* [1990] report, amounts to approximately two and half percent of direct labor costs. It includes salaries for safety professionals, safety meetings, inspections of tools and equipment, orientation sessions, site inspections, personal protective equipment, and so on. While expensive in the short term, effective program implementation offers cost reductions in the long run. Worker's compensation costs have risen steadily in recent years and may account for a significant portion of total construction costs. The cost of a comprehensive safety program is modest when compared to potential losses due to accidents and the increases in insurance costs if an effective program is not in place [Hislop 1991].

In "A Guide To Emergency Preparedness" by Potts [1992c], and "A Construction Safety Program" by Hislop [1991], the authors outline the steps needed to implement an effective construction safety program. Among these steps, they emphasize the total involvement of the company's management in the implementation and monitoring of the safety program, and the existence of a written safety policy. These steps give the worker a general idea of the high priority the management gives to safety, and clearly spell out the management's objectives and expectations regarding safety. The importance of implementing sound safety programs in the construction industry cannot be over-emphasized. A good safety program can prevent many accidents in the construction site or minimize their consequences if they occur. After implementing a safety program of this type, the Pizzagalli Construction Co. reduced its recordable injury rate from 14.7 in

1986 to 7.6 in 1988. This success was attributed to three major areas: worker training, awards and incentive programs, and drug and alcohol testing [Bruening 1989].

As a rule, factual information regarding falls and slips can be obtained from statistical reports. These reports provide information regarding the number of workers injured as a result of fall accidents. Reports like "Injuries Resulting From Falls From Elevations" by the Bureau of Labor Statistics help the industry identify the areas where improvements should be made. It also allows the industry to monitor whether the accident rates are increasing or decreasing with time. In the case of construction falls, reports like these will help to identify the surfaces or structure components where most of the accidents occurred (e.g. roof), the activity the worker was performing at the time of the accident, and some of the causes of falls (e.g. the worker wasn't using fall protection equipment).

The National Institute for Occupational Safety and Health (NIOSH) also publishes the NIOSH alert reports [1989, 1992] which are intended to focus the attention of the industry on problems. Examples of these reports are "A Request For Assistance In Preventing Worker Injuries And Deaths Caused By Falls From Suspension Scaffolds" and "A Request For Assistance In Preventing Worker Deaths And Injuries From Falls Through Skylights And Roof Openings." These two reports give a general background on the fall accidents problem, a summary of all the relevant regulations (OSHA), several sample case studies, and finally, recommendations for avoiding these falls.

At present, however, information regarding the basic and conditional causes of construction falls is very scarce. In fact, most of the information obtained regarding this topic came from case studies of previous fall accidents from different hazardous components (e.g. roof, scaffolding structure, wall opening, floor opening, floor edge, steel beam, ladder, and top of a wall). These case studies contain the following information: the occupation of the worker, the type of accident (falls), the work surface from which the fall occurred, and a small description of the incident. Among the sources of information regarding fall accident case studies are the following reports: "Occupational Fatalities Related To Miscellaneous Working Surfaces As Found In Reports Of OSHA Fatality/Catastrophe Investigations" by the Office of Statistical Studies and Analysis of OSHA [1982], "Injuries Resulting From Falls From Elevations" by the Bureau of Labor Statistics [1984b], "Occupational Fatalities Related To Ladders As Found In Reports Of OSHA Fatality/Catastrophe Investigations" by the Office of Statistical Studies and Analysis of OSHA [1979a], and "Occupational Fatalities Related To Roofs, Ceilings And Floors As Found In Reports Of OSHA Fatality/Catastrophe Investigations" by the Office of Statistical Studies and Analysis of OSHA [1979b].

Regarding fall prevention, it is important for the construction company to provide the worker with the right fall protection equipment for the given job. Sulowski [1979] provides general guidelines on selecting the proper fall arresting system and its components, depending on the job to be performed. By choosing its components carefully, the worker can be sure that the arresting system can effectively prevent falls and injuries in the case of a fall. These fall protection devices are effective only if they are used and maintained properly; however, that is not always the case. A large part of the worker injury rate in the industry is to some extent due to poor employee attitude toward safety devices, misuse of the available safety devices, and poor maintenance of these devices [Ellis 1989]. A safety plan including a training program for workers and the use of proactive monitoring systems may help to overcome these problems. The plan should also provide the employee with a hazard recognition approach, and a system to select the protective equipment required for a given job [Rademaker 1991].

In addition to all the previously mentioned articles and reports, there is J. Nigel Ellis's *Introduction to Fall Protection* [1989]. This book, published by the American Society of Safety Engineers, provides the reader with a general review of fall protection and all the related issues that construction companies and workers have to deal with in order to prevent falls from happening. This book introduces the user to all the issues involved in fall protection from a general historical perspective: the types of falls and their classification, the principles of fall protection, hazard analysis systems in order to recognize where and when protection is needed, an outline of steps to follow in order to organize a fall protection program, and ways to select the best fall protection equipment for a given job. The book also includes a description of the hazards associated with the use of fall protection equipment and the maintenance required to keep this equipment in top shape.

Code books published by government agencies are the most suitable sources of information regarding the prevention of construction accidents: *The Code of Federal Regulations 29 parts 1910 and 1926* [1994], *the Specific Safety Requirements of the Ohio Bureau of Workers' Compensation Relating to Construction* [1979], and *Construction Industry* [OSHA 2207, 1987], among others. These code books contain the minimum safety requirements and equipment to be used to maintain a safe work site, which supervisors and managers should understand and apply while also educating their workers.

2.3 Preliminary Studies of Construction Accidents and falls

The first study of construction accidents by the authors was based on a survey in which nearly 150 major structural failures that occurred worldwide between 1971 through 1981 were investigated [Hadipriono 1985]. This study was followed by another [Hadipriono and Diaz 1988] which limited the survey to 98 major structural failures that occurred in the United States between 1982 and 1988. Although the emphasis of both studies was on structural failures, many of the results reveal the significant role of construction accidents in such failures.

Another study was then conducted to investigate construction accidents [Hadipriono and Wang 1986]. A total of 85 major construction accidents involving concrete structures that occurred around the world over the past 23 years were investigated. The study examined major falsework accidents during the construction of concrete bridges and low-rise, multi-story, and plant-industrial buildings. Data accumulated from published reports were classified, evaluated, and interpreted, leading to the identification of the causes and events contributing to the accidents.

The causes of failures and accidents in the above studies were classified as internal, external, and procedural causes. The internal causes found in the studies were attributable to deficiencies in the design, erection, installation of the falsework, and problems with workers. The external causes were events, such as strong winds and equipment impact loads. The procedural causes were indirect causes that could produce the internal and external causes, such as problems with inspection, responsibilities, and communications among parties involved. Despite its importance, information concerning procedural causes is often difficult to obtain [Hadipriono 1985, Hadipriono and Diaz 1988].

Sponsored by the Center for Labor Research at The Ohio State University (CLR-OSU) [Hadipriono 1992a], the authors performed a study of the internal and external causes of falls. The study was limited to unintentional construction falls (not slips) from elevated floor openings. Furthermore, they assumed that the causes described below may have led to the fall, provided that there were no safety devices (these devices include safety belts, lanyards, safety lines, guardrails, handrails, and safety nets).

Since the worker was assumed to be working on the floor, he/she was not required to use safety belts, lanyards, and/or safety lines. However, guardrails to prevent the worker from falling are required. Therefore, it was assumed that a fall would occur if there were no guardrails or if the guardrails were inadequately installed. Nevertheless, such a condition does not apply to the failure (collapse) of the component directly supporting the worker, i. e., the floor. It was assumed that floor collapse would cause the worker's fall regardless of the provision of the guardrails.

The worker's internal causes was classified as attitude-, health-, and skill-related problems. These problems are closely related to behavioral and social aspects. For example, problems related to the worker's attitude are problems with alcohol, drugs, and personality. A worker could have been drunk or on drugs prior to the accident, leading to his or her impairment while performing the job. An example of a worker who has a personality problem is one who is reckless and sloppy, difficult to deal with, or who seldom follows the superintendent's instructions.

Problems with the worker's health include illnesses or weaknesses that could result in a sudden collapse of the worker while performing his or her job. These illnesses could have been ignored by the worker or overlooked by the superintendent. Examples of these problems are acute and chronic illnesses. The worker's skill-related problems include inadequate training, lack of experience, and inadequate aptitude. Inadequate training and lack of experience may be found in the worker's job record, and lack of aptitude can be detected from his or her work performance.

The external causes in are human-induced impacts and nature-induced impacts. Human-induced impacts include impacts by equipment or materials, and by another worker. For example, experience shows that construction equipment and falling materials (or materials being carried) can nudge workers and cause them to fall. Regarding impact by another worker, a worker may fall from a working platform if accidentally pushed by another worker who was horsing around. Another example is the collision of workers during an accelerated job performance.

Impact or near-impact due to equipment or materials, and due to another worker is also conditioned by the proximity of the worker to the equipment, materials, or another worker's work zone. An impact or near-impact can happen if the worker works within reach of the equipment or its moving components, or if the worker works in the path of other workers' activity. For instance, a worker may be within the designated equipment work zone or outside the designated zone but within the equipment's working range. The latter may be due to the equipment operator's error. External causes can also be naturally induced. For example, a strong wind or gust could blow in the direction of the worker, causing him or her to fall.

CHAPTER 3
KNOWLEDGE ACQUISITION

3.1 Introduction

Knowledge acquisition is the task during which comprehensive knowledge on construction safety and construction falls is obtained. It includes a review of the causes of falls from the same level, slips, and elevated components. Most of this knowledge is obtained from experts in the construction safety field. This chapter emphasizes the process followed in acquiring and capturing experts' knowledge. The first section of the chapter, "Introduction to the Knowledge Acquisition Process," provides a general overview of the knowledge acquisition process and the elements required for a successful process. The second section, "Knowledge Acquisition for SAFETY FIRST," illustrates the process of acquiring the knowledge from our experts for the purpose of this project.

3.2 Introduction to the Knowledge Acquisition Process

Knowledge acquisition is defined as "the process of eliciting and organizing the knowledge of an expert in a particular field (domain) so that this expertise can be coded into an expert system" [Brule and Blount 1989]. During this task most of the knowledge required to create an expert system is acquired, analyzed, and organized.

Knowledge acquisition is an area in the field of artificial intelligence that has grown significantly in recent years. A great deal of research has been done lately in this area due to challenges that come from attempts to obtain human intelligence and to transfer it to suitable artificial representations that can be handled by computers. Although this is a complex task, there are specific steps and techniques that can be used during the knowledge acquisition process to create a bond with the experts, to make them feel at ease, and to maximize the acquired knowledge. For example, when selecting the experts, their availability becomes one of the main factors to consider. If due to time constraints or other considerations, the experts are not accessible for interviews, their knowledge is of limited use. Further, an example of a technique to make the expert feel at ease with the knowledge acquisition process is to conduct the interview in a place or setting familiar to them (e.g., in their office). These and other techniques are discussed in more detail in the book *Knowledge Acquisition* by Brule and Blount [1989]. Hadipriono et al. [1992] adopted this technique for developing an expert system that is capable to evaluate and simulate the quality of agricultural water.

In general, there are three parties that play an important role in the success of a knowledge acquisition process: the knowledge elicitors, the knowledge programmers, and the domain experts. The knowledge elicitors are in charge of interviewing the experts and eliciting their knowledge. The knowledge elicitors also plan the topics to be covered during the interviews and lead the flow of the conversation so as to maximize the amount of useful information obtained from the experts. The knowledge programmers, sometimes called software engineers, are in charge of obtaining the knowledge elicited from the experts and converting it into structures and codes that can be represented in the computer. Both the knowledge elicitor and the software engineer are also known as knowledge engineers.

The domain experts are those whose knowledge and experience in a given domain are paramount and stand above other knowledgeable people in the same domain, and whose expertise is to be incorporated into the knowledge base of an expert system. The experts also verify the applicability and correctness of the expert system and indicate whenever changes are necessary. Brule and Blount [1989] also suggest that if the knowledge acquisition team consists of a large number of members, the team should also include a "team leader" whose functions include project analysis, task assignment, record keeping, and the role of technical coordinator of the project.

The knowledge acquisition process is generally divided into four phases: the preliminary, intermediate, advanced, and organization phases. The preliminary phase of the study includes activities like analyzing the project's feasibility; selecting the knowledge acquisition team; and choosing, contacting, and conducting a preliminary interview with the experts for the project. During the preliminary interview all of the parties of the project get to know each other and all of the ground rules for the process are discussed. This phase also involves the acquisition of general information about the subject from the experts and from literature reviews. The intermediate phase involves acquiring more specific information from the experts, reviewing this information, and after several interviews, creating a general representation of the experts' thought processes. The advanced phase allows the knowledge engineer to refine the knowledge representation by going over the specific details which need to be clarified or which cause disagreement among the experts. Conflicting information or misunderstandings are usually settled by providing the experts with more specific explanations of the variables and parameters involved in the subject at hand. Finally, the organization phase acts as a link between the knowledge acquisition task and the fault tree development task. At this phase, the knowledge acquired is translated into a preliminary graphic representation model.

3.3 Knowledge Acquisition for SAFETY FIRST

The first objective of the knowledge acquisition is to determine the causes of construction falls. To do this, we interviewed several experts in the field of construction safety. For this project, the authors acted as both the knowledge elicitor and knowledge programmer.

The preliminary phase of the knowledge acquisition process for the project involved several activities, including reading articles and any other literature available on the subject, selecting the professionals who qualify as experts in the field, and finally, meeting the chosen experts and asking them to participate in our project.

For the preliminary selection of the experts, we considered the following points: the person had to be recognized by people in the industry as knowledgeable in the general area of safety and specifically, in the construction falls area, and the experts have to live in Columbus or its vicinity. The latter is important since experts who live or work nearby could be easily reached for interviews and meetings. The final point to be considered was the amount of time the experts were willing to contribute to this project. All selected experts were willing to provide a reasonable amount of time to the project subject to their availability. The knowledge for this project was acquired from domain experts listed in Appendix I-D of this report. A brief summary of their background and work experience is included in same appendix.

After the experts were selected, we conducted the first interview with each of the experts. The main objective of this interview was to make the experts and the knowledge elicitors feel at ease with each other. During this interview, there was a preliminary discussion about the project, the characteristics of the research process, and the goals of the project. At that time, any questions the experts had regarding the project or the process required to develop the expert system were answered. Finally, during the interview, the knowledge elicitors and the experts decided on the best place and time to meet for future interviews and any other rules to be considered for future interviews (e.g., whether or not the expert(s) would allow the knowledge elicitor to record their conversations).

At the beginning of the first interviews, experts may be hesitant about the project and its objectives. For example, when the knowledge elicitor asked one of the experts if he could tape the conversation, the expert's reservations about the project were evident. The immediate response was "no." The expert cited legal problems to explain his answer. During the interview, the expert expressed his concerns and feelings toward the topic of the project (construction falls). At the same time, he got a clearer idea of what the project involved and its usefulness in the future. After this exchange of ideas had occurred, the expert's attitude toward the knowledge elicitors seemed to change for the better, allowing the participants the chance to get to know each other and to build ties for future interviews.

After the preliminary interviews, the objective was to focus the experts' attention on the subject matter (i.e., the intermediate phase). To do this, the authors created a questionnaire for the second interview with each of the experts. The questionnaire was developed with the objective of getting each expert to think about construction falls, first generally, and then, in more specific terms. The focus of this questionnaire was construction falls from high elevations. A copy of this questionnaire is included in Appendix I-E of this paper. After these interviews, the knowledge acquired was reviewed and the topics of the next interviews were determined. These topics included areas that were not explored enough in the previous interview, or which were not clear to the knowledge elicitors after review. At the end of the intermediate phase, we had developed preliminary fault tree models for all of the building components considered significant enough to be included in this project (e.g., a roof, a floor opening, etc.).

Finally, once the interview process had reached the advanced and organization phases, the interview topics concentrated on specific details regarding construction falls from the selected components. The experts also checked the preliminary fault trees, suggested changes to them (as needed), and any disagreements among the experts were resolved. For example, for a sloped roof, there was disagreement among the experts on whether or not devices like crawling boards, roofing brackets, and the so-called chicken ladders could prevent falls from happening. Some of them seemed to think so; while others did not. In this case, after further discussions with the experts, we agreed that those devices are useful tools that help the worker perform his or her job on a sloped roof, but they, by themselves, would not prevent the worker from falling and/or protect him or her from injuries if a fall occurs.

A sample of the types of questions, answers, and other events that occurred during a typical interview is presented in Appendix I-F of this report. Appendix I-F also includes a complete transcript of one of the interviews that took place in this project. It also provides summaries of some of the topics covered and the knowledge acquired from the interviews. The knowledge of the causes of construction falls obtained from the above process is presented next in Chapter 4.

CHAPTER 4
CAUSES OF CONSTRUCTION FALLS

4.1 Introduction

This chapter discusses the more common causes of falls in the construction industry. For this study, we limit the scope to falls that occur during vertical operations such as during building or residential home construction. Events such as falls during bridge construction, falls during trench operations, and falls from utility poles are excluded from this study. In addition, it should be noted that for this study, we classified falls the same way the Bureau of Worker Compensation does on their statistical reports: falls from higher elevation, falls from the same level, and slips.

It should also be noted that the focus of this study is on the causes of falls over which the worker had a certain degree of control or which acted upon the worker causing him or her to fall. This implies that causes of falls which are related to the component supporting the worker are mentioned but their overall analysis has been left undeveloped. The determination of these causes requires a different kind of technical expertise which requires a more comprehensive structural engineering background, a field of expertise which is not within our current experts' domain. The causes related to scaffolding structures are developed in detail because they are often the main cause of worker falls from these types of temporary structures.

Construction operations are often complex and one project may contain several elevated components or working surfaces from which a worker may fall. Given this fact and the previously named constraints, the next step is to decide which hazardous elevated components (surfaces) are of primary significance regarding construction falls. From our experience and after consulting with the experts, we decided to study the causes of falls for the following hazardous components: floor edge, floor opening, roof, wall opening, top of wall, steel beam, portable ladder, and six scaffolding structures. In addition to these, we discuss the causes of fall from both the same level and slips.

Please note that all causes described in this report are possible and potential causes that may result in construction falls. We recognized the innumerable parameters and variables that determine the enabling and triggering causes of falls. While these possible and potential causes are not exhaustive, those summarized in this chapter are based on our experts opinion, codes, and other related literature. We expect that these causes are representative of those commonly encountered in construction falls.

4.2 Causes of Construction Falls from Higher Elevation

The causes of falls from the above hazardous elevated components (surfaces) are discussed, first in general terms and then on an individual basis. Part of these causes are based on previous studies by Hadipriono [1992a] and Vargas [1993].

4.2.1 General discussion

The causes of worker falls from elevated working surfaces are classified into basic (primary) or conditioning (safety-related) causes. Both causes are described next. Please notice that the codes within parenthesis indicate a Basic (B) or Conditioning (C) cause. The codes used in this section refer to the codes used in fault tree models discussed in Volume II. To maintain the uniqueness of each cause, although similar causes may apply to many surface components, each cause is coded differently depending on the surface component (e.g., the code employed to represent the use of alcohol in the fault trees for a floor edge is different than that employed for a roof edge).

4.2.1.1 Basic causes

Basic causes are primary problems which either by themselves or in combination with a conditioning cause lead to the occurrence of a fall. There are three types of basic causes of a fall: enabling, triggering, and support-related [Hadipriono 1992a]. In general, most of the structural components studied have similar enabling and triggering causes. However, the significance of each cause vary depending on the component being analyzed. In contrast, the support-related causes vary with the component from which the fall occurred.

4.2.1.1.1 Enabling causes.

Enabling causes are those generated from an internal condition. For example, enabling causes that are related to a worker are physical (e.g., epilepsy) or mental (e.g., stress) problems affecting a worker's capacity to concentrate on the job at hand. These enabling causes can be grouped into health, attitude, and skill problems. Health problems include sudden illnesses (B64) that attack the worker on the job (e.g., heart attack) and could cause him or her to collapse while performing a job on a fall prone working area (e.g., near a floor edge). The illness could also be a chronic (B65) one (i.e., it has been affecting the worker for most of his or her life) such as epilepsy. A chronic illness is significant if, at a given moment, it could cause the worker to lose control of his or her actions. In addition, a chronic illness could act on the worker over time, weakening him or her and diminishing his or her concentration and ability to recognize hazards. Furthermore, the use of prescription or over-the-counter drugs (B66) may cause a worker to be drowsy or sleepy on the job. This is especially significant on fall prone areas where the consequences of a judgment error could be a serious injury, if not death.

Attitude problems, another type of enabling causes, are those caused by the worker's negative disposition toward his or her job. Within this group, we have the case when the worker goes to work drunk (B60) or drugged (B61) and is not in full control of all of his or her senses. As a consequence, he or she is not able to recognize hazards until it is too late to prevent an accident. In addition, drugs and alcohol use may lead to behavioral problems which may result in falls. The next group of causes are problems related to the worker personality (B62), which may cause a fall in several ways: if a worker chooses not to follow a supervisor's instructions regarding safety, if the worker tries to take short cuts which may help him or her to finish the job quicker but riskier, or if the worker behaves in a reckless manner in an area where falls are very likely. A final attitude-related enabling cause includes distractions due to stress (B63). Family, financial, and other personal problems can weaken a worker's concentration on a job and ultimately may enable a fall to occur.

Among the enabling causes related to skill, we have the following: lack of training, lack of experience, and low aptitude for learning. Lack of training (B68) can cause a fall because a worker may fail to recognize a hazard or to react properly when an incident happens. It is also accepted that the broader the experience of a worker, the less likely he or she is to fall. This is because he or she does not take any unnecessary risks and has the experience to identify hazards and to know what measures are necessary to avoid fall accidents. The experience (B67) of the worker should be directly related to the level of risk in the task he or she was performing (i.e., if the worker had 25 years of experience in the construction industry, but performed jobs where fall hazards never occurred, then this experience was of not value to him or her at the time of the fall). Finally, the lack of aptitude (B69) cause indicates a problem in which a worker's capacity both to learn from experience and/or training is questionable and therefore the worker may still take unnecessary risks or be unable to react properly to risky situations.

