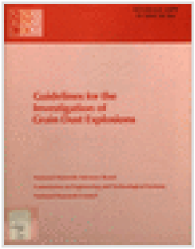

Guidelines for the Investigation of Grain Dust Explosions: Report (1983)

Pages
50

Size
8.5 x 10

ISBN
0309300703

Explosion Investigation Subpanel; Panel on Causes and Prevention of Grain Elevator Explosions; Committee on Evaluation of Industrial Hazards; National Materials Advisory Board; Commission on Engineering and Technological Systems; National Research Council

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1/83

GUIDELINES FOR THE INVESTIGATION OF GRAIN DUST EXPLOSIONS

Report of the Explosion Investigation Subpanel
of the Panel on Causes and Prevention
of Grain Elevator Explosions
of the
Committee on Evaluation of Industrial Hazards

NATIONAL MATERIALS ADVISORY BOARD
Commission on Engineering and Technical Systems
National Research Council

Publication NMAB 367-4
NATIONAL ACADEMY PRESS
Washington, D.C.

1983

NOTICE: The Panel on Causes and Prevention of Grain Elevator Explosions of the Committee on Evaluation of Industrial Hazards has made a study of the causes and prevention of grain elevator explosions and has published three reports: NMAB 367-1, The Investigation of Grain Elevator Explosions; NMAB 367-2, Prevention of Grain Elevator and Mill Explosions; and NMAB 367-3, Pneumatic Dust Control in Grain Elevators.

The panel obtained some of its information for the reports from the work of an Explosion Investigation Subpanel. Members of the subpanel were selected by the panel on the basis of recognized competence in the specific areas pertinent to that task.

The subpanel report comprises information that was submitted as background to the panel deliberations and, as such, has not been reviewed in accordance with usual NRC review procedures. The views presented in this document are those of the subpanel members only.

The project was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for the report were chosen for their special competences and with regard for appropriate balance.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which established the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

The project by the National Materials Advisory Board was conducted under Contract No. J-9-F-8-0137 with the Occupational Safety and Health Administration (OSHA). Funding was provided by OSHA, National Institute for Occupational Safety and Health, and the Department of Agriculture.

This report is for sale by the National Technical Information Service, Springfield, Virginia 22151.

Printed in the United States of America.

ABSTRACT

A methodology for investigating grain elevator explosions is presented. The information that forms the basis for the methodology was gathered by a subpanel of the Panel on Causes and Prevention of Grain Elevator Explosions who investigated a number of grain elevator explosions generally soon after they occurred. The panel used the information as an input to forming its conclusions and recommendations published in a series of reports.

In addition, several explosion incidents are described in detail to illustrate typical grain elevator explosion scenarios.

PREFACE

The Panel on Causes and Prevention of Grain Elevator Explosions was constituted as a unit of the parent Committee on Evaluation of Industrial Hazards. The panel's mission was to study dust explosions in the grain-handling industry and issue reports on the causes of explosions and recommendations for the prevention of further incidents. The work was sponsored by the Occupational Safety and Health Administration, the National Institute for Occupational Safety and Health, and the Department of Agriculture.

The panel published three reports: NMAB 367-1, The Investigation of Grain Elevator Explosions; NMAB 367-2, Prevention of Grain Elevator and Mill Explosions; and NMAB 367-3, Pneumatic Dust Control in Grain Elevators.

The information which formed the basis for the panel's conclusions and recommendations consisted of published material, prepared discussions of invited speakers at panel meetings, and the personal expertise of the panel members. In addition, the panel formed an explosion investigation subpanel to conduct on-site investigations of explosions generally soon after they occurred. Information and experience gained from investigating a number of explosion incidents were also used to make some of the judgments presented in the three reports of the panel.

This document is a description of the methodology for investigating grain dust explosions used by the investigation subpanel. In addition, several explosion incidents are described in detail to acquaint the reader with representative sequences of events and the information that can be derived from them. All information was considered by the panel in reaching the conclusions and recommendations stated in NMAB publications 367-2 and 367-3.

The subpanel report comprises information that was submitted as background to the panel deliberations and, as such, has not been reviewed in accordance with usual NRC review procedures. The views presented in this document are those of the subpanel members only.

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*All subpanel members did not visit every accident site.

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CONTENTS

Chapter 1

INTRODUCTION

Dust explosions have occurred with considerable frequency in grain processing facilities since the inception of the industry. All grain-handling facilities that receive and transfer grain, from country elevators collecting directly from the farm to huge export terminals, have been susceptible to explosions. A number of explosions near the end of 1977 and in early 1978, which caused many fatalities and tens of millions of dollars worth of damage, prompted action on the part of federal agencies to look for ways to reduce the frequency of explosions. Part of this action was the convening of a panel under the auspices of the National Materials Advisory Board (NMAB) of the National Research Council to study causes of grain elevator explosions and recommend ways to prevent them. The charge of this panel included conducting on-site investigations of explosions occurring during the panel's tenure. The purpose of the investigations was both to determine the causes of the explosions and to develop investigative methodology. The panel's investigation subpanel went to a number of explosion sites generally soon after the the occurrence of the explosions. Substantial expertise was developed by the subpanel members, some of whom were already familiar with explosion investigation, and they identified the probable sequence of events in all but one of the incidents investigated. The panel has published three reports on its study (National Materials Advisory Board 1980, 1982a, 1982b). The purpose of this report is to relate the methodology and philosophy of investigation based on the experience of the investigation subpanel and to describe some typical explosion scenarios.

Chapter 2 of this report discusses the investigation methodology and philosophy; Chapter 3 contains a summary of reports on some of the explosion events that the team investigated, and the Appendix contains more detail on those incidents. In each investigation the purpose was to determine the most plausible initiation and sequence of events, not to place blame for the explosion. The intent of this effort is to help identify the generic elements that lead to dust explosions in grain elevators and, thus, provide additional insight and knowledge to those in the industry so that explosions may be prevented.

Considerable literature has been developed in recent years on the causes of grain elevator explosions. One very extensive study (Verkade and Chiotti 1976) identified 126 explosions and reported that for 40 percent of them the causes were unknown. Many in the industry still believe that a large percentage of explosions are not explainable. However, the investigating subpanel believes that the causes of previous explosions were not identified either because there was no investigation or because there was no effective effort to determine the patterns of the explosions.

There are various reasons for the lack of investigation of individual explosions. In some cases management may not be committed to finding the cause. Insurance companies may simply pay off the loss without serious investigation due either to their own internal policies, the lack of time, or not being able to provide enough experienced investigators at the site. People not directly associated with the elevator often have no motivation to learn exact details other than to submit a report to a state agency on the most likely cause. Many times state or local agencies have no real commitment to ferret out the precise cause.

The grain industry in its dedication to determining the general causes and improving the preventive measures that are necessary to reduce the number of explosions could benefit from procedures established by other industries. For example, the chemical industry has always shared information concerning accidents that caused fatalities, injuries, and property damage. That sharing requires the willingness to expose to their fellow industry members those scenarios and events that could happen in other locations. It has helped the chemical industry to establish a safety record that is commendable. The grain industry is only beginning to look upon this sharing as a valuable procedure.

"Prevention of Grain Elevator and Mill Explosions" (National Materials Advisory Board 1982a) describes the major causes of grain dust explosions and recommends preventive measures based in part on investigations of the type described in this report. Many of the causes can be eliminated immediately, some require retrofitting, and others may be impossible to eliminate without rebuilding entire structures. Many of the major causes that now are repeated year after year (for example, overheating of bearings) could soon become minor causes. For example, microprocessors are now available to monitor even some of the simplest functions in a grain elevator, including whether or not belts are moving at proper speeds or are properly loaded or that bearings or bins are overheating, etc. In the near future, even small elevators will be able to afford some sort of micro-processor sensing. Already a small system can be installed for under $10,000. Nevertheless, the investigation of causes of grain dust explosions must be a continuing endeavor as all causes cannot be totally eliminated.

The panel hopes that in the near future a suitably placed, permanent investigating capability will be established to continue the work of grain elevator investigation and provide the industry and government with reports on incidents as they occur. The panel has already presented a positive recommendation for such an action (National Materials Advisory Board 1980).

