RISK ASSESSMENT OF A SECONDARY GRAIN DUST EXPLOSION IN A BUCKET ELEVATOR LEG USING FAULT TREE ANALYSIS

By

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As the end of my degree program approaches, I can appreciate fully one statement made by the author of Ecclesiastes. He proclaimed, "Better is the end of a thing than its beginning...." (Eccl. 7:8).

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CHAPTER I

INTRODUCTION

History of Grain Dust Explosions

Grain dust explosions in the grain handling industry have been reported in the United States since the 1800's. It was not until 1913, following an incident in a Buffalo, New York, feedmill in which 33 persons were killed, that concern was felt outside the industry. In 1913 the United States Department of Agriculture's Bureau of Chemistry initiated a study on the volatility of agricultural dusts (Chiotti and Verkade, 1976).

From December 21 to 28, 1977, there were 57 persons killed and 48 injured in just five elevator and feedmill explosions. In response, the U.S. Secretary of Agriculture, Bob Burgland, announced an "immediate and continuing effort to find the cause of and cures for grain dust explosions." A task force on grain elevator safety and explosions was appointed. A report of 250 explosions attempted to determine the relationship among them and find a common denominator (USDA, 1980).

The number of grain dust explosions has decreased since 1980. Table I documents current statistics of incidence of grain dust explosions and the associated number of deaths, injuries and estimated dollar losses since 1980.

The bucket elevator leg is identified as the most likely location for the occurrence of a grain dust explosion (NMAB, 1982). Bucket elevators are the primary vertical conveying component used by the grain industry. They consist of

TABLE I

SUMMARY OF GRAIN DUST EXPLOSION INCIDENCE IN THE U.S. SINCE 1980.*

Year	Number of Explosions	Number of Deaths	Number of Injuries	Estimated Damage to Facility (million $)
87	15	0	18	8.3
86	21	2	14	1.6
85	22	4	20	65.0
84	21	9	30	19.9
83	13	0	14	3.6
82	14	6	34	15.0
81	21	13	62	29.0
80	44	10	47	10.0
Total	171	44	239	152.4

*(Schoeff, 1988)

rows of metal or plastic buckets mounted on reinforced rubber or PVC belting and are enclosed by a sheet metal casing (see Figure 1).

Theory of Grain Dust Explosions

Before an explosion can occur, four components must be present: (1) grain dust serving as fuel must be suspended in the air at a level higher than the minimum explosive concentration (MEC); (2) sufficient oxygen is needed to support combustion; (3) an ignition source of sufficient energy and duration; and (4) the above three elements must occur within a confined space. When these conditions exist concurrently, a dust explosion may occur.

Fuel for a grain dust explosion is grain dust in suspension at or above the MEC, reported to be 50 g/m^3 (0.5 oz/ft^3) (Palmer, 1973). Grain dust in suspension at a concentration below the MEC will not fuel a grain dust explosion in the

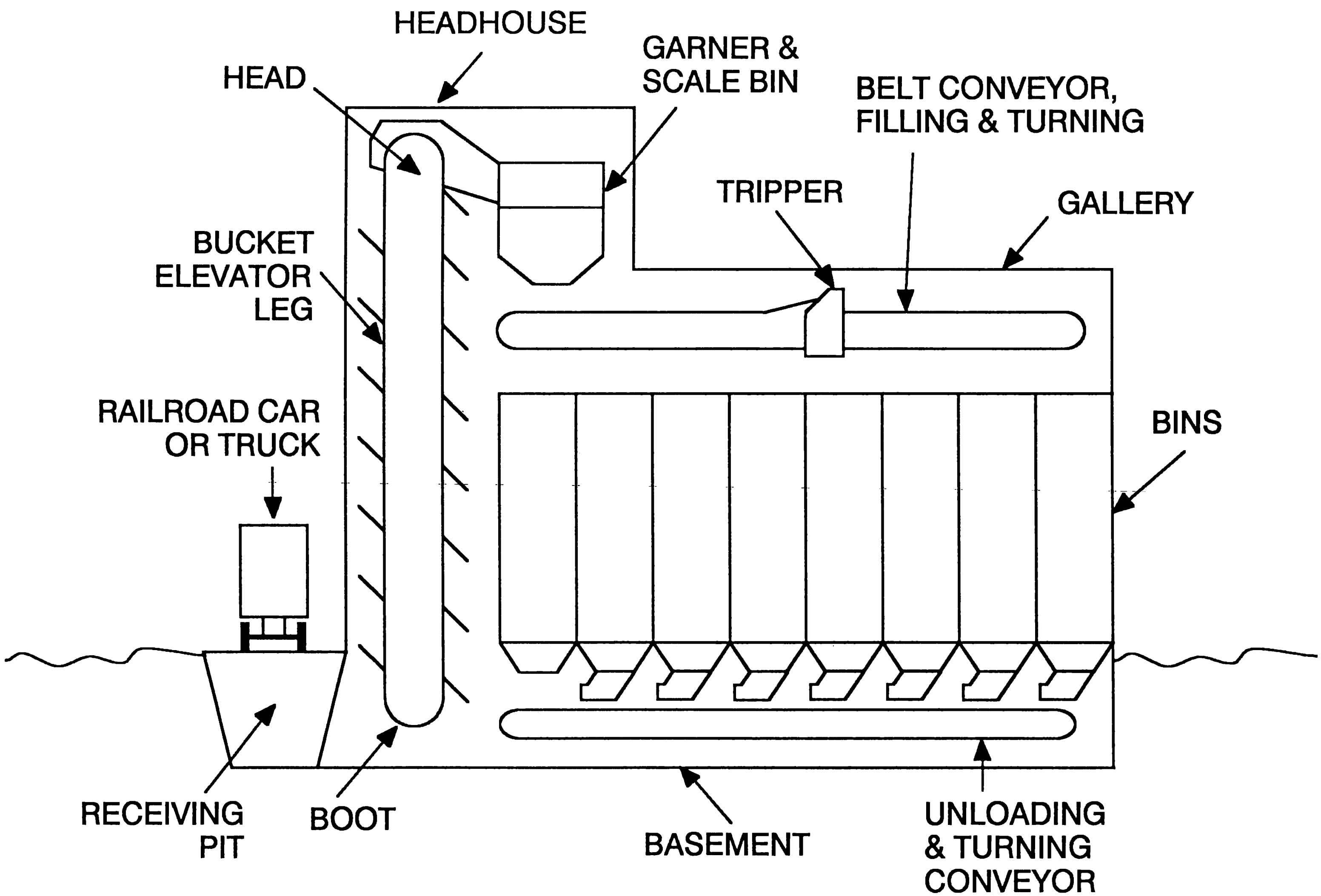


Figure 1. Schematic of Typical Grain Handling Facility

presence of the other three ingredients.

Oxygen and containment are likely to be present in certain areas within any grain handling facility. Containment contributes to a grain dust explosion in two ways. First, the restricted volume allows for the development of the MEC by restricting the dispersion of aerated grain dusts. The MEC for grain dust is so high that it is not likely that it could occur without confinement or in large open areas inside a grain handling facility. Sufficient confinement is provided by elevator legs, storage bins, and covered conveyors. Secondly, containment provides a means for the creation of a pressure gradient required for rapid combustion that results in the over pressure of the secondary structure.

The sources of ignition in a grain dust explosion are varied. They include smoldering grain and grain dust, hot surfaces created by over-heated bearings, or friction between drive pulley and belting material, use of improper welding and cutting safety practices, friction sparks from the binding of tramp metal or other foreign objects, electric sparks, the discharge of static electricity, and spontaneous heating from biological and chemical activity, to name a few.

A grain dust explosion is actually a series of explosions, consisting of a primary explosion followed by multiple secondary explosions. The primary explosion is usually a small over-pressure propagating a pressure front of approximately 13.8 kPA (2 psi). The pressure front expands from the point of ignition at an approximate velocity of 305 m/s (1000 ft/s) (Palmer, 1973). The pressure front may expand throughout a facility and aerate layered dust in its path. The subsequent fire front may serve as an ignition source for the newly formed dust clouds. In this way multiple secondary explosions can occur throughout a grain handling facility.

Secondary grain dust explosions are by far the most devastating. These explosions propagate a pressure front of approximately 552 kPa (80 psi) moving at over 305 m/s (1000 ft/s). No conventional grain handling structure can withstand this magnitude of internal pressure.

Systems Approach to Grain Dust Explosion Prevention

Research has identified many of the deterministic aspects of the grain dust explosion problem. The vast range of variables involved emphasizes the complexity of the problem. Other similar problems are often approached from a systems point of view.

A system can be described as "a collection of items from a circumscribed sector of reality that is the object of study or interest" (Pritsker, 1986). A primary objective of this type of problem solving technique is to chose the proper system. This involves adequately defining system boundaries, inputs, outputs and assumptions (known as the world view).

A systems approach to the grain dust explosion problem requires the interaction of the system inputs to be determined as well as their respective influence on the output of the system. In this case, the system output is the occurrence, or non-occurrence, of a secondary grain dust explosion. The subsequent determination of the probabilities of occurrence of the system inputs leads to the determination of the probabilities of occurrence of the system outputs.

CHAPTER II

PROBLEM STATEMENT

The problem of grain dust explosions has not been studied from a systems point of view. This void allows over-sight of critical components or practices. With a systems approach, the problem can be systematically dissected with less regard for individual biases and prejudices. This research is designed to analyze the problem of grain dust explosions in such a manner.

Objectives

The overall objective of this research is to predict the probability of the occurrence of a secondary grain dust explosion inside a bucket elevator leg. The occurrence of a secondary grain dust explosion in a bucket elevator leg is defined as a failure. A model is developed requiring the following specific steps;

1) Identify the known events leading to a failure.

2) Identify the combinations of base events necessary to cause a failure.

3) Assign point estimates of the probability of occurrence to each base event and determine which combinations of base events are most likely to occur.

4) Demonstrate the applicability of the model.

5) Develop recommendations for resource allocation to prevent a failure.

CHAPTER III

REVIEW OF LITERATURE

Research, in prevention of grain dust explosions has been limited to the physics and the factors contributing to the explosion phenomenon. These contributing factors include the deterministic aspects of the explosion, the physical and chemical properties of grain dust, and methods to minimize the dust concentration in grain handling facilities. Pratt (1979) and NMAB (1982) suggest that a systems approach to the problem of grain dust explosions would provide additional insight to this problem but fall short of providing a working model. Procedures used in reliability and hazard analysis offer conceptual techniques which are applicable to the problem of grain dust explosions.

Deterministic Aspects of Grain Dust Explosions

Palmer (1973) documents many of the explosive properties of explosive dusts. These properties include minimum ignition temperature, minimum explosive concentration, minimum ignition energy, maximum explosive pressure, maximum rate of pressure rise. This data although not applicable to every situation, gives good estimates.

Cross and Farrer (1982) Present theoretical discussion of the ignition process devoted primarily to the discharge of static electricity and the energy needed to cause ignition of a dust cloud.

Physical Properties of Grain Dust

The dispensability and combustion rates of grain dust are governed by chemical and physical properties of the dusts. The ease of grain dust aeration is dependent upon its particle size distribution and particle density. The rate of combustion is highly dependent on the exposed surface area of dust that can readily react with oxygen. These physical properties are the key to defining dust explosibility (Parnell et al., 1984).

Various laboratory techniques have been used to determine the different physical properties. A discussion of the techniques and the physical properties of corn, wheat, soybeans, rice and sorghum dusts are presented by Parnell et al. (1984).

Control of Airborne Concentrations of Grain Dust

Dust control is a problem that confronts all grain handling facilities. Normal elevator grain movement at elevators produces dust, estimated at 0.14% (by weight) of the moving grain (U.S. GMRL, 1982). In large elevators grain movement can amount to tons of dust per hour of operation.

In recent years much attention has been given to controlling dust for several reasons: (1) grain dust explosions have caused losses of millions of dollars and loss of lives; (2) rising energy cost are increasing the cost of dust collection and ventilation; (3) worker health problems have been related largely to dust inhalation; and (4) tightening of Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) air pollution standards are increasing industry investments for dust control equipment (Goforth, 1985).

Dust handling is a continuous process at every active elevator. Dust collection systems must operate each time grain is moved, requiring large volumes of air for collection and separation in filtering devices such as cyclones and bag-type filters. Inadequate design of ventilation systems and equipment breakdowns may result in clouds of dust exceeding the MEC. Wade and Hawk (1980) found that explosive conditions occurred consistently in bins and high speed bucket elevators during operation, and noted that the presence of dust control systems had no measurable effect on the dust concentration inside the elevator legs.

The lack of effective dust control inside elevator legs is not uncommon. Dust control systems are not designed to handle the quantity of dust being conveyed by the grain handling operation (Wade and Hawk, 1980). It is not uncommon therefore that complete separation of dust from grain, interpreted by some to be dust control, is never achieved.

Layers of settled dust on equipment, floors, and building structures that could fuel a secondary explosion (Schulman, 1983) are considered the chief hazard (Parnell and Barton, 1979). Good housekeeping has long been considered a major part of any dust management plan (Theimer, 1972; Marshall, 1983; NMAB, 1982). Schulman (1983), however demonstrated that layered dust was not essential to produce a secondary explosion. Dust from an initial explosion may be carried into otherwise clean areas and fuel a secondary explosion. The significance of this phenomenon is the implication that a pressure front can propagate in an elevator with little or no settled dust (except for the confined space of the initial explosion) and propagate a series of explosions with fuel provided by a leg, bin or enclosed conveyor.

The use of mineral oil additives to grain has been shown to be an effective technique for the suppression of aerated dust (Jones, 1986; Lai et al., 1986; Cocke et al., 1978). It has also been determined that the effectiveness of the mineral oil is dependent on the type of grain being treated and the mineral oil application rate (Jones, 1986). Further studies should be performed to determine the reduction of grain dust levels inside bucket elevator legs as a result of mineral oil applications.

Control of Ignition Sources

Reducing the number of ignition sources in a grain handling facility is a crucial element in preventing grain dust explosions. The use of electrical equipment in grain handling facilities which comply with National Electric Code standards is required by OSHA. Bearing monitors, motion sensors and other detection systems are suggested so that over heated bearings, misaligned belts and other abnormal operating conditions can be controlled. Grates, magnets or other separation devices should be used to decrease the possibility that foreign matter will enter the conveying equipment.

It is highly unlikely that 'normal' elevator operation will result in a grain dust explosion. Most programs or use of devices which reduce the occurrence of ignition sources contribute to the safety of the facility. However, injudicious use of such programs or devices can be wasteful and have limited effectiveness (NMAB, 1982).

Explosion Venting

Explosion venting is the controlled release of explosion pressure from a confined area. This process involves equipping the confinement with explosion relief panels (Gillis, 1981). The panels must be of adequate size and correct rupture strength so that the pressure developed from an explosion will be vented to the atmosphere before internal pressures can reach a destructive level.

The sizing and placement of the explosion vents is a complex process dependent on the geometry of the enclosure and the dynamics of the explosion process (NMAB, 1982). A probabilistic approach to sizing explosion vents has been examined (Echoff, 1986). This approach is similar to stress-strength consideration of structural designs except the panels are expected to fail therefore venting the internal pressure.

Explosion Suppression

The use of explosion suppression devices has been met with both praise and criticism. Opponents to this action site the unreliability of the explosion suppression systems. This unreliability stems from inadvertent releases of the Halon gas, slow response time of the detection systems and high capital investment. These opponents do, however, acknowledge their effectiveness in enclosed areas such as bucket elevators and dust collection systems (NMAB, 1982).

The theory of explosion suppression is based on the initial detection of the explosion and subsequent release of "oxygen absorbing" gases or suffocating powders which prohibit flame propagation (Gillis, 1981). The detection of the initial explosion is generally accomplished with pressure sensors located at various points throughout the elevator leg. The realization of a sudden pressure increase by the pressure sensors actuates the release of the extinguishing agent. The most common gases used for this application are Halon 1011 (Bromochloromethane) and Halon 1301 (Bromotrifluoromethane). These gases actually bond the available oxygen in the explosion environment rendering the atmosphere unable to support combustion (NMAB, 1982; Gillis, 1981).

Risk Assessment of Complex Systems

Risk assessment of complex systems involves aspects of probability theory, differential calculus, Boolean logic and algebras, and set theory. The combination of these fields of study result in a powerful analysis tool. Through the use of set theory and Boolean logic and algebras, the complex systems are heuristically decomposed into simpler subsystems. Concepts of probability theory and differential calculus are then applied to determine quantitative information about the system (Fussel, 1973).

Reliability analysis and probabilistic risk assessment is a by-product of the problems associated with electronic systems designed for use in World War II. A more rigorous method was needed to analyze these complex systems (Kapur and Lamberson, 1977).

Reliability has been, and will continue to be, defined in many ways. For the purposes of this discussion, 'reliability' will be considered to be "...the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered" (Carter, 1972).

Many researchers of systems reliability construct reliability diagrams which are representations of the operational relationships of each of the components. Researchers concerned with the safety or failure of a system often construct graphical models known as fault trees. It can be shown that these two approaches are equivalent in that they are complements of each other (Shooman, 1970). Equations 1 and 2;

$$R(t) = 1 - F(t) \tag{1}$$

$$P[T > t] = 1 - P[T < t] \tag{2}$$

where

$R(t)$ = reliability at time t;

$F(t)$ = probability of failure at time t;

$P[T > t]$ = probability that time to failure, T, is greater than time t;

$P[T < t]$ = probability that time to failure, T, is less than time t;

show specifically the implications of these concepts.

History of Fault Tree Analysis

Fault tree analysis (FTA) is a common method of systems safety analysis. FTA had its beginning in the early 1960's during the development of the Minute Man missile systems. The prime objective of the study was to analyze inadvertent missile launch (Barlow and Lambert, 1975). FTA was developed to determine quantitative probabilities, however it is commonly used for its qualitative aspects because of the systematic approach of the presentation of the factors involved in a system (Hammer, 1980).

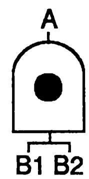
Fault Tree Logic and Construction

Fault trees are constructed of logic and event building blocks (Figure 2). The AND, OR, continuation, base event, and secondary event symbols are used in this particular study. A complete description of each of these symbols is shown in Figure 2.

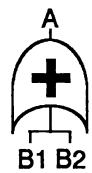
The first step in fault tree analysis is to select a top event. The top event is a state of the system in which information about the probability of occurrence is desired. The selection of the top event is generally a result of some type of hazard analysis, which would identify undesirable states, or by intuition about the system. As an example of a top event, consider an automobile as the system under consideration. "Brake failure" could be selected as the top event.

The fault tree is constructed so that the sequence of events that lead to the undesirable event are shown below the top event as a consequence of the AND and OR gates. These events are further developed until the sequence of events lead to the basic events. The basic events represent the resolution of the fault tree (Barlow and Lambert, 1975). This resolution is a function of the knowledge of the system and the availability of data.

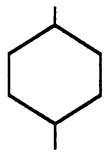
The structuring process identifies three failure mechanisms that contribute to the occurrence of the top event (Haasl, 1965). The failure mechanism were defined by Haasl (1965) as follows:



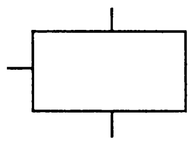
AND gate. A logical AND relation. Output A exists if and only if all of B1,B2,etc exist simultaneously.



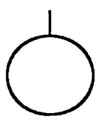
OR gate. A logical inclusive OR relation. Output A exists if any of B1, B2, etc., or any combination thereof, exists.



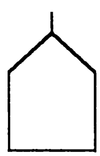
Inhibit gate. Permits applying a condition or restriction to the sequence. The input and condition or restriction must be satisfied for an output to be generated.



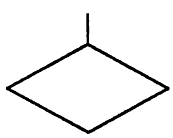
Identification of a particular event. When contained in the sequence, usually describes the output or an input of an AND or an OR gate. Applied to a gate, indicates a limiting condition or restriction that must be satisfied



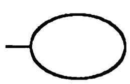
An event, usually a malfunction, describable in terms of a specific component



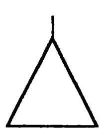
An event that is normally expected to occur; usually an event that always occurs unless a failure takes place



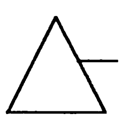
An event not developed further because of lack of information or of sufficient consequence. Could also be used to indicate further investigation is intended when additional information becomes available Symbol W with a numerical subscript is sometimes used also



Indicates and stipulates restrictions. With an AND gate, the restriction must be fulfilled before the event can occur With an OR gate, the stipulation may be that the event will not occur in the presence of both or all inputs simultaneously When used with an inhibit gate, stipulation is a variable condition.



A connecting symbol to another part of the fault tree within the same major branch Has the same functions, sequence of events, and numerical values



A connecting symbol to another part of the fault tree

Figure 2. Fault Tree Logic Symbols (Fussel, 1973)

1) primary failure - failure due to the internal characteristics of the system element under consideration (example: light bulb burns out).

2) secondary failure - failure due to excessive environmental or operational stress placed on the system element (example: light bulb burns out as a result of excess voltage).

3) command failure - failure due to inadvertent operation or non-operation of a system element due to failure(s) of initiating element(s) to respond as intended to system conditions (example: light bulb burns out as a result lack of maintenance of light bulb socket).

When the bottom leaves of the fault tree are a combination of the previously described failures, the tree is complete.

The construction of the fault tree is not an end but a means to learn more about the system. The completed tree can be used as a tool to identify failure combinations that might have been otherwise overlooked. The graphical format of the tree allows for the ease of communication of qualitative or quantitative information about system failures. Appendix A illustrates the construction and evaluation of an example fault tree.

Qualitative Evaluation

The qualitative evaluation of the fault tree involves determining the minimum cut sets of the logic tree. A cut set is a set of base events whose concurrent existence insures the occurrence of the top event (Barlow and Lambert, 1975). Another name for cut sets is Boolean Indicated Cut Sets (BICS). BICS are actually cut sets assuming that a primary event appears only once in the fault tree (Fussel and Vesely, 1972). A cut set is minimal if the set of failures cannot be reduced and still insure the occurrence of the top event. Minimum cut sets are useful because they identify the minimum combination of fault events which cause the top event.

With large fault trees it is difficult, if not impossible to determine all of the minimum cut sets by inspection. There exist many algorithms capable of determining minimum cut sets. Most of these algorithms, like most other algorithms, can be performed 'by hand' but are generally computer generated because of time and cost considerations. A concept common to all of the algorithms is that an AND gate will always increase the size of the cut sets while an OR gate will always increase the number of cut sets (Fussel and Vesely, 1972).

Quantitative Evaluation

Certain assumptions must be made to obtain quantitative information from a fault tree. The main assumption deals with the concept of independence of primary events. The assumption is common to reliability theory (Kapur and Lamberson, 1977). This assumption of independence indicates that the ultimate probability is only an approximation (but a good approximation) that can be used, at the very least, to rank the contributions of each base event or groups of base events to the occurrence of the top event.

The primary events of a fault tree are considered to be independent variables. The independent variables are assigned point estimates of their probabilities of occurrence (failure). These estimates are the inputs for the quantitative analysis. Quantitative analysis is motivated by the implications of the logical operators AND and OR in that an AND and OR represent the intersection and union of sets, respectively. The probabilistic details of the intersections and unions of sets are discussed in Mood, Graybill and Boes (1974).

The failure rates for the base components are generally considered to be independent and exponentially distributed. The approximation to an exponential distribution is generally accepted since more complex failure rates can be shown to approach the exponential distribution as the number of components increase (Kapur and Lamberson, 1977).

CHAPTER IV

METHODS AND PROCEDURES

System Selection

A systems problem begins by defining the proper world view or system. A bucket elevator leg is the focus of this study since it is considered the most hazardous component of a grain handling facility (NMAB, 1982). Bucket elevators legs are reported to be involved in approximately 40% of all grain dust explosion incidence (USDA, 1980). In 1987, at least 8 of the 15 grain dust explosions (53%) were attributed to the bucket elevator leg (Clary, 1988). To further define the world view, system boundaries must be adequately defined and respected. The system boundaries in this particular application constitute, in part, the types of explosion prevention devices and which practices are applied to the elevator leg.