Usually, enabling causes can lead to falls if they occur in combination with other conditioning causes and/or other basic causes. For example, a fall from a floor edge may be due to the worker tripping on a tool left on the floor of the working area (support-related cause) which he or she failed to notice due to his or her being distracted by problems at home (enabling cause). Such a distraction may prevent him or her from being alert as he or she should be. In addition, fall could occur due to the lack of a fall protection device such as a guardrail in the floor edge. There are some exceptional cases in which the fall may be directly due to an enabling problem such as when the worker collapses due to a health or intoxication problem.

4.2.1.1.2 Triggering causes.

Among the basic causes, we move now from enabling to triggering causes, which include any external event acting upon a worker. Triggering causes can be subdivided into those due to impact on the worker, those due to environmental conditions, and those due to distractions. Under the impact causes, we include all cases when a worker is directly hit by another worker (B611), a piece of material (B612), or a piece of equipment (B610) and as a result loses his or her balance or is rendered unconscious, and then falls. In addition, fall could occur due to the worker's attempt to avoid these hazards (e.g., move towards the floor edge while trying to avoid a falling material from hitting him or her).

Next, under the environmental causes, we include any natural event that may affect the working area, and can cause an environment propitious to falls. Among these weather-related factors are strong winds (gusts - B613), rain (B70), hail (B71), snow (B72), fog (B73), extreme cold (B74), and extreme heat (B75 & B614). These events can lead a worker to fall in different ways. A gust or strong wind may directly cause a fall due to its impact on the worker. Certain conditions, like fog, may reduce a worker's visibility and cause him or her to fail to recognize a hazard and fall, whereas others, like rain and frost, may create slippery footing conditions (B78 to B711). Extremely cold or hot conditions can contribute to accidents because of a corresponding reduction in the concentration and care with which a worker performs his or her job. Extremely hot conditions may also lead to a worker's dehydration (B614), while extremely cold conditions cause the worker to be bundled up, which will impede the worker's motor skills.

Finally, triggering causes due to distractions include any events in the work zone surroundings that divert a worker's attention for a given period of time and cause him or her to fall (e.g., if a traffic accident happens in a street near the work site, a worker may try to look and find out what happened and thus may not recognize a hazard to his or her life).

4.2.1.1.3 Support-related causes.

The final type of basic causes, support-related causes, includes by definition problems related to the structure or component supporting a worker while he or she performs a job. Therefore, these causes vary depending on the component being analyzed. However, there are two main ways in which support-related causes can cause a worker to fall: first, if the support structure or one of its support components collapses. In this case, it is assumed that the worker standing on it will also fall, and, so, the cause of the worker's fall is the one that caused the support component collapse. The second way is if the support component, such as the floor has a problem that may cause the worker to slip or trip and then fall. Support-related causes are discussed for each specific elevated component.

4.2.1.2 Conditioning Causes

Conditioning causes are problems or conditions in the system that, if combined with primary causes, enable the occurrence of a fall accident. They are significant since their avoidance can in most cases prevent accidents from happening. Furthermore, since these causes are mostly related to problems with the safety measures in a construction site, construction companies have a great deal of control over them. In this paper, we include two types of conditioning causes: one related to problems with general safety measures and the other related more specifically to problems with the fall protection/prevention safety measures in the site. Problems with general safety measures (C40) include the lack of or inadequate overhead protection when there is work going on above the working surface (if there is no overhead protection, falling materials may hit a worker and cause his or her fall) and poor housekeeping around the work zone (e.g., failure to keep the working surface clean from slippery substances and small materials and failure to cover small holes in a floor, problems which can cause a worker to slip or trip and lead to a fall accident).

Conditioning causes related to fall protection/prevention measures are analyzed in more detail since this study is concerned with determining the causes of construction fall accidents. There are two causes related to fall protection/prevention measures: the first occurs when there are no fall protection/prevention devices installed (C50); the second, when such a device or a combination of devices is provided, but is inadequate for the job (G58).

The inadequacy of fall protective equipment is harder to determine, because it depends on the device being used. Among the devices that may be used for an elevated component fall protection/prevention are the following: a standard guardrail, a safety belt system, a body harness system, a safety net system, the warning line system, a catch platform, and an opening cover. The use of these devices depends on the elevated structural component being studied. The devices used for one component may not be effective or practical for a different one. The specific devices used for each structural component are explained in the ensuing sections. The problems related to the inadequacy of each of the devices are discussed next.

4.2.1.2.1 Inadequate guardrail system conditioning causes

An inadequate guardrail system may be due either to the guardrail being inadequately erected or to the use of inadequate materials. According to the new fall protection standards of OSHA [CFR-29 1994], the erection of a guardrail should comply with several requirements; for example, the top rail elevation should be at an elevation of 42 plus or minus 3 inches (1100 plus or minus 80 mm), the mid-rail should be located half-way between the top rail and the floor, and the toe board should extend about 4 inches (102 mm) above the floor. In addition, the posts supporting the rail should be spaced 8 feet (2.4 m) apart or less (if required). Any violation of these requirements during construction could be considered a conditioning cause of a fall. For example, if the elevation of the top and mid rails is too high, then the space between the mid rail and the toeboard will be too large and the worker may fall through it (C82). The same case occurs if the spacing between the top and mid rails is too large. If the top rail is located at an elevation too low, the worker may fall over it. Further, if the post spacing is more than 8 feet (2.4 m), the guardrail may deflect too much in the case of impact and again fail to prevent a fall (C81). In addition to the problems with the elevations and rails spacing, There is the situation in which some components are missing from the guardrail (e.g., no mid-rail) and therefore some area of the guardrail is unprotected and a worker may fall through it (C80). Finally, if the guardrail is poorly installed (i.e., poor connection between the rails and the posts or between the posts and the working surface), it may also fail to fulfill its purpose (C83).

Among the conditioning causes of falls due to inadequate guardrail materials, we have two cases: first, when the original material is not up to strength standards (C84), and second, when the materials are not up to standards due to excessive wear (C85). In general, a guardrail when completely built should be able to withstand a load of at least

200 pounds (890 N) [29 CFR 1926.502 (b) (3) 1994]. In addition, the intermediate rail should be able to stand without breaking a minimum load of 150 pounds (666 N). Usually the strength of the guardrail components can be evaluated according to the material they are made of and their cross sectional size (e.g., in the case of pipe railing, the post and the rails should be at least 1.5 inches (38.1 mm) in diameter to comply with the required strength standard). The excessive wear conditioning cause includes cases in which the material components used to build the guardrail are up to size requirements, but excessive use has reduced their strength. Examples of excessive wear problems are corrosion, abrasion, and any other damage done while moving, assembling, or disassembling the guardrail.

4.2.1.2.2 Inadequate catch platform conditioning causes

The catch platform is a structure erected next to or underneath the structural component being protected. Usually, this structure is a scaffold and is mostly used to protect roof and floor edges. In a flat roof or a floor edge, the catch platform performs the same functions a guardrail does. In this case the structure should be erected next to and at the same level of the component being protected so that the scaffold's guardrail fulfills the main fall protection function.

In the case of a sloped roof, the platform erected underneath the roof edge will prevent the worker from falling all the way to the ground in the case the worker falls from the roof (i.e., if the worker falls, he or she will roll into the platform). They are also used to protect floor edges and flat roofs. It should also be noted that this device is not commonly used for surfaces which are on very high elevations, where its erection is not practical. A catch platform is inadequate to prevent falls if it is inadequately constructed (e.g., not installing all the bolts for the braces supporting the structure - C87) or the materials used to build it are faulty or of inadequate strength (C90 & C91). Both of these cases may cause the structure to collapse under the load generated by the worker's weight. The planks component of the platform is also very important given that the worker will fall on them. Therefore, the planks should be scaffold grade (C92 & C93) and show no signs of wear (C94). In addition to any of the aforementioned problems with the structure, the platform's guardrail may be a conditioning causes of fall if the guardrail is missing, or if it is inadequately erected and therefore fails to fulfill its purpose. The problems related to the guardrail's inadequacy have been discussed in the previous section (C100 to C105).

4.2.1.2.3 Inadequate fall arrest systems conditioning causes

The safety belt and body harness systems used to arrest or reduce the consequences of a fall (if it occurs) include all the components required to properly use them, including the belt or harness, safety line, lanyards, anchorage point, clips, shock absorbers, and/or any other accessories required. The two systems (safety belt and body harness) are very similar; the difference between them lies in whether or not a belt or a harness is worn by the worker. In general, experts prefer to use a body harness, because in an accident the shock of the fall is absorbed by a worker's skeletal frame, and the likelihood of serious injury is therefore minor. On the other hand, with a safety belt the shock of the fall is largely taken by a worker's waist and the likelihood of a disabling injury is high (even though the use of shock absorbers and other such devices may help reduce the shock). While the use of safety belts is still within OSHA compliance standards until December 31, 1997 (according to the new fall protection regulations by OSHA), it is our opinion and the general consensus in the industry that their use should be eliminated right now because of the high risk of disabling injuries (e.g., paralysis of the lower half of the body due to broken vertebrae in the waist area). Any problems with these devices could also be considered conditioning causes of a fall.

In general, the problems common to both the safety belt and body harness systems are due to inadequate system erection and inadequate material strength. The first cause includes any problems with the way the system was erected. For example, if the system allows a worker to fall more than 6 feet (1.8 m) (distance determined by OSHA - C89), the impact of the belt or harness on the worker may cause serious injuries and the breaking strength to which the system is subjected may be greater than that it was designed to withstand. In addition, if the falling distance is more than the distance between the working surface and the ground (C810), then the system serves no purpose (i.e., the worker falls all the way to the ground). In addition, a common problem with these systems is the use of non-locking snaphooks which may unknowingly disengage or "roll-out" during a construction operation or a fall (this problem is more common if the accessories used are not specifically designed for the fall arresting system in use - C811). The new fall regulations will eliminate this problem by requiring locking snaphooks starting on January 1, 1998.

Turning to problems caused by the strength of the system, OSHA standards require that most components of the belt or body harness systems (i.e., deerings, snap hooks) be able to support at least a 3600 pound (16 kN) load at all times. In addition, the safety line and the lanyard should be able to withstand a minimum tensile load of 5000 pounds (22.2 kN), while the anchorage point selected should be able to support a minimum dead weight of 5,000 pounds (22.2 kN) per employee attached. Any case in which the load-bearing capacity of the system is less than required should be considered a conditioning cause of a fall (e.g., in the case of corrosion, abrasion, or any other factor that damages the system's components and reduces their strength - C817). Finally, there is one conditioning cause of a fall that only applies to the safety belt system. If a worker wears the belt too loosely around his or her waist, and a fall accident happens, he or she may slide out of the belt and fall all the way to the ground.

4.2.1.2.4 Safety net system conditioning causes

The next device, the safety net system, has the advantage of not requiring the active participation of a worker in order to be effective. However, it has two disadvantages in that it is cumbersome to erect and it requires constant maintenance. A safety net system may be deemed inadequate if it is not properly built, if the materials used to build it are not up to standards (C823), or if the net is not kept clear of debris (C70). In addition, according to the new fall protection standards, the net should be located no more than 30 feet (9.1 m) below the working surface so that a worker will not get injured due to the impact with the net (C820). In addition, if a worker were to fall a significantly longer distance the net system might not be able to withstand the impact load and the worker could fall all the way to the ground or to the nearest surface. In addition, the net should be located at an elevation high enough so that there is enough clearance under the net to assure that the worker will not hit solid ground after the deflection due to impact (C819).

The net should also extend at least some distance beyond the edge of the working surface in order to be effective (C821). Previously, this distance was fixed at 8 feet (2.4 m); however, drop test studies have indicated that depending on factors such as the wind and the worker outward momentum at the time of the fall, and the falling distance to the net, the worker may go as far as 20 feet (6.1 m) from the floor edge. This is the reason why the new fall protection standards by OSHA specify three minimum outward distances: if the falling distance between the working surface and the net is less than 5 feet (1.52 m), the net projection can still be 8 feet (2.4 m); if the falling distance is between 5 and 10 feet (1.52 and 3.05 m), the projection has to be at least 10 feet (3.05 m); and if the falling distance is more than 10 feet (3.05 m) but less than 30 feet (9.15 m), the distance should be at least 13 feet (3.96 m). Any violation of these requirements may cause the net system to be deemed inadequate and fail to prevent the worker from falling all the way to the ground. These problems are considered conditioning causes of a fall due to poor construction. Poor or sloppy installation, such as a failure to fully fasten the net to its supports or poor connection between net panels is another factor to be considered (C822).

If the materials used to build the net are not up to impact resistance standards, the net system may collapse and fail to fulfill its function (C823). The new fall protection standards require that the net be able to stand an impact load similar to that generated through a drop test using a 400 pound (1780 N) bag of sand with a 30 inch (765 mm) diameter dropped onto the net from the highest working surface from which a fall may occur but no less than 42 inches (106.68 mm) above that surface (According to OSHA, this last measure is to take into consideration the center of gravity of the 95th percentile man). In addition, OSHA requires that the edge ropes provide a minimum breaking strength of 5,000 pounds (22.2 kN). These impact load resistance requirements would not be met either if the materials originally used were not up to standards (i.e., were undersized) or if the components were originally up to standards but have been worn out by excessive use (C824). Finally, the failure to keep the net clear of falling debris can be a cause of a fall, if some of the net's load-bearing capacity is taken up by the accumulated debris and as a consequence, the net may fail to prevent a worker's fall. Furthermore, even if the net is able to withstand the impact load, it may still fail to protect a worker from serious injury since he or she may incur serious injuries when he or she falls into the net and hits this debris.

4.2.1.2.5 Inadequate warning line system conditioning causes

The warning line is a preventive system designed to provide resistance to the worker's movement towards the edge of a floor or roof and let a worker know that he or she is getting too close to it. This system should be used only when the work being performed is in the interior of the floor or roof (i.e., not near the edge) and after the worker has been thoroughly trained to recognize that the lines indicate a dangerous proximity to the edge. In general, problems with this device are due to inadequate installation and materials. Inadequate installation includes cases when a warning line is erected too close to the edge (C71) and does not give the worker enough time to react and avoid a fall accident (if no mechanical equipment is being used, the line should be erected no less than 6 feet (1.83 m) from the edge; if mechanical equipment is used, the distance should be increased to 10 feet (3.05 m) in certain areas) or cases of poor or sloppy workmanship (C72) such as when the lines and the stanchions (posts) connections are such that impact in one section (between two stanchions) causes other sections to be affected (in this case the impacted section may deflect too much and fail its purpose). There are also cases in which the warning line elevation is either too high, in which case it may not warn the worker, or too low, in which case it may cause him or her to trip or lose his or her balance and fall. According to OSHA requirements, the warning line elevation should be between 34 and 39 inches (0.864 and 0.991 m) to be effective.

Finally, if the warning line materials fail to meet OSHA's strength and tension requirements they will be inadequate and may lead to fall accidents (C73). For example, OSHA requires that the warning line system be able to withstand a horizontal force of at least 16 pounds (71.04 N) without tipping; furthermore, the line should be able to withstand a minimum tensile strength of 500 pounds (2.2 kN).

4.2.1.2.6 Inadequate controlled access zone conditioning causes

A controlled access zone (CAZ) is an area that is used to prevent unauthorized access to a certain edge area where leading edge work is being performed, when precast concrete members are being erected, or when none of the other fall safety devices mentioned above can be used. According to OSHA standards the control line should be erected at a distance no less than 6 feet (1.8 m) but no more than 60 feet (18.2 m) from the floor edge if precast concrete members are being erected. For any other leading edge operation the distance should be between 6 and 25 feet (1.8 and 7.6 m) (C825).

The line should prevent access of unauthorized personal into the restricted area (C826). Therefore, it should either extend parallel to the edge the entire edge distance, or until it intersects a perpendicular wall or guardrail. As with the warning line, the material used for the line should be able to withstand a 200 pound (890 N) load without breaking (C828) and should be flagged every 6 feet (1.829 m) to make the line visible to the workers.

It should be noted that the CAZ only prevents unauthorized workers from entering the dangerous area; to protect workers inside it, a safety monitor should be in the area (C830) to monitor the safety of other employees. The monitor should orally warn workers when it appears that they are unaware of a fall hazard or are acting in an unsafe manner. Therefore, all workers should be within his or her visual and oral range of the monitor (C831 & C832). In addition. the monitor should not have any other functions that may distract him or her from monitoring the workers' safety (C833).

4.2.1.2.7 Inadequate standard hole cover conditioning causes

Finally, a standard hole cover is used to guard any floor or roof opening and it should comply with the following requirements: the cover should be able to guard the whole opening area; it should be secured in place over the opening to prevent any accidental displacement or removal which could leave part of the opening exposed and cause a fall to occur from this hole. To prevent accidental removal the cover should be color coded or labeled "cover" or "hole" to identify it. Finally, the cover should be able to withstand a load equal to twice the weight of the heaviest worker or piece of equipment [CFR 1994]. If these cautions are not followed, the worker may fall due to an unprotected hole, if the cover was removed or displaced, or due to the cover collapse if it was not strong enough.

4.2.2 Causes of falls from a floor edge

For this study, a "floor edge" structural component includes any section of the floor perimeter (edge) which is open or unprotected. This component only includes sections where a worker may fall toward the outside of the building (e.g., floor openings are excluded). This implies that any falls from this elevated component may cause serious (if not fatal) injuries to a worker. The enabling and triggering causes of the falls discussed above remain the same. Therefore, we only discuss the support-related causes of falls. In the case of a floor edge, a worker is supported by the floor. Any problem that causes the floor to collapse or creates hazardous floor conditions to the worker is classified as a support-related cause. Floor problems themselves can also be grouped into enabling, triggering, and support-related causes. The enabling causes (B20) of a floor component can be due to deficiencies in the design (e.g., excessive slope (B617), inadequate strength, excessive deflection), construction deficiencies (e.g., a bad connection between the floor and the joists), hazardous or unsafe floor conditions (e.g., floor holes (B615), floor elevation changes (B616), slippery floors (B78 to B711) or tools left on the floor (B713)). Triggering causes (B21) are external problems that can cause the floor to collapse, such as equipment impact or material impact on the floor. Support-related causes are due to the failure of the component directly supporting the floor--in this case, the joists. Here again the causes may be enabling (B30), triggering (B31), or support-related (B32). However, because the focus of this study is on the worker, we did not develop these causes further.

Among the devices that may be used for floor edge fall protection/prevention are the following: a standard guardrail, a safety belt system, a body harness system, a safety net system, a warning line system, and a catch platform. Of these, the standard guardrail is the most commonly used device for the floor edge fall protection. The safety net system is the second fall protection option considered for a floor edge component. If a guardrail system is not used due to operating reasons (e.g., the floor edge needs to be open to lift materials to the floor), then the safety net system is the next most commonly used device. A warning line and catch platform may also be used depending on the workers' training or the elevation of the working surface, respectively. Although the safety belt and body harness systems are not frequently used for the floor edge component, they are sometimes used if none of the previously mentioned devices are in place.

4.2.3 Causes of falls from a floor opening

This section includes all the primary and secondary causes of a worker's fall from an elevated floor opening. For the purpose of this study, a floor opening is defined as any opening through which persons may fall. All falls in this component occur in the interior of the building; however, their consequences can be as serious and lethal as those from an edge.

As mentioned previously, our focus is on the worker and on the causes of falls occurring during the vertical construction of residential or commercial buildings. The causes of falls related to the worker do not change much from component to component. Therefore, the primary causes of falls are enabling, triggering, and support-related causes; conditioning causes are related to the general safety conditions and the fall protection equipment provided in the site. However, the conditioning causes will change since the fall protection/prevention devices that can be used will change. In the case of a floor opening, a guardrail system and a hole cover are the most commonly used protection devices. The use of fall arrest devices such as safety belts or the body harnesses to prevent a floor opening fall may be theoretically possible but not as practical as those options (e.g., the floor opening cover) which are easier to implement and do not put the burden of safety on the worker. Regardless of these considerations and assuming that any of the aforementioned devices could be used, the conditioning causes of falls due to inadequate systems are similar to those mentioned earlier.

4.2.4 Causes of falls from a roof

This section includes all the causes (basic and/or conditioning) of falls from both residential and commercial roofing structures. For both types of roof structures, we assume that the worker is directly supported by the "roof sheeting" component, which in turn is supported by the "roof rafters" component. Residential structures are assumed to be wooden-framed; therefore, the roof sheeting is going to be plywood supported by wood rafters. In addition, we assume that most of the roofs for residential houses are pitched or sloped to prevent snow accumulation. On the other hand, a commercial structure is assumed to be a multi-story vertical structure whose roof has little or no slope. The supporting components of this type of roof change depending on the building material being used. For example, for a concrete shell roof the "roof sheeting" component is the concrete layer over which the worker is standing, whereas the "roof rafters" component is the load-bearing component providing support to the concrete roof.

Another important consideration is whether or not the roof has skylights. If it does not, only the causes of falls from the roof edge were examined. If it does, a worker may fall through a skylight-opening or from a roof edge, and the causes related to each component should be examined. The basic and conditioning causes of falls discussed in Section 4.2.1 remain unaltered. Of the above basic causes, the ones related to the support components and to the fall protection devices are explained further. It should be noted, however, that the consequences of enabling and triggering causes for a roof component may be more serious than those on other components. For example, a small distraction on a sloped roof may be enough to cause a worker to lose control and fall. Furthermore, a worker on a roof is exposed to all the elements and the effects of environmental causes can be more pronounced.

Regarding the support related causes on a roof, we again have triggering, enabling, and support causes; however, this time they are related to the roof sheeting support. The triggering causes include any external factor which influences the sheeting and makes it fail to fulfill its purpose (e.g., the sheeting is hit by a piece of falling material that causes it to break and fail to support a worker). The enabling causes include any problem internal to the sheeting, such as inadequate design strength. Finally, the support-related causes include any triggering and enabling problems of the "roof rafters" support.