A permanent, professionally recognized and accepted, objective investigating body would not be hampered by some of the problems faced by the investigating subpanel. For example, because of their professional commitments, the subpanel members were not always able to respond immediately when notified of an explosion. Also, although the subpanel assured grain elevator managers that its sole purpose was to seek causes and identify ways to prevent future explosions and not to place blame, some managers viewed the subpanel's activities as harassment.

This report describes the type of investigation that is envisioned for a permanent body to conduct.

Chapter 2

INVESTIGATIVE METHODOLOGY

NATURE OF EXPLOSIONS

The investigation of dust explosions begins with a basic understanding of what is involved in the explosion process. The best investigation plan is based on prior knowledge of the probable chain of events involved in the explosions. Although there are differences in explosion patterns at different locations, there is a general pattern that is repeated over and over again. Events at different locations often differ only in minor details.

Dust explosions occur when structures rupture due to the pressure generated by the very rapid combustion of suspended dust in air after ignition by a source with energy sufficient to ignite dust. In most cases ignition sources with energies of at least 10 to 20 millijoules are required, but, upon investigation, one finds that the primary ignition sources have generally many times the minimum energy required. When dust burns in a confined space in air, pressures of 80 to 120 psig are attained. In most cases the structure explodes since the most common membrane materials used in the construction of grain elevators fail at pressures ranging from 2 to 3 psig up to 30 psig (Brasie 1979). As the combustion proceeds, the pressure in the building and all the interconnected spaces increases at a rate that is a function of the type of fuel, the amount of fuel per unit volume, and the size of openings or vents that permits the pressure to be relieved. Whether or not a structure ruptures is then simply a function of the competition between the rate of pressure increase and the ability of the vent spaces to keep the pressure from rising above the failure point. Unfortunately, the basic design in most grain elevators is such that most of the confined spaces (for example, tunnels and legwells) have virtually no vent area. Some headhouses are virtually windowless, and combustions originating in those headhouses generally cause partial if not complete destruction.

There is no "explosion" until some part of the structure actually ruptures. The boom or noise heard exterior to the exploding structure is the noise caused by the air returning to the reduced pressure zone created by the explosion. In very large, complex structures, particularly those found in terminal or export elevators, the volumes of the interconnected spaces are very large. Tunnels running underneath silos may be hundreds of feet long. Galleries are of comparable lengths. The interior design of headhouses varies from some in which the bucket elevators are in steel enclosures in open areas to those in which the elevation equipment is inside hollow concrete wells or shafts. All elevators contain storage bins, either for primary storage or for use as "working bins," that are generally within the framework of the headhouse. Since the purpose of the elevator is to move grain into and out of all of these places, fire and pressurized combustion products can go through the various interconnections and reach many of the bins and working spaces. Since the rate of flame propagation and movement of pressurized gases is finite, an explosion in a given building complex may actually be a series of explosions with time intervals of fractions to greater than 1 second between them, depending on the distances and the precise circumstances.

In the most general scenario a bucket elevator casing will explode because of a fire inside and the resulting overpressurization. The resulting fireball that is emitted causes air movement, which raises the local dust that is lying around. This suspended dust burns, causing a greater fire and the acceleration of the movement of air throughout the facility, thus increasing the combustion zone volume. The hot gases generated can penetrate up, down, or laterally in the elevator complex, depending on the initial location. For example, the combustion front may traverse to the top of the headhouse, down along the gallery and into empty bins where new dust "fuel" may be found. One or more bins may then explode, generating more combustion gases, which then may enter the tunnel and proceed in both directions down the tunnel, enter more bins through spouting or perhaps proceed to other sections of the elevator complex. The entire process can easily last several seconds. Sturdier parts of the elevator may sustain pressures above 10 or even 20 psi. Other portions of less rugged construction may fail at lower pressures. When self-venting occurs, i.e., rupture of membranes to the exterior, the rate of expansion of the combustion gas is slowed down substantially and penetration along further interconnected spaces may not occur, particularly if there is insufficient fuel to be suspended to keep the concentration above the lower flammability limit of that particular dust combination.

One cannot predict with any accuracy what the pattern will be in a given elevator complex. However, an investigation of the normal amount of ambient dust in different locations (which is a function of housekeeping and dust collection procedures) will give some indication of the potential for an explosion and the likely extent of damage. The amounts and location of ambient dust that survive the fire and explosion process is sometimes a valuable clue in helping to pinpoint the original source. Sometimes flame front edges may be seen along dusty walls or on other surfaces delineating the size and extent of flame propagation. Obviously, if a flame front dies partway down a tunnel the origin of the flame must be at the burned end of the structure. These types of clues may be helpful in pinpointing the origin.

The above remarks are intended to help clarify what is a dust "explosion" in a grain-handling complex. Knowing that the basic process is one of pressurization with outward movement of gases towards available openings helps the investigator understand from which direction the pressurization occurred. In the cases in which an explosion reaches shock-speed levels, the propagation of the shock wave radially away from the source may be quite evident by the deformation of structural members in the path of the expanding high-speed shock wave. Hence, it is fairly important that the investigator have a mental picture of what the physics of the explosion process were in order to help locate the origin and identify the directions of propagation.

METHODOLOGY

The purpose of the investigation is to identify the original source of ignition and couple this with information concerning the available dust loading (i.e., quantity of layered dust per unit volume) to describe the explosion event in appropriate detail. Many different sources of facts must be investigated in order to put together a coherent, logical and defendable scenario for the explosion. There are several basic mechanisms:

1. The direct investigation of the site and examination of all of the areas and identification of those clues and pieces of information that help in describing the basic explosion process at this site.

2. Interviewing and talking with anyone who can provide some information on the event. These people include operating personnel on the site, people in nearby buildings such as offices, homes, or other industrial facilities, and even passers-by.

3. The post-explosion examination of individual items in a laboratory. This step might include, for example, the investigation of marks, fracture surfaces, deformation of parts, or things related to electrical components. In this phase, care must be taken to determine whether the damage to the individual components being examined resulted from the explosion process being investigated or from some earlier event. Individual judgment must be used in these examinations.

The general approach to investigation is to have a team of experienced investigation people. The tasks of the specific investigation are logically divided into the areas discussed above. Depending on the circumstances and the availability of witnesses, it may be desirable to have one or two team members do all the appropriate interviewing. Interviewing is not without its difficulties since witnesses may assume that an investigator is an adversary. In some cases it may not be possible to determine anything because of the potential for litigation.

Site Investigation

Those directly involved in looking at the structure and surroundings have a complex task. It is desirable to meet first with the owners and managers of the facility and local officials to apprise them of the mission and intent of the investigating team. The team can establish rapport with management by stating who they are, why they are at the facility, and what they plan to do and accomplish. After their preliminary investigation the team should once again meet with management to share information and findings. This will be helpful in the event that the team wishes to revisit the damaged site to witness, for example, salvage operations.

If possible, the team should obtain a building or drawing plan showing the various spaces and interconnecting design. The layout of the complex is sometimes not obvious if destruction is severe. Needless to say the investigating team should be properly prepared from the standpoint of safety. Hardtoed shoes, protective clothing, and hard hats are mandatory. Gloves should be worn. Excellent, portable lighting is extremely desirable. A powerful six-cell focusing flashlight is invaluable since there is often no power at the site and at night extra illumination is always needed. Furthermore, tunnels, the inside of bins, and galleries may be dimly lighted, if at all. The investigative team should have its own liability insurance and should assure management that the team is participating in the investigation at its own risk. Rules and restrictions of local officials, such as fire marshals or other safety people, should be followed. It may be necessary, however, to negotiate with these officials if the restrictions are arbitrary and unnecessarily severe. In some cases there is a preoccupation with immediate removal of rubble and wreckage to clean up the site. It is desirable to photograph and examine the wreckage before rubble and wreckage are removed, unless there is a time consideration involved (for example, injured personnel in the wreckage).