The physical system is considered to be a bucket elevator leg in a grain handling facility. The physical system will be generic in the sense that it could have "all" possible elements of a bucket elevator legs as well as the application of "all" safety practices. This approach is chosen because of its versatility and general applicability to the grain handling industry.

Specific operating characteristics of the physical system are shown in Table II. The operating characteristics are a composite of typical elevators in Western Oklahoma. These operating characteristics are determined from a series of interviews with elevator managers in Western Oklahoma. A sample of the questionnaire used in the interviews is shown in Appendix B. Table III presents

TABLE II

OPERATING CHARACTERISTICS
OF MODEL ELEVATOR

total throughput	35,117 m^3 (1,000,000 bu)
*turning rate	5
number of legs	3
leg capacity	229 m^3/hr (6,500 bu/hr)
type of grain	wheat (#1 hard red winter)
throughput/leg	58,528 m^3 (1,666,667 bu)
running time/leg	256 hrs
**maintenance time	64 hrs
bucket elevator season	320 hrs

* includes grain entering, exiting, and 3 turns during storage
** equates to 0.25 times the running time per leg

some of the findings of the survey.

The total throughput is considered to be the amount of grain that the elevator will handle in a typical season. The turning rate is defined as the number of times the incoming grain is moved through the elevator in a year. Movement of grain occurs when the grain is received and shipped out. Additional grain movement occurs as a result of turning activities such as fumigation, moisture control and grading. The number of bucket elevator legs, bucket elevator leg capacity and grain type is characteristic of the grain handling facilities found in Western Oklahoma. Throughput per leg is considered to be the amount of grain moved by each leg assuming the legs are in a parallel arrangement and that the legs have identical utilization. The running time per leg is computed as the throughput per leg divided by the capacity of the leg. Maintenance time is assumed to be 0.25 times the running time per leg. A bucket elevator leg season is defined as time in a given year that the leg is in operation plus the time it is subjected to maintenance activities.

TABLE III

OPERATING CHARACTERISTICS OF SURVEYED GRAIN ELEVATORS IN WESTERN OKLAHOMA

	mean	mode(s)	median	standard deviation	sample size
turning rate	4.7	4.0 5.0	5.0	1.2	13
leg height (m)	44.1	36.6 44.2 45.7	44.2	7.5	11
number of legs	4.5	3	3	3.8	12
annual throughput (m^3)	40600	26400	28100	28300	13
leg capacity (m^3/hr)	246	229	229	60.2	13
boot bearing life (yrs)	12.7	5	10.5	8.6	6
head bearing life (yrs)	14.2	5	10	11.1	6
welding and cutting frequency (yrs^{-1})	1.6	1	1	0.9	5

Data Collection

Sixteen country grain elevators in Oklahoma were visited in the fall of 1987, to gain a better understanding of current practices and equipment used in such facilities. Each elevator manager was interviewed to ascertain operating characteristics, equipment configurations, and other pertinent information about his particular facility. The results of these interviews were used to help identify the base events used as inputs to the model.

Mechanical components, such as bearings, have an exponential failure rate distribution (Carter, 1972) and approximates of mean-time-to-failures (MTF) are readily available for various commercial and military applications (RADC, 1985). Craig and Johnson (1983) published typical replacement intervals for bearings commonly used in the grain industry. The difficulty in interpreting failure data, is caused by the variability in environmental conditions. The bearings on a bucket elevator leg are subjected to a harsh environment and common failure data is not available for comparable environmental conditions.

CHAPTER V

MODEL DEVELOPMENT

Models have been developed to describe failure processes in many industries. The chemical and mining industries have developed models describing the explosion phenomenon using a deterministic perspective.

Fault Tree Development

To determine the relationships between the various components, spatial configurations, safety programs and other aspects of the physical system, some form of fault tree analysis must be performed. This analysis technique is versatile and both qualitative and quantitative types of information are available. For these reasons fault tree analysis is selected for this study.

Due to the physical arrangement of a bucket elevator leg, it may be divided into four distinct and independent sections. These sections are the boot (where the grain enters), head (where the grain exits), upside and downside. The system is further divided into normal elevator operation and maintenance operations. These divisions create eight independent sections of the system and consequently eight independent sections of the fault tree.

The top event in the fault tree is selected as the fault event "secondary grain dust explosion in a bucket elevator leg" and is designated as G0. This event will not occur unless a "primary explosion in a bucket elevator leg" occurs and "explosion suppression fails" and "explosion venting fails," designated as G1, G2, and G3, respectively. Each of these events are further developed until only base events appear at the bottom of the tree. A graphical representation of the tree is shown in Figures 3 through 13. Descriptions of the illustrated base events (i.e. B0, B1, etc.) and each secondary failure (i.e. G0, G1, etc.) are listed in Appendix C and D, respectively.

Assignment of Point Estimates

Data, for failure rates of maintenance programs, do not exist for grain handling facilities. Data for components commonly found in grain handling facilities are used in other industries but are confounded by the variability in environmental conditions. They are further confounded by the fact that a simple 'failure' (such as bearing failure) will not insure an ignition source. Approximations of the point estimates were a result of such difficulties. A list of the point estimates of the base events shown in Figures 3 through 13 are listed in column 3 of Appendix C.

Consider base events B69, B73, B87, B91, and B247 which represent the failure of bearings. Bearings, and other mechanical components are reported to follow an exponential failure rate distribution as shown in Equation 3 (Carter, 1972).

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)} \tag{3}$$

where

$F(t)$ = probability of failure at time t;

t = time, (t);

θ = mean time between failures, (t^{-1}).

By using the relationship of reliability and failure as shown in Equations 1 and 2, the reliability function of the exponential distribution is show in Equation 4.

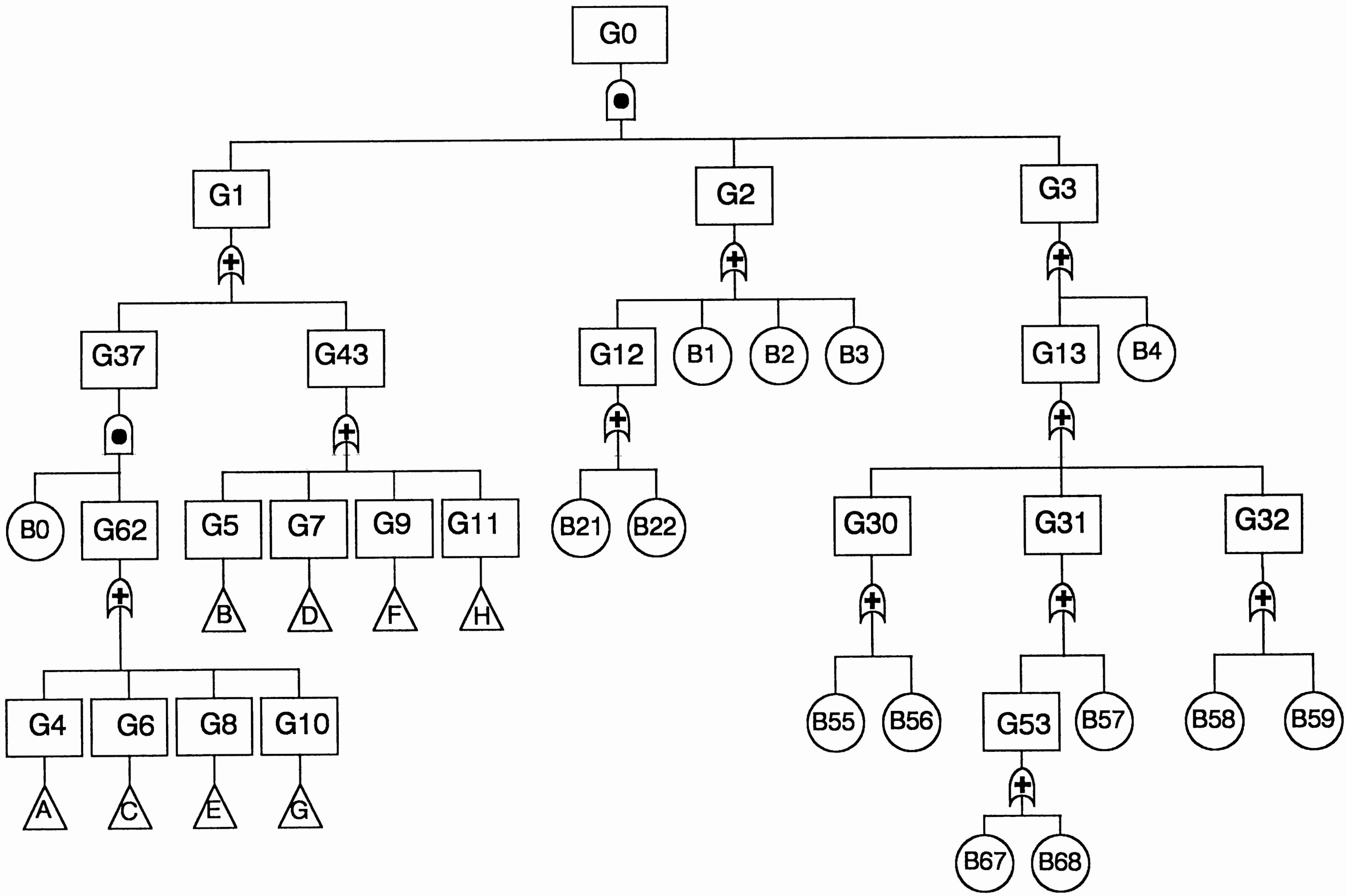


Figure 3. Top of Fault Tree

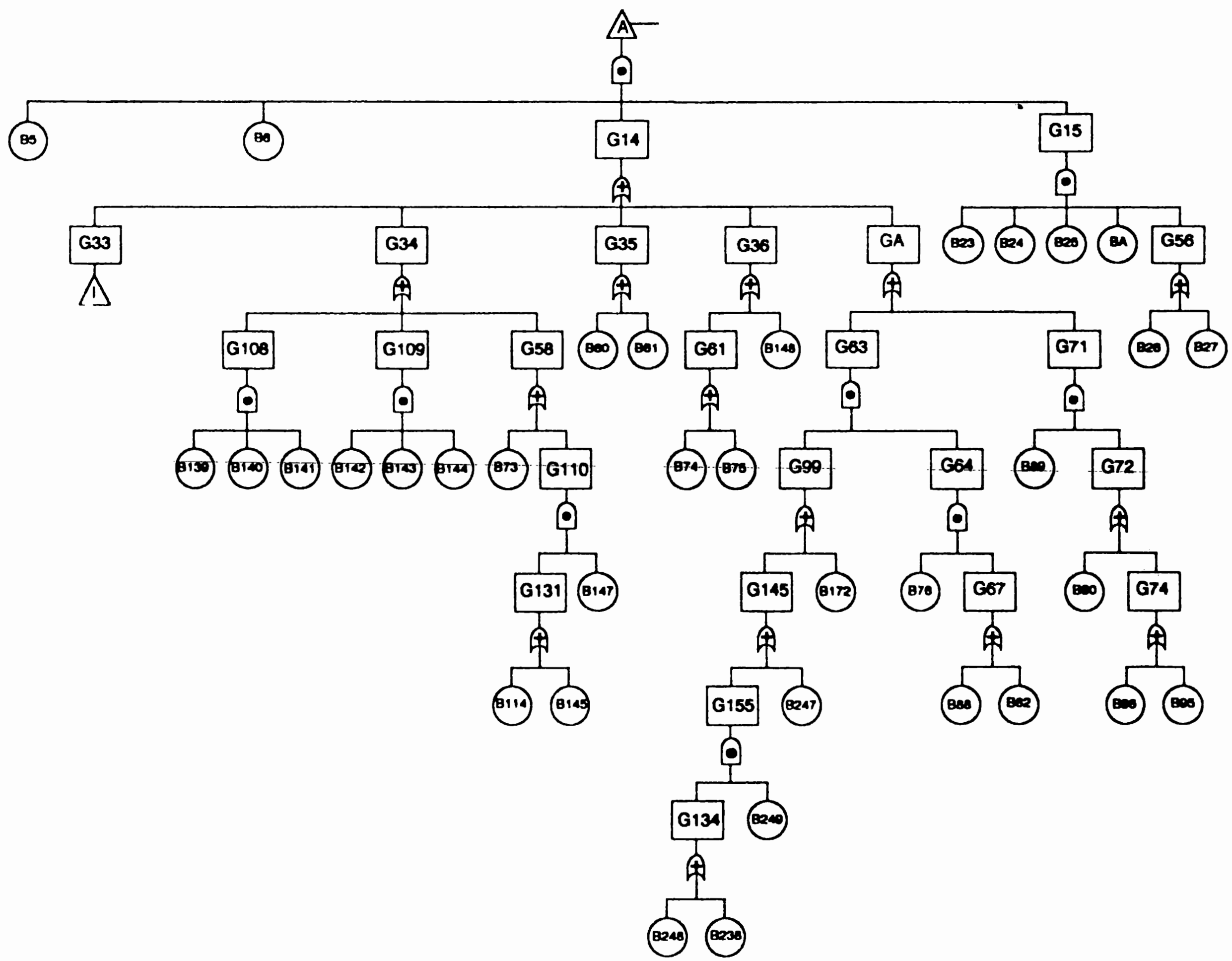


Figure 4. Portion of Fault Tree Describing Primary Explosion in Boot of Bucket Elevator Leg while Operating Normally

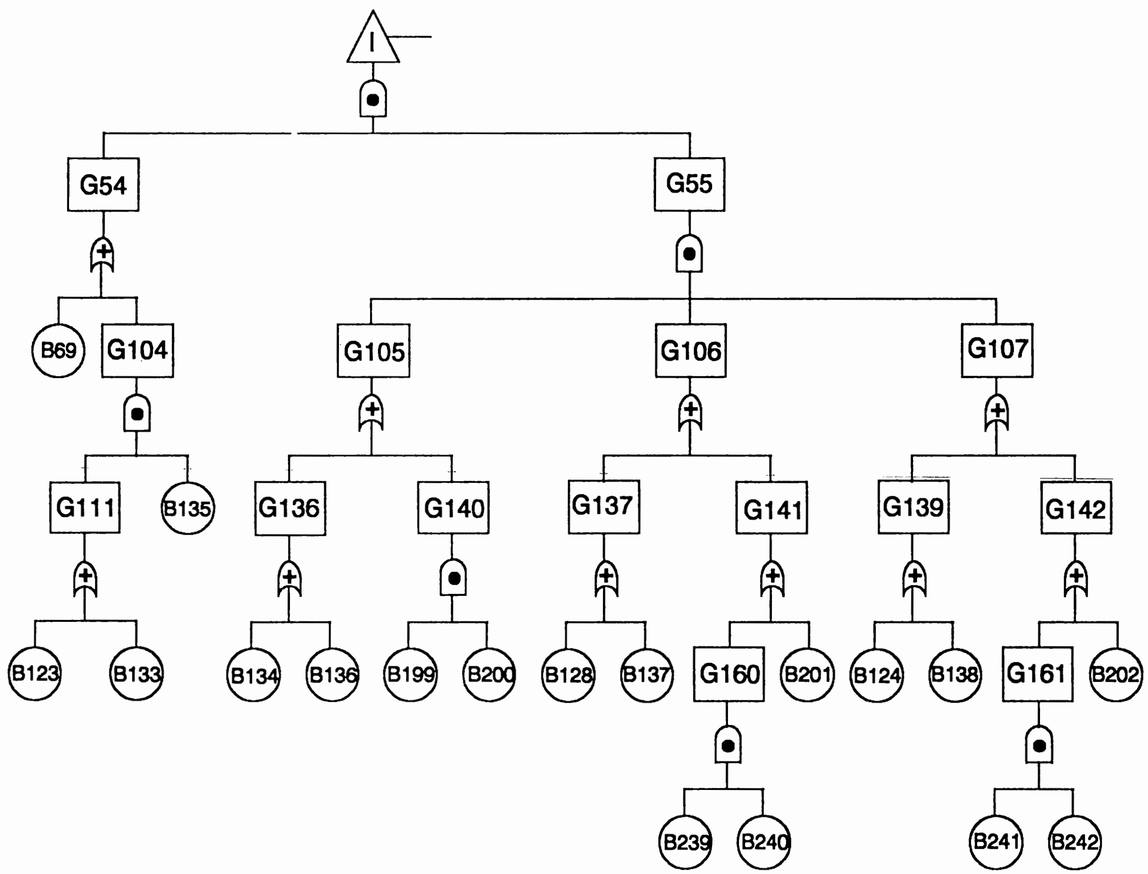


Figure 5. Portion of Fault Tree Describing Ignition from Overheated Bearing in Boot of Bucket Elevator Leg while Operating Normally

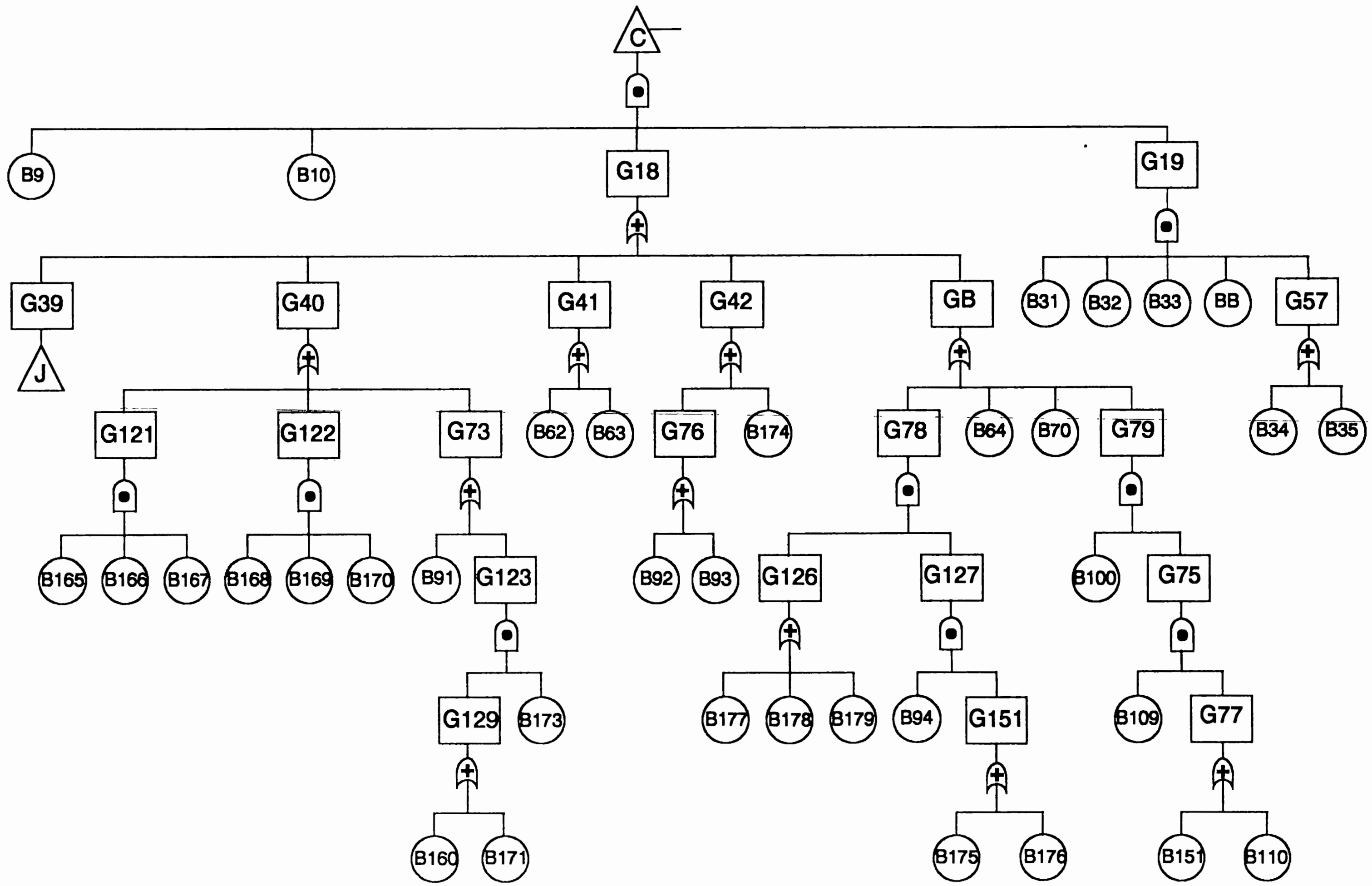


Figure 6. Portion of Fault Tree Describing Primary Explosion in Head of Bucket Elevator Leg while Operating Normally

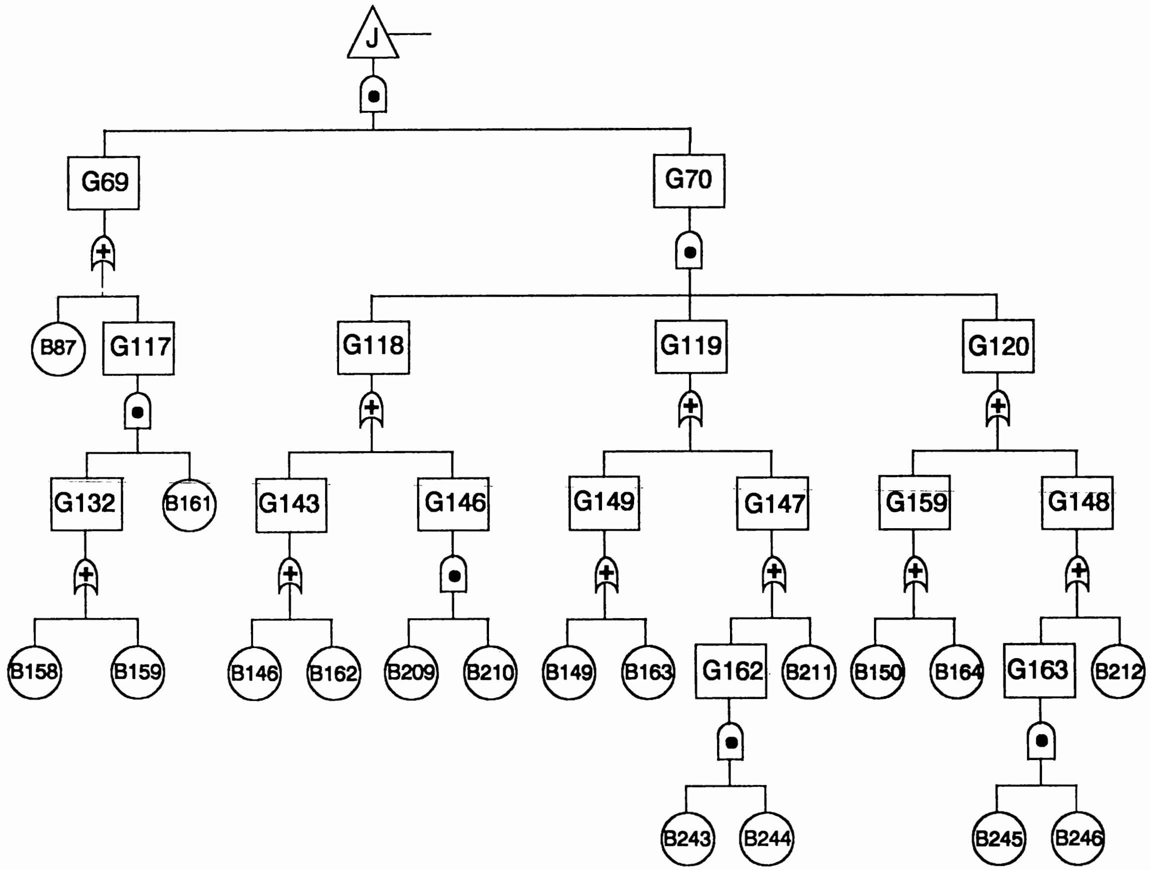


Figure 7. Portion of Fault Tree Describing Ignition from Overheated Bearing in Head of Bucket Elevator Leg while Operating Normally