Regarding the conditioning causes related to the use or non-use of fall protection or fall arresting devices, two factors are taken into account: the type of roof and whether or not it has any skylights. If a roof has skylights, the fall protection devices of two components (edge and openings) have to be considered. If it does not, then only the floor edge fall protection has to be considered.

The fall protection/prevention devices required for skylights, and flat and sloped roof edges change depending on the component being studied. For skylight openings the following devices are commonly used: guardrail, opening cover, body harness, and safety belt systems. The use of nets and catch platforms is unlikely due to space and practical considerations. The guardrails and cover systems are the favored systems if the skylights appear in a flat roof, while safety belt and body harness systems are more widely used in the case of a sloped roof.

For roof edges, the choice of protection devices depends on whether the roof is sloped or flat. If the roof is flat, the following devices may be used: guardrail, safety net, catch platform, and warning line systems. The use of safety belts and body harnesses is unlikely because a belt or harness system may require the installation of a temporary structure to act as an anchorage point or connector (catenary or horizontal lifeline). Any of the other previously named devices would be easier to implement. Now, if a roof is pitched, the following devices are likely to be used: guardrails, safety belts, body harnesses, safety nets, and catch platforms. The problems related to the inadequate use or installation of any of these systems remain as described previously.

A final factor to be noted in the protection of roof edges is the case when there is a perimeter wall around the roof. If the wall is higher than 3 feet (0.915 m), no additional fall protection has to be provided [29 CFR 1926.500 (b) 1994]. In this case, the 3 feet (0.915 m) wall acts as a barrier which prevents the worker from falls. If the wall is lower than 3 feet (0.915 m) and there are no fall protection devices installed, the conditioning cause of a fall would be due to a lack of fall protection.

4.2.5 Causes of falls from a wall opening

For this project a wall opening is defined as "an opening at least 30 inches (762 mm) high and 18 inches (457 mm) wide, in any wall or partition, through which persons may fall, such as a yard-arm doorway or a chute opening" [29 CFR 1926.501 (b) (14) 1994]. As with the other components, the focus in this case is on all the factors acting upon a worker and causing him or her to fall. The worker is assumed to be supported by the floor (working surface), which in turn is supported by joists.

In general, the worker causes of falls remain the same: the basic causes are enabling, triggering, or support-related; the conditioning causes are related to general safety problems or fall protection problems. The main difference is in the conditioning causes related to the use of fall protection devices. According to OSHA standards, wall openings have to be guarded when there is a drop of more than 4 feet (1.22 m) and the bottom of the opening is less than 3 feet (0.915 m) above the working surface. In this case, a standard guardrail system or an intermediate guardrail are the devices most commonly used and recommended. However, devices like safety nets and catch platforms may achieve the same results (unless space constraints restrict their use). Furthermore, devices like safety nets and body harnesses could theoretically be used; however, they would not be practical given that several other devices would be easier and more economical to implement. The problems related to the inadequate use or installation of the fall protection devices have already been discussed in previous sections.

4.2.6 Causes of falls from the top of a wall

This section discusses the causes of falls when the working surface is the top of a wall. The worker causes are similar to those already stated. However, space limitations play an important role in these falls. The likelihood of a worker falling due to enabling (e.g., worker drunk or distracted) or triggering causes (e.g., environmental or impact causes) is greater due to the smaller surface area. The limited working area requires the worker to be in full mental and physical control, or else risk a fall. In addition, the effects of external events acting upon a worker in a limited working area may be more serious. For example, if a worker is hit, or exposed to environmental forces, it may be harder for him or her to maintain his or her balance. In general, there is little room for errors on the worker's part.

The support-related causes of falls are related to enabling, triggering, and support problems of the wall supporting a worker. The enabling causes are problems inherent to the wall (e.g., poor design). The triggering causes include problems due to external factors, as is the case when a piece of equipment (e.g., a crane) hits the wall and causes it to fail. The support causes also involve enabling and triggering problems, but this time they are related to the beam supporting the wall.

The number of devices that can be used for fall protection/prevention at the top of a wall component is very limited due to space. Among them we have the safety belt, body harness, catch platform, and safety net systems. Of these, given no OSHA restrictions, the safety net and catch platforms may be the easiest to implement. The safety belt or harness systems could be implemented; however, the erection of a temporary structure may be required to act as an anchorage or connector point for the system. The conditioning causes related to fall protection/prevention for this component include the lack of safety devices (no protection provided) or inadequate use or erection causes which have already been discussed.

4.2.7 Causes of falls from a steel beam

This section discusses the possible causes of falls from a steel beam during a steel erection process on a multi-story building. We assume that the steel beam is already in place with either a temporary or permanent connection, and that an iron worker is standing on it. Furthermore, according to the OSHA standards for the construction industry, section 1926.750 (a) [1988], "the permanent floors shall be installed as the erection of structural members progresses, and there shall be no more than eight stories between the erection floor and the uppermost permanent floor." In addition, a temporary but substantial floor deck should be maintained within two stories or 30 feet (9.15 m) of the erection floor. That means that if the iron worker were to fall into the interior of the building, the greatest distance he or she could fall would be the equivalent of two stories. In contrast, if the worker were to fall toward the exterior of the building, he or she could fall a long distance, depending on the floor currently being erected. According to the same OSHA standard, section 1926.750 (b), if it is not possible to install a temporary floor deck, and/or if the potential falling distance exceeds two stories or 25 feet (7.6 m), safety nets should be installed and maintained.

We also assume that the iron worker is standing on the beam performing his or her job, and that the component supporting the beam is the connection to the column. In this case, the support-related causes of a fall are enabling (i.e., poor beam design), triggering (i.e., equipment impact), and support causes related (i.e., internal or external problems related to the beam-column connection) to the beam over which the worker is standing. The other basic causes remain the same; however, as for the "top of a wall" component, their consequences are more serious because the working area is very limited and there is little room for errors by the worker.

For problems related to fall protection/prevention equipment, there are two conditioning causes: a) if no protection is provided, and b) if the devices in place are somehow inadequate. The systems that could be used for the fall protection of a steel worker are the safety belt, body harness, safety net, and catch platform. Of these, the first three are most common. However, even they may not be easy to install, due to space or tie-up problems. The catch platform can be used by locating it under the working surface, so that if an accident happens, the worker will not fall to the ground. Possible problems with all these devices have been described previously.

4.2.8 Causes of falls from a portable ladder

Portable ladders are widely used on a construction site. In this section, the most common causes of falls from this component during the construction process is described. We include the causes of falls from portable ladders, like step or self-standing, straight (regular), and extension. A step-ladder stands by itself, is not adjustable in length, and has a hinged back. A straight ladder is portable, is not adjustable in length, and consists of two bars or ropes joined to each other by steps. Finally, an extension ladder is portable and light-weight, with two or more sections that travel in guides or brackets.

In general, the basic causes of falls from a ladder are similar to those described in Section 4.2.1; however, their effect is increased by the working surface (the ladder) on which the worker is standing. For example, if a worker is standing on a ladder where full concentration and physical control is required to avoid a fall, any attitude problem (e.g., stress, drug or alcohol problems) would make him or her more likely to fall. The same applies in the case of triggering problems, where the smallest impact may cause a worker on a ladder to lose his or her balance and fall.

There are three main causes of falls from a portable ladder: improper use, improper placement, and improper selection. Improper use causes include inadequate use of the ladder. For example, while standing on a ladder a worker should not have to over-reach to do his or her job. If the ladder is not high enough or is incorrectly placed, he or she should either replace it or move it to the right spot. Many accidents from ladders are due to over-reaching. The worker either does not have enough contact points with the ladder and therefore falls, or he or she causes the ladder to topple. In general, experts recommend that a worker keep at least three contact points with the ladder at all times (either two feet and a hand, or two hands and a foot). This means that the worker has only one free hand to perform his or her job, unless he or she ties up. Another example of improper ladder use is when a worker is on a step-ladder, and he or she sits or stands on the top step or ladder top. In this case, the worker is not able to maintain the three contact points and is likely to fall.

In contrast, the improper placement and improper selection causes are related to the ladder support component. To prevent falls due to improper placement, the ground or surface where a ladder is standing should be thoroughly inspected. Loose or uneven ground and slippery conditions should be avoided. In addition to checking for a firm level base, a worker should also consider the following factors before stepping on a ladder [Introduction to Fall Protection 1989 and 29 CFR 1926.450 1990]:

1. A step-ladder should be fully opened and locked.
2. An extension or straight ladder should be placed at around a 75° angle or pitch, so that the horizontal distance from the base of the ladder to the wall (or surface on which the ladder is sitting) is one-fourth of the vertical distance from the floor to the top of the wall.
3. An extension or straight ladder should be tied up, blocked, or otherwise secured (e.g., held by a co-worker) to prevent it from being displaced.
4. An extension or straight ladder should be placed so that it extends about three feet (0.914 m) above the working surface the worker is trying to reach.
5. The overlay of the sections in an extension ladder should be within standards. The worker should make sure of this, because if the overlay is less than that specified, the ladder may fail to support him or her and cause a fall. The overlays should be as follows: a 3 ft (0.915 m) overlap for a ladder up to 32 ft (9.76 m) long, a 4 ft (1.22 m) overlap for one up to 36 ft (10.98 m) long, a 5 ft (1.52 m) overlap for one up to 48 ft (14.64 m) long, and a 6 ft (1.83 m) overlap for one above 48ft (14.64 m) long.

6. Finally, unless it is protected by barricades or guards, a ladder should not be placed in a passageway, driveway, doorway or any other area where it may be displaced by activities being conducted by any other workers.

Falls due to improper selection can also be related to portable ladders whose load capacity is not enough for a given job. There are four types of portable ladders: Type 1A is an extra heavy duty ladder with a 300-pound (1.33 kN) capacity; Type 1 is a heavy-duty industrial ladder with a 250-pound (1.1 kN) capacity; Type 2 is a medium duty ladder with a 225-pound (1 kN) capacity; and, finally, Type 3 is a light-duty ladder with a 200-pound (888 N) capacity. The load capacity includes the weight of the worker and any tools or materials he or she is carrying. In addition, improper selection causes also include cases when the work must be performed around electric switches, outlets, or cables. For electrical work, metal ladders should be avoided. They are good electricity conductors, and if they make contact with electricity, they transfer it to the worker, causing him or her to fall. Wood ladders should be used instead. Finally, there are the problems related to poor inspection and maintenance. Before using a ladder, a worker should check for broken steps, corrosion, structural weaknesses, loose rails or side rails, loose connections, dents, and any other sign(s) that may indicate that it is not safe.

The only devices that could be used for fall protection/prevention on a portable ladder are the safety belt or body harness systems, which can be used to tie-up a worker while he or she is on the ladder. The use of these devices will also help free the worker's hands so that he or she can perform his or her job more effectively. It should be noted, however, that OSHA standards do not require the use of these devices to protect workers from portable ladder falls.

4.2.9 Causes of falls from a scaffolding structure

According to the Ohio Bureau of Workers' Compensation (OBWC) [1979], a scaffolding is "any temporary elevated platform and its supporting structure used for supporting employees, materials, or equipment." A sound scaffolding is essential to safety in construction. There are two general types of scaffolding. An access scaffolding provides a safer and more comfortable elevated working platform for the support of workers and materials than does, for example, a ladder. In addition, a support scaffolding (or falsework) is a temporary structure used to support parts of permanent structures. As mentioned before, only an access scaffolding is included in this study.

The focus in this section is on the support-related causes of falls from these structures given that a large number of fall accidents occurs due to these causes. A study of scaffolding accidents in 752 construction sites performed by the US Department of Labor in 1981 identified the scaffoldings' unsafe features listed in Table I-4.1 as significant causes of falls. A lack of guard rails and toe boards on scaffoldings was found in over sixty percent of the construction sites, while around forty percent of the sites had problems with the planks. In addition to these unsafe features, the misuse of scaffolding equipment, the lack of training in inspection, and the non-use of fall protection equipment can also be contributing causes to scaffolding-related accidents.

Furthermore, if workers have to work on elevated structures like scaffolding, fall protection is mandatory under most safety regulations. According to OSHA, guardrails should be installed on a scaffolding if its height is over four feet (1.219 m), because even at that height, a fall can bring serious injury to a worker. In addition, fall arrest equipment such as safety belts, body harnesses, lanyards and their attachments (e.g., rope grabbing devices and lifelines) should be provided to workers by the construction company. Such equipment cannot prevent a fall but can prevent injury to a worker. Unfortunately, only about ten percent of the suspended scaffolding workers who were killed by fall accidents between 1987 and 1988 were using these safety devices [Rademaker 1991]. In short, according to OSHA, scaffolding injuries and fatalities appear to result primarily from non-compliance with existing standards.

Table I-4.1 Unsafe Features in Scaffoldings [US Department of Labor 1981]

Unsafe feature	*Percentage*
No overhead protection	86
No guardrail	64
No toe board	61
Exposed sides	54
Loose and weak planks	23
Space between and missing planks	14
Slippery surface	7

According to OSHA's standards for construction [*Section 1926.451 Scaffolding*], there are twenty-four different kinds of access scaffolding structures; the requirements for each are unique, and, consequently, the safety conditions and the structural problems of each scaffolding are different. In addition, access scaffoldings are subdivided into two primary categories: self-supporting and suspension scaffoldings. Self-supporting scaffoldings are structures that are composed of one or more working platforms supported from below by brackets, poles, frames or similar supports. Examples include a tubular welded and a tube and coupler scaffolding. Next, suspension scaffoldings, like a single-point adjustable suspension scaffolding and a swinging scaffolding, involve one or more working platforms suspended by ropes or other means from an overhead structure.

To determine the worker support-related causes of construction falls from scaffoldings, all the components of each type of scaffolding must be analyzed to investigate the worker support-related causes of fall accidents. The minimum requirements of scaffolding design and erection are described in the *Specific Safety Requirements of the Ohio Bureau of Workers' Compensation (OBWC) Relating to Construction* and the standards of Occupational Safety and Health Administration (OSHA).

For our study, scaffoldings are classified into six types, as follows:

1. Tube and coupler scaffolding
2. Suspended scaffolding

(a) Masons' adjustable multiple-point suspension scaffolding

(b) Stone setters' adjustable multiple-point suspension scaffolding

(c) Two-point suspension scaffolding

(d) Single-point adjustable suspension scaffolding

(e) Float and ship scaffolding

(f) Boatswain's chair

3. Form scaffolding
4. Wood pole scaffolding
5. Tubular welded frame scaffolding
6. Mobile scaffolding.

All the possible causes of falls from these six types of scaffoldings are described in this section. Part of these causes are based on previous studies by Hadipriono [1992a] and Yoo [1994].

4.2.9.1 Causes of falls from a tube and coupler scaffolding

A tube and coupler scaffolding consists of steel tubes, which serve as posts, bearers, runners, and braces, and special couplers, which serve to connect these steel tubes. A worker is directly supported by planks making up the temporary working surface, i.e., the platform. The planks rest on bearers which, in turn, are supported by runners. Bearers are horizontal scaffolding members installed transversely between posts. Also horizontal members, runners are erected along the entire length of the scaffolding and located on both the inside and outside posts at even heights [OBWC 1979]. Bearers and runners are supported by posts both inside and outside, and the load from above is transferred to the foundations through these posts. "Worker support-related causes" and "worker general causes" of falls from a tube and coupler scaffolding are described in Sections 4.2.9.1.1 and 4.2.9.1.2, respectively.

4.2.9.1.1 Worker Support-Related Causes

These causes are related to the failure of the scaffolding structure supporting the worker. They are subdivided into each component's enabling, triggering, and supporting causes. The enabling causes are internal causes leading to the failure of a scaffolding structure. The triggering causes include any external event acting on a scaffolding structure. The causes of fall accidents are explained according to this classification.

4.2.9.1.1.1 Enabling causes. Enabling causes can be further subdivided into inadequate erection, inadequate design, defective components, and improper inspection. Each of these four problems is described below, and each component of a tube and coupler scaffolding is analyzed in light of them.

Inadequate Erection Some enabling causes are related to the planks. All planks should be securely fastened to the bearers by using tie wires. Otherwise, they may move their positions and a worker may fall through an opening between them (B44). In addition, they should overlap the bearers at least 6 inches (152 mm) at each end to prevent them from moving (B45) [OBWC 1979]. Furthermore, OSHA's standards limit the number of working levels; up to three levels can be occupied at the same time by workers in the case of light duty scaffolding, two levels if medium duty scaffolding, and only one level if heavy duty scaffolding, as shown in Table I-4.2 "Additional Planked Levels" in Table I-4.2 means the number of plank levels prepared as working surfaces beyond the number of working levels. Any deviation from these regulations may lead to a fall accident (B49). If a tube and coupler scaffolding that exceeds the guidelines in Table I-4.2 is to be installed, it should be designed by an engineer competent in the field [OBWC 1979].

Inadequate extension of planks over end supports could be another cause of a fall (B46). According to OBWC, planks should extend over end supports no less than 6 inches (152 mm) and no more than twelve inches (305 mm). Additionally, where the ends of planks abut each other to form a flush floor, the butt joint should be located at separate bearers (B47). Finally, all planks used for a scaffolding should be Scaffold Grade, or the equivalent, approved by Western Wood Product Association (WWPA) specifications (B48) [OBWC 1979]. According to WWPA, the minimum strength of Scaffold Grade planks should be at least 2,000 pounds per square inch (1.3953 kg/mm^2) [Ratay 1987].

Table I-4.2 Number of Working Levels and Heights [OSHA 1990]

Scaffolding	**Working Levels**	**Additional Planked Levels**	**Maximum Height**
Light Duty	1	8	125 ft (38.10 m)
	2	4	125 ft (38.10 m)
	3	0	91 ft (27.74 m)
Medium Duty	1	6	125 ft (38.10 m)
	2	0	78 ft (23.77 m)
Heavy Duty	1	6	125 ft (38.10 m)

Some other inadequate erection causes are related to the runners and bearers. Runners should be located at even heights both inside and outside the posts along the length of a scaffolding [OBWC 1979]. Otherwise, the bearers and planks cannot be installed properly, and may result in a fall (B524). Additionally, the misuse of tubes may lead to a fall accident (B526). If dissimilar structural metals from different manufacturers are combined in this type of scaffolding, the whole structure may collapse because of the different connection methods or the different thermal expansion coefficients of each metal (B525). According to OSHA, couplers should be made of structural type steel, and any violation of this rule could also be a problem.

Next, the bearers should be installed transversely between posts and usually coupled to the posts or runners. When bearers are connected directly to the runners, the location of a connection (coupler) should be as close to the posts as possible [OSHA

1990]. Otherwise, the runners receive loads from the bearers and planks at improper places and may break while a worker is performing his or her job (B527). Bearers should be long enough to project at least 3 inches (76 mm) over the runners of the inner and outer rows of posts [OBWC 1979]. Inadequate projection could be the cause of a fall (B528). Additionally, an inadequate splice of runners also could cause a fall (B529). Runners should not be spliced between posts, and their length should be longer than the space between the posts. In regard to the cross bracing, it should be correctly installed to prevent the movement of posts (B530). In accordance with OSHA, a cross bracing should cross the width of a scaffolding no less than every third set of posts horizontally, and every fourth runner vertically.

Furthermore, some fall accidents are caused by the inadequate erection of posts. It is very important, first of all, for all posts to be set plumb in order to keep a scaffolding structure rigid (B63). Additionally, the entire scaffolding should be tied to a permanent structure. Otherwise, it may collapse when a strong wind blows on it or equipment like a crane hits it (B64). In accordance with OBWC, the scaffolding should be secured to a permanent structure at intervals not to exceed thirty feet (9.144 m) horizontally and twenty-six feet (7.925 m) vertically. Misuse and inadequate splicing of posts could also lead to a fall, for the same reasons as those given for the horizontal members (B66 & B67). The ends of posts should be abutted each other for splicing. The longitudinal diagonal bracings on the inner and outer rows of posts should be installed properly to prevent the movement and buckling of posts (B65). According to OSHA, they should be installed at a forty-five degree angle from the first outer post, then at every fifth post thereafter, up to the top of the scaffolding. They should also be installed from the last post in the same manner.

Finally, some inadequate erection causes are related to foundations and soils. Mud sills and posts should be connected tightly. Base plates, which attach to the bottom of the posts, should be nailed to the mud sill. Otherwise, posts may lose their support, and this could lead to a fall (B615). In addition, an uneven ground condition or insufficiently compacted soil may cause a mud sill to break. Either of these could result in a fall (B71 and B72).

Inadequate Design The second type of enabling cause is an inadequate design. Being a temporary structure, a scaffolding is often not built according to construction drawings or specifications. As noted earlier, when the height of a scaffolding is below 125 feet (38.10 m), a field engineer who is in charge of the scaffolding structure should erect it in accordance with OSHA standards. Because any violation could lead to the failure of scaffolding, an engineer should thoroughly understand and follow OSHA's minimum requirements. Only if a scaffolding is over 125 feet (38.10 m) high does it need to be erected in accordance with drawings and specifications prepared by a qualified engineer.

A tube and coupler scaffolding should be designed to be capable of carrying at least four times a maximum rated load without a failure [OBWC 1979]. An intended load should be carefully determined. A scaffolding designed to carry a working load of no more than 25 pounds per square foot (121 kg/m^2) is considered a light duty scaffolding; if between 25 and 50 pounds per square foot (121 and 242 kg/m^2) or 50 and 75 pounds per square foot (242 and 363 kg/m^2), it is considered a medium or a heavy duty scaffolding, respectively. If a scaffolding is to be used by several sub-contractors in a job site, all of its intended loads should be carefully taken into account when determining the dimensions and the spacing of each of its components. Otherwise, the structure may collapse if a larger than anticipated load is applied (B410, B532, B68, and B614).

Each component of a tube and coupler scaffolding must be analyzed to investigate inadequate design causes. Some causes are related to the planks. Two by ten inch (51x254 mm) or wider Scaffold Grade planks should be used for this type of scaffolding. The maximum permissible spans for these planks are given in Table I-4.3. Using an inadequate plank length or thickness may lead to a fall (B411 and B412). Additionally, the number of working levels, which are installed with planks, is limited as shown in Table I-4.2. For instance, when two levels of a light duty scaffolding are used by workers at the same time, up to four additional planked levels can be installed. Having more than four levels could lead to a fall accident (B413).