The site investigative team should go through the entire structure systematically from top to bottom and from end to end as accessibility permits. Photographs should be taken of any places on the site that have any possible clues. A record of the location of the photographs should be maintained as they are obtained. It is desirable, if possible, to indicate the location of photographs on a site or elevation drawing. There are many things for the investigating team to seek. Some of the important clues include the direction rubble is thrown and the extent of damage of various structural elements such as I-beams, concrete walls, reinforcing bars, or other items.

In locations such as tunnels or galleries, where there may be light construction items such as spouting, particular attention should be paid to the extent of deformation and indications of the direction of the pressure wave. Even small details should not be overlooked, such as which pieces of rubble or wreckage are on top of which other pieces, whether glass is blown in or out, and whether the roof has been lifted and resettled.

Generally, after several tours through the accessible parts of the complex the basic explosion pattern should be discernible and the point of origin of the combustion can be determined. It is then important to go back to the area of origin and look for possible sources of ignition. Unfortunately, the damage in the area of origin may be so bad that it is not possible to find the critical evidence before clearing away the debris. Bucket elevator casings, buckets, belts, etc. may be buried under tons of wreckage. For example, the bottom bearing in the boot, which might be suspected as an ignition source, frequently is not accessible. In some cases the boot not only may be under wreckage, it may be under water from the firefighting action. In such cases, cooperation with those involved in removing the wreckage or demolishing the facility is required to be sure that at the time the critical elements are exposed someone is available to obtain them for investigation before they are thrown away. It may not always be easy to obtain this cooperation.

The second phase of the initial investigation can be described as looking for small details. This phase may include the collection of pieces and parts, (for example, components of electrical systems) or other things that may require detailed off-site examination. At the site the team should meticulously go through the wreckage and note minute details of the placement and location of wreckage with respect to the sequence in which the items are piled on top of each other. The team should carefully look for and examine evidence of flame fronts and the direction in which the flame fronts advanced. For example, frequently lights in tunnels will show char markings on one side of the light only. The deformation, bending or twisting of light-gauge metal objects is often a clue to the direction from which forces were applied. Photographs of these details are extremely valuable and sufficient records should be kept to indicate the location of these items.

Frequently the failure of electric components may be judged to be the cause of the initial ignition. However, one must be careful to be sure that broken or damaged electric components show positive evidence that they failed prior to the explosion. It is easy to misjudge a smashed, shorted-out section of conduit or wire as being responsible for the ignition when in fact the damage was done during the explosion process.

The placement and layering of rubble, as mentioned before, can provide important clues as to the sequence in which different portions of structures failed. Damage exterior to the main structure may also provide clues in some cases. Differences in damage adjacent to various openings in the main elevator structure can provide clues to the intensity of the pressure wave coming from the various apertures. This in turn can provide insight into the direction and strength of the pressurization process during the main explosion event(s).

Although these comments are broad and general, once some field experience is developed, it becomes relatively easy to sort out the various factors and to begin to pinpoint the probable initial zone of the explosion process. It is then important to try to estimate what was the single initial fire-explosion event that started the whole sequence. The experience of the investigating subpanel was that this was a discernible event in almost all of the cases investigated.

Sometimes the ignition source is a factor external to the basic operation of the terminal itself. For example, the leakage of propane into parts of structures associated with grain elevators and the subsequent ignition of the propane were the first steps in the destruction of a facility. The elevator, primarily of wood, was burned to the ground leaving no evidence of blast effects that may have occurred due to an initial dust explosion. However, from later examination and information provided by people associated with the operation, it was determined that there was an initial leakage of propane--from a line recently installed to provide fuel for a dryer--into an adjacent structure where ignition occurred during grain loading and unloading operations. The propane explosion propagated into the elevator proper and the rapid expansion of the propane fireball initiated a dust explosion. Indeed a dust explosion occurred and did heavy damage to the elevator, which, being made of wood, was soon totally engulfed in flames and destroyed. In a case like this, one must look at the operation of a total elevator complex to include not just those things associated with the movement or processing of grain but all those elements that are required to operate the complex.

Interviewing of Witnesses

Another major portion of the investigation is the interviewing of all witnesses who may have information leading to the determination of the cause of the explosion. Those who should be interviewed include operational people directly on the site, people in nearby offices or other functional buildings, truck drivers or railroad employees who may have been in the vicinity, maintenance people, people who may have been driving by or who live or work nearby. When an approximate timetable of the events leading up to the explosion has been determined, it may be advisable to re-interview some of the people in order to fill in details as the total picture begins to emerge. Hence, several different interviews may be desirable with various people. It is particularly desirable to interview people one at a time and to the extent possible not reveal statements of one individual to other witnesses.

After the first round of interviewing, it is important to try to reconcile the stories and viewpoints expressed by those interviewed. Discrepancies in descriptions of what happened will frequently occur and need to be resolved. The resolution of discrepancies generally requires very tactful reinterviewing. Witnesses may have hazy recollections and may exaggerate or present faulty opinions. They may collaborate on a "safe" scenario (i.e., nonincriminating). Therefore, to get the best cooperation from all concerned, it is important to convey to the interviewees that the interviews are nonpunitive and nonthreatening.

Other sources of information are those involved in the emergency processing after the explosion. They include firefighters, police or other local officials, and those who have treated the injured in cases where injuries occur. Frequently information is passed from those injured to those helping, such as ambulance drivers. The subpanel noted that at later times injured witnesses have a tendency to be nontalkative, particularly if there is any perceived liability threat. Witnesses tend to be vocal and cooperative soon after the event but tend to become more reticent as time passes.

After interviewing, an integration session should be held in which all of the investigators pool the information obtained. At this time, it may be possible to construct a scenario that appears to be reasonably verifiable. However, discrepancies frequently exist and it may be that no specific scenario can be stated. It is then necessary to go back for additional site investigation or investigation of pieces or parts that may supply the missing clues and to conduct additional interviews to try to fill in the gaps.

In some cases it may not be possible to pinpoint the actual initial event until rubble and wreckage are removed from key parts of the equipment that may yield clues. The removal may take place within hours or may be delayed for weeks for various reasons. If the original investigators cannot be present when the rubble is removed, the cooperation of some local person in segregating key evidence is important. Management personnel, if cooperative, may serve this function, or OSHA field people may be available. Insurance people may also want to be involved.

Laboratory Investigation

In some cases the critical evidence from items obtained from the site just after the explosion or when the rubble is cleared cannot be ascertained by visual examination alone. Laboratory tests may be necessary to determine fracture mechanisms, burn sequence, etc. It is important that appropriate laboratory facilities be available to the investigating team. The interpretation of laboratory data, of course, requires professional judgment and correlation with the rest of the information from the explosion site.

A report is the logical output of an investigation. Such a report should document the data and logic that led to the conclusion on probable chain of events. Photographs, site drawings, or related graphical information are valuable portions of such reports. Reports issued by the National Transportation Safety Board (NTSB) on transportation disasters, pipeline explosions, etc. are good models to follow. The format of the NTSB report is described in an earlier report by the panel (National Materials Advisory Board 1980).

Chapter 3

SUMMARY OF ON-SITE INVESTIGATIONS

In the Appendix detailed information is given on six explosion investigations conducted by members of the investigation subpanel. It is useful to point out how the previously discussed methodology was used in these investigations. Recapitulating, the major steps of the investigation methodology include physical site examination of pieces and parts of the elevator complex; determination from rubble, wreckage, etc. of the direction and origination of blast and combustion waves; and interrogation of witnesses. In the six incidents described, all of these steps were taken. In all cases the interviewing of witnesses played an important role in determining the probable scenario. On-site investigation was important in all except the second incident in which the cause was immediately obvious upon interviewing. In the incidents 1, 3, 4, and 5 the direction of blast and combustion waves also played an important role in determining probable sequence of events.

In the first incident, considerable site investigation and interviewing were necessary before the investigators were led to the conclusion that the ignition resulted from an electrical equipment failure in one of the bins. Although the precise cause of the initial propagation of the explosion is not fully deducible, the end result follows the assumption of a primary explosion in a loading bin connected directly to other portions of the facility.

In the second incident, the major explosion was definitely attributable to the use of firefighting procedures that stirred up dust and generated an explosive atmosphere. The initial fire was probably caused by a hot light fixture.