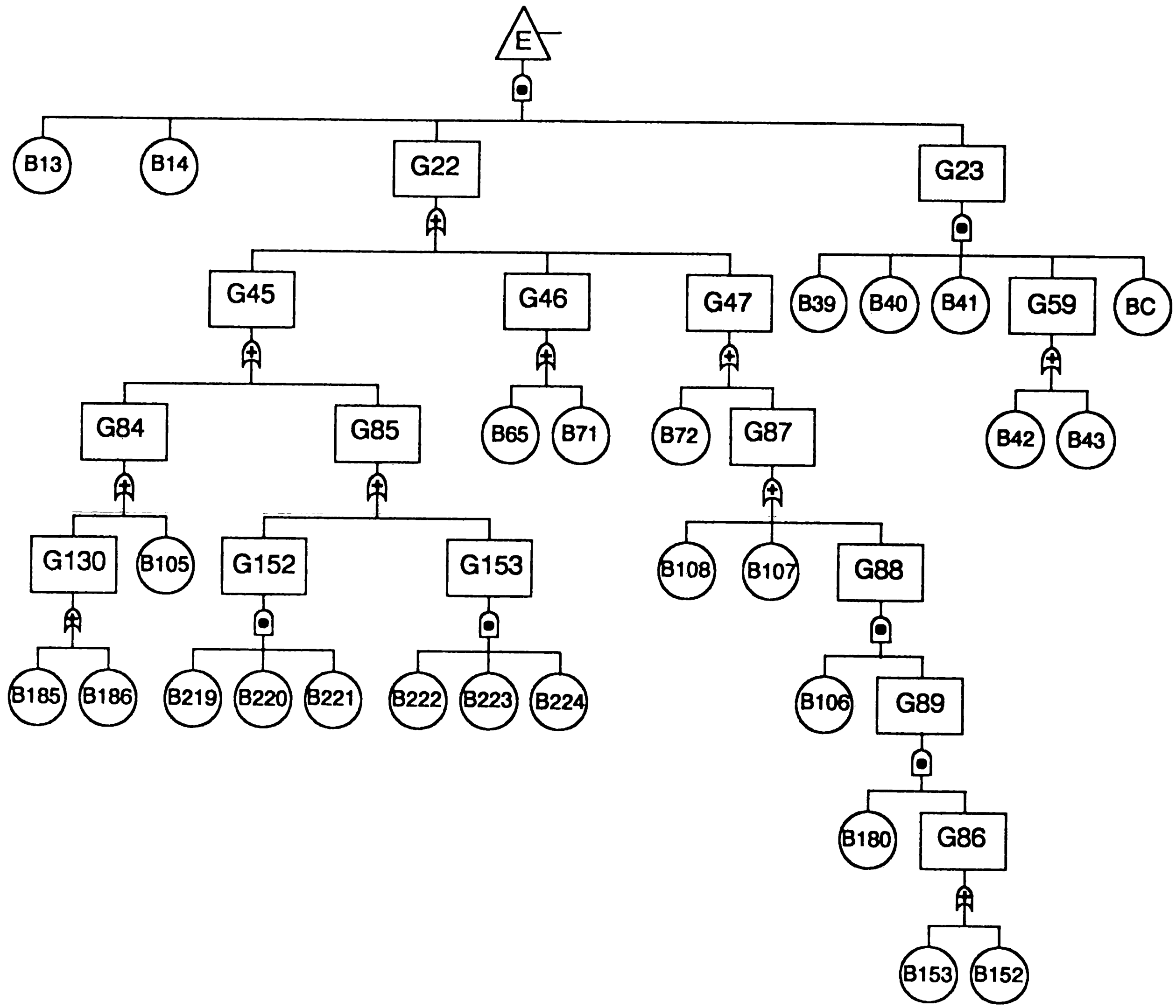


Figure 8. Portion of Fault Tree Describing Primary Explosion in Upside of Bucket Elevator Leg while Operating Normally

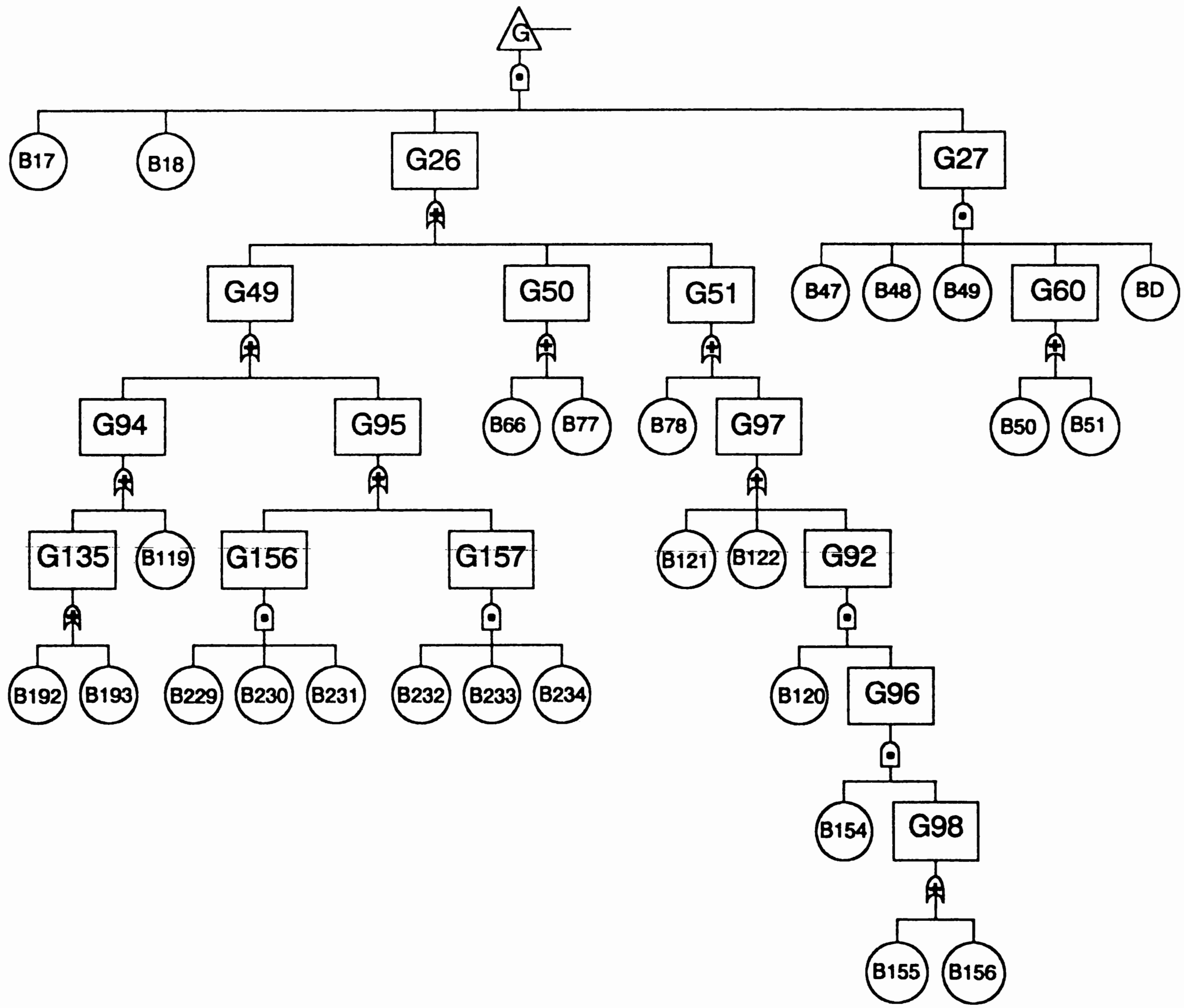


Figure 9. Portion of Fault Tree Describing Primary Explosion in Downside of Bucket Elevator Leg while Operating Normally

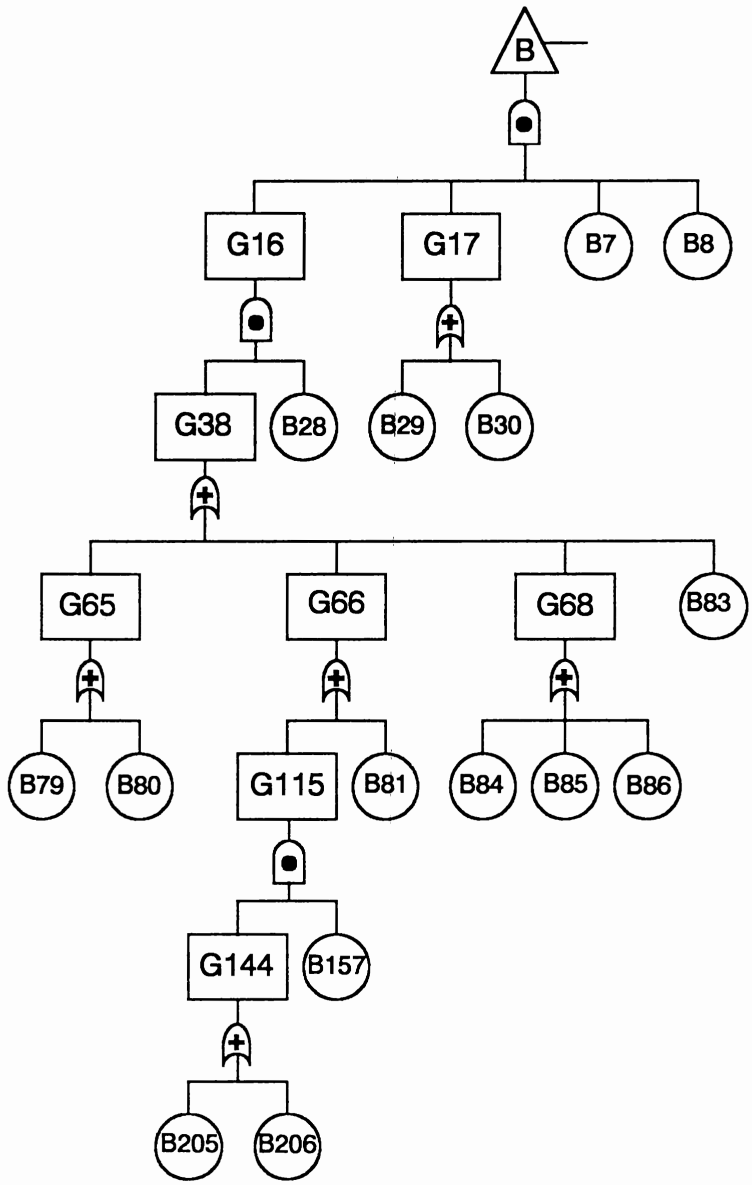


Figure 10. Portion of Fault Tree Describing Primary Explosion in Boot of Bucket Elevator Leg During Maintenance

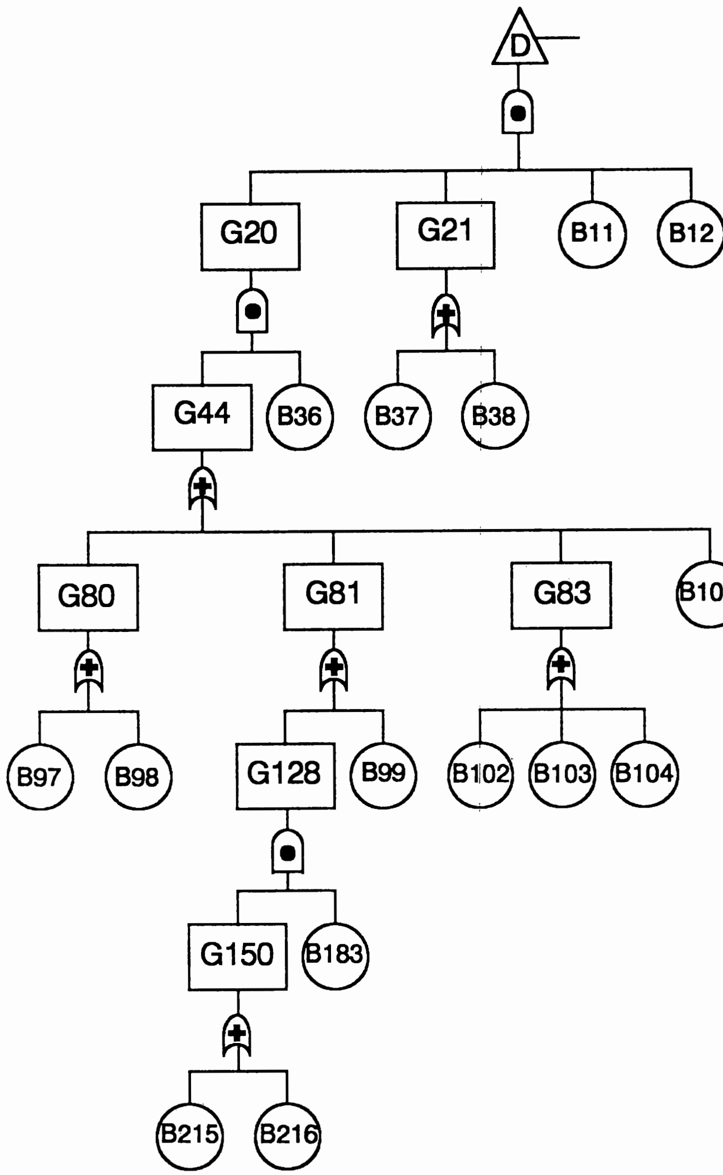


Figure 11. Portion of Fault Tree Describing Primary Explosion in Head of Bucket Elevator Leg During Maintenance

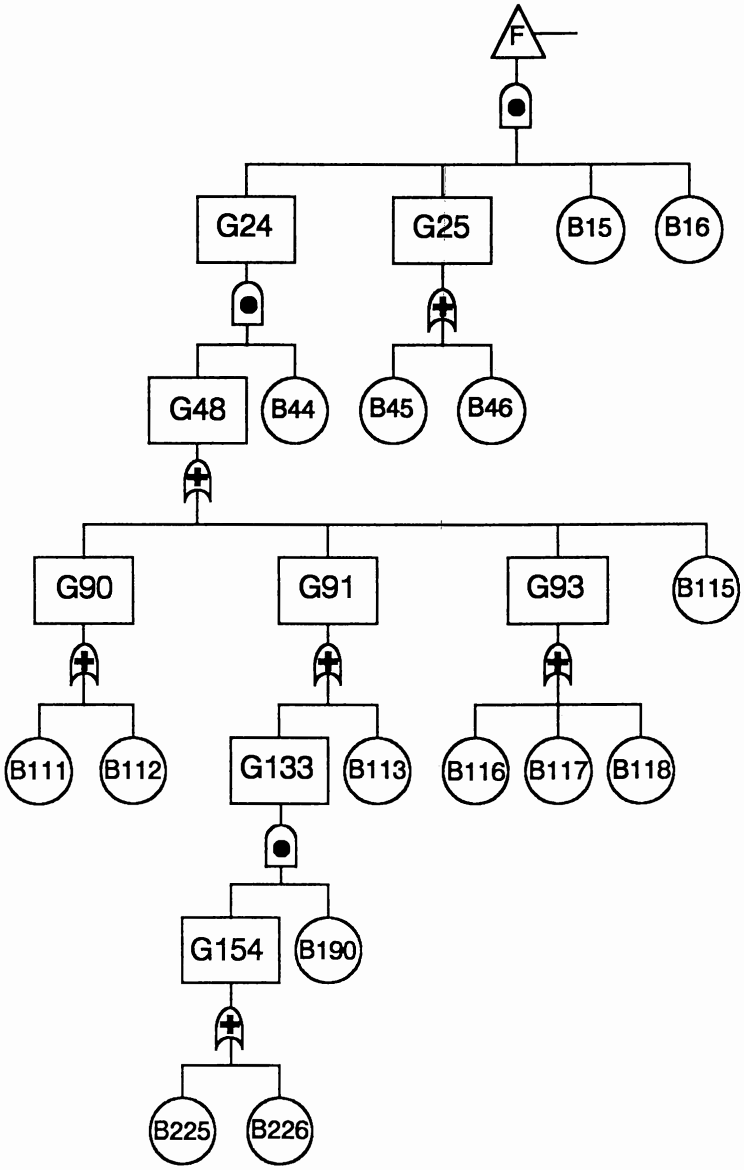


Figure 12. Portion of Fault Tree Describing Primary Explosion in Upside of Bucket Elevator Leg During Maintenance

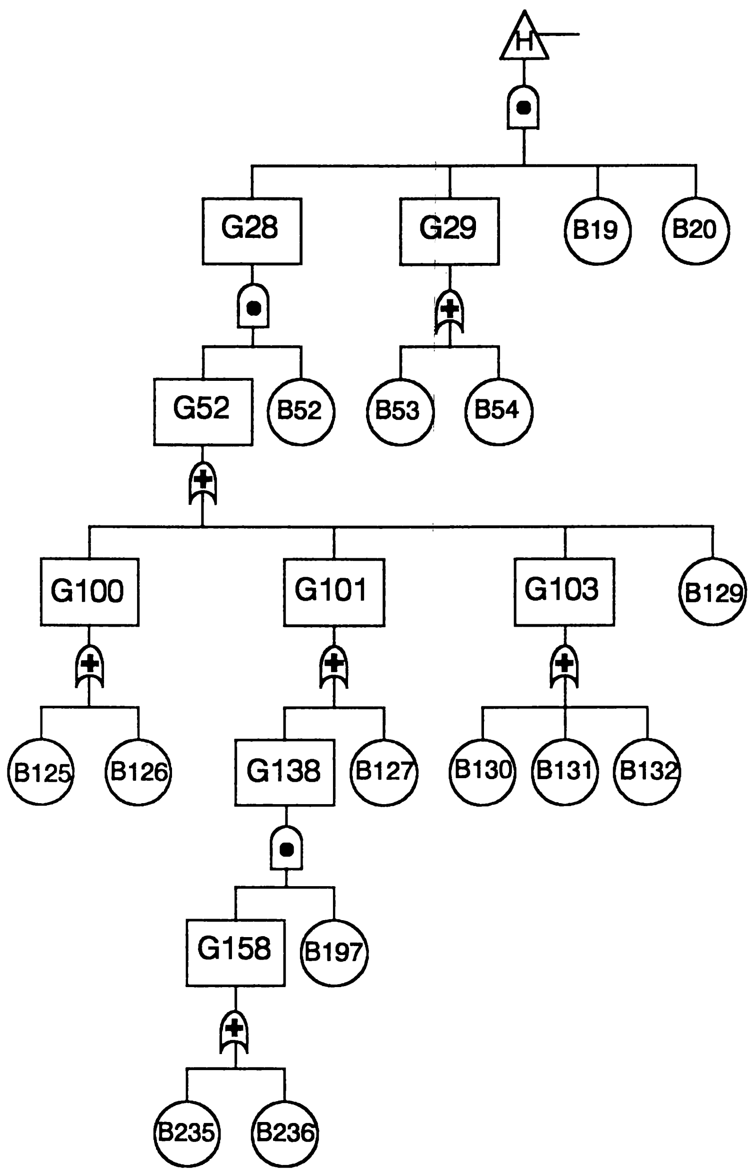


Figure 13. Portion of Fault Tree Describing Primary Explosion in Downside of Bucket Elevator Leg During Maintenance

$$R(t) = e^{-\left(\frac{t}{\theta}\right)} \tag{4}$$

where

$R(t)$ = reliability at time t;

t = time, (t);

θ = mean time between failures, (t^{-1}).

The point estimates of the probability of occurrence of each base event is actually the instantaneous failure rate, also known as the hazard function. The hazard function is defined as the limit of the failure rate as the time interval approaches 0. The hazard function is defined by Equation 5 (Barlow and Proschan, 1975).

$$h(t) = \lim_{\Delta t \to 0} \frac{R(t) - R(t+\Delta t)}{(\Delta t)R(t)} =$$

$$= \frac{1}{R(t)} \left[- \frac{d}{dt} R(t) \right] \tag{5}$$

where

$h(t)$ = hazard function at time t, (t^{-1});

Δt = time increment, (t);

$R(t)$ = reliability at time t;

$\frac{d}{dt}$ = derivative with respect to t.

The negative of the derivative with respect to time of the reliability function of the exponential distribution is given in Equation 6.

$$- \frac{d}{dt} R(t) = \frac{1}{\theta} e^{-\left(\frac{t}{\theta}\right)} \tag{6}$$

where

$\frac{d}{dt}$ = derivative with respect to t;

R(t) = reliability at time t;

t = time, (t);

θ = mean time between failures, (t^{-1}).

Equation 6 is recognized as the probability density function, f(t), of the exponential distribution. Therefore the hazard function is defined in Equation 7.

$$h(t) = \frac{f(t)}{R(t)} \qquad (7)$$

where

h(t) = hazard function, (t^{-1});

f(t) = probability density function, (t^{-1});

R(t) = reliability at time t.

The hazard function for the exponential distribution is shown in Equation 8.

$$h(t) = \frac{\frac{1}{\theta} \quad e^{-(\frac{t}{\theta})}}{e^{-(\frac{t}{\theta})}} =$$

$$= \frac{1}{\theta} \qquad (8)$$

where

h(t) = hazard function, (t^{-1});

t = time, (t);

θ = mean time between failures, (t).

Craig and Johnson (1983) reported average replacement intervals for bearings to be approximately 13 years. Using the running time of 256 hours per year per leg as specified for the model, results in a time to replacement of approximately 3328 hours. A bearing failure, however will not occur as frequently as bearing replacement. It is assumed that a bearing replacement occurs at a rate of 5 times that of bearing failures resulting in a mean time to failure of 16,640 hrs.

As previously stated this is confounded by the fact that only a portion of the failures are actually ignition sources. It is assumed that 2% of the failures will result in an ignition source from an over heated bearing, therefore the mean time to an ignition source is 832,000 hrs. The resulting point estimate of the probability of occurrence is 3.1×10^{-4} for base events B69 and B87 using equation 3 with the value of t being 256 hrs. It is also assumed that an ignition source from a sparking or seized bearing will occur in 1% of the bearing failures resulting in a point estimate of the probability of occurrence of 3.1×10^{-5} for base events B73, B91, and B247.

Software Development

The WAM-E fault tree analysis software is used to perform the necessary calculations. WAM-E is a set of FORTRAN programs which finds the point estimation of the top event, determines minimum cut sets of the input tree, and simulates a mathematically equivalent model to determine information about the distribution of the top event.

The cut set analysis used in WAM-E proceeds on the principle that a properly constructed fault tree can be described as a set of Boolean algebraic equations with the base events as independent variables and secondary events as dependent variables (EPRI, 1986). Through the manipulation of the principles of Boolean algebra, the top event can be described as the sum-of-products of combinations of the base events. The WAM-E code utilizes a bit manipulation scheme to process the Boolean algebra operations.

The point estimation algorithm in WAM-E utilizes the inclusion-exclusion principle of the unions of sets. These sets are actually the minimum cut sets and their associated point estimations.