Table I-4.3 Permissible Span of Planks [OSHA 1990]

DESCRIPTION	**FULL (2 X 10) THICK. UNDRESSED LUMBER**			**NOMINAL (2 X 10) THICK. LUMBER**	
WORKING LOAD *psf (kg/m^2)*	25 (121)	50 (242)	75 (363)	25 (121)	50 (242)
PERMISSIBLE SPAN) ft (m)	10 (3.05)	8 (2.4)	6 (1.8)	8 (2.4)	6 (1.8)

Next, some enabling causes are related to the inadequate design of the horizontal members. All steel tubes that serve as bearers and runners should have no less than a two-inch (51 mm) outside diameter (OD), except for the bearers where the posts are spaced apart at a greater distance than 5x8 feet (1.524x24.38 m) in medium duty scaffolding (B533). In this case, the size of the bearers should be at least a two and one-half-inch (12.7 mm) OD, but the spacing of the posts cannot be over six by eight feet (1.829x2.438 m) [OBWC 1979]. Additionally, the runners should not be spaced farther apart than 6.5 feet (1.98 m), center to center (B535) [OBWC 1979]. Furthermore, the spacing of the bearers should be no less than 4 inches (100 mm) and no more than 12 inches (305 mm) longer than the horizontal post spacing or the vertical runner spacing (B534) [OSHA 1990]. Finally, the width of this type of scaffolding is also described in the standards of OSHA. The maximum width is limited to six feet (1.829 m), and the violation of this requirement could lead to a fall (B531).

Some other causes are related to the posts. A two-inch (51 mm) OD steel tube is used for posts as for horizontal members (B69). According to OSHA, the maximum longitudinal spacing of light duty, medium duty, and heavy duty posts is ten feet (3.05 m), eight feet (2.44 m), and 6.5 feet (1.98 m), respectively. The maximum transverse spacing is the same as the maximum width of this type of scaffolding, which is six feet (1.83 m). The posts should be spaced properly to prevent a collapse of the structure

(B610). In addition, the maximum height of posts depends on the type of scaffolding and the number of levels, as indicated in Table I-4.2. For example, when two working levels are used at the same time in a light duty scaffolding, the maximum height of the posts is 125 feet (38.10 m). Any violation of scaffolding height requirements could lead to structural failure (B612). Finally, an improper distance between a scaffolding and a permanent structure could cause a worker to fall through the opening between them (B611). A distance of around four inches (102 mm) is usually considered proper for this type of scaffolding.

Defective Components The third type of enabling causes is a defective component. Any defective material of any component of a tube and coupler scaffolding could cause the failure of a scaffolding (B33, B416, B539, and B613). Because the components of a scaffolding are reused several times, many of them become defective. For example, the longitudinal separation of a plank may cause a worker to fall. Or, if a rusty steel coupler is used to join scaffolding members, the connection may not be tight. This could result in the collapse of a scaffolding even if it is carefully designed and erected. Therefore, to prevent construction falls due to defective components, all the materials of a tube and coupler scaffolding should be maintained in a sound condition, and repaired or replaced as soon as their faults are discovered.

No/Improper Inspection The final type of enabling causes is related to inspection problems (B34, B417, and B540). All parts of scaffoldings should be inspected carefully before their use. As mentioned before, defective scaffolding materials are easily found in a job site, because a scaffolding is a temporary structure and is reused several times. So, an inspector should replace or repair any damaged or sub-standard component. Additionally, he or she should check each component and joints of a scaffolding immediately after its erection. Finally, when a scaffolding is used by several sub-contractors for different purposes, an engineer should cooperate with them to guarantee its correct usage.

4.2.9.1.1.2 Triggering Causes. The triggering causes would include any external events acting on a scaffolding structure. These causes are grouped into causes due to environmental conditions and causes due to impact on the structure.

Such environmental conditions as strong wind (gusts), hail, and snow can lead to the collapse of a structure. Strong wind or hail may cause a worker to fall due to its impact force on each component of a scaffolding (B41, B42, B522, B523, B61, and B62). Accumulated heavy snow may break the planks, and then the worker may fall (B43). In addition, soil under a mud sill may be lost when rain falls or snow melts, and, consequently, a scaffolding may collapse (B73 and B74). Other environmental conditions, like fog, frost, extreme heat, and extreme cold, can cause the worker to fall in different ways. For instance, fog may reduce the worker's visibility and cause his or her fall. However, we are concerned at the moment only environmental conditions that could cause the failure of a scaffolding.

With regard to the impact causes, any scaffolding component may be hit by a piece of equipment (B31, B414, B536, and B541) or material (B32, B415, and B537).

Due to the impact, the scaffolding may collapse, and then a worker may fall. Furthermore, if a scaffolding is used as a shoring and, as a result, it collapses, that could be another cause of a fall (B538).

4.2.9.1.1.3 Supporting Causes. Besides the enabling and triggering causes, a fall accident may occur due to supporting causes. These are related to the failure of scaffolding components supporting a worker who is performing a job. Since a worker is directly supported by planks, as explained before, the first worker support-related causes are related to them. They are classified into "planks enabling causes," "planks triggering causes," and "planks support-related causes." Planks enabling and triggering causes have already been explained above; planks supporting causes are further subdivided into "bearer & runner enabling causes," "bearer & runner triggering causes," and "bearer & runner supporting causes." In the same way, bearer support-related causes are related to post causes, and post supporting causes are related to foundation and soil causes.

4.2.9.1.2 Worker General Causes

For the convenience of the readers, the "worker general causes" for scaffolding structures are introduced only in this section (about tube and coupler scaffoldings). They follow those already discussed in Section 4.2.1 of this report. However, these causes have been refined and adjusted to fit scaffoldings.

"Worker general causes" can be classified into two primary types: worker enabling and triggering causes. The former are internal causes, like a worker's attitude, health, and skill problems, and the latter are external causes affecting a worker, like strong winds, snow, and so on. These two types of causes are described next. In addition, we have to consider safety devices like guardrails, because, unless safety devices are provided, worker enabling and triggering causes may lead to fall accidents. Therefore, the safety conditions are discussed after the worker's enabling and triggering causes.

4.2.9.1.2.1 Worker Enabling Causes. Some enabling causes are related to a worker's attitude. When an intoxicated worker goes to a job site, he or she may not have the capability to control himself/herself, and this could cause a fall accident (B51). For the same reason, a worker who uses illicit drugs, such as cocaine and marijuana, may fall from a scaffolding (B52). Additionally, a worker's personality problem could lead to a fall accident (B53). For instance, a man who does not follow his supervisor's instructions, does not cooperate with other workers, or is reckless while performing a job may fall. A final cause in the attitude category is a worker's distraction due to stress (B54). Psychological stresses, such as family or financial problems, may disturb a worker's concentration, and this may result in a fall.

Some other worker enabling causes are related to health. A sudden illness, such as a heart attack or appendicitis, could cause a fall (B55). Besides acute illnesses, chronic illness, such as inveterate dyspepsia or asbestosis, may interfere with a worker's concentration and lead to a fall (B56). Furthermore, even prescription drugs that make a worker sleepy could result in a fall (B57). If the worker needs to use any such drugs during working hours, a supervisor should change his or her working place to one where the risk is low.

Finally, there are some worker enabling causes related to skill. As mentioned in the previous chapter, a worker's safety training is important in the prevention of construction accidents. He or she should be taught to recognize hazardous conditions, use proper safety devices, and so on. So, a lack of training may lead to a fall (B58). Additionally, a worker who is not accustomed to his or her job has a greater chance of falling than does an experienced worker, because experience lets him or her identify hazards and know what kinds of steps are necessary to avoid fall accidents (B59). Lastly, a lack of aptitude could cause a fall (B510).

4.2.9.1.2.2 Worker Triggering Causes. These causes can be classified into two types: human-induced impacts and nature-induced impacts [Hadipriono 1992a]. Under the human-induced impacts, when a worker is hit by a tool or equipment, by a piece of material, or by another worker, he or she may lose his or her balance and fall (B511, B512, and B513). For instance, the worker may lose his or her senses when falling material hits his or her head during work on a suspended scaffolding, and this impact may lead to a fall unless personal protective equipment or fall protection safety measures are provided. Another example is that a worker casting concrete on a scaffolding may fall due to the impact of a hose of a concrete pump equipment if there is no proper guardrail.

In regard to the nature-induced impacts, any natural event, such as strong wind (gusts), rain, hail, snow, frost, fog, extreme cold, or extreme heat, could lead to a worker's fall (B514 to B521). Rain or snow may make a platform slippery; fog may reduce a worker's visibility; extreme cold or heat may reduce a worker's concentration. Any such causes may result in a fall.

Finally, distractions that include any environmental conditions disturbing a worker's concentration, such as a noise and dust, could cause a fall accident (B418). If, for instance, a sand blasting job is being performed near a scaffolding structure, the raised dust may affect a worker's vision, and he or she may fall.

4.2.9.1.2.3 Worker Safety Conditioning Causes. Besides the enabling and triggering causes, we should consider the role of fall protection safety measures, such as guardrail, safety belt, and body harness systems, in the prevention of fall accidents from a tube and coupler scaffolding. A safety net system is excluded from the discussion because its use on a scaffolding is not for workers but for pedestrians against falling materials.

Guardrails should be installed on all open sides of any scaffolding. The minimum requirements for their installation are described in the standards of OSHA [*Section 1926.451 Scaffolding*]. For example, the height of a top rail should be approximately forty-two inches (1067 mm), a midrail about twenty-one inches (533 mm); a toe board should be installed at least four inches (102 mm) high; the spacing of posts, which support the rails, should be less than eight feet (2.438 m); posts and rails should be two by four inches (51x102 mm) in the case of wood guardrails, and one and a half inches (38.1 mm) in diameter in the case of pipe guardrails. Any violation of these requirements could be a conditioning cause of a fall accident. If the elevation of the rails is too high or too low, a worker may fall (C63). Inadequate spacing of posts or improper dimensions of each component could lead to a fall when a significant impact is applied to the rails (C65 and C66). In addition to these causes, the missing components of a guardrail (e.g., no mid-rail) could be a conditioning cause (C62). Furthermore, if a guardrail is poorly installed, it may fail to prevent a worker from falling (C61). Finally, any human-induced or nature-induced impact to a guardrail may break it, and it may fail to fulfill its purpose (C67 to C610).

Some other causes are related to the safety belt and harness systems. These devices are not intended to prevent a fall itself but to interrupt it so that a worker does not get hurt. Anyone who works on a suspended scaffolding should use one of these systems. Although their use is not required on a tube and coupler type scaffolding, they are still the final devices to prevent a fall accident. Their components are similar: safety line, lanyards, anchorage point, clips, shock absorbers, and any other accessories required. The only difference between them is that one system uses a belt and the other a harness. In general, although a body harness is somewhat more inconvenient to wear than a belt, experts recommend its use, because it helps to distribute deceleration forces over parts of the body, while a body belt transmits those forces only to the abdomen.

Any problem with these devices could be a conditioning cause of a fall. There are two possible conditioning causes due to using inadequate material, first, when the material has less than standard strength (C611 and C613), and, second, when the materials are not up to standards due to excessive wear (C612 and C614). In accordance with OSHA, all the components of these systems should be able to support at least 4000 pounds (17.8 kN) at all times. Beyond these inadequate material problems, improper installation of these systems could lead to a fall (C54 and C55). Finally, inadequate use of a safety belt could be a cause of a fall. When a worker wears a body belt too loosely around his or her waist, he or she may slide out of it and fall all the way to the ground (C53).

4.2.9.2 Causes of Falls from a Suspended Scaffolding

A suspended scaffolding is a scaffolding supported from above. Its platform is supported at more than two points from overhead outriggers which are fastened to the framework of the structure [OBWC 1979].

According to the OSHA standards for the construction industry, Section 1926.451, "Scaffolding," there are six types of suspended scaffoldings. The definitions of these six types, according to OBWC, are as follows:

(a) Masons' adjustable multiple-point suspension scaffolding

This has a continuous platform supported by bearers which are suspended by wire rope from overhead outrigger beams. It is designed to permit the raising or lowering of the platform to desired working positions by using a hoisting machine.

(b) Stone setters' adjustable multiple-point suspension scaffolding

This is the same as a masons' adjustable multiple-point scaffolding except that the intended working load is less. This scaffolding is capable of sustaining a working load of 25 pounds per square foot (121 kg/m^2), while the working load of (a) is 50 pounds per square foot(242 kg/m^2).

(c) Single-point adjustable suspension scaffolding

The platform of this type of scaffolding is supported by a single wire rope from an overhead support to permit the raising or lowering of the platform to desired working positions. It is a manually or power operated unit designed for light duty use.

(d) Two-point suspension scaffolding (swinging scaffolding)

The platform of this scaffolding is supported by stirrups or hangers at two points to permit raising or lowering by using a hoisting machine. The maximum width of the platform is three feet (0.914 m).

(e) Float or ship scaffolding

The platform of this scaffolding rests on and fastens to two parallel bearers at right angles to the span. It also has a diagonal bracing underneath. Its size is three feet (0.914 m) wide by six feet (1.829 m) long. No more than three workers can occupy this scaffolding.

(f) Boatswain's chair

A seat, which is designed to accommodate one worker in a sitting position, is supported by slings attached to a suspension rope. The wooden chair seat should be no less than twelve inches (0.305 m) wide by twenty-four inches (0.61 m) long by one-inch (25.4 mm) thickness.

In any type of suspended scaffolding, a worker is supported by a platform which is the temporary working space. Four different types of platforms are used: ladder-type, beam-type, plank-type, and plywood-type. In the case of a ladder-type platform, flooring strips are supported by rungs. The rungs are connected to side stringers with tie rods. Beam-type platforms have side stringers made of boards set on edge. These stringers support cross beams, which, in turn, support flooring boards. For plank-type and plywood-type platforms, at least a one-inch (25.4 mm) thickness of planks or plywood is cleated on the underside.

A platform is supported by a suspension system, which uses wire, synthetic, or fiber rope. The platform is fastened to the hangers by U-bolts or other equivalent means. Pulleys are provided to hoist it. It is suspended from overhead outrigger beams or iron brackets through the hangers. Outriggers are anchored to the frame or floor system of the building or structure.

Because the failure of any component of a suspended scaffolding may lead to a fall accident, each component was analyzed to investigate the support-related causes of falls. Only the enabling and supporting causes for each component are explained in this section, because the triggering causes are similar to those of the previous section.

4.2.9.2.1 Enabling Causes

As in the previous section, these enabling causes are expanded into inadequate erection, inadequate design, defective components, and improper inspection problems. Inspection problems are not detailed here since they are similar to those described earlier.

Inadequate Erection Some causes are related to ladder-type platforms. The side stringers should not be spliced, because they work as beams (B53). According to OSHA's standards [1990], the rungs should be mortised into the side stringers at least seven-eighths of an inch (22.2 mm); otherwise, they may be disconnected and lead to a fall (B52). In addition, the stringers should be tied together with tie rods. The tie rods should pass through the stringers and be riveted tightly against washers on both ends (B54). The flooring strips should be spaced not more than five-eighths inch (15.875 mm) apart, secured firmly on rungs, and form a flush floor (B55).

Like a ladder-type platform, each component of other types of platforms should also be secured to prevent movement. Especially for a plank-type and plywood-type platform, a bar or other effective means should be securely fastened at each end of the platform to prevent its slipping off the hanger (B531). For beam-type platforms, the upper edge of the cross beams should be at the same level as that of the stringers to form a flush floor (B516).

Other inadequate erection causes are related to the suspension system. The ends of suspension wires should be equipped with properly sized thimbles and securely connected to the outrigger beams. An insecure connection of the suspension cables to the outrigger beams may cause a scaffolding the failure (B541). Furthermore, tiebacks, which are an additional means of a suspension system, should be correctly installed. In the case of the failure of an existing suspension system which supports a platform, the tiebacks could play a role in preventing a fall accident. According to OSHA, tiebacks should be three-quarter-inch (19 mm) manila rope, or the equivalent, and secured to a frame of a permanent structure. Improper or lack of tie back installation could also cause a fall accident (B542).

The suspension cable (rope) in a suspension system should be kept vertical from the top of a structure to the bottom. Otherwise, when a platform goes up and down to desired working positions, it may lose its balance and the rope may receive an unnecessary load, leading to a fall accident (B544). Additionally, the size of sheaves and ropes should be matched to permit the safe lowering and raising of the platform (B543).

According to OSHA, heat-producing work like welding should not be performed on any suspended scaffolding, except one using wire ropes. Such work may damage the suspension cables and cause a worker fall (B548). Furthermore, when any work using corrosive substances or chemicals has to be performed on the suspended scaffolding, proper suspension cables should be used. Only synthetic or fiber ropes which are properly treated or protected are permitted as a suspension cable (B545). The ends of the suspension ropes should be securely attached to the hoisting drum, and at least four turns of ropes should remain on the drum [OBWC 1979]. Insufficient remainder of rope could cause a fall accident (B546). Finally, the incorrect hitching of ropes may allow their untying, and a fall could result (B547).

Some other inadequate erection causes are related to the anchorage system, meaning the outriggers above the platform that hold the suspension system. Because an anchorage system has to carry all the load from below, such as a platform, ropes, hoisting equipment, workers, and materials, it should be securely fastened to the permanent structure to prevent a failure of the entire scaffolding structure (B63). In addition, the anchorage system should be fixed not to auxiliary members, but to the frame(s) of a permanent structure or a building. Fixing the anchorage system to an unstable object could be another cause of a fall accident (B65).

When an I-beam is used for an outrigger beam, it should be installed in accordance with its web in a vertical position to utilize the whole strength of a beam. Otherwise the beam may break, and a worker may fall (B64). According to OSHA, a stop bolt should be installed in every outrigger beam to keep the suspension wire from slipping out of the outrigger beam and the platform from falling (B66).

Inadequate Design Inadequate design is the second type of enabling cause of a fall accident. Each component of a suspended scaffolding is analyzed here to investigate inadequate design causes. Some causes are related to the platforms. As described before, four types of platforms are used for suspended scaffolding. According to OSHA, every type of platform should be designed to be capable of supporting no less than four times the intended load. If it is designed for less than four times the intended load, it may collapse when a large load is applied (B57, B520, and B537).

To install a sound ladder-type platform, each component should be of the proper dimensions and material. According to OSHA, rungs should be made of straight boards, and their minimum diameter should be one-and-one-eighth inches (28.6 mm) (B59). In addition, the maximum spacing between rungs should be twelve inches (25.4 mm), center to center (B510).

The minimum dimensions of stringers (B58) are also described in the standards of OSHA, as shown in Table I-4.4. To prevent the failure of a platform, the stringers should be in accordance with these requirements.

Table I-4.4 Dimensions of Stringers [OSHA 1990]

DESCRIPTION	12 ft (3.65.8 m)	14-16 ft (4.267-4.877 m)	18-20 ft (5.486-6.096 m)	22-24 ft (6.706-7.315 m)	28-30 ft (8.534-9.144 m)
AT ENDS	1-3/4x2-3/4 in (44.5x69.9 mm)	1-3/4x2-3/4 in (44.5x69.9 mm)	1-3/4x3 in (44.5x76.2 mm)	1-3/4x3 in (44.5x76.2 mm)	1-3/4x3-1/2 in (44.5x88.9 mm)
AT MIDDLE	1-3/4x3-3/4 in (44.5x95.3 mm)	1-3/4x2-3/4 in (44.5x69.9 mm)	1-3/4x4 in (44.5x101.6 mm)	1-3/4x4-1/4 in (44.5x107.95 mm)	1-3/4x5 in (44.5x127 mm)

For the same reason as above, the dimensions of flooring strips should be at least one-half by two-and-three-fourths inches (12.7x69.85 mm) (B511). Besides rungs, the stringers should be tied with tie rods. The size of the tie rods should be at least one-quarter inch (6.35 mm) in diameter (B512) [OSHA 1990]. A ladder-type platform should not be less than twenty inches (508 mm) nor more than thirty-six inches (914 mm) wide (B513). No or inadequate inspection of the platform before use in a job site may be another cause of a fall accident (B36).

Next, the inadequate design causes of a beam type-platform are considered. The minimum dimensions and maximum spacing of each component of this type are set by OSHA. The side stringers and cross beams should be made of lumber no smaller than two inches by six inches (51x152 mm) (B521 & B523). Additionally, the maximum spacing of the cross beam is 4 feet (12.19 m) (B524), and the span between hangers should not exceed 12 feet (36.58 m) (B522). Finally, the dimensions of the flooring boards should be one inch by six inches (25.4x152 mm) (B525).

A plank and plywood type of platforms must be designed in accordance with OSHA regulations. It should be composed of no less than two-inch by ten-inch (51x254 mm) planks (B532), and the thickness of the plywood should be at least one inch (25.4 mm) (B535). In addition, planks should be properly cleated on the underside, starting at six inches (152 mm) from each end and continuing at intervals not to exceed four feet (1.219 m). Improper installation of the cleats could be a cause of the failure of the platform (B533). Finally, hangers should be spaced not more than eight feet (2.438 m) apart (B534).

Beyond platforms, some inadequate design causes are related to the suspension system. According to OSHA, all the components of this type of scaffoldings should be able to support at least four times the maximum rated load, except suspension system. The suspension system, which is made of wire, synthetic, or fiber rope, should have the capacity to support at least six times the intended load (B549). Furthermore, the machine used for hoisting the platforms should be carefully selected (B550). It should be tested and approved by the Underwriters' Laboratories or the Factory Mutual Engineering Corporation [OBWC 1979]. In addition to the normal operating brake, it should have an emergency braking system which can stop the platform automatically when the speed is faster than normal (B551). The designer should also select the type (B554), size (B553), and length (B552) of rope appropriate for a specific type of suspended scaffolding. OSHA especially emphasizes the minimum diameters of manila rope for the float or ship scaffolding (1 inch/25.4 mm) and the boatswain's chair (five-eighths inch/15.875 mm).