In the third incident, a light fixture also was the probable initial cause of a fire in the top of the headhouse cupola structure. The explosion that occurred after firefighters had arrived at the scene was inevitable because of the state of housekeeping of the building.

The second and third incidents were fairly easily identifiable events. However, in the fourth incident, considerable interviewing was necessary to ascertain the events that led to the explosion. The primary cause was a failing belt; however, only after detailed investigation was the whole story obtained. The single bucket elevator in the complex had been damaged so that choking and stoppage had occurred. There may have been a loose bucket on the belt. Jogging procedures apparently caused a friction fire that burned through the belt. The main explosion occurred in an inaccessible concrete legwell through which the bucket elevator passed. The explosion force propagated upward into the headhouse and downward into the tunnel. Because the concrete legwell shattered early in the explosion sequence, very little pressure was transmitted to the bulk of the elevator itself. The top of the headhouse was damaged because it did not have enough vent area to relieve the explosion pressures developed from the legwell directly below the headhouse. However, little damage was done in the tunnel as the explosion force had diminished because of rupture of the main headhouse walls. In this investigation an apparent discrepancy in the events just prior to the explosion was later explained when a hospitalized witness gave a different version of what had happened and refuted earlier testimony. This illustrates the importance of persistence in interviewing to validate the most probable scenario if it cannot otherwise be verified.

In the fifth incident, site investigation soon revealed that the initial explosion probably occurred in the headhouse itself or was communicated into the headhouse from the legwell. The initial explosion occurred someplace in the bucket elevator casing and propagated into the headhouse proper. The head pulley showed signs of scorching and evidence that the belt had caught on fire and broken. This was not confirmed until the wreckage was removed from the boot area several weeks afterwards. In this instance the communication from the headhouse to different bins through open spouting led to additional damage. However, the direction of propagation from leg to headhouse to other parts of the structure became fairly obvious early in the investigation. The ruptured bucket elevator confirmed the logical ignition source.

In the last event, witnesses confirmed that a belt had broken. The site investigation simply confirmed the expected propagation of blast and combustion wave damage after the leg and casing exploded on the bucket elevator.

In summary, the logical methodology described for the investigation of grain elevator explosions can be successful. Observations at the sites and interviews with witnesses are the principal mechanisms to determine cause. No investigation can be considered complete until all of the facts coincide and essentially verify the sequence scenario. Major inconsistencies must be resolved, or the cause will fall into the unknown (unverifiable) category.

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APPENDIX

INVESTIGATIONS

During the period November 1978 to July 1981, the sites of a number of grain elevator explosions were visited by members of the Explosion Investigation Subpanel of the Panel on Causes and Prevention of Grain Elevator Explosions. The elevators ranged in size from a small country elevator with a capacity of approximately 20,000 bushels to a large export elevator with a capacity of approximately 6,000,000 bushels. In all cases, excellent technical information on grain dust explosions was obtained. If one includes two recent European investigations--the Roland Flour Mill in Bremen and Eurosilo in Ghent--this information can probably be considered the most reliable contemporary data in existence. The six incidents described here are typical.

Information from each accident is presented separately in the form of an incident report. In the first section, Observations, factual information collected at the site of the accident is given. In the second section, Scenario, a plausible chain of events leading up to the accident is presented. Some of this material is speculative. In the third section, Conclusions, information relating to grain elevator safety and the successful conduct of investigations is discussed.

Incident No. 1

An explosion occurred at a concrete inland terminal elevator of medium size. There were truck dump and loading facilities and rail dump and rail loading facilities. A large headhouse was located between, but separated from two silo complexes. There were three bucket elevators within the headhouse having combination steel and concrete double legwells. One truck dump was adjacent to the headhouse and not enclosed, another was located a short distance away and enclosed. The rail dump and loading areas were alongside the headhouse on two lines; the inside line served the dump pits. There was a large drier between the headhouse and one silo complex with two bucket elevators. A machine shop was located on the opposite side of the headhouse. The office was located a moderate distance from the main elevator accident. There was a primitive dust control system. The level of housekeeping, as judged qualitatively by the subpanel, was not good.

Observations

The explosion occurred in mid-afternoon. Severe structural damage was done to almost all of the bins in the headhouse and moderate damage was done to most of the headhouse structure. The tops of almost all of the headhouse bins had blown off, essentially destroying the top of the bin floor and the top of the cleaner floor. In addition, some of these bins around the edge of the headhouse caused the failure of the outside wall. In the headhouse structure above the bin floor there were a large number of casement type windows. All of these windows were destroyed but there was little damage to the walls themselves. Fireballs had propagated through the basement, work floor, bin floor, and scale floors. Severe damage occurred to all elevator legs. Where the legs passed through the house bins in concrete legwells in some areas the concrete had completely shattered. This was especially true on the gallery floor where one of the legs vented. On other floors above and below the bins many of the the metal leg casings were split wide open. The one elevator leg showed severe fire damage with much of the belt and many plastic buckets burned. The exterior wet and dry drier legs also showed moderate explosion damage. Adjacent to the work floor the rail loading and dumping area showed fire damage but only slight blast damage. The two truck dumps showed evidence of fire and blast damage. The dust collection systems adjacent to the headhouse showed slight explosion damage. In the one silo complex severe explosion damage occurred to the catwalk connecting it to the headhouse, the gallery at the far end of the tunnel, and a small group of silos centered around an airshaft approximately one-third of the way along the gallery. This happened to be the location where the belt tripper was parted. Between the headhouse and this location, gallery sidewalls and the roof had been displaced and the windows were destroyed. At the location of this airshaft the gallery walls and roof had been completely destroyed. Beyond this point the explosion damage to the gallery was still significant but not as severe. At the location of the airshaft the grain in the surrounding tanks was on fire. The interior concrete bin walls had been extensively shattered leaving in many places only the reinforcing rod. The tripper rails above this area had been bent straight up. Concrete fragments from this area of the elevator had been thrown several hundred feet into the adjoining rail yard. In the tunnel under this silo complex only the portion from the airshaft to the far end showed any fire or explosion damage. An extremely strong blast wave had propagated down this tunnel shearing off the grain spouts at the level of the bin bottoms and completely destroying the end of the tunnel. The vertical slab had been moved several inches back into the earth. The other silo complex showed practically no explosion damage with the exception of an empty bin near the far end, which had exploded and caused moderate damage at its bottom. Damage to the tunnel was slight and a fireball had propagated down the gallery from the headhouse. Some damage from flying debris was done to the office building and cars parked near the elevator. At the time of the explosion milo had been unloaded from rail cars and corn was being loaded into rail cars. The leg that had been carrying the milo was running empty and another leg was carrying the corn. Both of the basement belts were running and neither gallery belt was being used. The first evidence of an explosion came from an employee in the basement near the north tunnel. He stated that he heard a "pop" and saw a fireball coming out of the boot of the leg that had been running empty. An employee on the scale floor felt the explosion and sought shelter under a desk in the scale shanty. An employee standing outside the office and looking at the basement of the headhouse saw dust coming out of the basement windows and heard five explosions. An employee on top of the railroad car saw a fireball come out of the loading spout and was knocked to the ground. He thought that he heard three explosions. Concrete fragments came through the roof of the office building but did not strike any of the occupants. An individual here described the explosion as sounding like a train wreck or the bumping of cars in a railroad yard. At this point the plant manager attempted to call the fire department but the telephone was inoperative. Personnel from surrounding industry called the fire department, who extinguished the fires in the headhouse but not in the grain tanks near the airshaft. After the explosion, regulatory agency personnel found extensive tramp metal in two of the elevator boot pits. Elevator employees unloaded the hopper cars that had been filled near the time of the explosion and found a bindicator (bin indicator) and a portion of electrical conduit. The bindicator had been located in the loadout bin. The fuse associated with this bindicator was blown and the wiring and conduit remaining in the bin showed evidence of arcing.