Consider a fault tree with top event E which has n minimum cut sets with the set of all minimum cut sets N, where $N = \{C_1, C_2, ..., C_n\}$ with associate point estimates of $\{P(C_1), P(C_2), ..., PC(_n)\}$. Via the definition of a minimum cut set

$$E = \bigcup_{i=1}^{n} C_i \quad \text{or} \quad E = C_1 \cup C_2 \cup \cdots \cup C_n \tag{9}$$

But when considering point estimates

$$P(E) = P(C_1 \cup C_2 \cup \cdots \cup C_n) \tag{10}$$

$$P(E) = \sum_{i=1}^{n} P(C_i) - \sum_{i=2}^{n} \sum_{j=1}^{i-1} P(C_i C_j) + \sum_{i=3}^{n} \sum_{j=2}^{i-1} \sum_{k=1}^{j-1} P(C_i C_j C_k) - \cdots + (-1)^{n-1} P(C_1 C_2 C_3 \ldots C_n) \tag{11}$$

Care must be taken to judiciously assign cut off probabilities when using WAM-E. The number of calculations required to determine the point estimation of the top event can be very large if the number of minimum cut sets is large. Consider the previous tree with n minimum cut sets. The number of calculations, Z, required to determine the point estimator can be determined as

$$Z = \sum_{i=1}^{n} \binom{n}{i} = \sum_{i=1}^{n} \frac{n!}{i!(n-i)!} \tag{12}$$

Model Features

The model includes 157 secondary events and 233 base events routed through 57 AND and 100 OR gates. The occurrence of each base event is assumed to be independent of any other base event. Input to the WAM-E program is shown in Appendix E. The first portion of the input describes the structure of the fault tree. The remainder of the input assigns each base event with a point estimate.

The model is developed in a modular manner such that modifications can be made easily. The model is versatile in that various equipment, managerial and procedural aspects of a bucket elevator leg are easily implemented into the model. The acquisition of newly acquired data can be incorporated into the model with little difficulty. The model is an excellent starting point for further work in this area.

The model can be described as immature in that portions of the model need to be verified and developed further. The most pronounced shortcoming of the model is the lack of data, much less that which is verifiable. The model needs to be refined to include more "field" data as it becomes available.

CHAPTER VI

RESULTS AND DISCUSSION

A fault tree analysis lends itself to both qualitative and quantitative analysis. The qualitative analysis includes the determination of the minimum cut sets which highlight critical base events representing failures in equipment or practices. The quantitative analysis includes the determination of the top event point estimation and the changes of this point estimation when different practices are included in the physical system.

Minimum Cut Sets

The minimum cut sets (the combinations of base events that will insure the occurrence of a secondary grain dust explosion) of the input fault tree with the highest probably of occurrence are listed in Table IV. Table IV lists the 6 minimum cut sets with the highest probability of occurrence of all combinations of events that lead to the occurrence of a secondary grain dust explosion in a bucket elevator leg.

Consider minimum cut set No. 1. Base event B135, shown in Figure 5, represents the failure of a maintenance activity leading to loss of lubrication leading to overheated bearing in the boot while operating normally. This event, logically, provides the necessary ignition source for the occurrence of a primary grain dust explosion. Base event B134, shown in Figure 5, represents the unavailability of heat sensors. Had heat sensors been available, corrective action could have been taken. Likewise base events B128 and B124, shown in Figure 5, represent the unavailability of heat sensitive tape and heat sensitive paint, respectively. Base event B123, shown

TABLE IV

MINIMUM CUT SETS WITH HIGHEST PROBABILITY OF OCCURRENCE

Minimum cut set no.	1	2	3	4	5	6
Probability of occurrence ($\times 10^{-5}$)	3.07	3.03	2.99	2.90	2.61	2.61
Base events	B0	B0	B0	B0	B0	B0
	B1	B1	B1	B1	B1	B1
	B4	B4	B4	B4	B4	B5
	B5	B9	B5	B9	B5	B6
	B6	B10	B6	B10	B6	B23
	B23	B31	B23	B31	B23	B24
	B24	B32	B24	B32	B24	B25
	B25	B33	B25	B33	B25	BA
	BA	BB	BA	BB	BA	B26
	B26	B34	B26	B34	B26	B123
	B123	B146	B69	B87	B123	B128
	B124	B149	B124	B146	B124	B134
	B128	B150	B128	B149	B134	B135
	B134	B158	B134	B150	B135	B241
	B135	B161			B239	B242
					B240	

in Figure 5, represents the unavailability of a auto-lubrication unit which would have alleviated the dependence of the maintenance activities.

Base events B23, B24, B25, BA and B26, shown in Figure 4, represent the occurrence of fuel in the boot while the elevator is operating normally. Events B5 and B6, confinement in boot and oxygen in boot, respectively, are also shown in Figure 4. These events are necessary for the occurrence of a primary grain dust explosion and occur in each minimum cut set which results in a primary explosion in the boot while the elevator is operating normally. The primary events B0, B1 and B4 are shown in Figure 3. The occurrence of B0 indicates that normal elevator operation is taking place, B1 indicates that explosion vents are not in use and B4 indicates that explosion suppression is not in use. Events B1 and B4, which occur in each minimum cut set, insure that a secondary explosion will occur.

Appendix F lists all of the minimum cut set with probability of occurrence greater that 1×10^{-8}. Base event descriptions are listed in Appendix C. Using the cut off probability of 1×10^{-8}, 408 minimum cut sets are identified. As the cut off probability is decreased the number of minimum cut sets identified increases. A cut off probability of 1×10^{-9} resulted in over 700 minimum cut sets yet did not affect the top event probability.

Top Event Point Estimation

The union of all minimum cut sets represents the occurrence of a top event. Therefore, the point estimation for the top of the fault tree (the occurrence of a secondary grain dust explosion in a bucket elevator leg) is computed by incorporating the point estimations of each minimum cut set into Equation 11. The resulting point estimation is 8.6×10^{-4}. This result suggests that approximately 9 secondary grain dust explosion in a bucket elevator leg will occur per 10,000 bucket elevator leg seasons.

The United States has approximately 14,000 grain handling facilities that can be described as either country, terminal, or export elevators (Federal Register, 1987). If it is assumed that each facility operates three bucket elevator legs, there are 42,000 bucket elevator leg seasons per year. According to the model there will be approximately 8.6 grain dust explosions per ten thousand bucket elevator leg seasons. The model therefore predicts that there will be 36.1 grain dust explosions per year occurring in bucket elevator legs. This compares to an average of actually 10.7 explosions per year from 1980 through 1987 when the actual number of occurrences (reported to be 21.4 as shown in Table I) is multiplied by the estimated percent of occurrences (50%) attributable to the bucket elevator leg.

A grain handling facility can measure its risk of a secondary grain dust explosion in the following manner. Consider a facility which has three (3) bucket elevator legs. The facility therefore experiences 3 bucket elevator seasons per year. A grain dust explosion could occur in any of the 3 legs. Therefore the probability of an explosion, P(E), can be calculated using Equation 11 and the point estimation of 8.6×10^{-4} for each of the 3 elevator legs. The resulting probability, P(E) = 2.6×10^{-3}, means that the facility has a 0.26% (1 in 390) chance of a secondary grain dust explosion in any of the 3 elevator legs in a season.

A grain handling facility can also effectively evaluate the practicality of installing safety equipment or incorporating safety procedures in its operation. The results of the cut set analysis indicates that absence of explosion vents (B1), explosion suppression devices (B4) and bearing heat sensors (B134 and B146) contribute greatly to the occurrence of a secondary grain dust explosion. Table V shows the change in the top event probability if any combinations of these practices are incorporated into a bucket elevator leg. In other words, the input tree uses 0.0 as point estimators for B1, B4, B134 and B146.

Sensitivity Analysis

The top event point estimate is dependent on the point estimates of the base events. The point estimates of selected base events are varied to determine the effect on the point estimate of the top event. The base events are identified as failures attributable to either personnel, housekeeping, maintenance, fuel, or bearings. These groups of failures are chosen because of there inherent relationship to the physical system. These failures are controllable and influenced by management decisions.

TABLE V

PROBABILITY OF A SECONDARY GRAIN DUST EXPLOSION WHEN THE MODEL BUCKET ELEVATOR LEG IS EQUIPPED WITH EXPLOSION SUPPRESSION DEVICES, EXPLOSION VENTS AND/OR HEAT SENSORS

Equipment configuration	Top event probability
Unequipped leg	8.6×10^{-4}
Heat sensors	8.5×10^{-5}
Explosion suppression	9.9×10^{-5}
Explosion vents	1.7×10^{-7}
Explosion suppression AND Heat sensors	9.9×10^{-6}
Explosion vents AND Heat sensors	1.7×10^{-8}

Table VI list the specific base events altered in this procedure. Figures 14 - 18 illustrate the change in the probability of a secondary grain dust explosion as a function of each of these classes of failures. The dashed marker on the curve indicates the assigned point estimation of the base events and the probability of occurrence of the top event as determined by the model.

Personnel

Base events designated as personnel include those failures associated with acknowledging failed states of the system. These failed states include such items as not correcting a misaligned or slipping belt but do not include ignition sources directly caused by personnel. The probability of occurrence of personnel failures is

TABLE VI

BASE EVENTS USED IN SENSITIVITY ANALYSIS

personnel	B94	B109	B154	B180	B201	B202	B211	B212
housekeeping	B240	B242	B244	B246	B249			
maintenance	B135	B147	B161	B173				
bearings	B69	B73	B87	B91	B247			
fuel	B23	B24	B25	BA	B31	B32	B33	BB
	B39	B40	B41	BC	B47	B48	B49	BD

varied from 0 to 1. Figure 14 shows the change in the probability of secondary grain dust explosion as a function of the probability of a personnel failure. The nature of the curve indicates a positive relationship between elevator personnel acting as detecting agents and the probability of a secondary grain dust explosion.

The range of values on the X-axis shown on Figure 14 extends beyond reasonable expectations of personnel at grain handling facilities, but examining the entire range reveals the dependency of the top event probability on the probability of occurrence of personnel failures as it approaches its extremes. Changing the probability of occurrence of a personnel failure by 0.1 results in a 1.1×10^{-4} change in the top event probability over the entire range of the probability scale.

The probability of occurrence of personnel failures used in the model is 0.2. This probability is affected by management and educational programs provided grain elevator personnel. The exact probability of occurrence of personnel failures associated with a particular grain handling facility is highly dependent on these and other considerations.

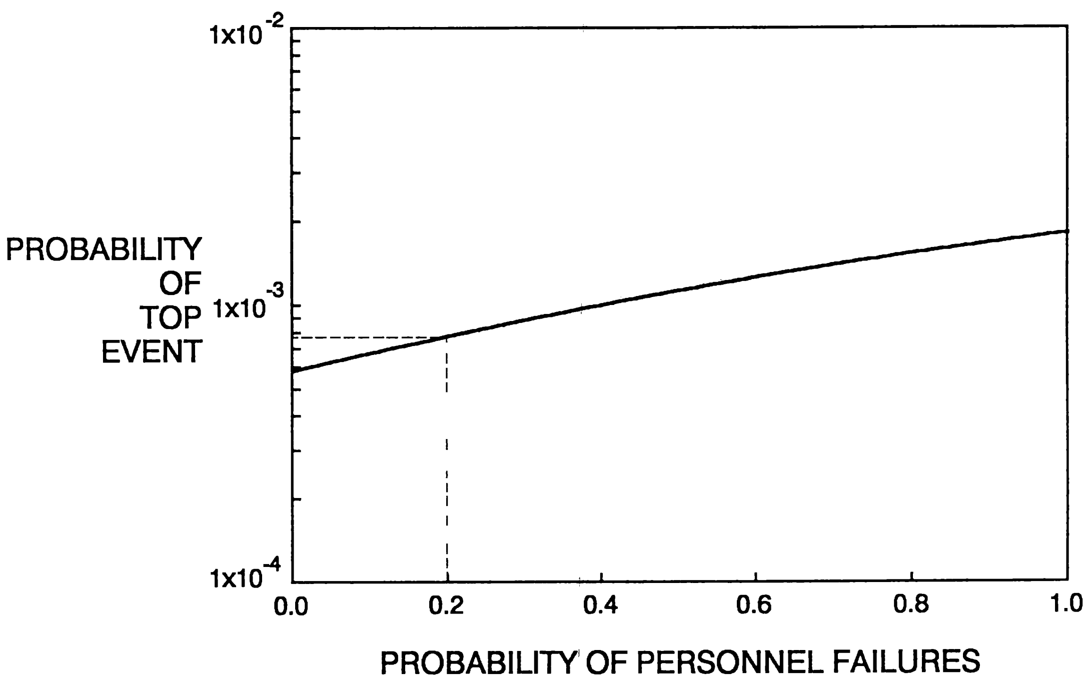


Figure 14. Effect of the Probability of Failures Attributable to Personnel on the Probability of a Secondary Grain Dust Explosion

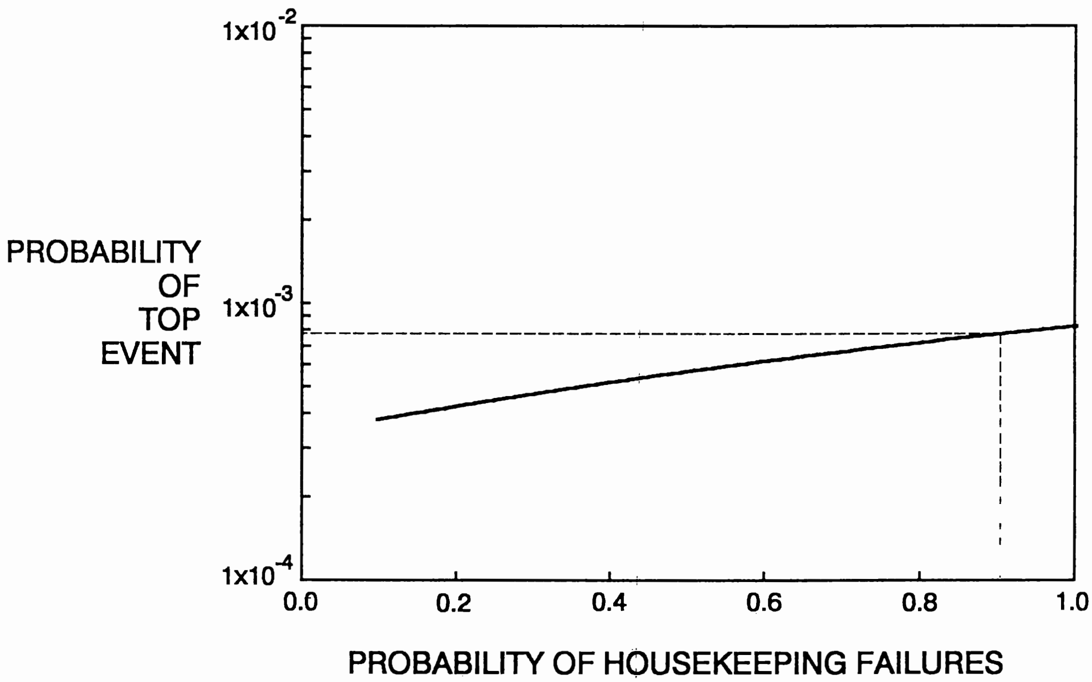


Figure 15. Effect of the Probability of Failures Attributable to Housekeeping on the Probability of a Secondary Grain Dust Explosion

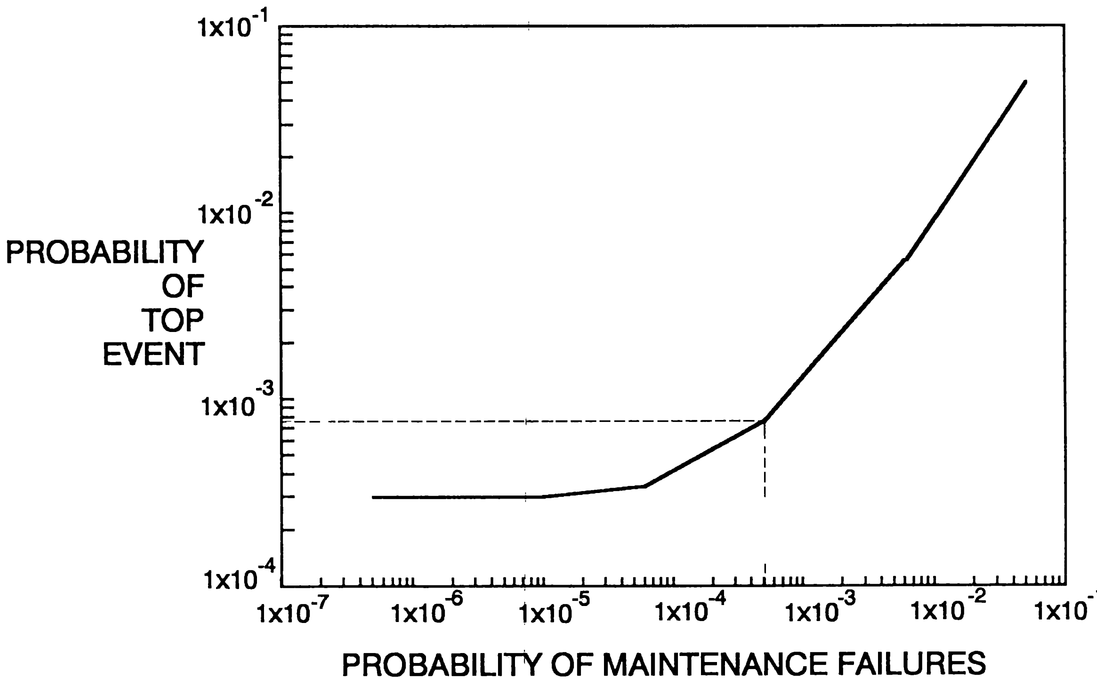


Figure 16. Effect of the Probability of Failures Attributable to Maintenance on the Probability of a Secondary Grain Dust Explosion

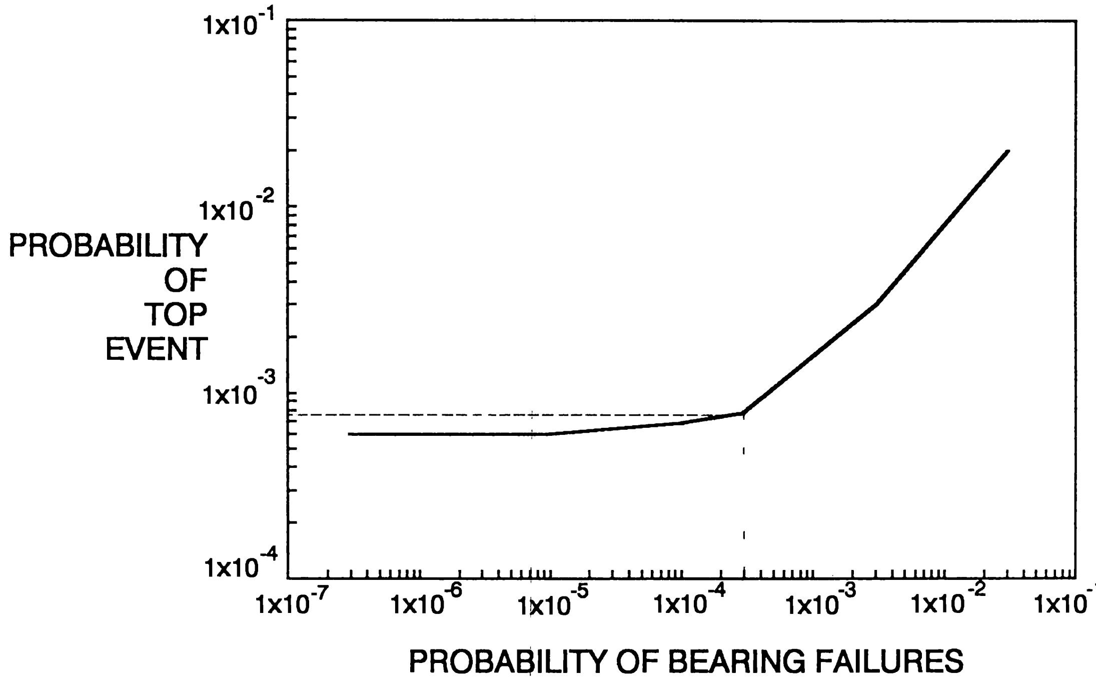


Figure 17. Effect of the Probability of Failures Attributable to Bearings on the Probability of a Secondary Grain Dust Explosion

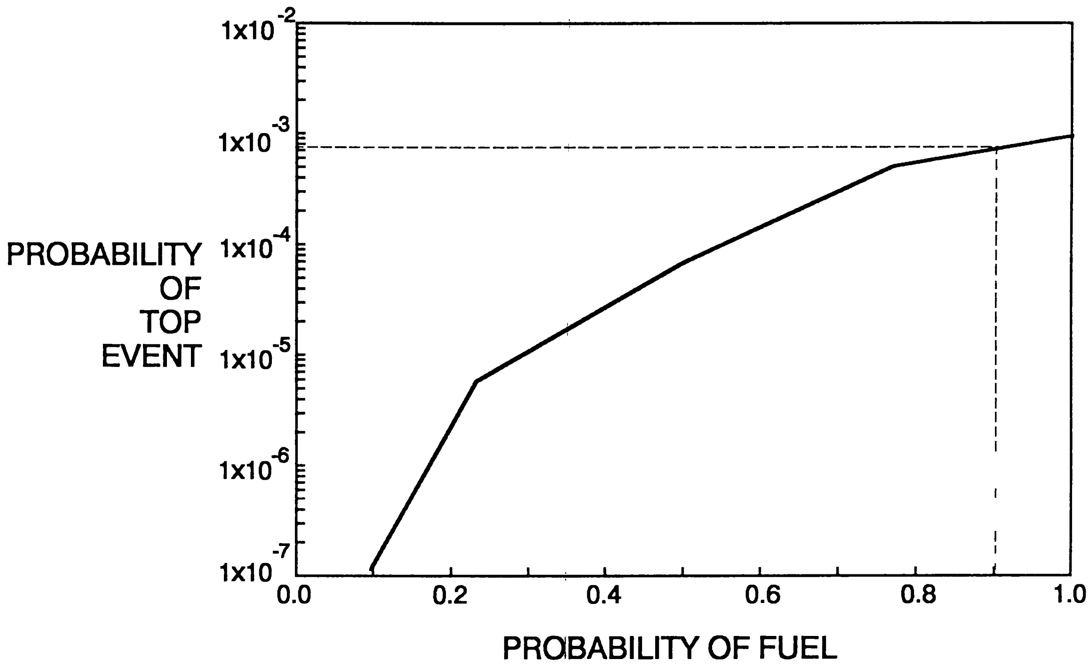


Figure 18. Effect of the Probability of Failures Attributable to Fuel on the Probability of a Secondary Grain Dust Explosion

Housekeeping

Base events designated as housekeeping failures include those failures associated with keeping boot and head bearings free of dust. This is even more critical when use is made of visual heat sensing devices such as heat sensitive tape or paint. The curve shown in Figure 15 suggests that housekeeping has little effect on the probability of a secondary grain dust explosion. This is explained by the definition of the physical system being only the bucket elevator leg and therefore, housekeeping efforts do little to minimize dust concentrations internal to the leg. This should not suggest, however, that housekeeping efforts should be minimized since good housekeeping has beneficial influences in other areas of the grain handling facility.

The probability of occurrence of housekeeping failures used in the model is 0.85. Particular grain handling facilities may experience different probabilities of occurrence of housekeeping failures but it is likely that most probabilities of occurrence of housekeeping failures will fall between 0.6 and 0.9. This range of probabilities produce top event probabilities of 7.0×10^{-4} and 9.1×10^{-4}. This small difference (approximately 2 secondary grain dust explosion per 10,000 bucket elevator leg seasons) indicates that the probability of occurrence of housekeeping failures is not critical in this study.

Maintenance

Base events designated as maintenance failures include those failures associated with maintenance procedures of bearings. The probability of occurrence of the base events is varied from 3.25×10^{-7} to 3.25×10^{-2}. The range of values on the X-axis shown in Figure 16, includes the reasonable expectations of maintenance programs. Examining this range reveals the tendency of the top event probability as the probability of occurrence of maintenance failures approach extremes. A ten-fold change in the probability of occurrence of maintenance failures used in the model results in a significant change in the top event probability. A probability of occurrence of maintenance failures of 3.25×10^{-5} result in a top event probability of occurrence of 4.9×10^{-4}, while a probability of occurrence of 3.25×10^{-3} results in a top event probability of occurrence of 4.2×10^{-3}.