Finally, there are some inadequate design causes which are related to the anchorage system. These should be considered and treated by an engineer as a permanent structure. Inadequate material (B71), strength (B72), and length (B73) of outriggers could cause a collapse of the entire structure.

Defective Components Besides inadequate erection and design causes, any defective material of any component of a suspended scaffolding could cause a fall accident (B33, B46, and B557). For instance, a manila rope which appears strong but actually frayed could result in worker fall, even if a scaffolding is designed and erected very carefully. So, any materials which are damaged or weakened from any reason should be repaired or replaced as soon as they are discovered.

4.2.9.2.2 Supporting Causes

The first support-related causes are related to the platforms. These are expanded into "platform enabling," "platform triggering," and " platform supporting" causes. The possible enabling and triggering causes have been discussed above; platform supporting causes are further subdivided into "suspension system enabling," "suspension system triggering," and "suspension system supporting" causes. In the same way, suspension system supporting causes are related to the anchorage system, and anchorage system supporting causes are related to the permanent structure causes.

4.2.9.3 Causes of Falls from a Form Scaffolding

A form scaffolding is a structure attached to the frame of a formwork by using brackets. The purpose of this scaffolding is to provide a working surface for concrete casting as well as for inspection of the form and re-bar works before the concrete is poured. There are two types of form scaffoldings: the metal bracket and the wooden bracket. In both types, the platform, which is the temporary working surface of the structure, consists of planks. The worker is directly supported by these planks, which rest on metal or wood brackets. The brackets consist of braces, which support the ledgers undergirding the planks, and are attached to the stringers or walers of a formwork.

To investigate the support-related causes of falls, each component of a metal and wooden form scaffolding was analyzed. The triggering causes are not discussed because they are similar to those of the previous section.

4.2.9.3.1 Enabling Causes

As in Section 4.2.9.1, the enabling causes are classified into inadequate erection, inadequate design, defective components, and improper inspection problems. Inspection problems are not discussed in this section, because they are almost identical to those discussed previously.

Inadequate Erection Some enabling causes of falls are related to the planks. Planks should be securely fastened to the brackets, either bolted to a metal bracket or nailed to a wooden bracket. Otherwise, they may move their positions and a worker may fall through an opening between them (B41). If they are not bolted or nailed, they should overlap the brackets at least six inches (152 mm) at each end (B42) [OBWC 1979].

Inadequate expansion of planks over the end supports could be another cause of a fall (B43). According to OBWC, planks of all form scaffoldings should expand over end supports no less than six inches (152 mm) and no more than twelve inches (305 mm). Where the ends of planks abut each other, they should be located at the center of the brackets or at separate brackets (B44). Additionally, all planks used for a scaffolding should be Scaffold Grade, or the equivalent, approved by WWPA specifications (B45) [OBWC 1979].

Other inadequate erection causes are related to the brackets. In the case of a wooden bracket, the greater dimension of a ledger should be set vertically so that it can endure the load from above (B51). All brackets should be firmly fixed to the stringers or walers of a formwork; otherwise, they may tip or turn and lead to a fall accident (B52). Furthermore, each bracket should be at the same level to prevent the platform from sloping (B53). Additionally, the width of the brackets should be greater than that of the planks in order to support the planks properly (B54), and the surplus area of the brackets should be used as a holder of the uprights that carry the handrails. Finally, an improper brace also could cause a fall (B55). A brace should be located at least three feet (0.914 m) from the formwork at an angle of approximately forty-five degrees; its lower end should be nailed to a vertical support when a wooden bracket is used, and bolted or welded in the case of a metal bracket.

Inadequate Design Besides inadequate erection, inadequate design could lead to a fall. A form type of scaffolding should be designed to be capable of carrying four times the maximum rated load without a failure [OBWC 1979]. Additionally, an intended load for a scaffolding should be carefully determined in order to ascertain the proper dimensions of each component. Otherwise the structure may collapse when a large load is applied (B46 and B56). The minimum dimensions of the planks in a form type of scaffolding and their maximum lengths are described in the standards of OSHA [1990]. At least two- by ten-inch planks and two by nine inch (52x229 mm) planks should be used for a wooden bracket and a metal bracket type of form scaffolding, respectively (B47). The permissible plank length for both types is eight feet (2.44 m) (B48).

Additional causes are related to the inadequate design of the brackets. Because metal brackets are usually provided together with form materials by a manufacturer, government regulations do not mention them, and the manufacturer's specifications should be followed. However, the minimum dimensions and maximum spacing of all the members of a wooden bracket are standardized by OSHA. The dimensions of support ledgers, braces, and uprights should be more than two by six (51x152 mm), one by six (25.4x152 mm), and two by four inches (51x101 mm), respectively (B57, 58, and 59). In addition, the spacing of brackets should not be over eight feet (2.44 m) (B510).

The maximum width of a form type of scaffolding is 3.5 feet (10.67 m) (B511) [OSHA 1990]. Furthermore, an engineer who designs the formwork should consider the load of a form scaffolding. However, inadequate design causes of formwork were not investigated because this study is limited to scaffolding structures.

Defective Components The third type of enabling causes involves defective components. Any defective material related to the planks or the brackets in any component of form scaffolding could cause a fall (B33 and B414). For instance, it is easy to see rusty metal brackets on scaffolding. Metal components are apt to rust, and they are usually used without being treated, because they are temporary materials. To prevent a fall due to a defective material, all the components of a form scaffolding should be maintained in a sound condition and replaced or repaired as soon as their faults are discovered.

4.2.9.3.2 Supporting Causes

The planks are the first support-related causes to investigate, because they most directly support a worker. They are expanded into "planks enabling," "planks triggering," and "planks supporting" causes. Enabling and triggering causes have already been discussed above. "Planks supporting" causes are further subdivided into "brackets enabling," "brackets triggering," and "brackets supporting" causes. In the same way, "brackets supporting" causes are related to the formwork.

4.2.9.4 Causes of Falls from a wood Pole Scaffolding

A wood pole scaffolding may be either a single pole or double pole scaffolding. A single pole scaffolding has a single row of poles along the outside length of the scaffolding; putlogs (to be explained later in this section) are supported by these outside poles and the wall of a building. A double pole scaffolding is an independent scaffolding which has two rows of poles, inside and outside.

In both types of wood pole scaffolding, a worker is supported by planks making the platform. The platform rests on bearers which, in turn, are supported by ledgers. Bearers are horizontal members of a scaffolding; in the case of a single pole scaffolding, they are called putlogs. Ledgers (stringers) are also horizontal scaffolding members; they extend from post to post at right angles to the bearers or putlogs. Bearers and ledgers are supported by poles, and finally a load is transferred to the foundations. Because the failure of any component of a wood pole scaffolding may lead to a construction fall accident, each component was analyzed to identify the support-related causes of falls.

As in Section 4.2.9.1, worker support-related causes are classified into each component's enabling, triggering, and support-related causes of fall accidents. However, the triggering causes are excluded from the following discussion, as they are similar to those discussed earlier.

4.2.9.4 Enabling Causes

Enabling causes related to each component are internal causes leading to the failure of a scaffolding structure. They can be subdivided into inadequate erection, inadequate design, defective components, and inspection problems. Inspection problems are excluded in this section, because they are similar to those in Section 4.2.9.1.

Inadequate Erection Some inadequate erection causes are related to the planks. All platform planks should be secured to the bearers to prevent movement. Improper fixing to the bearers could allow a plank to give way under a worker's weight and lead to a fall (B42). Planks should also overlap bearers at least twelve inches (304.8 mm); otherwise, they may move, and a worker may fall through an opening between them (B41). For the same reason, inadequate expansion of planks over end supports may lead to a fall accident (B43). According to the standards of OSHA, planks should expand over end supports no less than six inches (152 mm) and no more than twelve inches (304.8 mm). Where the ends of planks abut each other to form a flush floor, the butt joint should be located at the centerline of a pole, and the abutted planks should rest on separate bearers to distribute the load properly (B44) [OBWC 1979]. Furthermore, when moving platforms to the next level, an early removal of old platforms may cause a collapse of the entire wood pole scaffolding structure (B45). So, the old platforms should be left undisturbed until the new bearers or putlogs have been set in place, ready to receive the platform planks.

Other inadequate erection causes are related to bearers and ledgers. These should be set so that their greater dimension is vertical in order to utilize the whole strength of the timbers. Otherwise, they may be broken when a large load is applied, and a worker may fall (B51). In regard to the ledgers, because they receive a tremendous load from above, they should not be spliced between the poles (B54). Additionally, bearers should be long enough to project over the ledgers of the inner and outer rows of poles. Otherwise, they may cause fall accidents (B53). Finally, poor tie-up of either bearers or ledgers may also lead to a worker fall (B52).

Furthermore, there are causes of fall accidents related to inadequate pole erection of a wood pole scaffolding. It is very important for all poles to be set plumb to keep a scaffolding structure rigid (B61). In addition, a wood pole scaffolding should be securely guyed or tied to a permanent structure. Otherwise it may collapse when there is a strong gust of wind or the impact of equipment (B62). According to OSHA standards, when the height or length of a wood pole scaffolding exceeds twenty-five feet (7.62 m), the scaffolding should be secured at intervals no greater than twenty-five feet (7.62 m) vertically and horizontally. And, when it is necessary to splice the poles, their ends should be squared and the upper section should rest squarely on the lower section (B71). To prevent a collapse of an entire scaffolding structure, we also have to pay much attention to the pole splicing. Inadequate installation of the splice plates may lead to a fall accident. Their length should be at least four feet (1.219 m), and they should cover two or more adjacent sides of the poles (B82 and B83) [OBWC 1979]. Additionally, according to the OBWC, they should have the same width and strength of the poles (B81 and B84). In regard to the bracing, diagonal, cross, and diagonal face bracing should be installed properly to prevent the movement and buckling of poles (B64, B65, and B66). Cross bracing should be installed between inner and outer sets of poles, and a full diagonal face bracing should be erected in both directions across the entire face of a pole scaffolding [OBWC 1979].

Finally, some inadequate erection causes are related to foundations and soil. Poles should be securely nailed to the mud sills to prevent movement (B616). They should be connected by nailing so as to prevent their movement. Additionally, the ground should be even and the soil sufficiently compacted to keep a mud sill from breaking and leading to a fall accident (B72 and B73).

Inadequate Design The second essential type of enabling causes is inadequate design. Even if we are able to eliminate all possible erection causes of fall accidents, an accident may still occur if the wood pole scaffolding is not be designed properly. According to OSHA, this type of scaffolding should be designed to be capable of carrying at least four times a maximum rated load. The scaffolding's intended load should be carefully determined. Otherwise, it may collapse when a large load is applied (B46, B55, B67, and B615).

There are some potential inadequate design causes related to the planks. All planks should be Scaffolding Grade, or the equivalent. The maximum permissible spans for two by ten inch (51x254 mm) or wider planks are as shown in Table I-4.3 in Section 4.2.9.1. If the standards are violated, the planks may break during construction work when a large load is applied, and a worker may fall.

For the same reason, the minimum nominal sizes of planks are set by OSHA. All planks should be two by ten inches (51x254 mm), except for light duty scaffolding planks under twenty feet (6.096 m) high, which should be at least one and a quarter by nine inches (32x229 mm) (B47). The maximum permissible span for this latter size of planks is four feet (1.219 m) (B48).

Some other inadequate design causes are related to bearers, putlogs, and ledgers. The minimum nominal sizes of these three horizontal components are shown in Table I-4.5.

Table I-4.5 Minimum Nominal Sizes of Horizontal Members [OBWC 1979]

DESCRIPTION	**LIGHT DUTY (TO 20 ft / 6.10 m HIGH)**	**LIGHT DUTY (TO 60 ft / 18.29 m HIGH)**	**MEDIUM DUTY**	**HEAVY DUTY**
PUTLOG (TO 3 ft / 0.914 m WIDTH)	2x4 inches (51x102 mm)	2x4 inches (51x102 mm)	2x10 or 3x4 inches (51x254 or 76x102 mm)	2x10 or 3x5 inches (51x254 or 76x127 mm)
PUTLOG (TO 5 ft / 1.524 m WIDTH)	2x6 or 3x4 inches (51x152 or 76x102 mm)	3x4 or 2x6 inches (51x152 or 76x102 mm)		
BEARER (TO 3 ft / 0.914 m WIDTH)	2x4 inches (51x102 mm)	2x4 inches (51x102 mm)	2x10 inches (51x254 mm)	2x10 inches (51x254 mm)
BEARER (TO 5 ft / 1.524 m WIDTH)	2x6 or 3x4 inches (51x152 or 76x102 mm)	2x10 or 3x8 inches (51x254 or 76x203 mm)		
LEDGER (FOR SINGLE)	1x4 inches (25.4x102 mm)	1.25x9 inches (31.75x229 mm)	2x10 inches (51x254 mm)	2x10 inches (51x254 mm)
LEDGER (F/ DOUBLE)	1.25x4 inches (31.75x102 mm)	1.25x9 inches (31.75x229 mm)		

A wood pole scaffolding of lower than sixty feet (18.288 m) should be designed in accordance with this table (B57). When it is over sixty feet (18.288 m) high, it should be designed by a professional engineer competent in this field and should be erected in accordance with the design. Additionally, inadequate spacing of the horizontal members may lead to a structural collapse (B56). According to OSHA, their maximum spacing is nine feet (2.743 m), seven feet (2.134 m), and six feet (1.829 m) for light duty, medium duty, and heavy duty scaffolding, respectively. Light duty scaffolding means a scaffolding designed and constructed to carry a working load of no more than 25 pounds per square foot (121 kg/m^2) [OBWC 1979]. A working load of a medium duty and a heavy duty scaffolding should be between 25 psf (121 kg/m^2) and 50 psf (242 kg/m^2), and 50 psf (242 kg/m^2) and 75 psf (363 kg/m^2), respectively.

Every putlog should be designed to be reinforced by a steel strip secured to its lower edge along its entire length. Otherwise it may be damaged and then lose its strength (B510). Ledgers also should be reinforced, by bearing blocks fastened to the sides of the poles to form supports for the ledgers (B511) [OSHA 1990]. Furthermore, the width of a wood single pole scaffolding should not exceed five feet (1.524 m). Because the minimum nominal size of each member (Table I-4.5) is determined for the maximum five-foot (1.524 m) scaffolding width, the structure may collapse when the width of a scaffolding is greater (B512).

There are also causes of fall accidents related to the inadequate pole design of a wood pole scaffolding. Poles should be designed in accordance with Table I-4.6. Otherwise the entire scaffolding may collapse (B68). In addition, the proper spacing of poles is also important to prevent a collapse of a structure (B69). The maximum spacing of light duty, medium duty, and heavy duty poles is ten feet (3.048 m), eight feet (2.438 m), and six feet (1.829 m), respectively. As mentioned before, the maximum height of a pole of this scaffolding is limited to sixty feet (18.288 m) (B611). Finally, the proper distance (usually four inches/102 mm) between the scaffolding and a permanent structure should be considered when a scaffolding is designed (B610).

Table I-4.6 Minimum Nominal Sizes of Poles [OBWC 1979]

DESCRIPTION	**LIGHT DUTY**	**LIGHT DUTY**	**MEDIUM DUTY**	**HEAVY DUTY**
SINGLE POLE	2x4 inches (51x102 mm)	4x4 inches (102x102 mm)	4x4 inches (102x102 mm)	4x6 inches (102x152 mm)
DOUBLE POLE	2x4 inches (51x102 mm)	4x4 inches (102x102 mm)	4x4 inches (102x102 mm)	4x4 inches (102x102 mm)

Defective Components The third and final type of enabling causes involves faulty components. Even if a scaffolding is designed and erected very carefully, an accident may still occur unless all defective materials are replaced (B33, B415, B518, and B614). Because the materials of a wood pole scaffolding are reused several times, those that are defective are easily seen. All the materials of a wood pole scaffolding should be maintained properly and replaced as soon as their faults are discovered.

4.2.9.4.2 Supporting Causes

Besides the enabling and triggering causes, a fall accident may occur due to support-related causes. These causes are related to the failure of scaffolding components that support a worker who is performing a job. As explained before, a worker is directly supported by planks. So, the first worker support-related causes are related to the planks. These are classified into planks enabling causes, planks triggering causes, and planks support-related causes. Planks enabling and triggering causes have already been explained above; planks support-related causes are further subdivided into bearer enabling causes, bearer triggering causes, and bearer support-related causes. In the same way, bearer support-related causes are related to pole causes, and pole support-related causes are related to foundation and soil causes.

4.2.9.5 Causes of Falls from a Tubular Welded Scaffolding

A tubular welded scaffolding (also called a fabricated tubular frame scaffolding) consists of two types of components: prefabricated welded sections (metal panels) which serve as posts and horizontal bearers, and braces which serve to secure those metal panels together and to square and align the members of the scaffolding. Pin connections are usually used to link panels as well as panels and braces.

Planks are the first component of a scaffolding to support workers. They are supported by the horizontal members of metal frames. Through these metal frames, the load from above is transferred to the foundations. To figure out the support-related causes of falls, planks and metal frames must be analyzed. As in the previous section, the inspection problems of the enabling and triggering causes are excluded, because they are similar to those described in Section 4.2.9.1.

4.2.9.5.1 Enabling Causes

As in the previous section, the enabling causes are classified into each component's inadequate erection, inadequate design, defective materials, and inspection problems. Because the inadequate erection and design causes of planks are similar to those of a tube and coupler scaffolding, they are only described briefly.

Inadequate Erection Some inadequate erection causes are related to the planks. First of all, the planks should be securely fastened to the horizontal members of metal frames (B41). Additionally, the full width of platforms should be covered with planks to prevent a worker from falling between them (B42). Furthermore, planks should sufficiently extend over end supports to avoid the failure of platforms (B43). Finally, the misuse of planks could be a cause of a fall (B45). According to OBWC, all planks used for a scaffolding should be Scaffold Grade (or the equivalent), approved by WWPA specifications.

Some other inadequate erection causes are related to the metal frames. The horizontal members of metal frames, which are used for bearers, should be located at even heights, panel to panel. Otherwise planks cannot be installed correctly, and this could cause a fall (B51). Additionally, the distance from panel to panel should be consistent for all panels used for a scaffolding. Otherwise the braces cannot be installed correctly (B53). Because all members of metal frames are connected with metal pins, missing pins could lead to the collapse of an entire structure (B52).

In regard to the bracings, improper or lack of installation could cause a fall (B54). Diagonal and cross bracings are usually installed at each metal panel, but they should be installed in accordance with the manufacturer's manual, because they serve to secure the metal panels together. In addition, an erected scaffolding should always be plumb and square to keep it rigid (B55 and B56). Furthermore, the entire scaffolding should be secured to a building or other structure at intervals not to exceed thirty feet (9.144 m) horizontally and twenty-six feet (7.925 m) vertically [OSHA 1990]. Otherwise the whole structure may collapse when a strong wind blows on it or equipment like a crane hits it (B57). Finally, the misuse of frame material could lead to a fall (B58). If metals from different manufacturers are used together, the structure may fail because of a different connection method or a different thermal expansion coefficients for each metal. Because frame supporting causes, which are foundation problems, are the same as those described in Section 4.2.9.1 for a tube and coupler scaffolding, they are not elaborated here.

Inadequate Design A tubular welded scaffolding is the most widely used scaffolding in the industry, because it is easy to erect and dismantle. However, the shape, size, erection methods, and connection methods of these metal frames differ from manufacturer to manufacturer. So, the proper type of material for a specific construction job should be carefully selected from among ready-made products (B59). Additionally, in accordance with OSHA, the maximum height of this type of scaffolding should be limited to 125 feet (38.10 m) (B511). When it is necessary to install a scaffolding of a greater height, it should be designed by a registered professional engineer [OSHA 1990]. Next, if the distance between a scaffolding and permanent structure is too close, a worker may not perform a job properly. However, if that distance is too far (usually, more than four inches/102 mm), a worker may fall through the opening between them (B510).

Some other inadequate design causes of falls are related to inadequate design load, thickness, or length of the planks (B46, B47, B48, and B516). Because the causes of planks for a tubular welded scaffolding are similar to those for a tube and coupler scaffolding, they are not elaborated here; the reader is directed to Section 4.2.9.1 for more details.

Defective Components Any defective component could cause the failure of a structure (B33, B414, and B515). For instance, the frame of this type of scaffolding can be easily bent when it is stored or moved from one construction site to another. A bent frame is usually crudely stretched and repainted on-site to cover the marks of the bending. The treated frame looks adequate, but it could lead to a structural collapse. Therefore, an engineer should inspect all the components of a scaffolding before erection, and replace them as soon as possible if any faults are discovered.

4.2.9.5.2 Supporting Causes

Workers are first supported by planks. All the possible enabling and triggering causes of falls from planks have been described above. The second component which supports workers is the metal frame. So, "planks supporting causes" are divided into "metal frame enabling," "metal frame triggering," and "metal frame supporting" causes. In the same way, "metal frame supporting " causes are related to foundation and soil causes.

4.2.9.6 Causes of Falls from a Mobile Scaffolding

A mobile scaffolding is a portable rolling scaffolding equipped with casters which is usually used for interior finish work in building construction. This structure consists of a tubular welded scaffolding and four wheels. So, its support-related causes of falls are the same as those of a tubular welded scaffolding, as described in the previous section, but with two additions: causes related to the wheels and to the scaffolding height. Only these support-related causes are described in this section. In addition, some causes related to workers' inadequate activities are also identified.

Insufficient strength of wheels could cause a fall (B419). According to OSHA, all casters should support at least four times the maximum intended load. Furthermore, they should be bolted or welded to the frames. Otherwise they could be disconnected from the scaffolding, and this may lead to a fall (B420).

This type of scaffolding should not be higher than four times the minimum base dimension [OSHA 1990]. Because the ratio of length to width is usually two to one, four layers of metal frames are the maximum. Two layers of metal frames are usually used in a job site.