Scenario

A low level bindicator was installed in the loadout surge bin, which was between the scale and the car. Near the bottom of the bin a bindicator was installed inside the bin wall cantilevered on an electrical conduit elbow. The bindicator weighed perhaps 10 pounds, was approximately 10 inches in diameter, and had a depth of approximately 6 inches. The face was a rubber metal diaphragm, which made mechanical contact with a microswitch. Appropriate installation of this bindicator would have made the diaphragm flush with the bin wall. A load of grain that was dumped from the scale impacted upon the bindicator causing it to break loose from the conduit. This left exposed at the conduit the bindicator circuit wires with a live potential of 110 volts. After several additional grain dumps from the scale into the surge bin one of the dumps impacted upon the broken conduit and exposed wires. This caused the wires to contact each other and the conduit, producing an electrical arc. As the scale was continuing to dump the surge that was ignited by the electrical arc, an explosion occurred in the loadout bin and propagated into the adjoining house bins and the bin floor area through the destruction of the bin walls and tops. The explosion was able to go out the loadout spout to the car. The explosion also traveled up the spout into the scale and then through the common dust collection system into the bucket elevators. The legs blew out at various levels in the headhouse. The leg blowout on the gallery floor allowed the explosion to propagate in one direction toward the set of tanks where the airshaft was located. Progress of the advancing explosion down the gallery was impeded by the tripper, and the advancing airflow went down the ventilation shaft. This airflow in a vertical shaft would be ideal for producing a well-mixed dust-air mixture. The flame front then arrived as it too was deflected by the tripper down this shaft. A very rapid rate of combustion occurred. The combustion wave then came back up the shaft and returned toward the headhouse and went down the shaft into the tunnel where it went out the far end. In the gallery a flame front from the exploded leg casing traveled into the other silo complex. Conditions there were not as favorable for propagation and only a low velocity flame front traveled near the floor. However, at the end of the closed gallery it was reflected into the top of an empty tank. The dust inside the tank was disturbed and an explosion occurred.

Conclusions

Regulatory agencies have listed the tramp metal in the boot pit as the cause of this explosion. All reasonable efforts should be made to keep this foreign material out of the elevator equipment by the use of properly sized gratings on all dumps and the use of magnets on bucket elevator feeds. Regular cleaning of the boot pit will catch any foreign material that escaped the other collection system. However, there seems to be little information relating to the detailed mechanism of the heating and ignition of grain dust by tramp metal.

The ignition source considered by investigators from the subpanel to be more likely is the failed bindicator. Bindicators should, of course, be installed in the specified fashion. Moreover, only low voltage electrical circuits should be used in bindicator circuits to lessen the hazard caused by arcing. Guidelines for design of circuits that are incapable of igniting grain dust are contained in NFPA 493, "Intrinsically Safe Apparatus for Use in Division 1 Hazardous Locations."

Other possible ignition sources that were rejected as causes because they were not at the apparent point-of-origin were rubbing of the gallery belt on the frame and the dragging of rail cars through the car dump using a winch. The rubbing had begun to cut the frame and there is little doubt that the metal was red hot. This could have led to a smoldering fire. Friction sparks that could be caused by the dragging of the cars could have fallen into the dump pit.

It may have been possible to have detected the loss of the bindicator. If there had been a grating on the hopper car fill the broken bindicator would have been caught at this point. If a truck had been filling, presumably the driver would have seen it. Also, if the bindicator signal had been continually monitored, the loss of signal would have been immediately noticed. A minicomputer is more reliable than a human in this respect.

Once the explosion was initiated, it could propagate in several directions. A Mayo spout was used on the bin floor. Once the explosion reached this location it could enter every headhouse bin. Also, the dust collection systems on the scale and the legs were interconnected, allowing the explosion to propagate into the legs. European design practice is to use several smaller dust control systems. The one leg was running empty and there was probably a heavy suspended dust concentration. The legs effectively propagated the explosion downward. The headhouse had an unusually large window area for its volume; it was quite well vented and there was little structural damage. Most structural damage was done from the explosion of headhouse bins (garner bins). Concrete fragments were dispersed to rather distant places. Some of them impacted on the office building. The commonly mentioned rule of thumb that a distance from the elevator equal to the height of the headhouse should be a safe distance would appear to be inapplicable. A plate glass window in a shanty structure on the bin floor shattered and the fragments caused injuries. Within elevators only shatterproof, transparent materials should be used.

In a large elevator where there are many employees there must be an explosion-resistant emergency warning system to call for an evacuation if there is time. In addition, provisions must be made for locating personnel after a disaster. An assembly area should be designated in order to identify the missing. Time cards can be used for employees but gate records must be used for farmers, truckers, salespersons, etc. Some idea should exist as to the previous locations of missing personnel. Power, water hydrant, and telephone lines to the elevator should be blast resistant. This probably implies burial at some distance from the elevator foundation. Employees should wear fire-resistant or fire-retardant clothing over all portions of the body, including the head and hands, to minimize the severity of burns. This is perhaps most easily done by using coveralls or jump suits in conjunction with caps and gloves. Under no condition should employees go shirtless, wear only undershirts, or wear synthetic fiber (e.g., polyesters) clothing, which considerably exacerbates burn injuries.

Complete cooperation by management is most helpful in conducting an investigation. They can furnish blueprints, witness statements, flashlight batteries, and hospitality. One witness who was badly injured had been in a location where he could have clearly seen the course of the explosion but declined to cooperate on the advice of legal counsel. He was concerned that he would jeopardize any chance of financial compensation for his injuries. It is not known whether this difficulty is real or perceived, but whatever the reason it can be a significant impediment to investigations. Two visits were made to the site of the explosion. One was 2 days after the explosion and the other after 2 months. Both resulted in valuable information. A third meeting with members of the elevator management was made some 6 months after the explosion. Because of the size and complexity of the explosion it was not until after the third meeting that a reasonable scenario could be assembled.

Incident No. 2

An explosion occurred at a large wooden country elevator. There were rail loading and truck dump and truck loading facilities. There was a separate headhouse with two metal-encased bucket elevators. Two storage annexes were located on either side of the headhouse and two metal grain storage tanks were at the end of one annex. The level of housekeeping, as judged qualitatively by the subpanel, was not good.

Observations

The explosion occurred at mid-afternoon. Moderate damage was done to the metal-clad, frame-structure elevator buildings. The one annex building seemed to suffer slightly more damage than the other. The bins were essentially empty. An explosion propagated down the tunnel destroying the door at the end. Some of the bin bottoms were blown inward. The explosion was able to enter the empty bins in this fashion. The metal tank beyond the door was slightly burned on its side. The gallery and bin roof on this annex building were mostly destroyed. It had been displaced to the side and some of it was on the ground. The wooden bins were still intact but showed evidence of internal burning. The bin roof and gallery of the other annex were still intact but the gallery showed some bulging. This annex was mostly full and the explosion did not enter the bins. The two sides of the headhouse that did not face the annexes were blown off from the bin floor level to the roof. There was little damage to the bucket elevators and related equipment. A slight amount of burned grain was present. Before the explosion, the elevator had been unloading trucks of soybeans. Someone smelled smoke coming from the boot pit area that was covered by a hatch on the elevator work floor. The fire department was called and the elevator was evacuated. Upon the arrival of the fire department, three elevator employees and three firemen lifted the boot pit cover and observed flames. The fireman with a hoseline set the nozzle on fog and started to spray water into the burning boot pit. A "woosh" was heard and a ball of flame shot out of the pit. The people who were around this area promptly exited the elevator and after they had cleared the facility a blast was heard coming from the elevator. The fireman began to put water on the resulting fires, which were mainly confined to the grain. The watering was stopped when it was decided that the burning grain could be shoveled from the elevator. There was little fire damage to the structure.

Of the six persons standing around the boot pit only one was injured during the attempt to escape. His exit was by an indirect path to the outside that took him through part of the elevator, rather than by the direct exit door to the outside that the others used. This slight time difference was apparently enough to allow the expanding fireball to catch up with him.

Scenario

The boot pit area beneath the work floor had not contained a light fixture and a regulatory agency had ordered the installation of one. This area had not been recently cleaned (probably for a month) and the accumulated dust had buried the light fixture and the light was turned on. The hot fixture, well insulated by the grain dust, caused the dust to ignite. The application of the fog water stream dispersed the burning and unburned dust into the air and an explosion occurred. This partially vented into the work floor area but also traveled up the two bucket elevators to the top of the headhouse, into the two galleries, and down the one tunnel.