Realizing a ten-fold change in the probability of occurrence of maintenance failures may not be practical. The inherent variability of the initial estimate of the probability of occurrence of maintenance failures, however, suggest that this range (3.25×10^{-5} through 3.25×10^{-3}) is large enough to include realistic values. Also this range is adequate to include most probabilities of occurrence of maintenance failures found throughout the grain handling industry.

The curve shown in Figure 16, indicates that the probability of a secondary grain dust explosion increases significantly as the probability of a maintenance failure increases, especially beyond 3.25×10^{-4}. This result emphasizes the need for a comprehensive maintenance program to keep the probability of a maintenance failure below 3.25×10^{-4}.

Bearings

The probability of occurrence of bearing failures is varied from 3.1×10^{-7} to 3.1×10^{-2}. The range of values on the X-axis shown in Figure 17 includes the reasonable expectations of the probability of occurrence of bearing failures. Examining this range reveals the dependency of the top event probability on the probability of occurrence of a bearing failure as it approaches its extremes. Decreasing the probability of occurrence of a bearing failure from 3.1×10^{-4} to 3.1×10^{-5} (a ten-fold decrease) decreases the top event probability of occurrence from 8.6×10^{-4} to 5.1×10^{-4}, a decrease of approximately 3 secondary grain dust explosions per 10,000 bucket elevator leg seasons. Increasing the probability of occurrence of a bearing failure from 3.1×10^{-4} to 3.1×10^{-3} (a ten-fold increase) increases the top event probability of occurrence from 8.6×10^{-4} to 2.4×10^{-3}, an increase of more than 64 secondary grain dust explosions per 10,000 bucket elevator leg seasons.

Fuel

The base events designated as fuel include the type of grain, grade of grain, speed of transport, and type of aspiration system. The probability of occurrence of fuel is varied from 0.1 to 1.0. The range of values on the X-axis shown in Figure 18 includes the reasonable expectations of what can be expected for the probability of occurrence of fuel. Examining this range reveals the tendency of the top event probability as the probability of occurrence of fuel approaches extremes. Decreasing the probability of occurrence of fuel from 0.6 to 0.5 decreases the probability of occurrence of the top event from 8.6×10^{-4} to 4.1×10^{-4}. This is a decrease of 4.5 secondary grain dust explosions per 10,000 bucket elevator leg seasons. Likewise an increase in the probability of occurrence of fuel from 0.6 to 0.7 increases the probability of the top event from 8.6×10^{-4} to 1.6×10^{-4}, an increase of approximately 31 secondary grain dust explosions per 10,000 bucket elevator leg seasons.

The results indicate that a significant decrease in the probability of a secondary grain dust explosion can be achieved with a decrease in the probability of occurrence of fuel. This is significant in that the proper use and design of aspiration systems can significantly improve the safety of a grain handling facility. Other dust abatement activities such as the use of mineral oil additives would also significantly decrease the probability of fuel in a bucket elevator leg.

The probability of occurrence of fuel in any particular grain handling facility is highly variable depending on the factors previously mentioned. Grain handling facilities which transport different types or grades of grain, use different aspiration techniques or conveying speeds will experience different probabilities of occurrence of fuel.

Model Characteristics

The model predicts that there will be approximately 36.1 secondary grain dust explosions in a bucket elevator season. The model prediction over estimates the reported occurrences of secondary grain dust explosions in bucket elevator legs by a factor of approximately 3.4. The over prediction of the model is not unexpected given the conservative assignment of point estimates of base events due to lack of verifiable input data, lack of validation of the model, and the possibility of inconsistent reporting procedures of grain dust explosion incidence.

Failure rate information about components and practices found in the grain handling industry, for the most part, does not exist. This void of data leads to approximations of many of the point estimates needed to perform the qualitative analysis of the grain dust explosion problem. These approximations are based on individual experience and inferences from interviews with managers of grain elevators in Western Oklahoma.

The model has not been validated to determine where corrections should be made. At this point in the model development, the model has not been tested against historical data of explosion incidence. Further refinement of the model will increase the accuracy of the results.

CHAPTER VII

SUGGESTIONS FOR THE GRAIN HANDLING INDUSTRY

The results of this analysis lend themselves to several suggestions for the grain handling industry. The suggestions include installing equipment designed to protect facilities from devastating grain dust explosions as well as managerial aspects of operating a grain handling facility.

The sensitivity analysis identifies three classes of failures that greatly affect the probability of a secondary grain dust explosions. These areas are: 1) fuel (aerated grain dust), 2) bearings, and 3) maintenance. Any activity that will reduce the probability of these failures will be of great benefit.

Fuel

Aerated grain dust in a bucket elevator leg is affected by: 1) type of grain being transported, 2) grade of grain being transported, 3) speed of transport, and 4) type of aspiration system. The type of grain being transported is governed by the predominant crops in the geographic area and it is not practical to only transport rice, for example, because of the low organic content of rice dust. Likewise grain handling facilities have limited control on the grade of grain entering their facility.

The speed of transport can be controlled by installing low-speed high capacity elevator legs. These legs provide equal capacity while creating less dust due to reduced kernel damage. The dust in the grain mass is also retained in the grain mass upon exit from the head because the grain falls enmass instead of being hurled from the head.

Aspiration systems should be engineered to remove dust from the elevator housing. Poorly designed systems aid the entrainment of the dust by providing a turbulent atmosphere. Further research in this area is needed to adequately address design considerations including air flow rate, location, and configuration of aspirators in order to develop a system that will provide adequate aspiration for bucket elevator legs.

Aerated grain dust can also be reduced by using mineral oil additives for the suppression of aerated dust. These additives cause dust particles to adhere to the surface of the grain kernel preventing them from becoming airborne thus eliminating the attached dust as a fuel source.

Bearings

The proper selection and installation of bearings cannot be over emphasized. A slight increase in the probability of bearing failures significantly increases the probability of a grain dust explosion. Managers of grain handling facilities should strive to improve their current situation and should continue to emphasize the importance of bearing management. Management means strict and comprehensive maintenance and inspection programs, as well as the initiation of preventive maintenance programs.

Maintenance

The probability of a secondary grain dust explosions is sensitive to the probability of maintenance failures. Maintenance in grain handling facilities can be improved by giving it a high priority throughout the elevator season and not just in the pre-season. Well established maintenance programs systematically cover the physical facility on a regular, predetermined schedule. Maintenance records are crucial to identify and correct weaknesses in the program. Knowledgeable, well-trained personnel are needed to properly carry out the maintenance activities. The installation of automatic lubrication units can assist the maintenance program, but are not a substitute for the maintenance program.

Equipment

The benefits of installing bearing heat sensors, explosion suppression devices, and/or explosion vents are demonstrated in this analysis. Adhering to the "...ounce of prevention..." philosophy, it is essential to incorporate bearing heat sensors. These sensors, when properly installed, can accurately identify potential problem bearings that could ignite a grain dust explosion. Incorporating bearing heat sensors with explosion vents will greatly reduce the probability of a grain dust explosion. Explosion vents may not be practical in every situation (e.g. an interior leg) but explosion suppression devices provide an equally effective alternative where possible.

CHAPTER VIII

CONCLUSIONS

The occurrence of a secondary grain dust explosion in a bucket elevator leg is studied using the fault tree analysis technique. This particular analysis lends itself to this type of risk analysis by determining the combinations of events leading to a failure, the overall probability, and the sensitivity to variations in the input of base event probabilities of occurrence.

Each base event is assigned a point estimate of its probability of failure based on published failure rate data and from interviews with grain elevator managers in Oklahoma. The minimum cut sets of the fault tree are determined which identify the combinations of events necessary to cause a secondary grain dust explosion in a bucket elevator leg. This analysis reveals that the lack of 1) adequate bearing maintenance, 2) explosion suppression devices, 3) explosion venting and 4) bearings equipped with heat sensors all contribute significantly to the occurrence of secondary explosions.

The total probability of a secondary grain dust explosion in a bucket elevator leg is predicted to be 8.6×10^{-4} with the assumed point estimates. This overall probability indicates that a typical grain handling facility has a 0.26% chance of suffering a secondary grain dust explosion in a bucket elevator leg. Incorporating explosion suppression devices, explosion vents or bearing heat sensors will appreciably decrease this probability to 1.7×10^{-8} or a 5.1×10^{-6}% chance for a typical facility.

It is evident from the sensitivity analysis that the probability of aerated grain dust in a concentration above the minimum explosive concentration (fuel) in the bucket elevator leg, failure of bearings, and maintenance procedures have a most profound affect on the probability of a secondary grain dust explosion. Substantial reduction in the probability of a grain dust explosion can be realized if the probability of fuel can be reduced. This analysis also shows that the neglect of bearings and maintenance programs can significantly increase the probability of a grain dust explosion.

Specific conclusions for the model development are as follows:

1) Using Fault Tree Analysis and interviews with Oklahoma grain elevator managers, a model was developed by;

a) Identifying the known events leading to a secondary grain dust explosion (the fault tree).

b) Expressing the occurrence of a secondary grain dust explosion in terms of combinations of events (minimum cut sets of the fault tree).

c) Assigning a point estimate of the probability of failure to each base event of the fault tree, determining which combinations of events are most likely to occur and ranking the minimum cut sets of the fault tree as to their probability of occurrence.

2) The WAM-E computer program was used to compute the total probability of a secondary grain dust explosion to be 8.6×10^{-4}. This probability is largely influenced by the use of bearing heat sensors, explosion suppression devices or explosion vents which reduces the probability of failure to 8.5×10^{-5}, 9.9×10^{-5} and 1.7×10^{-7}, respectively. Using bearing heat sensors in combination with explosion suppression devices decreases the probability of a secondary grain dust explosion to 9.9×10^{-6}. Using bearing heat sensors in combination with explosion vents decreases the probability of a secondary grain dust explosion to 1.7×10^{-8}.

3) The model is useful in that it can easily;

a) Accept new data.

b) Be modified to accommodate various equipment, managerial and procedural differences.

c) Be used on a wide range of bucket elevator legs in grain handling facilities.

4) The inadequacies of the model are due to;

a) Lack of verifiable input data.

b) Verification through historical data is needed.

A sensitivity analysis revealed that maintenance and bearings have a large influence on the probability of occurrence of a secondary grain dust explosion while fuel, personnel and housekeeping influence to a lesser degree. Specific conclusions of the sensitivity analysis are as follows:

1) A change of 0.1 in the probability of occurrence of personnel failures results in a 1.1×10^{-4} change in the probability of a secondary grain dust explosion.

2) Housekeeping failures have little effect on the probability of a secondary grain dust explosion in a bucket elevator leg because they do little to minimize dust concentrations internal to the leg. Most grain handling facility should experience a probability of a secondary grain dust explosion between 7.0×10^{-4} and 9.1×10^{-4} as affected by housekeeping failures.

3) Increasing the probability of occurrence of a maintenance failure by a factor of ten results in 139 secondary grain dust explosions per 10,000 bucket elevator leg seasons. Likewise, decreasing the probability of occurrence of a maintenance failure by a factor of ten results in approximately 15 secondary grain dust explosions per 10,000 bucket elevator leg seasons. This compares to approximately 8.6 secondary grain dust explosions per 10,000 bucket elevator leg seasons when the probability of occurrence of a maintenance failure is 3.25×10^{-5}.

4) Increasing the probability of occurrence of a bearing failure by a factor of ten results in approximately 24 secondary grain dust explosions per 10,000 bucket

elevator leg seasons. Likewise, decreasing the probability of occurrence of a bearing failure by a factor of ten results in approximately 5 secondary grain dust explosions per 10,000 bucket elevator leg seasons. This compares to approximately 8.6 secondary grain dust explosions per 10,000 bucket elevator leg seasons when the probability of occurrence of a maintenance failure is 3.1×10^{-4}.

5) Decreasing the probability of occurrence of fuel from 0.6 to 0.5 decreases the probability of a secondary grain dust explosion from 8.6×10^{-4} to 4.1×10^{-4}. Increasing the probability of occurrence of fuel from 0.6 to 0.7 increases the probability of a secondary grain dust explosion from 8.6×10^{-4} to 1.6×10^{-3}.

The results of this analysis lead to the following suggestions for the grain handling industry.

1) Control the amount of aerated dust (fuel) inside the bucket elevator leg by using slower transport speeds, effectively designed aspiration systems and dust suppressing additives on the grain.

2) Proper selection, use, installation, inspection and maintenance of bearings should not be compromised.

3) Maintenance programs should be given a higher priority in that the programs adhere to a regular and predetermined schedule of inspections, repairs and replacements of components.

4) Bearing heat sensors and, depending on bucket elevator leg configuration, explosion vents or explosion suppression devices should be equipped on all bucket elevator legs.

CHAPTER IX

RECOMMENDATIONS FOR FUTURE STUDY

The modeling processes is dependent on the availability of data. Failure data for components and practices used in the grain handling industry are scarce at best. Efforts should be increased to collect and disseminate failure data for components and practices found in grain handling facilities.

Data should be collected in the following areas:

1) Bearing failure data. Craig and Johnson (1983) solicited information from grain handlers about replacement intervals for bearing. These data should be reinforced with additional testing of bearings in the field and laboratory subjected to the environmental condition found in a grain handling facility.

2) Detection and sensing equipment. Detection and sensing equipment provide a great service to the grain handling industry. The prevailing attitude of managers of grain handling facilities is that these devices are unreliable and add little to the safety of the facility. Demonstrating the reliability of these components will provide data for input to this model and gain the confidence of elevator managers.

3) Maintenance activities. The reliability of individual maintenance programs is needed to evaluate their effectiveness. This data can be collected by examining detailed maintenance logs and comparing them to the specifications of equipment manufactures. The data should also include the frequency of general maintenance activities as well as specific activities such as welding and cutting activities, use of power tools, housekeeping activities, and inspections of belting,

bearings, etc.

4) Occurrence of grain dust explosions. Grain dust explosion information needs to be detailed in such a way that would insure that all incidence of a grain dust explosion would be reported, the origin of the explosion can be identified, and the history of the facility is evident.

The model describing the occurrence of a secondary grain dust explosion in a bucket elevator leg should be improved with newly obtained data. Information about the distribution of the point estimation of the probability of a secondary grain dust explosion should be investigated. This is possible via a Monte Carlo simulation of a mathematically equivalent model of the fault tree using the WAM-E computer software.

The model should be verified. The verification can be accomplished by studying grain dust explosion data and developing a probability of occurrence by incorporating historical information about each damaged facility. Using reliability techniques, a mean-time-to-failure can be computed. This mean-time-to-failure can be compared to the probability of occurrence determined by the model.

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APPENDIXES

APPENDIX A

EXAMPLE OF FAULT TREE ANALYSIS TECHNIQUE

EXAMPLE OF FAULT TREE ANALYSIS TECHNIQUE

The following is an example of how Fault Tree Analysis is used to systematically decompose a system. A simple system is analyzed and a fault tree is constructed, the minimum cut sets are determined, point estimates are assigned to the base events and the top event point estimate is determined. The symbols used in the construction of the fault tree in this example are shown in Figure 2.

Consider the simple circuit shown in Figure 19. It is assumed that all connections are functional. The first step in this analysis is to chose the top event or undesirable state of the system to be considered. The top event is considered to be that the light bulb will not function and is denoted as shown in Figure 20.

It is recognized that the light bulb will not function if there is no current to the light bulb or the light bulb is faulty. These states of the system are added to the fault tree as shown in Figure 21. The failed light bulb is considered a base event.

Event G1 must be further developed. For there to be no current to the light bulb, there must be no current through switch #1 and no current through switch #2. These events, denoted as G2 and G3, respectively, are shown in Figure 22.

There are two situations that can result in there being no current through switch #1. First, switch #1 could fail open, or second, the battery could fail. Likewise for there to be no current through switch #2, the switch could fail open, or the battery could fail. The resulting structure of the fault tree is shown in Figure 23. Each of these events are considered base events and need no further development. The fault tree is now completed since the bottom leaves of the tree are all base events.

The minimum cut sets can now be determined from the completed tree. To find the minimum cut sets, the tree must be decomposed from the top downward. Consider gate G0.

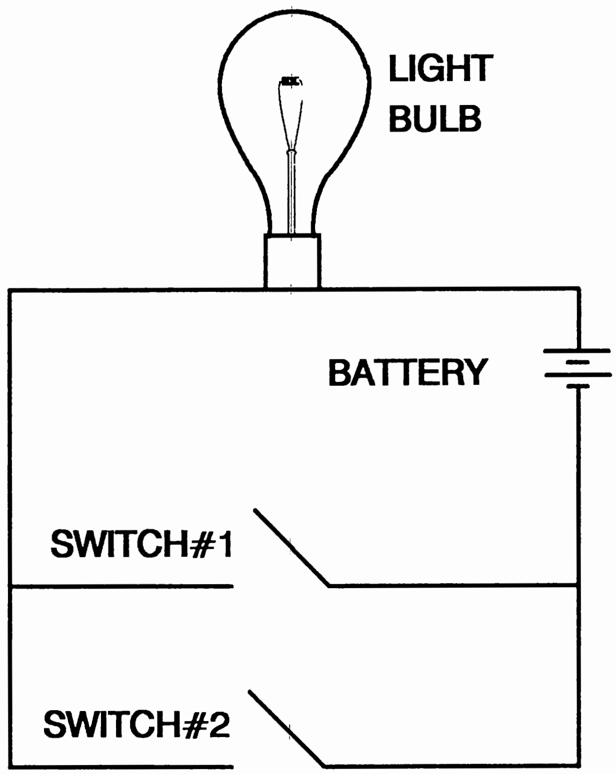


Figure 19. Simple Circuit for Example Problem

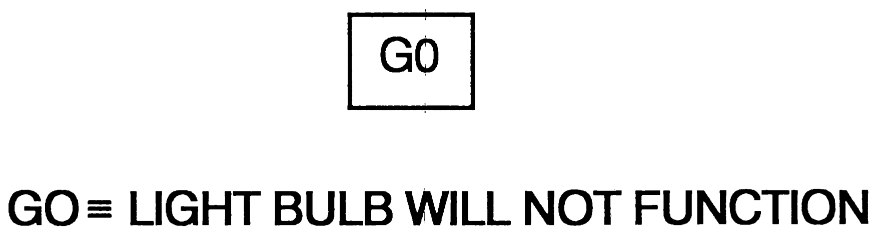


Figure 20. Top Event of Example Fault Tree

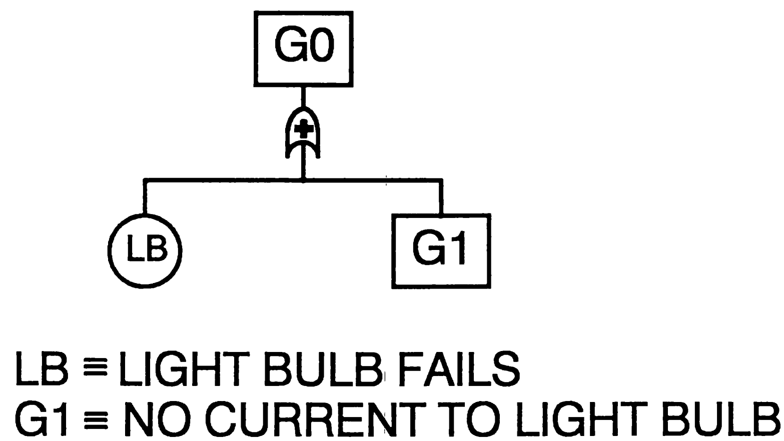
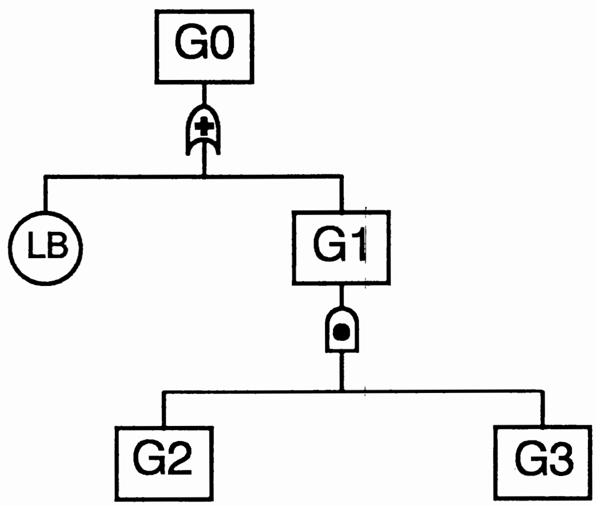


Figure 21. First Level Development of Example Fault Tree



G2 ≡ NO CURRENT THROUGH SWITCH#1
G3 ≡ NO CURRENT THROUGH SWITCH#2

Figure 22. Second Level Development of Example Fault Tree

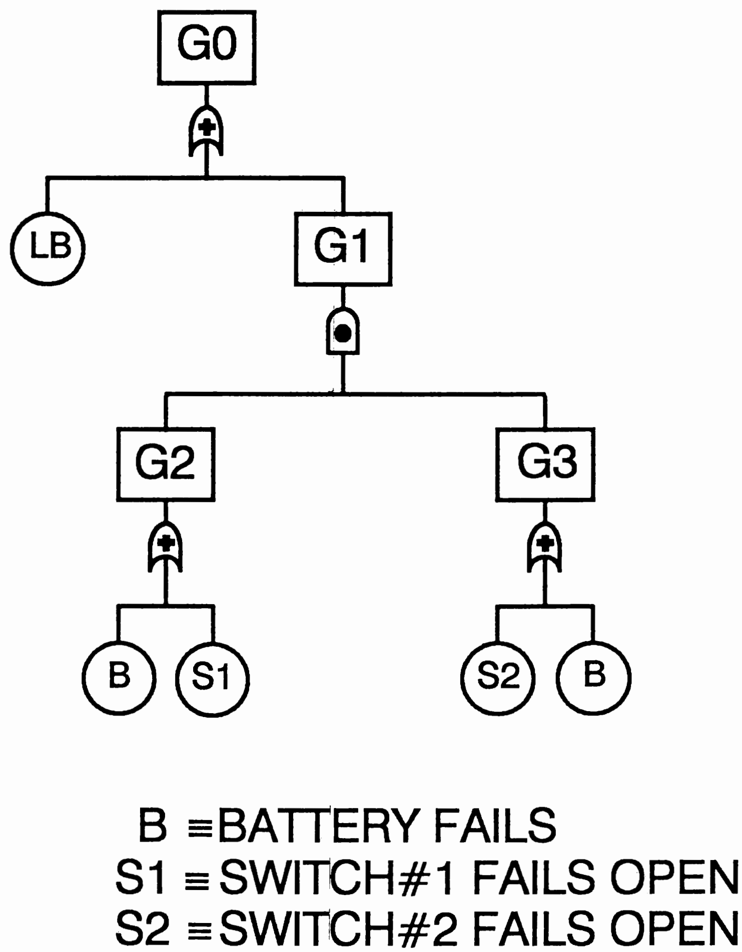


Figure 23. Completed Example Fault Tree

G0

Gate G0 proceeds from an OR gate, therefore G0 is replaced with each event immediately preceding the OR gate. In this example G0 is replaced by events LB and G1.

LB
G1

Event LB is a base event and proceeds from no gate, therefore it will not be further decomposed. Event G1 proceeds from an AND gate, therefore G1 is replaced with each event preceding the AND gate and expanded along the same row of the array. In this example G1 is replaced with events G2 and G3.

LB
G2 G3

Gate G2 proceeds from an OR gate, therefore G2 is replaced with each event immediately preceding the OR gate. In this example G2 is replaced by events B and S1.

LB
B G3
S1 G3

Gate G3 also proceeds from an OR gate, therefore G3 is replaced with each event immediately preceding the OR gate. In this example G3 is replaced by events B and S2 and the resulting cut sets are

LB
B B
S1 S2

Since each member of the cut sets is a base event all of the cut sets have been determined.