Besides these worker support-related causes, inadequate activities performed by workers may also lead to a fall accident. When it is necessary to change the location of a mobile scaffolding, a worker should either get down or stop working and firmly hold the guardrails during the move. Otherwise he or she may lose his or her balance and fall (B41). Additionally, all the wheels should be equipped with a locking device to hold a scaffolding in position [OSHA 1990]. If a worker forgets to lock these devices before starting work on a scaffolding, a fall could result (B42). Furthermore, in accordance with OSHA, a ladder or stairway should be provided for proper access to or exit from a scaffolding. When a large mobile scaffolding is used, the landing platform should be attached to the ladder or stairway at least every thirty-five feet (10.67 m) (B43) [OSHA 1990]. Finally, the working floor should be leveled to a slope of no more than three degrees. Otherwise a worker may fall during the move of a scaffolding (B44).

4.3 Causes of Falls From the Same Level

When a fall starts and ends on the same level, it is within this section's classification. The frequency of falls on the same level is high; however, their severity is generally low. The minor injuries resulting from them are usually sprains and strains. Regardless of the working surface, the worker-related causes of falls from the same level are similar to those described in Section 4.2.1, and none of them is due to a lack of fall protection/prevention devices. However, in order for these falls to occur, other safety problems must be present in the site (e.g., failure to keep the working area clean and clear of obstacles).

In addition to the more general worker-related causes discussed above, there are four more specific and important cases of falls on the same level: slippery conditions, falling material or equipment hitting a worker, medical reasons (e.g., fainting, dizziness), and trips. Of these, the causes of falls due to slippery conditions are examined in the next section. Falls due to any kind of impact are within the category of triggering causes. However, in order for this type of accident to occur, a safety problem must also exist, e.g., a lack of overhead protection to protect a worker from falling objects, or a case in which a worker is hit by equipment due to the poor definition of work zones. If the worker is within the equipment work zone which he or she has been instructed to avoid, the accident cause may be a worker attitude problem (i.e., personality). However, if the worker is within his or her work area, the accident may be an operator's fault and may fall within the scope of any of the enabling causes previously discussed (attitude, health, or skill). If the accident is not an operator's fault, it may be caused by a loss of control of the equipment, and this, in turn, may be caused by poor maintenance (i.e., safety problem).

Finally, a trip is defined as "a loss of balance due to the foot (or leg) contacting an object or obstruction" [Ellis 1989]. Ellis also adds that, on occasion, too much friction between a shoe and a working surface may also cause a trip. In general, a trip can be due to materials or objects left on the ground, to minor changes in elevation within the surface, and to small openings left unprotected. All of these problems could be prevented by a good safety program, which includes good worker training (so that everyone knows where to place tools and store materials), good planning to define storage areas and open traffic areas for workers, and making sure that places where there are openings or changes of elevation are protected.

4.4 Causes of Slips

This section studies the case in which a worker slips but regains his or her balance or catches him or herself before falling. Usually, this type of accident is minor, resulting in, for example, a back injury. In most cases, however, this type of accident results in no injuries, and, therefore, very few of them are reported. In the construction industry such accidents are often ignored.

When the friction between a shoe and a working surface is inadequate, a worker may lose his or her balance and either fall or slip. The use of inadequate footwear is a common cause of slips on the construction site. The sole, heel, and shape of a shoe should provide adequate surface contact to control slips. All workers should be required to wear adequate work shoes; failure to do so may be considered a general safety problem.

Another cause of slips is the presence of small objects (e.g., small beads, gravel, rocks) on the floor. The worker may step on these objects lose his or her balance, and slip or fall. This mishap is a common occurrence in the construction industry. A final common cause of slips is a change of friction between working surfaces. Such friction changes may be due to the presence of different types of adjoining surface materials (e.g., concrete next to a tile floor), or they may result from spills on the working surface. The surface area where spills have occurred has a lower coefficient of friction than a dry surface does. A solution to both of these problems may be the use of mats and protective coatings to help deal with wet or more slippery surfaces. Another solution is to provide the workers with enough training so that they can identify such hazardous conditions and take appropriate measures.

Among the worker-related causes discussed in the section "Causes of Falls from Higher Elevation," the worker enabling causes are important, because in order to avoid slips the worker should be in top shape, both physically and psychologically. For example, if a worker is distracted, he or she may not notice a spill and slip, as a consequence. As for triggering causes, some of the environmental causes (e.g., rain, snow, and frost) are capable of creating slippery conditions if a working surface is exposed to the elements. Finally, impact-related causes are of little significance for slips, unless they are combined with other safety problems (e.g., surface not clear of debris or spills).

CHAPTER 5
SUMMARY AND CONCLUSION

5.1 Summary

Prior to the development of SAFETY FIRST, common possible and potential causes of unintentional construction falls occurring during construction operations were identified. The knowledge for SAFETY FIRST was obtained through a knowledge acquisition process. The knowledge from literature includes fall- and safety-related causes was acquired from codes, standards, and pertinent reports. Several articles we encountered during our study are reports or news releases of construction worker accidents, statistics of such accidents, and regulations and codes to avoid construction falls.

A knowledge acquisition process also involves selecting, meeting, interviewing, and procuring experts knowledge. For SAFETY FIRST, the process encompassed eliciting knowledge from domain experts and organizing the knowledge for use in the development of fault tree models. The study in Volume I was performed during the first year of the project period; however, communication with experts and updates from current literature were continued until the end of project period.

The parties involved in the knowledge acquisition process were the knowledge engineers and experts. All authors acted as the knowledge engineers. The knowledge engineers can be divided into two groups: the knowledge elicitors (those who interview the experts and elicit their knowledge) and the knowledge programmers (those who convert the knowledge into a computer software). The experts are those whose knowledge and experience in a given domain are incorporated into the knowledge base of SAFETY FIRST. These experts are recognized as knowledgeable in the general area of safety, and specifically, in construction falls.

The knowledge acquisition process for this project was divided into four phases: the preliminary, intermediate, advanced, and organization phases. In this study, the preliminary phase included analyzing the project's feasibility, performing a review of the existent literature, and choosing, contacting, and interviewing experts for the project. During the intermediate phase, the knowledge engineers focused on experts' knowledge regarding the subject matter (construction falls). In this phase, a questionnaire was developed with the objective of acquiring more specific information from the experts, reviewing this information, and after several interviews, creating a general representation of the experts' thought processes.

The advanced phase allowed the knowledge engineers to refine the knowledge by going over specific details which needed to be clarified or which caused disagreement among the experts. Finally, the organization phase acted as a link between the knowledge acquisition task and the fault tree development task. In this phase, the knowledge acquired from the experts was converted into preliminary graphic models to represent the experts' knowledge regarding the causes of construction falls. The process was followed by the development of the graphic fault tree models discussed in Volume II of this study.

After consulting with our experts, it was decided that fall accidents from floor edges, floor openings, roofs, top of a wall, wall openings, steel beams, ladders, and scaffolding structures (tube and coupler, suspended, form, wood pole, tubular welded frame, and mobile) were significant enough to be considered and have their fault trees developed. For this study, the scope of falls was limited to those that occur during vertical construction operations, such as during building or residential homes construction. Hence, events such as falls during bridge construction, falls during trench operations, and falls from utility poles are beyond the scope of this study.

Further, the focus of this study was on the worker-related causes of construction falls, including enabling, triggering, and support related causes. Out of these, the worker enabling (causes of fall internal to the worker) and worker triggering (causes of fall due to external events acting on the worker) causes were explored in detail. In addition, the conditioning causes of falls (mainly due to safety problems which varied depending on the type of falls and hazardous components) were also investigated.

Finally, since the knowledge for SAFETY FIRST was acquired qualitatively from experts and literature, quantitative analyses are beyond the scope of our study. Hence, the results and conclusions presented in the next section are based on the experts' opinion, experience, heuristic judgment, educated guesses, rules-of-thumb, codes, regulations, and standards.

5.2 Conclusions

Although injuries, illnesses, and deaths during construction occur at a rate that is 54% higher than the rate for all industries, our study of the literature reveals that causes of construction. worker accidents, and in particular, construction falls are seldom discussed in detail. Besides falls from higher elevation, this study discusses the causes of slips and falls from the same level. While the frequency of occurrence of these types of accidents is higher, their severity is usually lower than that for higher elevation falls. In fact, according to our experts, because of the light consequences (if any) of their occurrence, cases in which the worker slips but does not fall are seldom reported, and therefore few statistics are available regarding this type of accident.

We also found that the basic causes of falls that are related to the worker are similar for all components; however, the significance of the causes varied depending on the component or type of fall being studied. Further, the conditioning causes of falls varied both among elevated components and types of falls. The emphasis of the conditioning causes for falls from higher elevation is on the fall protective or preventive devices provided on the site. In contrast, for same level falls and slips, the focus of conditioning causes is on the general safety measures in the working area, such as whether or not overhead protection was provided to prevent the worker from being hit by falling materials which, subsequently, would cause the fall, or whether or not the working area was kept clean and clear from spills which, in turn, could cause the worker to slip and fall.

More specifically, our study reveals the following potential causes of construction falls:

1. We found that the basic causes of falls as they relate to the worker could be classified into enabling, triggering, and support related. The enabling causes are causes of falls internal to the worker like behavioral, physical and psychological, or social problems. These problems were grouped into attitude problems, which are problems that are caused by the worker's attitude towards his or her job; health problems, which are physical problems that suddenly or over time affect the worker and cause the fall; and skill problems that are related to the capacity of the worker to recognize latent hazards on the site.

2. The attitude problems can be further divided into the following problems: cases in which the worker is not in full control of all of his or her senses, such as when he or she is drugged (after using an illicit drug like cocaine) or drunk; cases when the worker's personality causes his or her fall, for example when he or she does not follow the supervisor's instructions or ignores established safety procedures; and cases when psychological (stress, personal, or financial problems) or environmental (related to events happening in work zone surroundings) distractions cause him or her to fall.

3. Health problems include cases in which the worker falls due to a sudden illness that could result in a collapse and fall. Examples of sudden illnesses are heart attacks and fainting. Another cause of falls is a chronic illness that acts on the worker over time, weakens and causes his or her concentration and the ability to recognize hazards to diminish. Finally, another cause that appears among the health problems is the case when the worker used over-the-counter drugs that caused him or her to be drowsy or sleepy during a construction operation.

4. The final group of enabling causes includes problems with the worker's skill. Because of these problems the worker does not recognize hazards or know how to react when an incident out of the ordinary happens. These problems happen when the worker lacks training or experience. All experts agreed that the more experienced the worker, is the less likely he or she is to fall. The worker's experience allows him or her to identify hazards and to know what measures to take to avoid the fall. However, experts warned that some times experienced workers get overconfident and careless. If that is the case and the worker falls, we can classify this fall within the attitude causes of fall. Finally, a lack of skill by the worker may be caused by problems with the worker's capacity to learn from experience and training. This case would be

similar to the case in which the worker falls due to lack of training or lack of experience.

5. The triggering causes affecting the worker include any external event acting on him or her and causing the fall. Under these causes we studied the potential of having a worker hit by another worker, by a piece of material, or by a piece of equipment, and when environmental conditions are the cause of fall. Under the environmental conditions, we include any natural event that could lead to the worker's fall, including strong winds (gusts), rain, hail, snow, frost, fog, extreme cold, and extreme heat. These factors can lead the worker to fall in different ways. The gust or strong wind may cause the worker to fall due to its impact force. Fog may reduce the worker's visibility and cause his or her fall, whereas others like rain and frost may cause slippery conditions which favor the occurrence of falls. Extremely cold or hot conditions could be the cause of accidents just by reducing the concentration and care with which the worker performs his or her job.

6. The support related causes are causes of falls related to the component supporting the worker while he or she performs a job. These causes vary depending on the component assumed to be supporting the worker. These support components are defined for each of the fault tree structures developed. Since the focus of this study was on worker related causes of fall, these causes were not developed in great detail, and in most cases were merely mentioned. This is especially true for elevated components. In the case of same level falls and slips (not falls), these causes are important since many of these falls are due to problems with the support components.

7. The conditioning causes are secondary causes. The presence of these causes enables the basic causes to be a factor in the worker's fall. However, these causes alone can not cause the worker to fall. Usually, these causes are related to safety problems. In the case of falls from higher elevation, these causes are mainly related to the fall safety systems on the site. Two main problems relate to the fall systems. The first is when no fall protection or prevention devices are provided to prevent or reduce the chances of worker fall accidents. The second problem is when the fall protection or prevention device provided is not adequate. These problems vary depending on the device being used and may include problems due to inadequacy in its use, installation, material, and/or design. Among the fall protection or prevention devices often used in elevated components are standard guardrails, intermediate rails, safety belts, body harnesses, warning lines, opening covers, safety nets, and catch platforms.

8. In the case of same level falls and slips (not falls), this study shows that the lack or inadequacy of any of the fall prevention or protection devices is not significant. The conditioning causes related to general safety problems in the working surface are more important. For example, falls from the same level may be caused by falling materials hitting the worker. In this case, the falling material has to come from another working surface, and overhead protection should have been provided for the lower surface. The lack of this protection would be a conditioning cause of the fall. The failure to keep the area clear from obstacles that could cause trips is also included among these conditioning causes. Spills and small objects on a floor could also cause

the worker to slip and possibly fall. These accidents are considered conditioning causes of fall since they could be prevented by good housekeeping and maintenance of the working area, and other safety procedures like marking the hazardous area with signs or barriers so that workers can be more cautious while working on the floor.

Other salient features regarding the causes of unintentional worker falls that were obtained from this study are as follows :

1. Triggering causes due to environmental factors (rain, fog, etc.) often play a significant role in causing falls from roofs, steel beams, and tops of the walls. This is due to the fact that such components are usually exposed to these factors.
2. For steel beams, tops of walls, and portable ladders, the significance of both the enabling and the triggering causes is increased due to the space limitations in the working area. There is usually little space and time to react to hazards.
3. If a roof is surrounded by a wall of at least 3 feet (.914 m) high, there is no need to provide additional protection along the edge. Skylight openings of a roof should be protected, otherwise lack of such protections could be a conditioning cause of falls.
4. For portable ladders, enabling causes (attitude or skill) play an important factor in worker falls. If the ladder is not high enough or incorrectly placed, a worker may have a tendency to over-reach from the ladder and, in turn, may cause the worker to fall. For a self-standing ladder, the worker's tendency to stand or sit on the ladder top is also a common problem.
5. Fall protection or prevention devices are rarely used for portable ladders. However, experts recommend that the worker should always keep three contact points with the ladder (two hands and a foot, or two feet and a hand). If the worker needs both hands to perform his or her job experts recommend the use of safety belts or body harnesses.
6. For falls from same level, slips, trips, and triggering (impact) causes are the main causes of falls.
7. For slips, the main cause of falls is the low friction between the shoe and the working surface. In addition to the presence of spills and small objects on the floor, another significant cause of slips is the use of inadequate shoes at the work site.

The causes of falls from scaffoldings were classified into the enabling and triggering causes of the scaffolding components. The enabling causes are internal causes leading to the failure of a scaffolding components, while the triggering causes include external events acting on a scaffolding component. Each cause was expanded to reach the basic causes requiring no further development. Since a worker is directly supported by planks in any scaffolding, "worker support causes" were divided into "planks enabling," "planks triggering," and "planks supporting" causes. Each component's enabling and triggering causes were further expanded to reach the basic causes. Hence, "planks supporting" causes were further subdivided into the enabling, triggering, and supporting causes of the next supporting component, such as the bearers. Different scaffoldings may have different components, and therefore, different causes were identified. However, common potential support related causes for scaffolding structures incorporated into this study are due to inadequate erection procedures. They are described as follows:

1. Any component of a scaffolding that is not securely fastened to the next supporting component may lead to a fall. For example, if the planks are not fixed to the bearers, a worker may fall through an opening between them.
2. Inadequate splicing may lead to the collapse of a scaffolding. This happens, for instance, when poles in a wood pole scaffolding are not spliced with splice plates having the proper size, shape, number, and strength.
3. The misuse of a component may cause a fall. For example, if steel tubes from different manufacturers are combined in a tube and coupler scaffolding, the structure may fail because of a different connection method or a different thermal expansion coefficient for each metal.
4. A missing component may lead to a fall. If, for instance, just one pin in a tubular welded scaffolding is missing, the entire structure may collapse.
5. The incorrect location of components may cause a fall. For example, if the runners are located at uneven heights both inside and outside the posts along the length of a tube and coupler scaffolding, and the connections for the bearers and runners are not located close to the posts, the runners receive loads from the bearers and planks at improper places and may break while a worker is performing his or her job.
6. If a scaffolding is not set plumb, it may become unstable and lead to a fall.
7. Improper installation of bracings may lead to the movement and/or buckling of a scaffolding, which may result in a fall.
8. Uneven and insufficient soil compacting may cause a mud sill to break and the worker to fall.
9. If an entire scaffolding is not tied to a permanent structure, it may collapse when a strong wind blows on it or equipment, such as a crane hits the scaffolding.

Some other causes are related to inadequate design. Frequently, a scaffolding is not built based on construction drawings. However, it should be erected in accordance with the OSHA standards, which define the minimum strength, size, and spacing of each component, and the maximum height and width of each scaffolding. Because any violation of these standards could lead to the failure of a scaffolding, an engineer should thoroughly understand and follow these standards. In addition, all types of scaffoldings, except a suspended scaffolding, should be designed to be capable of carrying at least four times a maximum rated load without a failure [OSHA 1990]. The suspension system of a suspended scaffolding should have at least six times a maximum rated load. An intended load should be carefully determined to select proper design factors, such as the spacing and size of components. Especially if a scaffolding is to be used by several sub-contractors in a job site, all of its intended loads should be taken into account when determining the dimensions and the spacing of each of its components. Otherwise, it may collapse if a larger load than anticipated is applied, and a worker may fall. Finally, an improper distance between a scaffolding and a permanent structure could cause a worker to fall through the opening between them. A distance of around four inches (101.6 mm) is usually considered proper.

The triggering causes of falls related to a scaffolding are grouped into human-induced and nature-induced impacts. Human-induced impacts include the impact of equipment and material. Nature-induced impacts include strong wind (gusts), hail, rain, and melting snow. A strong wind or hail may cause a worker to fall due to its impact force on each component of a scaffolding. Soil under a mud sill may be eroded when rain falls or snow melts and, consequently, lead to a scaffolding collapse. Any of these impacts may lead to a worker fall. Other notable causes leading to falls from scaffoldings are as follows:

1. Any defective component material could be a cause of a scaffolding failure. Because scaffolding components may be reused several times, many of them could become defective. Therefore, scaffolding components should be maintained in a sound condition.
2. Inspection of all parts of a scaffolding should be performed thoroughly before their use. Any damaged or sub-standard components should be repaired or replaced. Additionally, inspection should be made of each component and joint of a scaffolding immediately after its erection.
3. When a scaffolding is used by several sub-contractors for different purposes, an engineer should monitor the scaffolding to guarantee its correct usage.
4. An access scaffolding used as a supporting scaffolding, such as a shoring, may collapse since, in general, it is not designed for this purpose.
5. The combination of components from different fabricators with different design concepts may lead to a fall. In many cases, components are rented separately by a company and then they are incorporated into a scaffolding. Renting a complete scaffolding is recommended to reduce the risk of an accident. In addition, the proper type of scaffolding for a specific construction job should be carefully selected from among ready-made products.

Finally, the identification of the causes of construction falls from hazardous working components most frequently encountered during construction operations is expected to benefit those concerned with construction safety to take appropriate countermeasures in order to reduce the number of falls, and eventually, to achieve a safer working environment. For SAFETY FIRST, these causes are organized, used, and modeled as fault trees as described in the next volume.

APPENDIX I-A

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APPENDIX I-B

GLOSSARY

ACCIDENT: An unplanned event which has a probability of causing personal injury or property damage [King and Hudson 1985].

ANCHORAGE: A secure point of attachment for lifelines, lanyards, or deceleration devices [ANSI 1991].

ARRESTING FORCE: The force generated by arresting the test weight that is transmitted through the fall arresting system components to the anchorage or load cell [ANSI 1991].

BASIC CAUSE: A basic initiating fault requiring no further development [Roberts et al. 1981].

BEARER: A horizontal member of a scaffolding upon which the platform rests and which may be supported by ledgers [OBWC 1979].

BODY BELT (Safety Belt): A strap that both secures around the waist and attaches to a lanyard, lifeline, or deceleration device [ANSI 1991].

BODY HARNESS: Straps that are secured about an employee in a manner that distributes the arresting forces over at least the thighs, shoulders, and pelvis, with provisions for attaching a lanyard, lifeline, or deceleration device [ANSI 1991].

CATCH PLATFORM: Device erected at the outside edge of the roof and prevents the worker from falling all the way to the ground (usually a scaffolding structure).

CHICKEN LADDER: Specially designed device that looks like a ladder and is used as a crawling board when installed on the roof.

COMPETENT PERSON: Person capable of identifying existing and predictable hazards in the surroundings or working conditions that are hazardous or dangerous to employees, and who has the authority to take prompt corrective measures to eliminate such hazards [ANSI 1991].

CONDITIONING CAUSE: Specific conditions or restrictions that apply to any logic gate [Roberts et al. 1981]. In SAFETY FIRST, they are conditions present on the site which contributed to the fall accident (i.e., safety problems).

CONNECTOR: Device which is used to couple parts of a personal fall arrest system together, or it may be an integral part of the system, such as a buckle or a deering sewn into the belt or body harness.

CONTROLLED ACCESS ZONE (CAZ): Area in which certain work (e.g., overhand bricklaying) may take place without the use of a guardrail system, personal fall arrest system, or safety net system. Access to the zone is limited.

COVER: It covers holes in floors, roofs, and other walking/working surfaces. If located on roadways, they have to be able to withstand the maximum axle load of the largest vehicle expected to cross the cover. Other covers should be able to support without failure at least twice the weight of employees, materials, and equipment that may be imposed on it. They should be secured to prevent accidental displacement and color coded or labeled to identify them [29 CFR 1926.502 (i)].

DECELERATION DEVICE: Any mechanism that serves to dissipate energy during a fall [ANSI 1991].

DECELERATION DISTANCE: Vertical distance a falling worker travels before stopping (excluding lifeline elongation), from the point the deceleration device begins to operate. Distance between the location of the body belt or harness attachment point just prior to the activation of the deceleration device during a fall and the location of that attachment point after the employee comes to a full stop [ANSI 1991].