Conclusions

Proper and correctly installed electrical equipment can cause problems if the surrounding environmental conditions change. The accumulation of dust not only presents a fire hazard but also an explosion hazard. In elevator designs, all areas, boot pits included, must have easy access, be well lighted, and be conducive to the performance of routine tasks such as housekeeping. Dust must not be allowed to accumulate in hidden areas where its danger goes undetected.

The fighting of elevator fires is a sensitive procedure. There seems to be a general belief that a fog stream will not disturb the dust and lead to an explosion. Until better methods are devised it is probably best to remove burning grain and dust from the elevator by the use of buckets and shovels. Fire department personnel in areas where grain elevators are located must be educated concerning tactics for combating fires in grain elevators. Wooden elevators would appear to be leaky enough that the overpressure resulting from the explosion cannot build up to a high enough level to do major structural damage. Therefore, if the few resulting fires from the explosion can be initially controlled, the wooden structure need not burn down. The response time of the fire department is critical. When bins are empty the most severe explosion damage may occur. Every effort should be made to ensure that the bins are substantially sealed off from the tunnel, that the bin bottoms cannot collapse upward, and that the bins are sealed off from the gallery or distributor.

Although the employees were aware of the possibility of explosions, none of them seemed aware that a dust explosion could literally tear an elevator apart. It is important that the grain industry trade organizations, the agricultural extension services, and the government regulatory agencies publicize this problem.

Incident No. 3

A fire and explosion occurred at a small country elevator and mill combined in the same wooden structure. There were rail loading and truck dump and truck loading facilities, the latter of the drive-through type. A wooden flat storage shed and an office building were located near the elevator mill building. A metal bucket elevator with twin legs ran through the central part of the structure. There was no headhouse structure as the head pulley was located on the roof. The bins had open tops. The level of housekeeping, as judged qualitatively by the subpanel, was not good.

Observations

The explosion occurred late at night. Minor structural damage was done to the wooden structure by the blast wave in the mill area, which was not well vented. A slight separation of the roof and walls occurred. Substantial fire damage occurred in the cupola where there was a sustained fire before and after the explosion. Slight charring of the wooden structure occurred in the truck dump area and in the mill. Substantial structural damage due to the blast occurred to the leg casing in approximately the lower one-half portion. The belt had parted and dropped. It had burned through, but did not look as if it had caught on fire from frictional heating. Another area on the belt also showed evidence of burning. Prior to the explosion, milo had been ground and screened, mechanical repairs had been made on the screener, and wheat had been loaded into a truck. This activity had gone on from mid-afternoon until late evening, during which time the lights in the elevator had been left on continuously. At the completion of the loading, the 2 workers closed the elevator and went to the office to relax before going home. As they prepared to leave the office they noticed a flickering light in the cupola window and identified it as a fire. The workers called the fire department and proceeded to the roof (approximately 30 feet off the ground) on the external ladder to fight the fire with small hand fire extinguishers. When they looked through the window of the cupola they saw a fire raging on the bin floor and on one wall where there had been a lighting fixture. They discharged the fire extinguishers with little effect and the one worker left to get more. An explosion occurred. At approximately this time, the fire department arrived and successfully suppressed the continuing fire in the cupola. A fireman who was responding to the alarm was approximately 100 yards away from the elevator at the time of the explosion. He heard a "woosh" sound and saw a fireball come out of the cupola, out of the one open truck dump door, and out from around a large hanging door on the feed mill. The resulting fire was successfully suppressed.

Scenario

A vapor-proof light fixture was installed on the cupola wall with its axis of symmetry perpendicular to the wall. There was as much as several inches of dust on horizontal surfaces including the top of the light fixture. The light fixture became hot enough to ignite layered dust and this in turn fell onto the dust layer on the floor and ignited it. The wooden bin floor surrounded the metal leg casing. The fire surrounding this casing caused the bucket elevator belt to catch fire and burn through. Since the one side of the leg was closer to the ignition source than the other side, the latter had only started to burn by the time the belt dropped. When the belt with its metal buckets fell down the leg, accumulated dust was disturbed, creating a combustible dust-air mixture in the presence of burning belting or sparking metal cups. The leg casing exploded, discharging a fireball into the truck dump area. This fireball vented out the one open door and into the feed mill where additional layered dust was stirred up, producing a secondary explosion, which vented through the hanging door on the feed mill. The fire in the cupola still continued out of control.

Conclusions

An accumulation of dust on the vapor-proof light fixture probably led to this accident. Presumably problems had not occurred before because the lights had not normally been left on for this length of time. Had there been a sprinkler system in the wooden elevator, the fire may have been initially contained. Had not the leg belt dropped, an explosion probably would not have occurred. In this case an outside ladder allowed the workers access for fire fighting. Perhaps they would have been more successful in fighting the fire had a standpipe been available. Considerable care must be exercised in the fighting of dust fires because it is easily possible for the fire to become an explosion. The firemen were successful in containing the fire because they were equipped with a snorkel truck and the elevator was not very tall, approximately 30 feet. The blast damage to the structure was not severe because of the large venting area afforded by the one open truck dump door and the hanging door. Also, wooden structures are for the most part rather porous. Because of its low density, wood does not make effective projectiles.

The subpanel investigators arrived at this elevator a week after the explosion had occurred. It had not been reported to federal authorities. The accident was noted in news accounts. It is necessary that a system be instituted so that the occurrence of an accident is promptly reported. In some investigations equipment other than that normally carried by the investigators is required--ladders, boots for deep water, and winches. (In this particular case the fire department provided such equipment.) It is desirable not to let witnesses confer before they are interviewed. It is also best to interview witnesses first separately and then as a group. The investigators should be able to spend as much time at the site as required for a thorough analysis. Some investigation tasks, such as the removal of a dropped belt, are physically impossible for investigators to attempt. Therefore, it is important that an investigating team have the means to obtain the necessary assistance to handle heavy manual tasks.

Incident No. 4

An explosion occurred at a country elevator of medium size with an associated mill. The elevator was of concrete construction. It had truck loading and unloading facilities and rail loading facilities. There was a single set of silos with a large Butler bin at one end and the headhouse and mill building at the other. There was no gallery. There was a screw conveyor in the tunnel. Housekeeping, as judged qualitatively by the subpanel, seemed adequate.

Observations

The explosion occurred during morning operations. Severe structural damage was limited to the concrete structure under the headhouse. This structure was external to the grain silos and contained the manlift shaft and the legwells. Approximately the top one third of two of the walls had been totally blown away. One of the damaged walls was opposite the bin wall and the other orthogonal to it. Moderate structural damage was sustained by the headhouse. The headhouse was connected to the leg wells and manlift shaft through holes in the floor. The walls of the headhouse were bulged and the casement windows in the headhouse were broken and blown open. The boot area was full of rubble resulting from the collapse of the upper legwells and manlift shaft. The tunnel area showed evidence of burning and the door at the far end of the tunnel was destroyed by the overpressure. At the time of the explosion a rail car was being loaded with corn, and alfalfa pellets were being unloaded at the feed mill. The corn was being screened and trouble had been reported with the screener clogging. Subsequently it was reported that the entire system had plugged--screw conveyor, bucket elevator, and feed spout. Several witnesses heard the explosion and said that there was only one. Only one individual actually saw the explosion and he stated that the north side of the structure under the headhouse blew out spewing concrete and two bodies. The witnesses stated that 3 days before the explosion a fatal accident had occurred causing substantial mechanical damage to the bucket elevator. During the day preceding the explosion considerable time was spent repairing that damage. Observations made by OSHA employees subsequent to the team's first visit and during elevator reconstruction revealed that the bucket elevator belt was covered by concrete rubble in the boot area. It had metal buckets and was parted. At the break in the belt there was evidence of combustion. The lagging in the head pulley was only partially intact showing signs of being burned off.