Consider the cut set containing B and B. The definition of a cut set states that the base events of a cut set are related by the intersection of the events. The intersection of B AND B is logically just B. Therefore this set is minimized by reducing the cut set to simply the event B. The minimum cut sets are therefore

LB
B
S1 S2

The minimum cut sets are used by identifying which combinations of events will produce the top event. In this example, the light bulb will not function if (1) the light bulb is failed, (2) the battery is failed or (3) switch #1 and switch #2 fail open.

The probability of occurrence for each base event is listed in Table VI. The probability of occurrence of each minimum cut set is computed using Equation 11 and shown in Table VII.

TABLE VII

PROBABILITY OF OCCURRENCE OF BASE EVENTS IN EXAMPLE PROBLEM

LB	0.001
B	0.0001
S1	0.00005
S2	0.00005

The probability of occurrence of the top event is computed using Equation

11 and the probability of occurrence of each minimum cut set. The resulting probability of occurrence of the top event is 1.2×10^{-3}.

TABLE VII

MINIMUM CUT SETS OF EXAMPLE PROBLEM WITH HIGHEST PROBABILITY OF OCCURRENCE

minimum cut set no.	1	2	3
probability of occurrence	0.001	0.0001	0.0001
base events	LB	B	S1 S2

APPENDIX B

SAMPLE QUESTIONNAIRE USED IN INTERVIEWS OF GRAIN ELEVATOR OPERATORS IN WESTERN OKLAHOMA

Name of Facility: ______________________________

Type of Facility: ______________________________

Location: ______________________________

Date of Interview: ______________________________

Name of Contact: ______________________________

Position of Contact: ______________________________

Phone Number: ______________________________

Questionnaire

I. General information:

1. How old is your facility? ________
2. How many elevator legs are in your facility? ________
3. What is your typical annual throughput? ________
4. What is your typical in-house turning rate? ________

II. Leg information:

5. Are any legs adjacent to grain driers or conditioners? ________
   If so, briefly describe.
6. What is the range of nominal leg belt speeds? ________
7. What is the range of nominal heights of the legs? ________
8. What is the range of the nominal capacities of the legs? ________

III. Belt information:

9. What is the belt material? ________
10. How often do you inspect the belt? ________
11. Briefly describe how you inspect the belt.
12. Briefly describe how the belt is repaired (include repair material).
13. How often do you replace the belt? ________
14. Briefly describe how you determine when to replace the belt.
15. Are your elevator leg drives or boot pulleys or belts equipped with any type of sensors or monitors? ________
    If so, briefly describe.
16. Do you have backstops (anti-rotational devices) installed on all legs to prevent "back legging"?__________
    If no, why not?

IV. Bucket/Cup information:

17. What is the bucket/cup material? ________
18. How are the buckets/cups fastened to the belt? ________

19. How often are buckets/cups replaced? ________

20. Describe how dislodged buckets/cups are detected.

21. Describe how dislodged buckets are removed.

22. Describe the bucket/cup replacement procedure.

V. Bearings, General:

23. Who do you ask for technical bearing specifications? __________

24. What bearing manufacturer do you primarily use? _________

Concerning boot/head bearings what/who is the:

		Boot	Head
25.	Manufacturer	___________	___________
26.	Service Life	___________	___________
27.	Material	___________	___________
28.	Rating	___________	___________
29.	Lubrication	___________	___________

VI. Bearings, Boot:

30. Are the boot bearings external to the elevator housing? _________
If no, why not?

31. Describe your boot bearing maintenance policy.

32. Describe your boot bearing replacement policy, including specifications on replacement bearings (seals, bearings, lubrication, duty, etc).

33. What is the boot bearing replacement interval? ________

34. Are the boot bearings equipped with monitors? ________
If so:

a) What type? ________

b) Who is the manufacturer/model number? _________

c) Describe your boot bearing monitor maintenance procedure.

d) What is the replacement interval of the (boot) bearing monitors?

VII. Bearings, Head:

35. Are the head bearings external to the elevator housing? _________
If no, why not?

36. Describe your head bearing maintenance policy.

37. Describe your head bearing replacement policy.

38. What is the head bearing replacement interval? ________

39. Are the head bearings equipped with monitors? ________
If so:

a) What type? ________

b) Who is the manufacturer/model number? ________

c) Describe your bearing monitor maintenance procedures.

d) What is the replacement interval of the head bearing monitors?
____

VIII. Pits:

		Rail	Truck
40.	Number of pits?	________	________
41.	Method of transfer from pit?	________	________
42.	Size of grate openings?	________	________
43.	Equipped with magnets?	________	________

If so:

a) What type and size of magnets are used?

b) Describe how the magnets are cleaned and the cleaning interval.

c) Describe the types of metals collected.

d) How effective do you feel your pit magnets are?

IX. Explosion Vents:

44. What percent of legs are equipped with explosion vents? ________

45. What is the rated relief pressure of the vents? _______

46. Describe the location of the vents.

47. What are the vent sizes? ________

48. Describe any maintenance operations performed on the vents.

49. How effective are your vents?

X. Explosion Suppression:

50. What percent of legs are equipped with explosion suppression devices? ________

51. What type of suppression agent is used? ________

52. What is the operating pressure of the suppression agent? _______

53. What type of pressure sensors are used? ________

54. Who is the manufacture/model of the sensors? ________

55. What is the activation pressure of the system? ________

56. Describe the location of the pressure sensors.

57. Describe the location of the outlet jets.

58. Describe any maintenance operations performed on the explosion suppression system.

59. How effective is your explosion suppression system?

XI. Dust Control, Ventilation:

60. Describe the location of aspirators inside the elevator legs.

61. What is the volumetric air flow rate inside the elevator legs? ________

62. What is the nominal working pressure of the ventilation system on the inside of the elevator leg? ________

63. What type of dust/air stream separation device is used? ________

64. How effective is your ventilation system?

XII. Dust Control, Additives:

65. What type of dust control additives do you use? ________

66. What is the application rate? _________

67. At what point in the facility are the additives applied? _______

68. Describe how the additives are applied to the grain.

69. How effective are the dust control additives?

XIII. Elevator Leg Operating Procedures:

70. Describe the elevator leg start-up procedures (including control interlocks if used).

71. Describe the elevator leg shut-down procedures (including control interlocks if used).

72. Describe the major elevator leg maintenance procedures.

73. Do welding and cutting operations take place in or around the elevator leg? ________ How often? ___________

74. Describe safeguards used when welding and cutting operations take place.

XIV. General:

75. Are the elevator legs equipped with opacity sensors? ________ If so, describe.

76. Are the elevator legs equipped with heat detectors? ________ If so, describe.

77. Are the elevator legs equipped with smoke detectors? ________ If so, describe.

APPENDIX C

BASE EVENT DESCRIPTIONS

BASE EVENT ID	BASE EVENT DESCRIPTION	POINT * ESTIMATION
BA	Speed of transport in boot while normal.	0.6
BB	Speed of transport in head while normal.	0.6
BC	Speed of transport in upside while normal.	0.6
BD	Speed of transport in downside while normal.	0.6
B0	Normal elevator operation (elevator running).	0.8
B1	Explosion vents not in use.	0.98
B2	Explosion vents undersized.	1.0×10^{-6}
B3	Vent cover has too high of yield strength.	1.0×10^{-6}
B4	Explosion suppression not in use.	0.99
B5	Confinement in boot while normal.	0.9999
B6	Oxygen in boot while normal.	1.0
B7	Confinement in boot while maintenance.	0.998
B8	Oxygen in boot while maintenance.	1.0
B9	Confinement in head while normal.	0.999
B10	Oxygen in head while normal.	1.0
B11	Confinement in head while maintenance.	0.998
B12	Oxygen in head while maintenance.	1.0
B13	Confinement in upside while normal.	0.999
B14	Oxygen in upside while normal.	1.0
B15	Confinement in upside while maintenance.	0.998
B16	Oxygen in upside while maintenance.	1.0
B17	Confinement in downside while normal.	0.999
B18	Oxygen in downside while normal.	1.0
B19	Confinement in downside while maintenance.	0.998
B20	Oxygen in downside while maintenance.	1.0

B21	Explosion vents blocked.	1.0×10^{-4}
B22	Explosion vents sealed shut.	1.0×10^{-4}
B23	Type of grain being transported in boot while normal.	0.6
B24	Grade of grain in boot while normal.	0.6
B25	Aspiration system in boot while normal.	0.6
B26	Other dust abatement activities not available in boot while normal.	0.99
B27	Failure of dust abatement activities in boot while normal.	0.4
B28	Maintenance activities in boot.	0.08
B29	Dust not allowed to clear before maintenance begins in boot.	1.0×10^{-8}
B30	Dust cloud formed by disturbed grain/dust pile in boot while maintenance.	1.0×10^{-8}
B31	Type of grain being transported in head while normal.	0.6
B32	Grade of grain being transported in head while normal.	0.6
B33	Aspiration system being used in head while normal.	0.6
B34	Other dust abatement activities not available in head while normal.	0.99
B35	Failure of dust abatement activities in head while normal.	0.4
B36	Maintenance activities in head.	0.04
B37	Dust not allowed to clear before maintenance begins in head.	1.0×10^{-8}
B38	Dust cloud formed by disturbed grain/dust pile in head while maintenance.	1.0×10^{-8}
B39	Type of grain being transported in upside while normal.	0.6
B40	Grade of grain being transported in upside while normal.	0.6
B41	Aspiration system being used in upside while normal.	0.6
B42	Other dust abatement activities not available in upside while normal.	0.99
B43	Failure of dust abatement activities in upside while normal.	0.4
B44	Maintenance activities in upside.	0.04
B45	Dust not allowed to clear before maintenance begins in upside.	1.0×10^{-8}

B46	Dust cloud formed by disturbed grain/dust pile in upside while maintenance.	1.0×10^{-8}
B47	Type of grain being transported in downside while normal.	0.6
B48	Grade of grain being transported in downside while normal.	0.6
B49	Aspiration system being used in downside while normal.	0.6
B50	Other dust abatement activities not available in downside while normal.	0.99
B51	Failure of dust abatement activities in downside while normal.	0.4
B52	Maintenance activities in downside.	0.04
B53	Dust not allowed to clear before maintenance begins in downside.	1.0×10^{-8}
B54	Dust cloud formed by disturbed grain/dust pile in downside while maintenance.	1.0×10^{-8}
B55	Pressure sensors fail.	1.27×10^{-1}
B56	Signal from pressure sensors is interrupted.	6.07×10^{-4}
B57	Canister valve fails.	1.0×10^{-5}
B58	Canister leaks down.	2.05×10^{-3}
B59	Improper system design.	1.0×10^{-4}
B60	Other processes leading to flames in boot while normal.	1.0×10^{-8}
B61	Personnel causing flames in boot while normal.	1.0×10^{-8}
B62	Other processes leading to flames in head while normal.	1.0×10^{-8}
B63	Personnel causing flames in head while normal.	1.0×10^{-8}
B64	Overheating of motor drive leading to hot surfaces (non-bearing) in head while normal.	1.4×10^{-4}
B65	Personnel causing flames in upside while normal.	1.0×10^{-8}
B66	Personnel causing flames in downside while normal.	1.0×10^{-8}
B67	Canister leaks completely leading to canisters are empty.	2.05×10^{-4}
B68	Canisters not filled after use leading to canisters are empty.	1.0×10^{-6}
B69	Bearing wear out leading to overheated bearing in boot while normal.	3.1×10^{-4}
B70	Overheating of motors, fuses, switches leading to hot surfaces in head while normal.	1.4×10^{-4}

B71	Other processes leading to flames in upside while normal.	1.0×10^{-8}
B72	Other processes leading to hot surfaces in upside while normal.	1.0×10^{-8}
B73	Bearing wear out leading to bearing failure leading to sparking in boot while normal.	3.1×10^{-5}
B74	Belt-to-ground leading to discharge of static electricity in boot while normal.	1.0×10^{-9}
B75	Dust-to-ground leading to discharge of static electricity in boot while normal.	1.0×10^{-9}
B76	Belt slippage ignored leading to overheating of shaft lagging in boot while normal.	1.0×10^{-3}
B77	Other processes leading to flames in downside while normal.	1.0×10^{-8}
B78	Other processes leading to hot surfaces in downside while normal.	1.0×10^{-8}
B79	Welding/cutting with torch leading to flames in boot while maintenance.	1.0×10^{-3}
B80	Personnel leading to flames in boot while maintenance.	1.0×10^{-8}
B81	Arc welding leading to electric sparks in boot while maintenance.	1.0×10^{-3}
B82	Slow down device unavailable in boot while normal.	0.7
B83	Grinding leading to friction sparks in boot while maintenance.	1.0×10^{-3}
B84	Welded surfaces leading to hot surfaces in boot while maintenance.	1.0×10^{-3}
B85	Cut surfaces leading to hot surfaces in boot while maintenance.	1.0×10^{-3}
B86	Ground surfaces leading to hot surfaces in boot while maintenance.	1.0×10^{-3}
B87	Bearing wear out leading to overheated bearing in head while normal.	3.0×10^{-4}
B88	Slow down device fails in head while normal	0.25
B89	Misaligned belt in boot while normal.	1.0×10^{-7}
B90	Personnel ignore misaligned belt in boot while normal.	0.9
B91	Bearing wear out leading to bearing failure leading to sparking in head while normal.	3.0×10^{-5}
B92	Belt-to-ground leading to discharge of static electricity in head while normal.	1.0×10^{-9}

B93	Dust-to-ground leading to discharge of static electricity in head while normal.	1.0×10^{-9}
B94	Personnel ignore belt slippage in head while normal.	0.2
B95	Belt tracking device unavailable in boot while normal.	1.0×10^{-3}
B96	Belt tracking device fails in boot while normal.	0.5
B97	Welding/cutting with torch leading to flames in head while maintenance.	1.0×10^{-3}
B98	Personnel leading to flames in head while maintenance.	1.0×10^{-7}
B99	Arc welding leading to electric sparks in head while maintenance.	1.0×10^{-3}
B100	Misaligned belt in head while normal.	1.0×10^{-7}
B101	Grinding leading to friction sparks in head while maintenance.	1.0×10^{-3}
B102	Welded surfaces leading to hot surfaces in head while maintenance.	1.0×10^{-3}
B103	Cut surfaces leading to hot surfaces in head while maintenance.	1.0×10^{-3}
B104	Ground surfaces leading to hot surfaces in head while maintenance.	1.0×10^{-3}
B105	Other processes leading to electric sparks, leading to sparks in upside while normal.	1.0×10^{-7}
B106	Misaligned belt leading to rubbing belt in upside while normal.	1.0×10^{-7}
B107	Deformed casing leading to rubbing belt in upside while normal.	1.0×10^{-7}
B108	Deformed bucket leading to rubbing bucket in upside while normal.	5.0×10^{-8}
B109	Personnel ignore misaligned belt in head while normal.	0.2
B110	Belt tracking device unavailable in head while normal.	1.0×10^{-3}
B111	Welding/cutting with torch leading to flames in upside while maintenance.	1.0×10^{-3}
B112	Personnel leading to flames in upside while maintenance.	1.0×10^{-7}
B113	Arc welding leading to electric sparks in upside while maintenance.	1.0×10^{-3}
B114	Auto-lubrication unit not available leading to sparking in boot while normal.	0.98
B115	Grinding leading to friction sparks in upside while maintenance.	1.0×10^{-3}
B116	Welded surfaces leading to hot surfaces in upside while maintenance.	1.0×10^{-3}
B117	Cut surfaces leading to hot surfaces in upside while maintenance.	1.0×10^{-3}

B118	Ground surfaces leading to hot surfaces in upside while maintenance.	1.0×10^{-3}
B119	Other processes leading to electric sparks, leading to sparks in downside while normal.	1.0×10^{-7}
B120	Misaligned belt leading to rubbing belt in downside while normal.	1.0×10^{-7}
B121	Deformed casing leading to rubbing belt in downside while normal.	1.0×10^{-7}
B122	Deformed bucket leading to rubbing bucket in downside while normal.	5.0×10^{-8}
B123	Auto-lubrication unit not available leading to overheated bearing in boot while normal.	0.98
B124	Heat sensitive tape not available in boot while normal.	0.99
B125	Welding/cutting with torch leading to flames in downside while maintenance.	1.0×10^{-3}
B126	Personnel leading to flames in downside while maintenance.	1.0×10^{-7}
B127	Arc welding leading to electric sparks in downside while maintenance.	1.0×10^{-3}
B128	Heat sensitive paint not available in boot while normal.	0.99
B129	Grinding leading to friction sparks in downside while maintenance.	1.0×10^{-3}
B130	Welded surfaces leading to hot surfaces in downside while maintenance.	1.0×10^{-3}
B131	Cut surfaces leading to hot surfaces in downside while maintenance.	1.0×10^{-3}
B132	Ground surfaces leading to hot surfaces in downside while maintenance.	1.0×10^{-3}
B133	Failure of auto-lubrication unit leading to loss of lubrication leading to bearing failure leading to overheating in boot while normal.	2.8×10^{-3}
B134	Heat sensors not available leading to over heated bearing in boot while normal.	0.99
B135	Failure of maintenance program leading to loss of lubrication leading to bearing failure leading to overheating in boot while normal.	3.25×10^{-4}
B136	Bearing sensors fail leading to heat sensors do not signal leading to overheated bearings in boot while normal.	3.39×10^{-3}
B137	Heat sensitive paint fails leading to heat sensitive paint does not signal in boot while normal.	1.0×10^{-3}

B138	Heat sensitive tape fails leading to heat sensitive tape does not signal in boot while normal.	1.0×10^{-3}
B139	Foreign material in grain stream leading to foreign material in boot while normal.	1.0×10^{-5}
B140	Foreign material not removed by grate leading to foreign material in boot while normal.	0.45
B141	Foreign material not removed by magnets leading to foreign material in boot while normal.	0.9999
B142	"Large" foreign material in grain stream leading to "large" foreign material enters leg in boot while normal.	1.0×10^{-7}
B143	Grate does not remove leading to "large" foreign material enters leg in boot while normal.	1.0×10^{-3}
B144	Magnet does not remove leading to "large" foreign material enters leg in boot while normal.	0.99999
B145	Failure of auto-lubrication unit leading to loss of lubrication leading to bearing failure leading to sparking in boot while normal.	2.8×10^{-4}
B146	Bearing sensors not available leading to overheated bearing in head while normal.	0.99
B147	Failure of maintenance program leading to loss of lubrication leading to bearing failure leading to sparking in boot while normal.	3.25×10^{-5}
B148	Shorting of electric power supply leading to electric sparks in boot while normal.	1.0×10^{-7}
B149	Heat sensitive tape not available leading to overheated bearing in head while normal.	0.99
B150	Heat sensitive paint not available leading to overheated bearing in head while normal.	0.99
B151	Belt tracking device fails in head while normal.	0.5
B152	Belt tracking device unavailable in upside while normal.	1.0×10^{-3}
B153	Belt tracking device fails in upside while normal.	0.5
B154	Personnel ignore misaligned belt in downside while normal.	0.9
B155	Belt tracking device unavailable in downside while normal.	1.0×10^{-3}
B156	Belt tracking device fails in downside while normal.	0.5
B157	Power tools in use leading to power tools leading to electric sparks in boot while maintenance.	0.1

B158	Auto-lubrication unit not available leading to overheated bearing in head while normal.	0.98
B159	Failure of auto-lubrication unit leading to loss of lubrication leading to bearing failure leading to overheating in head while normal.	3.0×10^{-3}
B160	Auto-lubrication unit not available leading to sparking in head while normal.	0.98
B161	Failure of maintenance program leading to loss of lubrication leading to bearing failure leading to overheating in head while normal.	3.2×10^{-4}
B162	Bearing sensors fail leading to heat sensors do not signal leading to overheated bearings in head while normal.	3.39×10^{-3}
B163	Heat sensitive paint fails leading to heat sensitive paint does not signal in head while normal.	1.0×10^{-3}
B164	Heat sensitive tape fails leading to heat sensitive tape does not signal in head while normal.	1.0×10^{-3}
B165	Foreign material in grain stream leading to foreign material in head while normal.	1.0×10^{-5}
B166	Foreign material not removed by grate leading to foreign material in head while normal.	0.45
B167	Foreign material not removed by magnets leading to foreign material in head while normal.	0.9999
B168	"Large" foreign material in grain stream leading to "large" foreign material enters leg in head while normal.	1.0×10^{-7}
B169	Grate does not remove leading to "large" foreign material enters leg in head while normal.	1.0×10^{-3}
B170	Magnet does not remove leading to "large" foreign material enters leg in head while normal.	0.99999
B171	Failure of auto-lubrication unit leading to loss of lubrication leading to bearing failure leading to sparking in head while normal.	3.0×10^{-3}
B172	Slack in belt leading to belt slippage in boot while normal.	2.0×10^{-3}
B173	Failure of maintenance program leading to loss of lubrication leading to bearing failure leading to sparking in head while normal.	3.2×10^{-5}
B174	Shorting of electric power supply leading to electric sparks in head while normal.	1.0×10^{-7}
B175	Slow down device fails leading to belt slippage in head while normal.	0.25
B176	Slow down device not available in head while normal.	0.7

B177	Slack in belt leading to belt slippage in head while normal.	5.0×10^{-4}
B178	Lagging fails leading to belt slippage in head while normal.	1.0×10^{-7}
B179	Excessive load on belt leading to belt slippage in head while normal.	1.0×10^{-4}
B180	Personnel ignore misaligned belt in upside while normal.	0.2
B183	Power tools in use leading to power tools leading to electric sparks in head while maintenance.	0.1
B185	Dust-to-ground leading to static electric discharge in upside while normal.	1.0×10^{-9}
B186	Belt-to-ground leading to static electric discharge in upside while normal.	1.0×10^{-8}
B190	Power tools in use leading to power tools leading to electric sparks in upside while maintenance.	0.1
B192	Dust-to-ground leading to static electric discharge in downside while normal.	1.0×10^{-9}
B193	Belt-to-ground leading to static electric discharge in downside while normal.	1.0×10^{-8}
B197	Power tools in use leading to power tools leading to electric sparks in downside while maintenance.	0.1
B199	Interlock fails leading to bearing sensor signal ignored in boot while normal.	1.49×10^{-1}
B200	Personnel ignore leading to bearing sensor signal ignored in boot while normal.	0.01
B201	Personnel ignore leading to heat sensitive paint signal ignored in boot while normal.	0.2
B202	Personnel ignore leading to heat sensitive tape signal ignored in boot while normal.	0.2
B205	Shorting of power tools leading to spark from power tool in boot while maintenance.	7.0×10^{-4}
B206	Power tool does not have enclosed motor leading to spark from power tool in boot while maintenance.	0.999
B209	Interlock fails leading to bearing sensor signal ignored in head while normal.	1.49×10^{-1}
B210	Personnel ignore leading to bearing sensor signal ignored in head while normal.	0.01

B211	Personnel ignore leading to heat sensitive paint signal ignored in head while normal.	0.2
B212	Personnel ignore leading to heat sensitive tape signal ignored in head while normal.	0.2
B215	Shorting of power tools leading to spark from power tool in head while maintenance.	7.0×10^{-4}
B216	Power tool does not have enclosed motor leading to spark from power tool in head while maintenance.	0.999
B219	Foreign material in grain stream leading to foreign material in upside while normal.	1.0×10^{-6}
B220	Foreign material not removed by grate leading to foreign material in upside while normal.	0.45
B221	Foreign material not removed by magnets leading to foreign material in upside while normal.	0.9999
B222	"Large" foreign material in grain stream leading to "large" foreign material enters leg in upside while normal.	1.0×10^{-8}
B223	Grate does not remove leading to "large" foreign material enters leg in upside while normal.	1.0×10^{-3}
B224	Magnet does not remove leading to "large" foreign material enters leg in upside while normal.	0.99999
B225	Shorting of power tools leading to spark from power tool in upside while maintenance.	7.0×10^{-4}
B226	Power tool does not have enclosed motor leading to spark from power tool in upside while maintenance.	0.999
B229	Foreign material in grain stream leading to foreign material in downside while normal.	1.0×10^{-8}
B230	Foreign material not removed by grate leading to foreign material in downside while normal.	0.45
B231	Foreign material not removed by magnets leading to foreign material in downside while normal.	0.9999
B232	"Large" foreign material in grain stream leading to "large" foreign material enters leg in downside while normal.	1.0×10^{-9}
B233	Grate does not remove leading to "large" foreign material enters leg in downside while normal.	1.0×10^{-3}
B234	Magnet does not remove leading to "large" foreign material enters leg in downside while normal.	0.99999

B235	Shorting of power tools leading to spark from power tool in downside while maintenance.	7.0×10^{-4}
B236	Power tool does not have enclosed motor leading to spark from power tool in downside while maintenance.	0.999
B238	Auto-lubrication unit not available leading to seized bearing leading to belt slippage in boot while normal.	0.98
B239	Dusty area leading to dust covers paint in boot while normal.	0.99
B240	Inadequate housekeeping leading to dust covers paint in boot while normal.	0.85
B241	Dusty area leading to dust covers tape in boot while normal.	0.99
B242	Inadequate housekeeping leading to dust covers tape in boot while normal.	0.85
B243	Dusty area leading to dust covers paint in head while normal.	0.95
B244	Inadequate housekeeping leading to dust covers paint in head while normal.	0.8
B245	Dusty area leading to dust covers tape in head while normal.	0.95
B246	Inadequate housekeeping leading to dust covers tape in head while normal.	0.8
B247	Bearing wear out leading to seized bearing leading to belt slippage in boot while normal.	3.0×10^{-5}
B248	Failure of auto-lubrication unit leading to seized bearing in boot while normal.	2.8×10^{-4}
B249	Failure of maintenance program leading to loss of lubrication leading to seized bearing leading to belt slippage in boot while normal.	3.25×10^{-5}

* point estimate of probability of occurrence per bucket elevator leg season

APPENDIX D

GATE DESCRIPTIONS

GATE ID	GATE DESCRIPTION
G0	Secondary grain dust explosion in bucket elevator leg.
G1	Primary grain dust explosion in bucket elevator leg
G2	Explosion vents fail.
G3	Explosion suppression devices fail.
G4	Failure in boot while normal.
G5	Failure in boot while maintenance.
G6	Failure in head while normal.
G7	Failure in head while maintenance.
G8	Failure in upside while normal.
G9	Failure in upside while maintenance.
G10	Failure in downside while normal.
G11	Failure in downside while maintenance.
G12	Explosion vents not operative.
G13	Explosion suppression fails.
G14	Ignition in boot while normal.
G15	Fuel in boot while normal.
G16	Ignition in boot while maintenance.
G17	Fuel in boot while maintenance.
G18	Ignition in head while normal.
G19	Fuel in head while normal.
G20	Ignition in head while maintenance.
G21	Fuel in head while maintenance.
G22	Ignition in upside while normal.
G23	Fuel in upside while normal.
G24	Ignition in upside while maintenance.