ENABLING CAUSES: Depending on the component being analyzed, enabling causes are internal problems related to that component. For example, worker enabling causes are causes internal to the worker, such as attitude problems.

FAILURE: Load refusal, breakage, or separation of component parts.

FAULT TREE: A fault tree is a graphic model that shows parallel and sequential causes or events contributing to predetermined top undesired event [Roberts et al. 1981].

FREE FALL: Act of falling before the personal fall arresting system begins to arrest the fall [ANSI 1991].

FREE FALL DISTANCE: The vertical distance an employee falls before the fall arresting system begins to arrest the fall [ANSI 1991].

GUARDRAIL: A temporary barrier which consists of a top rail, an intermediate rail and posts and whose main objective is to provide the worker with support. It is usually placed on unprotected edges and openings where there is a drop of more than 4 feet.

HARNESS: Component of fall arrest system which consists of straps worn by the worker around his shoulders an chess to hold him/her in case of an accident.

HAZARD: A condition with potential for an accident or ill health [King and Hudson 1985].

HEAVY DUTY SCAFFOLDING: A scaffolding designated and constructed to carry a working load in excess of fifty pounds but no more that seventy-five pounds per square foot [OBWC 1979].

JOIST: A steel or wood beam providing direct support for a floor.

LANYARD: A flexible line used to secure a body belt or body harness to a lifeline or directly to a point of anchorage [ANSI 1991].

LEDGER: A horizontal scaffolding member which extends from post to post at right angles to the putlogs or bearers, supports the putlogs and bearers, and forms a tie between posts [OBWC 1979].

LIFELINE: Line provided for direct or indirect attachment to a worker's body belt, body harness, lanyard, or deceleration device. Those lifelines may be vertical or horizontal in application [ANSI 1991].

LIGHT DUTY SCAFFOLDING: A scaffolding designed and constructed to carry a working load of no more than 25 pounds per square foot [OBWC 1979].

LOAD REFUSAL: The point where the ultimate strength is exceeded.

MECHANICAL EQUIPMENT: All motor or human propelled wheeled equipment, except wheelbarrows and mopcarts.

MEDIUM DUTY SCAFFOLDING: A scaffolding designed and constructed to carry a working load in excess of 25 pounds but no more than 50 pounds per square foot [OBWC 1979].

OVERHAND BRICKLAYING AND RELATED WORK: The process of laying bricks and masonry units such that the surface of the wall to be jointed is on the opposite side of the wall from the mason, requiring the mason to lean over the wall to complete the work. Related work includes mason tending and electrical installation incorporated into the brick wall during the overhand bricklaying process [CFR 1994].

PERSONAL FALL ARREST SYSTEM: System used to arrest an employee falling from a working level. It consists of an anchorage, connectors, a body belt or harness, and may include a lanyard, deceleration device, lifeline, or suitable combinations of these. After January 1, 1998, the use of belts for fall arrests is prohibited.

PITCHED ROOF: Roof with some kind of slope involved. OSHA standards differ depending on the pitch or slope of the roof.

PLANK: A heavy board with thickness of 2-4 inches and a width of at least 8 inches [McGraw-Hill, 1984].

PUTLOG: Same as a bearer (see bearer definition).

RETRACTING LINE: An automatic tensioning system that pays out and retracts a line at a certain speed and locks or brakes when that speed is exceeded [ANSI 1991].

ROOF: Exterior surface on the top of a building. This does not include floors or formwork which, because a building has not been completed temporarily become the top surface of a building.

ROOFING BRACKETS: Allow the worker to have a level surface over which he/she can perform his/her job.

ROPE GRAB: A deceleration device that attaches to a lifeline as an anchoring point to provide a means for arresting a fall. The device travels on the line and automatically by friction engages the lifeline and locks so as to arrest the worker fall [ANSI 1991].

SAFE: A working environment is "provisionally deemed as safe if its risks are deemed known and in the light of that knowledge judged to be acceptable" [King and Hudson 1985].

SAFETY BELT: See "Body Belt."

SAFETY NET: Net erected underneath the working surface to catch workers in the case of a fall. Safety nets should be provided when the use of guardrails, catch platforms, or fall arrest devices is not practical or possible. The net should be installed as close as practicable under the walking/working surface on which employees are working, but in no case more than 30 feet below such level. Other regulations for the net erection can be found on the Code of Federal Regulations (CFR), section 1926.502 (c).

SCAFFOLD: A temporary or movable platform supported on the ground or suspended; used for working at considerable heights above the ground [McGraw-Hill, 1984].

SELF-RETRACTING LIFELINE/LANYARD: Deceleration device containing a drum-wound line which can be slowly extracted onto the drum under slight tension during normal employee movement, and which after onset of a fall automatically locks the drum and arrests the fall.

SHOCK ABSORBERS: A component of a system that allows dissipation of energy by extending the deceleration device [ANSI 1991].

SLIP (NOT FALL): A slip results in a sliding motion when the friction between the supporting surface and the foot gear is inadequate. In this case, the accident results in the worker losing his/her balance but not falling [Ellis 1989].

SNAPHOOK: A self-closing device with a keeper, latch, or other similar arrangement that will remain closed until manually opened. This includes locking and non-locking snaphooks.

TOE BOARD: Component of a standard guardrail system consisting of a board with about 4 in. vertical height which is securely fastened to the floor.

TRIGGERING CAUSES: Active external events that cause the worker to fall. For example, the worker is hit by a piece of equipment.

WALL OPENING: A gap or void at least 30 inches height and 18 inches width, in a wall or partition and through which employees can fall to a lower level.

APPENDIX I-C
LIST OF ABBREVIATIONS

B: Basic Cause

BLS: Bureau of Labor Statistics

BWC: Bureau of Workers Compensation

C: Conditioning Cause

CAZ: Controlled Access Zone

CFR: Code of Federal Regulations

CLR-OSU: Center for Labor Research at the Ohio State University

CM: Construction Manager

DOE: Department of Energy

FHA: Fault Hazard Analysis

FMEA: Failure Mode and Effect Analysis

FTA: Fault Tree Analysis

G: Gate

HSE: Health and Safety Executive

MCS: Minimal Cut Sets

NIOSH: National Institute for Occupational Safety and Health

NSC: National Safety Council

NTOF: National Traumatic Occupational Fatality

OSHA: Occupational Safety and Health Administration

PHA: Preliminary Hazard Analysis

APPENDIX I-D

NAME AND BACKGROUND OF THE EXPERTS

The following are the experts (listed alphabetically) who agreed to provide their expert for the development of the SAFETY FIRST decision support system:

- Mr. Dan Feeney. Safety consultant on the safety & hygiene division of the Ohio Bureau of Workers' Compensation. He has about 10 years of experience in the construction industry being involved both as a layman in the site, and lately as a consultant for BWC.
- Dr. Fabian C. Hadipriono. The principal investigator for this project has been working in the construction area for almost 30 years and published over 150 safety and simulation related papers. He is also a member of the Architecture and Engineering Performance Information Center (AEPIC) research center at the University of Maryland, which is involved with worldwide accident cases. Furthermore, Dr. Hadipriono has been working closely for the last eight years with safety experts at SOCOTEC (the world's largest private company for safety and performance control) in Paris, France.
- Dr. Richard E. Larew. A professor in the Construction Engineering and Management department at the Ohio State University. He is a renowned expert in construction accidents and has been working as a forensic engineer for over 40 years.
- Mr. Greg Mather, ALCM. Safety consultant on the safety & hygiene division of the Ohio BWC. He has about three years of experience in the construction industry working on construction sites as a layman and safety consultant.
- Mr. John Sahayda. Director on the industrial safety division of OSHA, Columbus, OH. He is a recognized expert on the area of safety whose experience working for OSHA, and before that, for the Ohio State University as a teacher have proven very important in facilitating the knowledge acquisition process.
- Mr. Mike G. Ypsilantis. Assistant area director of OSHA, Columbus, OH. He has a vast experience in the area of construction safety. Since 1966, he has worked as a safety engineer for an insurance company (i.e., investigating fall accidents), as a safety engineer during the construction of the Sears tower in Chicago, and as an Occupational Safety and Health Administration (OSHA) officer investigating fatality accidents.

All of these experts are recognized professionals in the area of construction safety and we feel that their combined knowledge and experience should provide a good foundation upon which to build the knowledge representation structures needed for the SAFETY FIRST program.

Table D-1 Name and affiliation of experts (summary)

Name	Discipline and Affiliation	Expertise
Mr. Dan Feeney	Bureau of Workers Compensation (BWC)	Safety Consultant
Dr. Fabian C. Hadipriono	Civil Engineering, Construction (OSU)	Construction Safety
Dr. Richard Larew	Construction Management (OSU)	Construction Forensics, Construction Safety
Mr. Greg Mather	Bureau of Workers Compensation (BWC)	Safety Consultant
Mr. John Sahayda	Occupational Safety and Health Administration (OSHA)	Construction Safety and Training
Mr. Mike Ypsilantis	Occupational Safety and Health Administration (OSHA)	Safety Engineer and OSHA Enforcing Officer

APPENDIX I-E
FIRST QUESTIONNAIRE

GENERAL QUESTIONS

- What kind of disciplines do you think should be involved in a study of construction falls? Why?
- How many years have you been involved with construction falls? In what capacity?
- Have you had any direct experience with construction fall accidents?
- How significant do you think construction fall accidents are when compared to other construction accidents? (In terms of number of injuries and fatalities).
- How significant is the avoidance of construction fall accidents for a construction company?
- According to your experience, have construction fall accidents decreased or increased during the last years? What do you think is the main reason for this trend?
- What criteria would use to classify construction falls?
- Where would you look for information regarding construction falls? Government agencies? Case studies? Literature?

SPECIFIC QUESTIONS REGARDING CONSTRUCTION FALLS

- What factors (variables) do you consider when determining the cause of a construction fall accident? Weather? Safety conditions? Worker related?
- What do you consider a safe working site? Why?
- During a site inspection, in term of construction fall accidents, what conditions do you consider hazardous to the worker?
- What safety measures would you take to avoid construction fall accidents?
- If there are several possible causes of fall, how do you determine which cause was the main problem causing the accident?
- What kind of safety-related equipment do you think should be provided by the employer to the worker?

SPECIFIC QUESTIONS REGARDING FALLS FROM HIGHER ELEVATION

- Regarding falls from higher elevation, what structure component do you think should be studied?
- What do you think are the main causes of falls from elevated surfaces?
- How would you determine if a scaffolding structure is strong enough to support the worker?
- What safety conditions would you like the scaffolding structure to fulfill? Design conditions?
- How would you determine if a roof is safe to work on?
- What safety devices should be used to prevent higher elevation falls?

SPECIFIC QUESTIONS REGARDING THE WORKER

- What variables would you consider to determine if a fall accident is the worker's fault?
- How would you evaluate the worker's state of mind at the time of the accident?
- Is the worker experience and training a factor to consider? Why?
- Does the company's management play any role in preventing worker fall accidents? What role?

APPENDIX I-F
INTERVIEW TRANSCRIPT AND SUMMARY SAMPLES

I-F.1 Third Interview with Mr. John Sahayda (Transcript)

The interview happened on May 3, 1993 at 2:30 p.m. After all the salutations and a brief discussion of the objectives of the interview, we started it. The following is a transcript of the recorded interview with Mr. Sahayda:

Question: As I mentioned, we are trying to decide what kind of structures to include in our study. So far for falls from higher elevation, we have floor openings, scaffolding, wall openings, and roofs. What other structures do you think should be considered?

Answer: The only one I can think is fall from beams. That would be another area that isn't included on the areas you mentioned before. From the skeleton of the building, I should say. Outside of that...

Q. Well, we are also considering falls from the same level and slips...

A. Yeah, I was thinking about falls from higher elevation. Right now I think that about covers it all. I can't think of any other thing... I was trying to think of other occupations, but that wouldn't be considered construction.

Q. Other occupations...?

A. Yeah, there is times when you climb things like ladders, towers, and things like that. Yeah, like your radio tower when you have to go up and do repairs; things like that. Then, they would have to be tied up. You still have a structure skeleton kind of thing, it is not like a finished building, so you can also use the same premises for them. [long pause] There is the electrical thing too, which could be considered construction too. Doing repairs, you know, like climbing electrical poles and light towers. Obviously, those are specific areas, O.K.? but still the proper safeguards should be employed. Of course, you have to tie up...

Q. By the way, I've been reading the OSHA standards, but sometimes they are confusing. sometimes...

A. Oh, really?

Q. Yeah. [everybody laugh] Let me see if I understand, I think the code says that if the work is above 25 ft, there has to be a safety net, you know... But, if it is above 15 ft. elevation from the ground, you have to have a harness and...

A. Safety belts and lanyards.

Q. Uh huh, O.K. then you have your guardrail also. You have to have it when the work is... above 4 feet?

A. Right, the scaffold is even different there. For most scaffolds, you don't guardrail unless you are up 10 ft. O.K.? Unless, there is a very narrow working platform. Then you have to have a replacement. The general standard is 4 ft. or higher. But you know if you are in the general industry, you may find that there are different elevations depending on the different occupations. The reason that it is different in some occupations is because when the standards were adopted, they adopted them from different consensus standards that were... not in effect, but they were uhm.... Let me put it this way, there were what we call voluntary standards, you know, you didn't have to follow them. They were voluntary. The only ones who really had to follow these standards were companies that had government contracts. O.K.? If you were a contractor in a government job, you had to follow those standards, but there wasn't any thing else for any other type of work. Well, when OSHA came into being, these provisions were in the act: that they want it to adopt all these consensus standards. The National Electrical code was a consensus standard here. The National Fire Protection Association (NFPA) was also a consensus standard. Your ANSI standards were a set of national standards.... Those are consensus standards, just an agreement of a committee that it would be a good idea to do those things. They were not enforceable. What OSHA did was look at all these different standards and to get it going quickly, the congress said, you can adopt these within a certain time frame and then these will be enforceable. There were several committees. Well, this committee was looking at this issue, that committee was looking at that issue. No one was looking at the total picture. Anyway, they put all these things together. The idea being that they would then review them, update them, and get them more consistent. Some of those standards were adopted in the 40's and were still adopted in the 70's by OSHA. Well, there are still a lot of them and it takes a lot of time for these things to change. So that's why you are getting 4 ft. here, 10 ft., 15 ft., and sometimes there is no consistency.

Q. O.K. Let's say that you are doing a work [task] about 30 ft. high. Is the contractor required to provide the three safety devices (net, guardrails, and tie up system)... or can he choose which one to provide. Is that how it works?

A. Uhm. Generally one doesn't work well if the other is in place. In other words, you can't have a guardrail in a place that doesn't have a floor already. You know, for example you see beams people, walking on them is part of their job, so you need to have a net or use a safety belt. Guardrailing would come into play after the installation of the floor and now you don't need the net because of the fact... Well, you could still use the net as long as it projects out. I think it should project out at least 6 ft. from the edge of the floor. However, what happens is that they don't like to use nets period. Because it takes some time and they are a little difficult to set up. So they'll try to go either with the tie ups or the guardrail. Then again, the only time when you can actually say that tying up is O.K. is when it is unpractical to provide nets. So the nets are better unless something like the design of the building precludes their use or they can't be tied up properly to provide good protection. Then, you go to the safety belts or lanyard system. Your last option is the lanyards.

Q. The last option? Why?

A. Because if you fall 25 ft., you can still, you know, feel it. You won't hit the ground and you'll probably be all right. But you'll still feel the impact, I dare you to tie up around the waist, fall about 6 ft., and then just stop. They are not that elastic. They are not like a bungy cord. You know... [laugh] They are thinking to change them, but once again who knows when that is going to happen. So, anyway, that's the difference, and no, they don't have to put the three systems. They take the most...you are supposed to go with the most protective, when it is practical to do so. Sometimes it is impossible to use some of the systems because of the nature of the job. That doesn't happen very often, but it does [happen]. So one has to look at the situation. I don't know of any place that uses all three systems. However, sometimes you have a safety net and guardrails installed together.

Q. O.K. Let's change topics a little bit. I would like you to take a look at this fault tree designed for "WORKER FALL FROM FLOOR OPENING". We'd like to get your opinion regarding the system and where [it] could be improved. [long pause- expert reviewing the tree]

A. The joist to me wouldn't be a particular thing to include for the floor opening. From the fall point of view, they definitely fall if the joist gives. We know that... and this is all getting down to one basic cause?

Q. Yes, this tree is supposed to go down and get the most likely cause of fall. I don't know if this tree is completely comprehensive...

A. Well, yeah, but sometimes you have a combination of things. Most times, there is a combination of causes. What I'd like is if there could be some kind of interrelationship between the two. O.K. Let me give you an example of what happens a lot of times when you see somebody fall through an opening. Sometimes there is a cover in the opening, instead of guardrails. These would work too, but they are supposed to be, you know, anchored in place. What happens sometimes is that a worker sees the covers and thinks it is O.K., he is experienced, he knows what to do, and is pretty cautious; but he is busy doing his job. A lot of times what he is doing is backing up. He thinks that all covers are anchored down, but they may not be anchored and may be hanging on the edge; though one may not necessarily know that because you don't know how big the opening is. So the worker may just step down on the side and down he goes, O.K.? It has nothing to do with his personality. In fact, he is doing his job. May be he should have paid a [little] more attention before backing up. So there is a little part of worker fault, but [it] is also the condition. So that is a combination of things. You see where I'm getting at? Most times you see a lot of that type of combinations. Myself I'd like to see a little bit more of that. The interrelation of triggering and enabling type[s] of things. Sometimes the guy is drunk and you could get right down to it, but at some point it could be, you know, two ends where there is a 60/40 or that kind of chance.

Q. O.K. I think that does it for today. Thank you.

After this, we set up the time for the next interview. I told Mr. Sahayda that during that interview we would be discussing some of the other fault trees developed. Mr. Sahayda asked if he could get a copy of the trees before the interview. He gave me his fax number so that we could send this material to him.

I-F.2 Third Interview with Mr. John Sahayda (Summary)

The interview took place on May 3,1993 at 2:30 p.m. After salutations and a brief discussion of the objectives of the interview, we began. The following is a summary of the interview with Mr. Sahayda:

The first question we asked the expert regarded the type of structure components that should be included in our study. We explained that so far we had considered floor openings, wall openings, scaffolding, and roofs. He replied that the only addition to this list would be falls from beams during the steel erection phase. He also mentioned that maybe ladders, radio towers, electrical poles, and electrical towers could be considered.

The next question concerned safety systems such as the safety net, the guardrails, and the lanyard/harness, and when to use them. He explained that in general only one of these systems has to be used, depending on the type of job being performed. He also mentioned that the ease of the safety system's installation plays an important role in its selection. For example, he mentioned that net systems are not very popular because they are hard to install properly. He added that sometimes the design of the building precludes their use (e.g., they can't be tied up properly to provide good protection). However, Mr. Sahayda added that safety nets are preferable to lanyard systems. He said that the lanyards should be the last option because they can still cause injuries to the worker wearing them, even though they would save the worker's life in a fall accident.

Mr. Sahayda also explained that some of the differences in the OSHA standard regulation for the different safety systems came from the days when OSHA was first established. According to him, to speed up the process of making the codes and regulations, at that early time, many of the voluntary standards existent were taken and used. The idea, he explained, was to establish these codes and later review them for accuracy and consistency. This has not happened, and that is the reason for some of the inconsistencies in the code books.

During this interview, we also discussed the fault tree designed for the top event WORKER FALL FROM FLOOR OPENING. In general, he agreed with the fault tree design. However, he did not think that the joist (support-related) component should be included in the fault tree. He argued that joists have nothing to do with a floor opening and therefore there was no need to include them. He also said that many fall accidents are caused by a combination of factors and he thought that our fault tree could be improved in this area (being able to handle a combination of factors). He said he would review the tree in more detail and would give us any further suggestions during the next interview.

I-F.3 Fourth Interview with Mr. John Sahayda (Summary)

The interview took place on July 28,1993, at 2:30 p.m. at OSHA's industrial division building. The interview's objective was to review the previously developed fault trees and to ask Mr. Sahayda for his opinion regarding some of the changes suggested by the other experts. The following is a summary of the interview.

Before the interview, Mr. Sahayda was provided with a copy of the preliminary fault trees. He had the following comments: he said that the fault tree regarding the FALL FROM SCAFFOLDING top event considers only one type of scaffolding structure and he thought that the other scaffolding structures should be included (e.g. mobile scaffolds). He pointed out that with some types of scaffolds, like suspended scaffolds, both guard railing and tie up systems must be provided in order to comply with OSHA standards. In this case the guard railing would be the primary protection system and the tie up system would act as a secondary (back up) fall protection device. Other suggestions Mr. Sahayda had regarding the FALL FROM SCAFFOLDING fault tree are the following: the inclusion of cross bracing problems on the support related branch, and the condition of the ground or surface over which the scaffold is standing.

Additionally, Mr. Sahayda noticed that under the lack of SAFETY CONDITIONS gate there were several devices missing. For example on the fault tree for WORKER FALL FROM ROOF, the safety nets were not included. He mentioned that even if a safety device is not the most commonly used, it may still comply with OSHA's requirements. Therefore, in order to make the fault trees as general and comprehensive as possible all these devices should be included.

Regarding the safety devices, he also said that safety belts and body harnesses should be considered as different systems with different advantages and disadvantages. For example, the safety belt may cause injuries to the worker if not used properly. In addition, if not tied up properly the belt may let the worker slide out and fall. The body harness allows a better distribution of the impact due to the fall and does not allow the chance of the worker sliding out of it during the fall. Both devices are more useful as back up systems and should be used as primary only when no other options are available (e.g., during steel erection).

When asked if he thought that a catch platform was a *fall protection* device by itself, Mr. Sahayda answered "yes" because it protects the worker from falling all the way to the ground and getting seriously injured. He said that the system should be included among the safety devices; however, he made the distinction that a catch platform is not a *fall prevention* device since it does not prevent the worker from falling, it only lessens the consequences. Regarding the roofing brackets, the chicken ladder, and the crawling board devices, he said he considers these neither fall prevention, nor fall protection devices: at least not by themselves. He said these devices will help the worker's footing and provide him/her with a better working surface, but they cannot prevent the worker from falling due to loss of balance. So, in order to use these devices, a supplementary fall protection device should be provided (e.g., guardrails).