Scenario

The bucket elevator was jammed either because of the mechanical damage that had been previously done to it or because of a choke brought about by the clogging of the screener. An attempt was made to "jog" the leg. It is not clear who turned the motor on as the only controls were at ground level outside the elevator near the boot. The two injured employees were blown out of the headhouse and the employee in the feed mill stated that he had not been in the elevator for the 5 minutes preceding the explosion. The slipping belt on the head pulley caused a friction fire that burned through the belt. The belt then fell down the legwells and dislodged accumulated dust. The flaming belt end or the metal cups striking the concrete wall acted as an ignition source for the suspended dust-air mixture. An explosion then occurred in the legwell and propagated upward into the headhouse. The headhouse then exploded, venting through the headhouse windows to some extent. Also, the leg explosion was partially reflected off the headhouse floor causing the top portion of the legwells and manlift shaft to fail. This vented the high pressure gases. The explosion also traveled down the legwell into the boot. The explosion vented into the tunnel, in which it appeared an explosion was not sustained.

Conclusions

This accident may have occurred as a result of events 3 days before. The elevator equipment had been damaged and the employees were still thinking about the fatal accident and the funeral. Generally, accidents occur more frequently when employees are under stress or distracted--Monday mornings, Friday afternoons, shift changes, graveyard shifts, overtime, etc.

If modern devices are employed it should be possible to prevent a leg choke. The leg feed should be controlled by a torque-sensing device on the drive motor. As the torque required increased, the feed rate would be decreased. The jogging of legs should be physically prevented through the use of interlock devices. The elevator boot should be easily accessible so that if a choke does occur it can be cleaned out. Shovel size access ports should be put in the boot, and the boot pit should be well lighted and free of obstructions. Provisions must be made to remove the excess grain from the pit.

Concrete legwells allow little explosion venting. Pressures up to one atmosphere can probably develop before failure occurs allowing continued propagation of the explosion. When they do fail, concrete fragments act as projectiles and high pressure gas is released. In this case, however, since the legwell was on the exterior of the structure, the damage occurred to the surrounding area and not in the interior of the elevator. The truck dock was unfortunately within the distance of travel of some of the fragments.

The destruction of the manlift shaft broke the only connection between the top and ground level of the elevator. The only access to the roof was by a crane bucket. Secure, blast-resistant means of egress must be provided so that injured employees can be removed from the top of an elevator.

The bin bottoms and gates were of particularly substantial construction. Although a combustion wave did travel down the tunnel, it did not get into the silos and cause them to explode. Also, the absence of a gallery to some extent prevented the explosion from entering the bins. It is possible, however, for a distributor to propagate the explosion into the bins through the spouts.

The arrival of the subpanel members within 24 hours of the explosion aided considerably with the investigation. Some public safety officials--State Fire Marshall--were still available. Furthermore, the witnesses were still willing to talk freely and events were still quite fresh in their minds. An investigator was able to return to the site during the period of reconstruction. He was able to examine items of interest as they were removed from the rubble. At the time of the first visit the bucket elevator belt and the head pulley were not accessible. During return visits it was also possible to visit with injured personnel who were not initially available because of hospitalization.

Incident No. 5

An explosion occurred at a large concrete country elevator. There were truck dump and truck loading and rail loading facilities. A very large headhouse was located on the top of the silos and approximately in the center. There were two concrete double-leg bucket elevators, one used for unloading and one used for outloading. The truck dump was of the drive-through type located toward one end of the structure. An abandoned brick soy mill was at this end of the elevator. At the other end of the elevator was a large steel storage tank. Along the one side of the elevator was a wooden building used for storage. The office was in a separate building some distance from the elevator. The level of housekeeping, as judged qualitatively by the subpanel, was poor.

Observations

The explosion occurred in early afternoon. Slight damage was done to the adjacent wooden storage building whose end was parallel to the drive entering the truck dump. The blast, which came out of the truck dump, removed some of the weatherboard structure from the framing. The soy mill also received slight blast and missile damage resulting from high pressure gases venting from a personnel door on the end of the elevator. Fire, blast, and missiles moderately damaged the hopper-bottom trailer that was standing on the truck dump. The fire damage seemed to engulf the truck; however, the blast and missile damage was the worst on the side toward the bucket elevators. The truck dump area showed a uniform scorching due to fire. Much grain from broken house bins had fallen into this area. The elevator control room adjacent to the truck dock and the leg was also burned by the passage of a fireball. Both bucket elevators were severely damaged by blast in the vicinity of the truck dump. The legwells for each elevator were located on either side of the manlift-ladder shaft and the up- and down-legs were separate. Both down-legs had shattered completely, spewing concrete fragments into the control room and across the truck dump. The leg casings showed decreasing damage to the level of the screener floor approximately half way to the top of the elevator. The failure of the leg casings made both the manlift and ladder nonoperative. Fumigant had been stored near the legwells and as a result of the explosion had been dispersed around the work floor and truck dump area. The tunnel under the bins toward the steel storage tank showed slight evidence of an explosion. At the far end some damage had been done to the auger for the steel storage tank. Moderate damage was done to the tunnel area going to the other side. The tunnel terminated in a room with a personnel door and this door had blown off. It was clear that a rather large explosion had occurred in the truck dump area but to a large extent was able to vent through the open entrance and exit doors. Access to the upper part of the elevator was difficult as the ladder in the manlift shaft had been destroyed. Entrance was gained by climbing to the top of a grain drier that was located on the side of the elevator opposite that of the storage shed. At this level, which was approximately 50 ft above the ground, there was also a window in the elevator. A 20 ft extension ladder was laid from the top of the grain drier to the window. This was the level of the screener. Looking into the house bins it could be seen that the legwells had also exploded into the bins. The damage to the legwells was below this level. From this level it was possible to use the ladder to the headhouse. At the bin floor level there was a Mayo spout coming from the distributor with a circle of holes for the respective bins. The floor was covered with much accumulated grain and dust. The walls were covered with dust to such a thickness that it almost resembled a layer of cork. A ladder and catwalk encompassed the distributor floor and at the highest level within the headhouse was the head pulley and drive motor. The head pulley covers had been blown off. The lagging on the unloading leg had bunched on one side of the head pulley. This caused the belt to slide to one side and it and the metal buckets were rubbing against the leg casing, which was metal at this point. The headhouse was moderately damaged. The broken windows and bulged sides indicated that an explosion had occurred within the headhouse. An inspection of the roof showed that the headhouse had apparently separated from the roof and that it had slid along spouts passing diagonally through the walls. It thus appeared as if the headhouse had to some extent lifted vertically. The roof on the end of the elevator toward the steel tank appeared to have hinged upward to relieve the pressure when some of the tanks exploded. Witnesses reported that it seemed as if the entire roof of the elevator had lifted. All of the bin covers were displaced. The spout feeding the large steel tank had fallen. Many of the spouts within the elevator were worn through and were patched with rags, boards, and wire. Fires had occurred in many of the tanks. At the time of the explosion rail cars were being loaded with corn and corn was being unloaded from the hopper bottom truck. The truck driver was apparently closing his hopper bottom from the side of the truck toward the bucket elevators. An elevator employee was in the control room, and another at the scales whose controls were located in the wooden storage shed.

Scenario

The metal cups rubbing the metal leg casing near the head pulley caused either a hot spot or sparks and this leg exploded. This explosion then propagated down the leg and into the distributor. After accelerating down the leg, it blew out at the work floor and boot pit level causing additional explosions in the truck dump area, the dump pit, and the two tunnels. From the distributor it was able to get into the second leg, the headhouse, and the various silos.

Conclusions

Out-of-alignment belts in bucket elevators may act as ignition sources either because they rub on a metal casing or their metal buckets strike a metal casing. Belt alignment monitors should be used and plastic buckets should be considered. Regular inspections should be made of the head pulley to check the conditions of the lagging. Inspection should be facilitated through the use of conveniently located doors, catwalk, and ladders.

Through the application of suction it may be possible to remove the explosive dust concentration within the leg so that if an ignition source does appear, an explosion need not result. Headhouses should be designed so that all horizontal and vertical surfaces may be regularly swept to remove dust.