G25 Fuel in upside while maintenance.

G26 Ignition in downside while normal.

G27 Fuel in downside while normal.

G28 Ignition in downside while maintenance.

G29 Fuel in downside while maintenance.

G30 Pressure sensors do not signal.

G31 Canisters fail to discharge.

G32 Insufficient agent to extinguish flame front.

G33 Overheated bearing in boot while normal.

G34 Friction sparks in boot while normal.

G35 Flames in boot while normal.

G36 Electric sparks in boot while normal.

GA Hot surfaces in boot while normal.

G37 Explosion in elevator leg while normal

G38 Ignition from maintenance activities in boot.

G39 Overheated bearing in head while normal.

G40 Friction sparks in head while normal.

G41 Flames in head while normal.

G42 Electric sparks in head while normal.

GB Hot surfaces (Non-bearings) in head while normal.

G43 Explosion in elevator while maintenance

G44 Ignition from maintenance activities in head.

G45 Sparks in upside while normal.

G46 Flames in upside while normal.

G47 Hot surfaces in upside while normal.

G48 Ignition from maintenance activities in upside.

G49 Sparks in downside while normal.

G50 Flames in downside while normal.

G51 Hot surfaces in downside while normal.

G52 Ignition from maintenance activities in downside.

G53 Canisters are empty.

G54 Bearing failure leading to overheating in boot while normal.

G55 Heat sensors do not signal overheated bearing in boot while normal.

G56 Other dust abatement activities in boot while normal.

G57 Other dust abatement activities in head while normal.

G58 Bearing failure leading to sparking in boot while normal.

G59 Other dust abatement activities in upside while normal.

G60 Other dust abatement activities in downside while normal.

G61 Discharge of static electricity causing electric sparks in boot while normal.

G62 Primary explosion in elevator leg while normal

G63 Overheated shaft lagging in boot while normal.

G64 Belt slippage ignored leading to overheated shaft lagging in boot while normal.

G65 Flames from maintenance activities in boot while maintenance.

G66 Electric sparks from maintenance activities in boot while maintenance.

G67 Slow down device does not signal leading to belt slippage ignored in boot while normal.

G68 Hot surfaces from maintenance activities in boot while maintenance.

G69 Bearing failure leading to overheating in head while normal.

G70 Heat sensors do not signal overheated bearing in head while normal.

G71 Rubbing belt leading to hot surfaces in boot while normal.

G72 Alignment not corrected leading to rubbing belt in boot while normal.

G73 Bearing failure leading to sparking in head while normal.

G74 Belt tracking device does not signal leading to rubbing belt in boot while normal.

G75 Alignment not corrected leading to rubbing belt in head while normal.

G76 Discharge of static electricity causing electric sparks in head while normal.

G77 Belt tracking device does not signal in head while normal.

G78 Overheating of shaft lagging leading to hot surfaces (Non-bearings) in head while normal.

G79 Rubbing belt leading to hot surfaces in head while normal.

G80 Flames from maintenance activities in head while maintenance.

G81 Electric sparks from maintenance activities in head while maintenance.

G83 Hot surfaces from maintenance activities in head while maintenance.

G84 Electric sparks leading to sparks in upside while normal.

G85 Friction sparks leading to sparks in upside while normal.

G86 Belt tracking device does not signal in upside while normal.

G87 Rubbing belt leading to hot surfaces in upside while normal.

G88 Misalignment not leading to rubbing belt in upside while normal.

G89 Misalignment not corrected leading to rubbing belt in upside while normal.

G90 Flames from maintenance activities in upside while maintenance.

G91 Electric sparks from maintenance activities in upside while maintenance.

G92 Rubbing belt leading to hot surfaces in downside while normal.

G93 Hot surfaces from maintenance activities in upside while maintenance.

G94 Electric sparks leading to sparks in downside while normal.

G95 Friction sparks leading to sparks in downside while normal.

G96 Misaligned belt not corrected leading to rubbing belt in downside while normal.

G97 Hot surfaces in downside while normal.

G98 Belt tracking device does not signal in downside while normal.

G99 Belt slippage leading to overheated shaft lagging in boot while normal.

G100 Flames from maintenance activities in downside while maintenance.

G101 Electric sparks from maintenance activities in downside while maintenance.

G103 Hot surfaces from maintenance activities in downside while maintenance.

G104 Loss of lubrication leading to bearing overheating in boot while normal.

G105 Bearing sensors do not signal leading to overheated bearing in boot while normal.

G106 Heat sensitive paint does not signal leading to overheated bearing in boot while normal.

G107 Heat sensitive tape does not signal leading to overheated bearing in boot while normal.

G108 Foreign material in boot leading to friction sparks in boot while normal.

G109 "Large" foreign material enters leg leading to dislodged bucket leading to friction sparks in boot while normal.

G110 Loss of lubrication leading to bearing failure leading to sparking in boot while normal.

G111 Auto-lubrication fails in boot while normal.

G115 Power tools leading to electric sparks in boot while maintenance.

G117 Loss of lubrication leading to bearing overheating in head while normal.

G118 Bearing sensors do not signal leading to overheated bearing in head while normal.

G119 Heat sensitive paint does not signal leading to overheated bearing in head while normal.

G120 Heat sensitive tape does not signal leading to overheated bearing in head while normal.

G121 Foreign material in head leading to lodged foreign material leading to friction sparks in head while normal.

G122 "Large" foreign material enters leg leading to dislodged bucket in head while normal.

G123 Loss of lubrication leading to bearing failure leading to sparking in head while normal.

G126 Belt slippage leading to overheated shaft lagging in head while normal.

G127 Belt slippage ignored leading to overheated shaft lagging in head while normal.

G128 Power tools leading to electric sparks in head while maintenance.

G129 Auto-lubrication unit fails leading to bearing failure leading to sparking in head while normal.

G130 Static electric discharge leading to electric sparks in upside while normal.

G131 Auto-lubrication unit fails leading to sparking in boot while normal.

G132 Auto-lubrication unit fails leading to loss of lubrication leading to over heated bearing in head while normal.

G133 Power tools leading to electric sparks in upside while maintenance.

G134 Auto-lubrication unit fails leading to seized bearing leading to belt slippage in boot while normal.

G135 Static electric discharge leading to electric sparks in downside while normal.

G136 Bearing sensors fail leading to overheated bearing in boot while normal.

G137 Heat sensitive tape fails leading to over heated bearing in boot while normal.

G138 Power tools leading to electric sparks in downside while maintenance.

G139 Heat sensitive paint fails leading to over heated bearing in boot while normal.

G140 Bearing sensors signal ignored leading to heat sensors do not signal leading to overheated bearings in boot while normal.

G141 Heat sensitive paint ignored leading to heat sensitive paint does not signal in boot while normal.

G142 Heat sensitive tape ignored leading to heat sensitive tape does not signal in boot while normal.

G143 Bearing sensors fail leading to over heated bearing in head while normal.

G144 Spark from power tool leading to power tool leading to electric sparks in boot while maintenance.

G145 Seized bearing leading to belt slippage in boot while normal.

G146 Bearing sensors signal ignored leading to heat sensors do not signal leading to overheated bearings in head while normal.

G147 Heat sensitive paint ignored leading to heat sensitive paint does not signal in head while normal.

G148 Heat sensitive tape ignored leading to heat sensitive tape does not signal in head while normal.

G149 Heat sensitive tape ignored leading to heat sensitive paint does not signal in head while normal.

G150 Spark from power tool leading to power tool leading to electric sparks in head while maintenance.

G151 Slow down device does not signal leading to belt slippage in head while normal.

G152 Foreign material leading to lodged foreign material in upside while normal.

G153 "Large" foreign material enters leg leading to friction sparks in upside while normal.

G154 Spark from power tool leading to power tool leading to electric sparks in upside while maintenance.

G155 Loss of lubrication leading to seized bearing in boot while normal.

G156 Foreign material leading to lodged foreign material in downside while normal.

G157 "Large" foreign material enters leg leading to friction sparks in downside while normal.

G158 Spark from power tool leading to power tool leading to electric sparks in downside while maintenance.

G159 Heat sensitive paint ignored leading to heat sensitive paint does not signal in head while normal.

G160 Dust covers paint leading to signal ignored in boot while normal.

G161 Dust covers tape leading to signal ignored in boot while normal.

G162 Dust covers paint leading to signal ignored in head while normal.

G163 Dust covers tape leading to signal ignored in head while normal.

APPENDIX E

INPUT TO WAM-E PROGRAM

WAMCUT DATA IN FILE 'U13212A.WAMCUT.DATA'

N		2	1.0E-08		3			
G0	AND	3	0	G1	G2	G3		
G1	OR	2	0	G37	G43			
G2	OR	1	3	G12	B1	B2	B3	
G3	OR	1	1	G13	B4			
G4	AND	2	2	G14	G15	B5	B6	
G5	AND	2	2	G16	G17	B7	B8	
G6	AND	2	2	G18	G19	B9	B10	
G7	AND	2	2	G20	G21	B11	B12	
G8	AND	2	2	G22	G23	B13	B14	
G9	AND	2	2	G24	G25	B15	B16	
G10	AND	2	2	G26	G27	B17	B18	
G11	AND	2	2	G28	G29	B19	B20	
G12	OR	0	2	B21	B22			
G13	OR	3	0	G30	G31	G32		
G14	OR	5	0	G33	G34	G35	G36	GA
G15	AND	1	4	G56	B23	B24	B25	BA
G16	AND	1	1	G38	B28			
G17	OR	0	2	B29	B30			
G18	OR	5	0	G39	G40	G41	G42	GB
G19	AND	1	4	G57	B31	B32	B33	BB
G20	AND	1	1	G44	B36			
G21	OR	0	2	B37	B38			
G22	OR	3	0	G45	G46	G47		
G23	AND	1	4	G59	B39	B40	B41	BC
G24	AND	1	1	G48	B44			
G25	OR	0	2	B45	B46			
G26	OR	3	0	G49	G50	G51		
G27	AND	1	4	G60	B47	B48	B49	BD
G28	AND	1	1	G52	B52			
G29	OR	0	2	B53	B54			
G30	OR	0	2	B55	B56			
G31	OR	1	1	G53	B57			
G32	OR	0	2	B58	B59			
G33	AND	2	0	G54	G55			
G34	OR	3	0	G108	G109	G58		
G35	OR	0	2	B60	B61			
G36	OR	1	1	G61	B148			
GA	OR	2	0	G63	G71			
G37	AND	1	1	G62	B0			
G38	OR	3	1	G65	G66	G68	B83	
G39	AND	2	0	G69	G70			
G40	OR	3	0	G121	G122	G73		
G41	OR	0	2	B62	B63			
G42	OR	1	1	G76	B174			
GB	OR	2	2	G78	G79	B70	B64	
G43	OR	4	0	G5	G7	G9	G11	
G44	OR	3	1	G80	G81	G83	B101	
G45	OR	2	0	G84	G85			
G46	OR	0	2	B65	B71			
G47	OR	1	1	G87	B72			
G48	OR	3	1	G90	G91	G93	B115	
G49	OR	2	0	G94	G95			

G50	OR	0	2	B66	B77		
G51	OR	1	1	G97	B78		
G52	OR	3	1	G100	G101	G103	B129
G53	OR	0	2	B67	B68		
G54	OR	1	1	G104	B69		
G55	AND	3	0	G105	G106	G107	
G56	OR	0	2	B26	B27		
G57	OR	0	2	B34	B35		
G58	OR	1	1	G110	B73		
G59	OR	0	2	B42	B43		
G60	OR	0	2	B50	B51		
G61	OR	0	2	B74	B75		
G62	OR	4	0	G4	G6	G8	G10
G63	AND	2	0	G99	G64		
G64	AND	1	1	G67	B76		
G65	OR	0	2	B79	B80		
G66	OR	1	1	G115	B81		
G67	OR	0	2	B82	B88		
G68	OR	0	3	B84	B85	B86	
G69	OR	1	1	G117	B87		
G70	AND	3	0	G118	G119	G120	
G71	AND	1	1	G72	B89		
G72	AND	1	1	G74	B90		
G73	OR	1	1	G123	B91		
G74	OR	0	2	B95	B96		
G75	AND	1	1	G77	B109		
G76	OR	0	2	B92	B93		
G77	OR	0	2	B110	B151		
G78	AND	2	0	G126	G127		
G79	AND	1	1	G75	B100		
G80	OR	0	2	B97	B98		
G81	OR	1	1	G128	B99		
G83	OR	0	3	B102	B103	B104	
G84	OR	1	1	G130	B105		
G85	OR	2	0	G152	G153		
G86	OR	0	2	B152	B153		
G87	OR	1	2	G88	B107	B108	
G88	AND	1	1	G89	B106		
G89	AND	1	1	G86	B180		
G90	OR	0	2	B111	B112		
G91	OR	1	1	G133	B113		
G92	AND	1	1	G96	B120		
G93	OR	0	3	B116	B117	B118	
G94	OR	1	1	G135	B119		
G95	OR	2	0	G156	G157		
G96	AND	1	1	G98	B154		
G97	OR	1	2	G92	B121	B122	
G98	OR	0	2	B155	B156		
G99	OR	1	1	G145	B172		
G100	OR	0	2	B125	B126		
G101	OR	1	1	G138	B127		
G103	OR	0	3	B130	B131	B132	
G104	AND	1	1	G111	B135		
G105	OR	2	0	G136	G140		

G106	OR	2	0	G137	G141	
G107	OR	2	0	G139	G142	
G108	AND	0	3	B139	B140	B141
G109	AND	0	3	B142	B143	B144
G110	AND	1	1	G131	B147	
G111	OR	0	2	B123	B133	
G115	AND	1	1	G144	B157	
G117	AND	1	1	G132	B161	
G118	OR	2	0	G143	G146	
G119	OR	2	0	G147	G149	
G120	OR	2	0	G148	G159	
G121	AND	0	3	B165	B166	B167
G122	AND	0	3	B168	B169	B170
G123	AND	1	1	G129	B173	
G126	OR	0	3	B177	B178	B179
G127	AND	1	1	G151	B94	
G128	AND	1	1	G150	B183	
G129	OR	0	2	B160	B171	
G130	OR	0	2	B185	B186	
G131	OR	0	2	B114	B145	
G132	OR	0	2	B158	B159	
G133	AND	1	1	G154	B190	
G134	OR	0	2	B238	B248	
G135	OR	0	2	B192	B193	
G136	OR	0	2	B134	B136	
G137	OR	0	2	B128	B137	
G138	AND	1	1	G158	B197	
G139	OR	0	2	B124	B138	
G140	AND	0	2	B199	B200	
G141	OR	1	1	G160	B201	
G142	OR	1	1	G161	B202	
G143	OR	0	2	B146	B162	
G144	OR	0	2	B205	B206	
G145	OR	1	1	G155	B247	
G146	AND	0	2	B209	B210	
G147	OR	1	1	G162	B211	
G148	OR	1	1	G163	B212	
G149	OR	0	2	B149	B163	
G150	OR	0	2	B215	B216	
G151	OR	0	2	B175	B176	
G152	AND	0	3	B219	B220	B221
G153	AND	0	3	B222	B223	B224
G154	OR	0	2	B225	B226	
G155	AND	1	1	G134	B249	
G156	AND	0	3	B229	B230	B231
G157	AND	0	3	B232	B233	B234
G158	OR	0	2	B235	B236	
G159	OR	0	2	B150	B164	
G160	AND	0	2	B239	B240	
G161	AND	0	2	B241	B242	
G162	AND	0	2	B243	B244	
G163	AND	0	2	B245	B246	
END						
G162		G163				

B0	8.0000E-01
B1	9.8000E-01
B2	1.0000E-06
B3	1.0000E-06
B4	9.9000E-01
B5	9.9900E-01
B6	1.0000E-00
B7	9.9800E-01
B8	1.0000E-00
B9	9.9900E-01
B10	1.0000E-00
B11	9.9800E-01
B12	1.0000E-00
B13	9.9900E-01
B14	1.0000E-00
B15	9.9800E-01
B16	1.0000E-00
B17	9.9900E-01
B18	1.0000E-00
B19	9.9800E-01
B20	1.0000E-00
B21	1.0000E-04
B22	1.0000E-04
B23	6.0000E-01
B24	6.0000E-01
B25	6.0000E-01
BA	6.0000E-01
B26	9.9000E-01
B27	4.0000E-01
B28	8.0000E-02
B29	1.0000E-08
B30	1.0000E-08
B31	6.0000E-01
B32	6.0000E-01
B33	6.0000E-01
BB	6.0000E-01
B34	9.9000E-01
B35	4.0000E-01
B36	4.0000E-02
B37	1.0000E-08
B38	1.0000E-08
B39	6.0000E-01
B40	6.0000E-01
B41	6.0000E-01
BC	6.0000E-01
B42	9.9000E-01
B43	4.0000E-01
B44	4.0000E-02
B45	1.0000E-08
B46	1.0000E-08
B47	6.0000E-01
B48	6.0000E-01
B49	6.0000E-01
BD	6.0000E-01

B50	9.9000E-01
B51	4.0000E-01
B52	4.0000E-02
B53	1.0000E-08
B54	1.0000E-08
B55	1.2700E-01
B56	6.0700E-04
B57	1.0000E-05
B58	2.0500E-03
B59	1.0000E-04
B60	1.0000E-08
B61	1.0000E-08
B62	1.0000E-08
B63	1.0000E-08
B64	1.4000E-04
B65	1.0000E-08
B66	1.0000E-08
B67	2.0500E-04
B68	1.0000E-06
B69	3.1000E-04
B70	1.4000E-04
B71	1.0000E-08
B72	1.0000E-08
B73	3.1000E-05
B74	1.0000E-09
B75	1.0000E-09
B76	1.0000E-03
B77	1.0000E-08
B78	1.0000E-08
B79	1.0000E-03
B80	1.0000E-08
B81	1.0000E-03
B82	7.0000E-01
B83	1.0000E-03
B84	1.0000E-03
B85	1.0000E-03
B86	1.0000E-03
B87	3.0000E-04
B88	2.5000E-01
B89	1.0000E-07
B90	9.0000E-01
B91	3.0000E-05
B92	1.0000E-09
B93	1.0000E-09
B94	2.0000E-01
B95	1.0000E-03
B96	5.0000E-01
B97	1.0000E-03
B98	1.0000E-07
B99	1.0000E-03
B100	1.0000E-07
B101	1.0000E-03
B102	1.0000E-03
B103	1.0000E-03

B104	1.0000E-03
B105	1.0000E-07
B106	1.0000E-07
B107	1.0000E-07
B108	5.0000E-08
B109	2.0000E-01
B110	1.0000E-03
B111	1.0000E-03
B112	1.0000E-07
B113	1.0000E-03
B114	9.8000E-01
B115	1.0000E-03
B116	1.0000E-03
B117	1.0000E-03
B118	1.0000E-03
B119	1.0000E-07
B120	1.0000E-07
B121	1.0000E-07
B122	5.0000E-08
B123	9.8000E-01
B124	9.9000E-01
B125	1.0000E-03
B126	1.0000E-07
B127	1.0000E-03
B128	9.9000E-01
B129	1.0000E-03
B130	1.0000E-03
B131	1.0000E-03
B132	1.0000E-03
B133	2.8000E-03
B134	9.9000E-01
B135	3.2500E-04
B136	3.3900E-03
B137	1.0000E-03
B138	1.0000E-03
B139	1.0000E-05
B140	4.5000E-01
B141	9.9990E-01
B142	1.0000E-07
B143	1.0000E-03
B144	9.9999E-01
B145	2.8000E-04
B146	9.9000E-01
B147	3.2500E-05
B148	1.0000E-07
B149	9.9000E-01
B150	9.9000E-01
B151	5.0000E-01
B152	1.0000E-03
B153	5.0000E-01
B154	2.0000E-01
B155	1.0000E-03
B156	5.0000E-01
B157	1.0000E-01

B158	9.8000E-01
B159	3.0000E-03
B160	9.8000E-01
B161	3.2000E-04
B162	3.3900E-03
B163	1.0000E-03
B164	1.0000E-03
B165	1.0000E-05
B166	4.5000E-01
B167	9.9990E-01
B168	1.0000E-07
B169	1.0000E-03
B170	9.9999E-01
B171	3.0000E-03
B172	2.0000E-03
B173	3.2000E-05
B174	1.0000E-07
B175	2.5000E-01
B176	6.0000E-01
B177	5.0000E-04
B178	1.0000E-07
B179	1.0000E-04
B180	2.0000E-01
B183	1.0000E-01
B185	1.0000E-09
B186	1.0000E-08
B190	1.0000E-01
B192	1.0000E-09
B193	1.0000E-08
B197	1.0000E-01
B199	1.4900E-01
B200	1.0000E-02
B201	2.0000E-01
B202	2.0000E-01
B205	7.0000E-04
B206	9.9900E-01
B209	1.4900E-01
B210	1.0000E-02
B211	2.0000E-01
B212	2.0000E-01
B215	7.0000E-04
B216	9.9900E-01
B219	1.0000E-06
B220	4.5000E-01
B221	9.9990E-01
B222	1.0000E-08
B223	1.0000E-03
B224	9.9999E-01
B225	7.0000E-04
B226	9.9900E-01
B229	1.0000E-08
B230	4.5000E-01
B231	9.9990E-01
B232	1.0000E-09