Mr. Sahayda agreed with the other experts in that DISTRACTIONS can be the basic cause of falls. However, he said he didn't know exactly where to classify them. He said they could be under the WORKER ENABLING branch of the fault tree if the cause of the distraction was psychological like known personal or family problems which make the worker's concentration and performance decrease over time. He also said that the distraction may be temporary like some unexpected event which may startle the worker, cause him/her to lose his/her concentration and fall. This distraction may belong under the WORKER TRIGGERING branch of the fault tree.

Moreover, Mr. Sahayda agreed that all the environmental conditions (not only strong winds) could be triggering causes of a fall. For example, he said that snow, ice, and rain could create slippery conditions which can cause workers to fall. Fog can reduce the worker's visibility and reduce his/her capacity to react to any fall hazard. In addition, to these conditions Mr. Sahayda added excessive heat and cold as possible causes of falls. For example, he said, extremely cold temperatures can reduce the worker's capacity to function properly, it may reduce his/her concentration, it may reduce his/her ability to handle tools properly, or it may cause him/her to rush work and get careless.

The final question to Mr. Sahayda regarded whether he thought that the basic causes under the worker ENABLING, TRIGGERING, and SUPPORT I gates could cause the top event of the fault tree individually (without a lack of SAFETY CONDITIONS cause). He answered that he thought that the causes under the WORKER SUPPORT I and WORKER ENABLING gates could cause the worker to fall even if the fall protection equipment was in place. If the component immediately supporting the worker fails, the worker will fall even if guardrails or warning lines are in place. If the worker is drunk he/she may choose to ignore all the safety warnings and equipment existent in the site (employee misconduct) and fall. Even though the company's management has complied with all the safety requirements, the accident still occurs due to the worker's misconduct. This accident would not have happened under normal conditions, for example, if the worker had been sober.

Regarding the causes under the WORKER TRIGGERING gate, Mr. Sahayda said that he did not think that these alone could be the cause of fall because in order for these to happen there has to be an underlying safety problem. He also said that most of these causes are related to the worker's being hit either by equipment, materials, or another worker; and in order for this to happen there has to be a problem with the working environment safety. For example, he said, if there are workers working under another working surface, some kind of overhead protection should be provided so that falling materials won't hit the worker and possibly cause him/her to fall.

I-F.4 First Interview with Mr. Feeney and Mr. Mather (Summary)

During the first thirty minutes of the interview the experts' (Mr. Feeney and Mr. Mather) and the knowledge elicitors' (Dr. Hadipriono, Hong Ta Chen, and Carlos Vargas) discussions centered around the project, its objectives, and the possible benefits to be attained from it. The knowledge elicitors answered questions the experts had regarding their role in the research project, and then, during the rest of the interview time, proceeded to start the knowledge acquisition process. The questions asked are the same used for the second interview with each of the other experts. The following is a summary of the most important topics covered during the interview.

The first question given to the experts concerned their experience with construction safety. Mr. Feeney has about 10 years of experience, five of which he spent working as a layman both on the ground and at higher elevations. The last five years he has been working as a safety consultant for the Bureau of Workers Compensation (BWC). Mr. Mather has about 3 years of experience in the construction industry working on construction sites and as a safety consultant for BWC.

The next question regarded the significance of construction falls. Both experts agreed that construction falls are very significant because they produce the most serious injuries and the largest number of fatalities. The experts also mentioned that only electrocutions may be as significant as construction falls. They also think that in recent years the number of fall accidents has increased, and that is the reason that government agencies like OSHA and BWC are trying to put an emphasis on the prevention of construction falls.

When asked what kind of disciplines should be involved in a study of construction falls, the experts named civil engineers, safety engineers, safety consultants, estimators, designers, and labor unions. They suggested that all of these groups would play an important role in construction safety. According to the experts, even the estimators play a very important role because if they don't allocate any moneys for safety equipment, chances are strong that safety requirements will be ignored.

In addition, the experts believed that all the factors that could cause fall accidents should be included in the study. Among those factors they named the lack of safety equipment, environmental conditions, and conditions related to the worker (e.g., physical problems (health), inadequate aptitude, inadequate experience, etc.). Another factor they mentioned is working conditions. For example, they said that if you need to move something that weights about 2 tons and your company owns a machine that can support 1.75 tons, you'll go ahead and use your machine and hope to get away with it. Sometimes, time constraints and lack of working space also play an important role on these decisions.

Regarding the role of environmental conditions in construction falls, the experts agreed that the weather can contribute in several ways to construction fall accidents. Rain can make the working area slippery and affect the footing on the structure. This could make a fall accident more likely to occur. They also mentioned factors such as mud which also may make the worker more likely to slip and fall.

Moreover, the experts agreed that safety equipment should be provided according to OSHA regulations. However, they also said that they would like to see the risks eliminated (engineered out) rather than reduced by providing personal protective equipment . For example, it would be better to have a scaffold well assembled instead of having a safety belt holding the worker when the scaffold fails. The best way to find out what type of safety equipment should be provided for the worker is to read the OSHA codes. However, they caution that those regulations are minimum standards which could be greatly improved. For example, they mentioned that they recommend the use of full body harness (whose use is not mandatory by law as of today).

One of the experts also mentioned the importance of using safety glasses during certain operations. For example, when treating a new brick wall, the worker has to scrape it, spray it with acid, and then rinse it off. This is the operation used to age the brick. When performing any of these activities, the worker should wear safety glasses; otherwise, something may fall in his eyes and he may become so concerned with his injury that he may stumble and fall. Another time when safety glasses are required is whenever the worker has to use power tools.

Regarding the classification of construction falls, the experts agree with BWC's classification: from higher elevation, from same level, and slips. Concerning falls from higher elevation they said falls should be separated into falls to the exterior of the building and falls to the interior of the building. They argue that falls to the exterior are more serious because the worker will probably fall all the way to the ground and receive a serious injury. If the worker falls to the interior, hopefully he won't fall more than 2 floors (if the company is following OSHA regulations).In general, the experts agreed with the structure components proposed for the study: roofs, floor openings, wall openings, and scaffolds. They suggested to add to these components: steel erection, loading docks, chimneys, and ladders. When asked if they would consider the perimeter of the floor a component different from the floor opening component, the experts answered "yes".

When asked about the kind of structures to include in the study (in addition to building and residential construction), the experts mentioned the following structures: water tanks, falls into deep trenches, radio towers, and high tension power line towers. They also mentioned maintenance activities like window cleaning, repair of fire protection systems, and any work on the roof or the outside of a building.

Finally, we asked the experts about information regarding construction falls. They provided us with copies of some of the BWC publications regarding construction safety . In addition, they mentioned OSHA's regulations. For articles and general information regarding construction falls, they suggested checking the BWC reference library located on the third floor of the William Green building in downtown Columbus. They also mentioned that BWC has a video library available for public use.

At the end of the interview, we thanked the experts for their time and scheduled the next interview for May 24, 1993, at 9:30 AM.

I-F.5 Second Interview with Mr. Feeney and Mr. Mather (Summary)

The following transcript contains a summary of the answers obtained from the second interview with Mr. Feeney and Mr. Mather. The interview took place in the Bureau of Workers Compensation (BWC) offices on May 24, 1993. The focus of the interview was falls from the roof component of the structure.

The first question we asked the experts was about the significance of studying all types of roof structures. They answered that right now there is concern regarding pitched roofs which are mainly found in residential structures. They said that the residential construction industry is having all kinds of problems protecting their workers from falls. Because of the configuration of these residential roofs and the variability associated with their shapes and pitches, there are more problems associated with this type of roof, and the worker is exposed to more risks. However, the experts said that flat roofs mainly found in commercial construction are also significant. Even though, in flat roof construction, workers seem more easily protected against falls.

When asked if they thought that the reason for fewer accidents in commercial construction is that companies involved in the construction of commercial flat roofs are more careful than those in residential construction, the experts answered no. They said that flat roof construction is a little more routine. They usually use the standard guardrail as a protective device, and use the same procedure to place it over and over. In contrast, pitched roofs offer several challenges: the pitch changes, the configuration of the roof changes, the number of valleys on the roof change, the number of safety devices available changes, etc.

Regarding pitched roofs, Mr. Feeney and Mr. Mather also said that the pitch or slope is the main factor to consider. The steeper the roof, the higher the risk of falling. They said that according to the code books when working on roofs with a pitch above 4-12, the worker has to be protected by using any of the safety devices available. Among these devices the experts named personal protective equipment like the safety belts; and other devices like chicken ladders, catch platforms, and roofing brackets.

To explain, the catch platform is a device erected at the outside edge of the roof -- if the worker starts to slide down and off the roof, this platform will prevent the worker from falling all the way to the ground. The experts explained that this is an after-the-fact device because its objective is to "catch" the worker after he or she has already lost control and is falling off the roof. They also mentioned that this is the most used safety device because it is easy to erect and does not require the worker's active participation in order to be effective (this is in contrast to safety belts or lanyards devices).

The chicken ladder, the experts said, is a specially designed device that looks like a ladder placed it flat on the roof. This device will act as a crawling board and provide the workers with a surface to hold on to. The device is usually used after the roof sheeting surface is already in place. It could be a hook ladder type where the ladder is hooked over the ridge of the roof and the worker crawls up the ladder or it could be nailed to the roof itself.

The roofing brackets allow the worker to have a level surface over which he/she can perform his/her job. The bracket can be standard for a given roof pitch or it can be adjustable to different pitches.

Concerning skylight-related accidents and their significance in pitched roofs falls, the experts said that falls from skylights openings are more significant on commercial construction (flat roofs) than on residential construction (pitched roofs). They also said that the workers have the tendency to walk and stand over skylights covers which are designed to protect from weather, not to support heavy loads. According to OSHA standards, the cover material should support at least a two hundred pound load.

Instead of covering the skylight opening, the experts also said that a standard guardrail system could be used on all sides of the opening. A standard guardrail has by definition a forty-two inch high top rail, a twenty-one inch high mid rail and a four inch high toe board (29-CFR section 1926.500). The experts also said that a guardrail system is the most often used device to prevent falls from flat roof edges. The also explained that the codes mentioned other preventive measures such as having a roofing monitor system. This will include a warning line which only has to withstand fifty pounds. The objective of this line is to warn the worker that he/she is getting close to the edge of the roof. The experts also explained that if there is a perimeter wall around the roof and this wall stands thirty-six inches above the roof, then there is no need to provide a perimeter guardrail.

On pitched residential roofs, the experts said that one of the main causes of falls is electrocution. The worker touches a power line and due to the electric shock falls from the roof. To prevent these accidents, the experts mentioned that preplanning is very important. Whenever possible, the worker should stay at least 10 feet away from the power line. If that is not possible, the worker should use non-conductive materials and the contractor should check on the possibility of shutting down the power (de-energizing) for a few hours until the work close to the power lines is completed.

Safety lines were not mentioned by the experts among the safety devices most often used in pitched roof construction. The experts said that employers and employees do no favor this device because it tends to obstruct and slow down the work. The usefulness of safety devices, according to the experts, depends on the willingness of the worker to use them, and workers do not seem willing to use this device.

Regarding the main factors that should be considered when determining the causes of falls from a roof, the experts mentioned the following factors:

- The employee's mental attitude. One of the experts said that drunkenness could be considered a mental problem because the alcohol slowed down the worker's reaction time.
- The employee's physical condition. The experts said that sometimes workers have to work injured in order to keep their jobs.
- The working surface condition. This surface should be clear of obstacles that could cause the worker to stumble and fall.
- The type of equipment being used and its maintenance. The equipment should be reviewed periodically and replaced if it is not in good condition. The experts said that usually the equipment is only replaced when it breaks down .
- Distractions. Anything that keeps the worker from concentrating in his/her job.
- The employee training. Many construction companies have no training programs and the employee has to learn by watching the more experienced employees.

- Environmental conditions (high winds, rain, frost, snow). Work should be stopped, if any of these occurs. However, this does not happen often. Usually the work continues until all the openings in the roof are covered.
- Whether or not the workers are carrying anything up to the roof (e.g., shingles).
- Sometimes to save time or to impress coworkers, a worker overloads himself/herself and tries to carry twice as much load as other workers. However, the extra load causes the worker to lose his/her balance and fall.

Finally, I asked the experts what safety procedure should be used if the roof sheeting or decking was not already in place. They said that in this case the exposure was clearly higher. However, the codes have no specific regulations regarding the safety precautions to be taken in this case. They said that in this case they have to look at different codes and try to determine the best ways to prevent accidents. They also said that they would like to see a roofing standard developed to get a better definition of the requirements for law compliance.

I-F.6 Third Interview with Mr. Feeney and Mr. Mather (Summary)

The following transcript contains a summary of the third interview with Mr. Feeney and Mr. Mather. The interview took place in the Bureau of Workers Compensation (BWC) offices on July 22, 1993. The objective of the interview was to review the preliminary fault trees developed so far and to ascertain the experts opinion of them.

The focus of the interview questions was on the WORKER CAUSES branch of the fault trees. The first area where the experts thought some improvement could be made was under the lack of SAFETY CONDITIONS gate. They said that in order to make the fault tree comprehensive all fall protection devices should be included. Right now, these branches contain only the most commonly used devices in the field. When talking about the inadequate guardrailing system gate, the experts said that this gate could be further expanded into the following: guardrails allowing too much deflection, improper construction, and improper materials (not as strong as required by OSHA standards).

When asked whether or not they thought the safety belts complied with the fall protection standards, they said that as of now and according to the codes, safety belts are considered fall protection devices, if used and installed properly. That includes the use of shock absorbers and other accessories recommended by the manufacturer. In addition, the safety line the worker is tied up to should be located above the working surface. Finally, they said that the worker should be wearing a belt for vertical fall prevention which has the tie up ring on the back, instead of a positioning belt which has the tie up ring on the sides. However, they also said that they do not recommend the use of safety belts because they can cause serious internal injuries to the worker in the case of a fall. Instead, they said, all the government regulatory agencies are trying to push a law that makes the use of a full body harness required. They said these harnesses have the advantage of transferring the load from the fall impact to the skeleton of the body preventing internal injuries from happening.

In a final observation regarding the lack of SAFETY CONDITIONS for the fall from flat roof fault tree, the experts said that if the roof has a wall thirty inches or higher bordering the edge, no additional fall prevention devices have to be provided. However, if any part of the work has to be performed on the top of that wall, then a different fault tree should be used to analyze the risks and safety devices needed.

We also asked the experts if they thought that the causes under the ENABLING, TRIGGERING, and WORKER SUPPORT I gates could cause the top event by themselves (without a lack of SAFETY CONDITIONS cause). They answered "yes". They said that the best a safety engineer can do is to reduce the likelihood of an accident. They said that due to the unpredictability of the human nature, it is not possible to be 100 percent certain that the safety devices installed will prevent an accident from happening. For example, the use of warning lines is a fall prevention method that complies with OSHA standards; however, a worker may ignore them and fall.

Regarding the causes under the WORKER ENABLING gate, the experts agreed with the classification used. However, they said that the basic causes under WORKER HEALTH could be more specific. For example, they said that asbestosis and toxic fumes emanated during welding could cause the worker to faint and fall. They also named vibration, noise, and fumes as problems on the construction site. They also said that the use of Personal Protection Equipment (PPE) comes into play for the prevention of some of these health problems.

Regarding environmental conditions, currently, the fault tree only contains WORKER GUST IMPACT as a basic cause. However, the experts felt that all of these conditions (rain, fog, snow) could be causes of fall at one time or another, and should be included in the tree. Finally, Mr. Feeney and Mr. Mather said that a basic gate for DISTRACTIONS should be included on the fault tree. These distractions may be due to personal problems (psychological) or to the surroundings (physical or environmental).

I-F.7 Second Interview with Mr. Mike Ypsilantis (Summary)

This transcript contains a summary of the answers obtained from the second interview with Mr. Mike Ypsilantis. He did not agree to the use of a tape recorder during our interviews due to the legal problems that could arise from recording these conversations. However, he provided us with written answers for most of the given questions. During the interview he explained the reasons for his answers and then we went over some questions that were not clear or specific enough for him to answer before hand.

The first question we asked Mr. Ypsilantis regarded his experience with the construction industry, and more specifically, with construction fall safety. He answered that he has been involved with the industry both as a student and then as a safety professional. Since 1966, he has worked as a safety engineer for an insurance company investigating fall accidents, as a safety engineer during the construction of the Sears tower in Chicago, and as an OSHA officer investigating fatality accidents. Mr. Ypsilantis added that while working on the Sears tower project, he witnessed a fall accident in which a worker's life was saved by the tie up system. Mr. Ypsilantis provided us with a copy of his resume, which describes his experience in more specific terms.

Regarding the significance of construction fall accidents, Mr. Ypsilantis said that they are very significant because of the serious injuries they cause. Most of the worker fatalities in the industry are due to falls. They also generate a lot of indirect costs to the employer. Among these costs are: delay costs, medical costs, costs in penalties, among others. Mr. Ypsilantis added that too many of these expenses in a year could push a construction company into bankruptcy.

Mr. Ypsilantis also said that he thinks that the number of fall accidents has increased in the last few years. He said the main reason for this trend is that many companies fail to voluntarily comply with OSHA standards. The upper management of small to medium companies has not accepted safety methods as a viable means to reduce expenses and accidents. This is because they fail to understand that safety control measures are cheaper in the long run.

When asked what kind of disciplines he thought should be involved in a construction falls study, Mr. Ypsilantis replied that structural steel engineers should be involved because safety should be incorporated in the design stage of a construction project. In addition, he said that safety engineers should be involved to tackle all the hazards that cannot be eliminated during the design phase.

Regarding the classification of construction falls, Mr. Ypsilantis said that there are many possible ways to do so (e.g., according to the craft type, according to the phase of construction, or according to the task being performed). The expert also argued that any known hazard that could cause a fall should be included when determining the cause of a construction fall accident. Some of the factors to consider are the following: the worker's qualifications, the job duties (assignments), the location of the job site, the environmental conditions when the task was being performed, the safety and health system in place when the accident occurred, the experience and training of the worker, and whether or not there was a plan to prevent accidents and comply with the law.

A safe working site according to the expert is a site where the owner has hired a qualified architect, construction manager, prime contractors, and subcontractors that have proven to be conscious of all the hazards arising from construction work and have taken all the measures possible to eliminate or reduce predictable hazards. He added that safety awareness should start during the design phase and should continue all the way through the end of the project.

Finally, we asked Mr. Ypsilantis where we could go for information regarding construction falls. He mentioned the following sources: the new OSHA office of record keeping and data analysis, OSHA handbooks and standards, NCS standards, ANSI standards, and NIOSH.

I-F.8 Third Interview with Mr. Mike Ypsilantis (Summary)

This transcript contains a summary of the answers obtained from the third interview with Mr. Mike Ypsilantis. He did not agree to the use of a tape recorder during our interviews due to the legal problems that could arise from recording these conversations. Therefore, this summary is based on written notes taken by the knowledge elicitor during the interview. The interview took place in The Ohio State University's Bolz Hall, room 417 on July 20, 1993. The objective of the interview was to review the preliminary fault trees developed for the roof, wall opening, floor opening, scaffolding, and steel beam components.

The first question we asked the expert was about the previously mentioned structure components selected for the study and their significance. He said that all components discussed were important enough to be included. However, he also said that we should add other components like ladders, towers, and floor edges.

While reviewing the fault trees developed, the expert also mentioned that the lack of safety conditions gates did not include all the possible safety systems and, therefore, should be improved. For example, the fault tree for WORKER FALL FROM ROOF for pitched roofs did not include the catch platform which is an often used fall prevention device in the field. For flat roofs, the fault tree only included the lack of guardrails event; however, the contractor could comply with the law by using other devices such as tie up systems or catch platforms. In fact, if the work on the flat roof were to take place only on the inside, the contractor would be required only to provide a warning line around the working area.

When asked about the use of safety belts as a protection system for vertical falls, Mr. Ypsilantis said that their use is not recommended for fall protection because they can inflict serious injuries to the workers wearing them during a fall. He said that he usually recommends the use of a body harness instead. He also mentioned that the only way safety belts can be used for fall protection is if they are used according to the manufacturer's suggestions, which include the use of shock absorbers or deceleration devices to reduce the impact of the fall.

Furthermore, Mr. Ypsilantis also said that under the WORKER GENERAL CAUSES, we should add causes due to environmental conditions. He said that rain, snow, fog, or strong winds can be very significant causes of falls. Either by causing the worker to slip, by reducing his/her visibility, or by pushing him/her off the structure component.

Finally, when we asked him if he thought that the WORKER ENABLING, WORKER TRIGGERING, or WORKER SUPPORT I causes alone could cause the worker's fall, he answered "yes". He explained that even when the fall prevention devices are in place, the worker may fall. He said that employee misconduct is common on construction sites, for example the worker may ignore warning lines and fall. He also said that in order to avoid misconduct, it is important to train and supervise the worker so as to make him/her aware both of the risks he/she faces on the site and the company's commitment to preventing them.

APPENDIX I-G
LIST OF PUBLICATIONS

The following publications are related to the topic of this volume. Other publications are listed on their pertinent volumes.

I-G.1 Present Publications

Vargas C.A. (1993). *Construction Falls: Knowledge Acquisition and Fault Tree Development*, A Thesis Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science in the Graduate School of The Ohio State University.

I-G.2 Future Publications

More papers will be published in the future; however, the following are those that can be anticipated to be published immediately:

Vargas C.A., Hadipriono F.C., and Larew R.E., "Causes and Prevention of Falls and Slips in Construction Operations," abstract submitted for presentation in the *International Conference on Implementation of Safety and Health on Construction Sites*, Lisbon, Portugal, September, 1996.

Yoo W.H., Hadipriono F.C., and Vargas C.A. "Causes and Preventive Measures for Construction Falls from Scaffoldings" a paper to be submitted to the *Proceedings of the Annual Conference of the Associated Schools of Construction.*