Elevators should be designed so as not to have interior concrete legwells. These allow explosion pressures to rise to a high level, vent high pressure gases into confined spaces such as bins where additional explosions occur and spew out concrete fragments. All too frequently these are slip-formed to include the elevator or manlift and ladder. These are, of course, also destroyed when the casing fails. It is necessary to provide ladders giving access to the top of the elevator in other locations. Control rooms should not be located inside elevators especially next to legwells. As far as possible personnel should not be in the truck dump area. With hydraulic lifts this is possible to some extent. The elevator roof should not be tied to the tank structure. It would then be possible for the high pressure gases to lift the roof and not cause a failure in the side of the tank. Open truck dump doors are very effective venting areas for explosions.

Although some concern has been expressed about ignition by hot surfaces of a running or recently run truck, it seems unlikely that a significant hazard exists. A surface must exceed 400°C and be exposed to a cloud of dust with a concentration above the lower explosive limit. It seems unlikely that this will occur when a truck dumps or is dumped because the heaviest clouds are at the grating and the truck body shields the exhaust system from the high concentration dust clouds.

Incident No. 6

An explosion occurred at a large concrete country elevator. There were truck loading and unloading facilities as well as rail loading facilities. There was a large flat storage shed near the elevator and the office building and scales were separate from the elevator. The elevator was of unusual design in that there was no headhouse or gallery and the silos were arranged in a single circle about a steel-cased double-leg bucket elevator. Another elevator was external to the bin structure. Additionally, the entire elevator interior was slightly pressurized to help prevent the escape of dust into the elevator. The level of housekeeping, as judged qualitatively by the subpanel, appeared to be adequate.

Observations

The explosion occurred in mid-morning. There was a fatality and several injuries. Severe damage occurred to the elevator control room, the penthouse that covered the interior legwell, and the truck that was located on the truck dump. Moderate damage occurred to all leg casings and the flat storage shed. A significant explosion occurred in the basement of the elevator and the escape of these high pressure gases caused the severe damage. Part of the gases went up the center of the circle of tanks where the outloading bucket elevator and the manlift were located. This destroyed the penthouse, which was situated on top of the vertical shaft. Six-inch steel channels that supported the structure were bent by this blast. Additional high-pressure gas escaped through the tunnel to the truck dump. The elevator control room was located on top of this tunnel between the elevator structure and the truck dump. The floor of the control room was lifted to almost ceiling height when the top of the tunnel failed. Burned gases escaped around the metal dump pit and through the hydraulic truck hoist and lifted the truck that had just dumped. The remaining high-pressure gases vented through a personnel door forming a high-velocity jet that impacted upon the flat storage shed approximately 75 feet away. Some of the 2" x 4" structural members were broken and some of the sheet metal covering was torn off. The damage to the interior outloading leg was caused by the belt dropping. The ends of the belt were badly burned and the head pulley lagging was partially missing and showed evidence of combustion. The outside unloading leg exploded causing the metal casing panels to separate at the corners. Some of the bin covers had been lifted off and there had been fires in several of the bins.

Just before the accident, corn was being loaded into a string of rail cars and corn had been dumped into the truck pit, but it was yet to be elevated. The interior leg, which was feeding the rail cars at this point, choked. Help was sought to dig out the choke, but none could be found. A decision was made to jog the leg and thus defeat the interlocks. A drop in amperage of the bucket elevator motor caused the supervisor to go outside and look at the head pulley and then go to the boot area and open the inspection door to see if the belt had dropped. The belt had not dropped and the supervisor took the manlift to the top of the elevator to inspect the head pulley. At this time the explosion occurred. The supervisor was approximately two thirds of the way to the top when struck by the blast. He managed to get out of the manlift and up the inside ladder to the top of the elevator and then proceeded to climb down the outside ladder. A farmer in his truck cab was slightly injured when his truck was displaced by the blast. The elevator employee at the truck tail gate was thrown into an adjoining field by the blast. The elevator operator in the control room was crushed when the control room floor was lifted to the ceiling. The local fire company arrived at the scene, strung hose lines to the 100 foot high elevator roof, and extinguished the bin fires by hosing down the grain.

Scenario

For some reason a choke occurred in the outloading leg. As help was not readily available to dig out the choke, it was decided to jog the leg. This caused a belt and lagging fire at the head pulley. The boot inspection door was opened, allowing pressurized air from the elevator interior to flow into the leg and escape to the outside. This flow of air intensified the belt and lagging fire. The belt burned through and dropped down the leg. For some reason the leg did not explode. The collapsing belt pushed a cloud of dust out of the open boot inspection door and caused the leg casing to split. Burning pieces of lagging and belt fell out of the casing and into the dust cloud in the basement of the elevator, which subsequently exploded.

Conclusions

The bucket elevator choked and in spite of interlock devices an attempt was made to jog the leg. Chokes can be prevented with motor torque or belt tension devices controlling the bucket elevator feed gate. The boot area was quite accessible, so it should have been relatively easy to have removed the choke. Employees must be educated that jogging a leg may be a fatal mistake.

The blast demolished the control room and the employee lunch and break room. Areas where personnel normally congregate must be removed from the elevator. Since escaping jets of gas from doorways and windows can travel large distances, buildings should not be placed opposite the elevator.

It is clear that fighting fires on the top of an elevator is difficult and may not be desirable from the point of view of grain salvage. Dry standpipes to the top of the elevator are probably desirable, but for a severely burning bin fire it is not clear that water is effective. Indeed combustion of grain in a limited oxygen environment may produce carbon which then reacts with water through the water gas mechanism to produce quite dangerous carbon monoxide and hydrogen. It still remains to be determined whether water will effectively penetrate a bin fire. The water-logged grain also expands and if not quickly removed can place nondesign mechanical loads that lead to failure on the silos.

Bin covers may, if large enough, effectively vent the high-pressure gases from exploding partially filled tanks. Silos that are nearly full do not explode effectively. However, the bin covers must be securely fastened to the bin tops with a short piece of cable or chain or they become effective missiles. Distributors are effective in multiplying the paths of explosion propagation as numerous spouts are interconnected at this point. If an explosion comes down from the bucket elevator feed, it can usually get into each bin. The truck dump is an effective large high-pressure vent for the basement area. (Personnel located in this area are likely to be injured in an explosion. Therefore, only personnel actually participating in the operations should be in this area. Truck drivers and visitors should be encouraged to wait elsewhere.)

During this investigation, cooperation with personnel from the investigative agencies was good. Also, additional people had been brought in to assist with elevator operation and repair; thus, the work load was considerably lightened and employees were able to spend much more time with the subpanel investigators. Blueprints and flow diagrams provided to the investigators aided the investigation considerably.

BIBLIOGRAPHIC DATA SHEET	1. Report No. NMAB 367-4	2.	3. Recipient's Accession No.
4. Title and Subtitle Guidelines for the Investigation of Grain Dust Explosions			5. Report Date February 1983
			6.
7. Author(s) Panel on Causes and Prevention of Grain Elevator Explosions			8. Performing Organization Rept. No. NMAB 367
9. Performing Organization Name and Address National Materials Advisory Board National Academy of Sciences 2101 Constitution Avenue, N.W. Washington, D.C. 20418			10. Project/Task/Work Unit No.
			11. Contract/Grant No. J-9-F-8-0137
12. Sponsoring Organization Name and Address U.S. Department of Labor Occupational Safety and Health Administration 200 Constitution Avenue, N.W. Washington, D.C. 20210			13. Type of Report & Period Covered Final
			14.

15. Supplementary Notes * With additional funding from: National Institute for Occupational Safety and Health (NIOSH) and U.S. Department of Agriculture.

16. Abstracts A methodology for investigating grain elevator explosions is presented. The information that forms the basis for the methodology was gathered by a subpanel of the Panel on Causes and Prevention of Grain Elevator Explosions who investigated a number of grain elevator explosions generally soon after they occurred. The panel used the information in forming its conclusions and recommendations published in a series of reports.

In addition, several explosion incidents are described in detail to illustrate typical grain elevator explosion scenarios.

17. Key Words and Document Analysis. 17a. Descriptors

Grain-handling facilities
Grain dust
Dust explosions
Ignition sources
Explosion investigation methodology

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
This report is for sale by the National Technical Information Services, Springfield, Va. 22151	UNCLASSIFIED	42
	20. Security Class (This Page) UNCLASSIFIED	22. Price

FORM NTIS-35 (10-70) USCOMM-DC 40329-P71