B233	1.0000E-03
B234	9.9999E-01
B235	7.0000E-04
B236	9.9000E-01
B238	9.8000E-01
B239	9.9000E-01
B240	8.5000E-01
B241	9.9000E-01
B242	8.5000E-01
B243	9.5000E-01
B244	8.0000E-01
B245	9.5000E-01
B246	8.0000E-01
B247	3.0000E-05
B248	2.8000E-04
B249	3.2500E-05
END	
END	
STOP	

APPENDIX F

MINIMUM CUT SETS OF FAULT TREE

MINIMUM CUT SETS FOR GATE G0 ORDERED BY PROBABILITY

1.	3.07E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B128	B134	B135	
2.	3.03E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B149	B150	B158	B161	
3.	2.99E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B124	B128	B134		
4.	2.90E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B149	B150		
5.	2.61E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B134	B135	B239	B240
6.	2.61E-05	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B123	B128	B134	B135	B241	B242	
7.	2.54E-05	B0	B4	B5	B6	B23	B24	B25	BA
		B26	B69	B128	B134	B241	B242		
8.	2.54E-05	B0	B1	B4	B6	B23	B24	B25	BA
		B26	B69	B124	B134	B239	B240		
9.	2.32E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B150	B158	B161	B243	B244
10.	2.32E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B149	B158	B161	B245	B246
11.	2.22E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B149	B245	B246	
12.	2.22E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B150	B243	B244	
13.	2.22E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B134	B135	B239	B240	B241
		B242							
14.	2.16E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B134	B239	B240	B241	B242
15.	1.78E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B158	B161	B243	B244	B245
		B246							
16.	1.71E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B243	B244	B245	B246

17.	1.39E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B64					
18.	1.39E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B70					
19.	1.24E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B124	B128	B134	B135	
20.	1.22E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B149	B150	B158	B161	
21.	1.21E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B124	B128	B134		
22.	1.17E-05	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B149	B150		
23.	1.06E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B124	B134	B135	B239	B240
24.	1.03E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B128	B134	B241	B242	
25.	1.03E-05	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B124	B134	B239	B240	
26.	9.39E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B149	B158	B161	B245	B246
27.	9.39E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B150	B158	B161	B243	B244
28.	8.98E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B149	B245	B246	
29.	8.98E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B150	B243	B244	
30.	8.97E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B134	B135	B239	B240	B241
		B242							
31.	8.74E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B134	B239	B240	B241	B242
32.	7.21E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B158	B161	B243	B244	B245
		B246							
33.	6.90E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B243	B244	B245	B246

34.	6.21E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B134	B135	B201	
35.	6.21E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B128	B134	B135	B202	
36.	6.12E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B149	B158	B161	B212	
37.	6.12E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B150	B158	B161	B211	
38.	6.05E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B124	B134	B201		
39.	6.05E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B128	B134	B202		
40.	5.97E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B94	B176	B177			
41.	5.85E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B150	B211		
42.	5.85E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B149	B212		
43.	5.63E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B64					
44.	5.63E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B70					
45.	5.28E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B134	B135	B202	B239	B240
46.	5.28E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B134	B135	B201	B241	B242
47.	5.14E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B134	B202	B239	B240	
48.	5.14E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B134	B201	B241	B242	
49.	4.69E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B158	B161	B211	B245	B246
50.	4.69E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B158	B161	B212	B243	B244
51.	4.49E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B212	B243	B244	

52.	4.49E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B211	B245	B246	
53.	3.94E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B124	B128	B134	B135	
54.	3.88E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B149	B150	B158	B161	
55.	3.84E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B124	B128	B134		
56.	3.71E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B149	B150		
57.	3.35E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B124	B134	B135	B239	B240
58.	3.35E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B128	B134	B135	B241	B242
59.	3.26E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B124	B134	B239	B240	
60.	3.26E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B128	B134	B241	B242	
61.	3.17E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B114	B147				
62.	3.12E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B160	B173				
63.	3.08E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B73					
64.	2.98E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B150	B158	B161	B243	B244
65.	2.98E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B91					
66.	2.98E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B149	B158	B161	B245	B246
67.	2.85E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B149	B245	B246	
68.	2.85E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B134	B135	B239	B240	B241
		B242							
69.	2.85E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B150	B243	B244	

70.	2.77E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B134	B239	B240	B241	B242
71.	2.51E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B128	B134	B135	B202	
72.	2.51E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B124	B134	B135	B201	
73.	2.49E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B94	B175	B177			
74.	2.47E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B150	B158	B161	B211	
75.	2.47E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B149	B158	B161	B212	
76.	2.44E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B128	B134	B202		
77.	2.44E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B124	B134	B201		
78.	2.41E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B94	B176	B177			
79.	2.36E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B150	B211		
80.	2.36E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B149	B212		
81.	2.29E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B158	B161	B243	B244	B245
		B246							
82.	2.19E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B243	B244	B245	B246
83.	2.13E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B134	B135	B201	B241	B242
84.	2.13E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B134	B135	B202	B239	B240
85.	2.08E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B134	B201	B241	B242	
86.	2.08E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B134	B202	B239	B240	

87.	1.90E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B158	B161	B211	B245	B246
88.	1.90E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B158	B161	B212	B243	B244
89.	1.81E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B211	B245	B246	
90.	1.81E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B212	B243	B244	
91.	1.79E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B70					
92.	1.79E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B64					
93.	1.59E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B124	B128	B134	B135	
94.	1.57E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B149	B150	B158	B161	
95.	1.55E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B124	B128	B134		
96.	1.35E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B128	B134	B135	B241	B242
97.	1.35E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B124	B134	B135	B239	B240
98.	1.32E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B124	B134	B239	B240	
99.	1.32E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B128	B134	B241	B242	
100.	1.30E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B149	B150		
101.	1.28E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B114	B147				
102.	1.26E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B160	B173				
103.	1.25E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B134	B135	B201	B202	
104.	1.25E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B73					

105.	1.24E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B158	B161	B211	B212	
106.	1.22E-06	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B134	B201	B202		
107.	1.21E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B91					
108.	1.20E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B150	B158	B161	B243	B244
109.	1.20E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B149	B158	B161	B245	B246
110.	1.19E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B94	B176	B179			
111.	1.18E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B211	B212		
112.	1.15E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B149	B245	B246	
113.	1.15E-06	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B150	B243	B244	
114.	1.15E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B134	B135	B239	B240	B241
		B242							
115.	1.12E-06	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B134	B239	B240	B241	B242
116.	1.00E-06	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B94	B175	B177			
117.	9.25E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B158	B161	B243	B244	B245
		B246							
118.	8.85E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B243	B244	B245	B246
119.	7.97E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B124	B134	B135	B201	
120.	7.97E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B128	B134	B135	B202	
121.	7.85E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B149	B158	B161	B212	

122.	7.85E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B150	B158	B161	B211	
123.	7.76E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B124	B134	B201		
124.	7.76E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B128	B134	B202		
125.	7.66E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B94	B176	B177			
126.	7.50E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B149	B212		
127.	7.50E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B150	B211		
128.	7.22E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B64					
129.	7.22E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B70					
130.	6.77E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B134	B135	B202	B239	B240
131.	6.77E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B134	B135	B201	B241	B242
132.	6.59E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B134	B202	B239	B240	
133.	6.59E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B134	B201	B241	B242	
134.	6.02E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B158	B161	B212	B243	B244
135.	6.02E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B158	B161	B211	B245	B246
136.	5.76E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B212	B243	B244	
137.	5.76E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B211	B245	B246	
138.	5.07E-07	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B134	B135	B201	B202	
139.	4.99E-07	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B158	B161	B211	B212	

140.	4.97E-07	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B94	B175	B179			
141.	4.93E-07	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B134	B201	B202		
142.	4.82E-07	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B94	B176	B179			
143.	4.78E-07	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B211	B212		
144.	4.48E-07	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B139	B140	B141			
145.	4.48E-07	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B165	B166	B167			
146.	4.06E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B114	B147				
147.	4.00E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B160	B173				
148.	3.96E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B73					
149.	3.83E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B91					
150.	3.22E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B128	B134	B135	B202	
151.	3.22E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B124	B134	B135	B201	
152.	3.19E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B94	B175	B177			
153.	3.17E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B150	B158	B161	B211	
154.	3.17E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B149	B158	B161	B212	
155.	3.13E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B124	B134	B201		
156.	3.13E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B128	B134	B202		
157.	3.09E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B94	B176	B177			

158.	3.03E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B150	B211		
159.	3.03E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B149	B212		
160.	2.74E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B134	B135	B202	B239	B240
161.	2.74E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B134	B135	B201	B241	B242
162.	2.66E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B134	B201	B241	B242	
163.	2.66E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B134	B202	B239	B240	
164.	2.43E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B158	B161	B212	B243	B244
165.	2.43E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B158	B161	B211	B245	B246
166.	2.33E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B212	B243	B244	
167.	2.33E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B211	B245	B246	
168.	2.01E-07	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B94	B175	B179			
169.	1.81E-07	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B165	B166	B167			
170.	1.81E-07	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B139	B140	B141			
171.	1.64E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B114	B147				
172.	1.62E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B160	B173				
173.	1.61E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B134	B135	B201	B202	
174.	1.60E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B73					
175.	1.58E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B158	B161	B211	B212	

176.	1.57E-07	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B134	B201	B202		
177.	1.55E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B91					
178.	1.53E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B94	B176	B179			
179.	1.52E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B146	B211	B212		
180.	1.39E-07	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B76	B82	B172			
181.	1.29E-07	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B94	B175	B177			
182.	1.05E-07	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B128	B135	B136	
183.	1.04E-07	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B149	B150	B158	B161	B162	
184.	1.02E-07	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B124	B128	B136		
185.	9.92E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B149	B150	B162		
186.	9.27E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B149	B150	B159	B161	
187.	8.95E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B128	B135	B136	B241	B242
188.	8.95E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B135	B136	B239	B240
189.	8.78E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B124	B128	B133	B134	B135	
190.	8.71E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B128	B136	B241	B242	
191.	8.71E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B124	B136	B239	B240	
192.	7.96E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B149	B158	B161	B162	B245	B246
193.	7.96E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B150	B158	B161	B162	B243	B244

194.	7.61E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B149	B162	B245	B246	
195.	7.61E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B150	B162	B243	B244	
196.	7.61E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B135	B136	B239	B240	B241
		B242							
197.	7.47E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B124	B133	B134	B135	B239	B240
198.	7.47E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B128	B133	B134	B135	B241	B242
199.	7.40E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B136	B239	B240	B241	B242
200.	7.11E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B150	B159	B161	B243	B244
201.	7.11E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B149	B159	B161	B245	B246
202.	6.50E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B123	B134	B135	B201	B202	
203.	6.40E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B146	B158	B161	B211	B212	
204.	6.38E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B94	B175	B179			
205.	6.37E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B123	B124	B128	B134	B135	
206.	6.35E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B133	B134	B135	B239	B240	B241
		B242							
207.	6.33E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B69	B134	B201	B202		
208.	6.27E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B146	B149	B150	B158	B161	
209.	6.20E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B69	B124	B128	B134		
210.	6.19E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B94	B176	B179			

211.	6.13E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B87	B146	B211	B212		
212.	6.11E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B158	B161	B162	B243	B244	B245
		B246							
213.	6.00E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B87	B146	B149	B150		
214.	5.84E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B162	B243	B244	B245	B246
215.	5.74E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B165	B166	B167			
216.	5.74E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B139	B140	B141			
217.	5.63E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B76	B82	B172			
218.	5.46E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B159	B161	B243	B244	B245
		B246							
219.	5.41E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B123	B124	B134	B135	B239	B240
220.	5.41E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B123	B128	B134	B135	B241	B242
221.	5.27E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B69	B128	B134	B241	B242	
222.	5.27E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B69	B124	B134	B239	B240	
223.	4.97E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B76	B88	B172			
224.	4.81E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B146	B149	B158	B161	B245	B246
225.	4.81E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B146	B150	B158	B161	B243	B244
226.	4.63E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B128	B135	B199	B200
227.	4.60E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B123	B134	B135	B239	B240	B241	B242

228.	4.60E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B87	B146	B149	B245	B246	
229.	4.60E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B87	B146	B150	B243	B244	
230.	4.56E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B149	B150	B158	B161	B209	B210
231.	4.50E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B124	B128	B199	B200	
232.	4.48E-08	B0	B1	B4	B13	B14	B39	B40	B41
		BC	B42	B219	B220	B221			
233.	4.48E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B69	B134	B239	B240	B241	B242
234.	4.36E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B149	B150	B209	B210	
235.	4.25E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B124	B128	B135	B136	
236.	4.19E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B149	B150	B158	B161	B162	
237.	4.14E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B124	B128	B136		
238.	4.01E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B149	B150	B162		
239.	3.93E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B128	B135	B199	B200	B241
		B242							
240.	3.93E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B135	B199	B200	B239
		B240							
241.	3.83E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B124	B199	B200	B239	B240
242.	3.83E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B128	B199	B200	B241	B242
243.	3.74E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B149	B150	B159	B161	
244.	3.69E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B146	B158	B161	B243	B244	B245
		B246							

245.	3.62E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B124	B135	B136	B239	B240
246.	3.62E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B128	B135	B136	B241	B242
247.	3.55E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B124	B128	B133	B134	B135	
248.	3.53E-08	B0	B1	B9	B10	B31	B32	B33	
		BB	B34	B58	B87	B146	B243	B244	B245
		B246							
249.	3.52E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B128	B136	B241	B242	
250.	3.52E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B124	B136	B239	B240	
251.	3.50E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B149	B158	B161	B209	B210	B245
		B246							
252.	3.50E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B150	B158	B161	B209	B210	B243
		B244							
253.	3.35E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B149	B209	B210	B245	B246
254.	3.35E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B150	B209	B210	B243	B244
255.	3.34E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B135	B199	B200	B239	B240
		B241	B242						
256.	3.25E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B199	B200	B239	B240	B241
		B242							
257.	3.22E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B150	B158	B161	B162	B243	B244
258.	3.22E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B149	B158	B161	B162	B245	B246
259.	3.11E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B128	B134	B135	B138	
260.	3.11E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B134	B135	B137	

261.	3.08E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B149	B162	B245	B246	
262.	3.08E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B150	B162	B243	B244	
263.	3.07E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B135	B136	B239	B240	B241
		B242							
264.	3.06E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B149	B158	B161	B164	
265.	3.06E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B150	B158	B161	B163	
266.	3.02E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B124	B133	B134	B135	B239	B240
267.	3.02E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B124	B134	B137		
268.	3.02E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B128	B133	B134	B135	B241	B242
269.	3.02E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B128	B134	B138		
270.	2.99E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B136	B239	B240	B241	B242
271.	2.93E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B149	B164		
272.	2.93E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B150	B163		
273.	2.88E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B70					
274.	2.88E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B64					
275.	2.87E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B150	B159	B161	B243	B244
276.	2.87E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B149	B159	B161	B245	B246
277.	2.69E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B158	B161	B209	B210	B243	B244
B245		B246							

278.	2.64E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B134	B135	B138	B239	B240
279.	2.64E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B134	B135	B137	B241	B242
280.	2.58E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B94	B175	B179			
281.	2.57E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B58	B123	B124	B128	B134	B135	
282.	2.57E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B134	B137	B241	B242	
283.	2.57E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B134	B138	B239	B240	
284.	2.57E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B209	B210	B243	B244	B245
		B246							
285.	2.56E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B133	B134	B135	B239	B240	B241
		B242							
286.	2.53E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B146	B149	B150	B158	B161	
287.	2.50E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B58	B69	B124	B128	B134		
288.	2.47E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B158	B161	B162	B243	B244	B245
		B246							
289.	2.42E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B87	B146	B149	B150		
290.	2.36E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B162	B243	B244	B245	B246
291.	2.35E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B158	B161	B163	B245	B246
292.	2.35E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B158	B161	B164	B243	B244
293.	2.32E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B55	B165	B166	B167			
294.	2.32E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B55	B139	B140	B141			

295.	2.25E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B163	B245	B246	
296.	2.25E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B146	B164	B243	B244	
297.	2.21E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B159	B161	B243	B244	B245
		B246							
298.	2.19E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B58	B123	B124	B134	B135	B239	B240
299.	2.19E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B58	B123	B128	B134	B135	B241	B242
300.	2.13E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B58	B69	B124	B134	B239	B240	
301.	2.13E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B128	B135	B136	B202	
302.	2.13E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B58	B69	B128	B134	B241	B242	
303.	2.13E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B124	B135	B136	B201	
304.	2.09E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B149	B158	B161	B162	B212	
305.	2.09E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B150	B158	B161	B162	B211	
306.	2.07E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B124	B136	B201		
307.	2.07E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B128	B136	B202		
308.	2.01E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B76	B88	B172			
309.	2.00E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B150	B162	B211		
310.	2.00E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B149	B162	B212		
311.	1.97E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B134	B135	B137	B241	B242
312.	1.94E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B146	B149	B158	B161	B245	B246

313.	1.94E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B146	B150	B158	B161	B243	B244
314.	1.89E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B123	B124	B128	B134	B135	
315.	1.87E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B149	B159	B161	B212	
316.	1.87E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B124	B128	B135	B199	B200
317.	1.87E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B150	B159	B161	B211	
318.	1.86E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B87	B146	B149	B245	B246	
319.	1.86E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B58	B123	B134	B135	B239	B240	B241
		B242							
320.	1.86E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B56	B146	B149	B150	B158	B161	
321.	1.86E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B87	B146	B150	B243	B244	
322.	1.84E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B149	B150	B158	B161	B209	B210
323.	1.83E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B69	B124	B128	B134		
324.	1.82E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B124	B128	B199	B200	
325.	1.81E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B135	B136	B201	B241	B242
326.	1.81E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B27	B58	B69	B134	B239	B240	B241	B242
327.	1.81E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B123	B135	B136	B202	B239	B240
328.	1.81E-08	B0	B1	B4	B13	B14	B39	B40	B41
		BC	B43	B219	B220	B221			
329.	1.79E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B76	B82	B172			

330.	1.78E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B56	B87	B146	B149	B150		
331.	1.77E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B124	B133	B134	B135	B201	
332.	1.77E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B128	B133	B134	B135	B202	
333.	1.76E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B149	B150	B209	B210	
334.	1.76E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B136	B201	B241	B242	
335.	1.76E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B69	B136	B202	B239	B240	
336.	1.61E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B158	B161	B162	B211	B245	B246
337.	1.61E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B158	B161	B162	B212	B243	B244
338.	1.60E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B123	B128	B134	B135	B241	B242
339.	1.60E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B123	B124	B134	B135	B239	B240
340.	1.60E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B123	B124	B134	B135	B239	B240
341.	1.59E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B128	B135	B199	B200	B241
		B242							
342.	1.59E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B124	B135	B199	B200	B239
		B240							
343.	1.56E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B69	B124	B134	B239	B240	
344.	1.56E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B69	B128	B134	B241	B242	
345.	1.55E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B128	B199	B200	B241	B242
346.	1.55E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B124	B199	B200	B239	B240

347.	1.54E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B162	B212	B243	B244	
348.	1.54E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B87	B162	B211	B245	B246	
349.	1.51E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B133	B134	B135	B202	B239	B240
350.	1.51E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B26	B133	B134	B135	B201	B241	B242
351.	1.49E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B146	B158	B161	B243	B244	B245
		B246							
352.	1.44E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B159	B161	B212	B243	B244
353.	1.44E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B34	B146	B159	B161	B211	B245	B246
354.	1.43E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B87	B146	B243	B244	B245	B246
355.	1.42E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B56	B146	B150	B158	B161	B243	B244
356.	1.42E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B56	B146	B149	B158	B161	B245	B246
357.	1.41E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B150	B158	B161	B209	B210	B243
		B244							
358.	1.41E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B149	B158	B161	B209	B210	B245
		B246							
359.	1.36E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B56	B87	B146	B150	B243	B244	
360.	1.36E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B123	B134	B135	B239	B240	B241
		B242							
361.	1.36E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B56	B87	B146	B149	B245	B246	
362.	1.35E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B149	B209	B210	B245	B246
363.	1.35E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B150	B209	B210	B243	B244

364.	1.35E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B135	B199	B200	B239	B240
		B241	B242						
365.	1.35E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B124	B128	B135	B136	
366.	1.33E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B149	B150	B158	B161	B162	
367.	1.33E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B56	B69	B134	B239	B240	B241	B242
368.	1.31E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B199	B200	B239	B240	B241
		B242							
369.	1.31E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B124	B128	B136		
370.	1.29E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B123	B124	B134	B135	B201	
371.	1.29E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B123	B128	B134	B135	B202	
372.	1.27E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B146	B150	B158	B161	B211	
373.	1.27E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B87	B149	B150	B162		
374.	1.27E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B146	B149	B158	B161	B212	
375.	1.25E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B69	B124	B134	B201		
376.	1.25E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B128	B134	B135	B138	
377.	1.25E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B69	B128	B134	B202		
378.	1.25E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B124	B134	B135	B137	
379.	1.24E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B94	B176	B177			
380.	1.24E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B149	B158	B161	B164	

381.	1.24E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B146	B150	B158	B161	B163	
382.	1.22E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B128	B134	B138		
383.	1.22E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B124	B134	B137		
384.	1.21E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B87	B146	B149	B212		
385.	1.21E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B58	B87	B146	B150	B211		
386.	1.19E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B146	B149	B150	B159	B161	
387.	1.18E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B149	B164		
388.	1.18E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B146	B150	B163		
389.	1.17E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B70					
390.	1.17E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B35	B58	B64					
391.	1.15E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B128	B135	B136	B241	B242
392.	1.15E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B123	B124	B135	B136	B239	B240
393.	1.13E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B124	B128	B133	B134	B135	
394.	1.12E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B128	B136	B241	B242	
395.	1.12E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B55	B69	B124	B136	B239	B240	
396.	1.09E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B56	B146	B158	B161	B243	B244	B245
		B246							
397.	1.09E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B123	B134	B135	B201	B241	B242
398.	1.09E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B123	B134	B135	B202	B239	B240

399.	1.08E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B158	B161	B209	B210	B243	B244
		B245	B246						
400.	1.07E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B123	B134	B135	B138	B239	B240
401.	1.06E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B69	B134	B201	B241	B242	
402.	1.06E-08	B0	B1	B5	B6	B23	B24	B25	BA
		B26	B58	B69	B134	B202	B239	B240	
403.	1.05E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B56	B87	B146	B243	B244	B245	B246
404.	1.04E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B134	B137	B241	B242	
405.	1.04E-08	B0	B1	B4	B9	B10	B31	B32	B33
		BB	B35	B87	B209	B210	B243	B244	B245
		B246							
406.	1.04E-08	B0	B1	B4	B5	B6	B23	B24	B25
		BA	B27	B69	B134	B138	B239	B240	
407.	1.02E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B149	B158	B161	B162	B245	B246
408.	1.02E-08	B0	B1	B9	B10	B31	B32	B33	BB
		B34	B55	B150	B158	B161	B162	B243	B244

VITA

David Don Jones

Candidate for the Degree of

Doctor of Philosophy

Thesis: RISK ASSESSMENT OF A SECONDARY GRAIN DUST EXPLOSION IN A BUCKET ELEVATOR LEG USING FAULT TREE ANALYSIS

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