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Hazard Identification and Risk Assessment in Title 14 CFR Part 137 Operations

August 2008

Final Report

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16. Abstract

A task was recently awarded under contract DTFA03-00-D-00019 to support the Risk Management Decision Support for the General Aviation (GA) Research and Development Program. The purpose of this task is to provide research, project planning, and program support to accomplish task GA-03, which involves Hazard Identification and Risk Assessment.

Two main elements are specified in the GA-03 task: hazard identification and risk assessment. This report focused on the identification of high-risk accident and incident events and used subject matter experts' (SME) input to construct the chain of hazards that lead to such events. SMEs also identified certificate holder characteristics, risk indicators, and risk controls that influence the likelihood of these events. Likelihood values were assigned to each hazard chain allowing for the computation of risk.

This report lays the foundation for a system safety measurement model, which will use information gathered from certificate holders to estimate the risk to safety that each certificate holder poses. The identification of risk controls, risk indicators, and certificate holder factors provide Federal Aviation Administration inspectors with specific guidelines relating to hazard identification when performing a Title 14 Code of Federal Regulations Part 137 inspection.

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LIST OF ACRONYMS

AIDS	Accident Incident Database System
AMS	Acquisition Management System
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
FTA	Fault Tree Analysis
GPS	Global positioning system
MIL-STD	Military Standard
NTSB	National Transportation Safety Board
SASO	System Approach for Safety Oversight
SME	Subject matter expert

EXECUTIVE SUMMARY

The purpose of this project was to research the manner in which system safety engineering principles can be applied to the Agricultural Aerial Operations area of Title 14 Code of Federal Regulations (CFR) Part 137. The current work culminated in the planning and implementation of a hazard chain construction and risk analysis session, which will serve as the basis for the future development of a system safety metric.

The overall goal of the System Approach for Safety Oversight project, relative to 14 CFR Part 137 operations, was to develop a method of evaluating the relative safety of a specific operator by collecting information without conducting a full onsite inspection of the certificate holder. Furthermore, this metric should assess potential hazards within the certificate holder's operation in a diagnostic fashion, providing the certificate holder with some guidance about areas within the operation that need attention.

Empirical data were used to identify high-risk accident and incident events associated with 14 CFR Part 137 operations. The vast majority of these unwanted events occurred during dispensing (60.4%), takeoff (23.6%), and landing (10.7%). Collision with wires or poles was the most common single event (13.4%), followed by controlled collision with the ground (12.0%). Most unwanted events were associated with some sort of pilot error and only a small portion was associated with mechanical failures. The empirical data were used to identify those event types that accounted for a majority of the recorded accidents and incidents (i.e., over 80%). These events were retained for additional analysis.

Hazard chains were constructed for the retained unwanted events. The purpose of the chains was to understand how accidents and incidents unfold and to identify the root causes of events. The chains also provided a context within which risk indicators, risk controls, and certificate holder characteristics could be identified. The presence or absence of these elements allows for the estimation of risk at the local certificate holder level. Hazard chain data gathered from subject matter experts showed that lack of attention and lack of experience were the most common recorded causes of accidents and incidents. Both of these causes, as well as many of the other causes identified during the hazard chain construction process, are linked with organizational factors. That is, many accidents and incidents may have their roots in the way that the certificate holder operates his or her business. Training was identified as a common risk control.

Risk analysis was performed via the estimation of event likelihoods. Specifically, the likelihood of each proximate cause resulting in a specific unwanted event was evaluated. The impact of certificate holder characteristics and the presence of risk controls on these likelihood values were also estimated. These data will serve as the basis for the system safety metric that will be developed in the next phase of this project.

The methodology was developed to identify unwanted events of interest, to understand why those events occur, and to assess the risk associated with those events. It was demonstrated effective and useful in this phase of the project.

1. BACKGROUND.

This project is part of the System Approach for Safety Oversight (SASO) project, which is designed to incorporate systems safety engineering concepts into Federal Aviation Administration (FAA) oversight and regulation procedures. The project theory is that a systematic process to identify hazards, prioritize risks, and identify controls can be used to focus the inspection and oversight process, improving efficiency without sacrificing safety. The goal of this project is to determine whether the application of systems safety engineering concepts into existing FAA oversight functions related to general aviation is feasible. As such, this project is considered by the SASO office as a proof of concept and is designed to provide the foundation for future field implementation of system safety concepts.

The current phase of work is focused on identifying the hazards associated with Title 14 Code of Federal Regulations (14 CFR) Part 137 operations and evaluating the risk posed by these hazards. This information is valuable to both inspectors and operators, as it provides systematically derived insight into the common causes of accidents and incidents during agricultural aviation operations. The work done during this phase of the project will also serve as the foundation for the development of a system safety measurement model, which will produce a standardized measure of operator-level risk using operator-supplied data. The system safety measure will allow the FAA Flight Standards District Offices to evaluate the relative risk levels of operators in their jurisdiction so resources can be allocated to those operators that pose the greatest level of risk. Also, the measure can be used to identify general areas of safety concerns at the operator level, providing the certificate holder with guidance on how to improve operational safety.

The scope of the SASO project for 14 CFR Part 137 has been altered since its inception in 2003. Originally, the project plan included efforts to modify existing oversight and inspections functions by developing and integrating safety measurement and feedback tools into the process along with field evaluation of such modifications. Currently, research into Title 14 CFR Part 137 operations is scheduled to terminate with the development of a system safety measurement model.

Overall, the revised SASO project for 14 CFR Part 137 can be divided into three major components: (1) understanding 14 CFR Part 137 operations and the FAA oversight thereof, (2) identifying hazards and risks associated with operations (the focus of the current phase of work), and (3) constructing a system safety measurement model that will use information about the certificate holder to estimate the risk of unwanted events at the certificate holder level. As such, the functional models and data gathered during the first phase of work serve as key inputs into the current hazard identification and risk analysis phase. The development of a viable system safety measurement model will be based on the results of the current phase of work.

It is important to note that research being conducted for 14 CFR Part 137 operations has application beyond the scope of agricultural aviation. Methods for functional modeling, hazard chain construction, risk assessment, and measurement model construction can be applied to many other areas of aviation. The agricultural domain is just a workspace to develop, test, and evaluate these methods. To be sure, some aspects of the methods are tailored to meet the

specific needs posed by 14 CFR Part 137 operations, but for the most part, the theoretical underpinnings and methodologies are applicable to any number of sociotechnical systems.

This report details the following activities related to the project:

- Work performed from January 1, 2005 to July 1, 2005.
- The development of techniques to identify key accident and incident events, the construction of hazard chains, and the collection of risk assessment data.
- The planning and implementation of the hazard chain and risk assessment data collection process.
- The results of the hazard chain and risk assessment data collection process.

2. GOALS AND OBJECTIVES.

The goals and objectives for the SASO project relative to 14 CFR Part 137 operations has changed over time, but the research team has defined a set of key goals for this project. The first goal is to develop and document methodologies that apply systems safety engineering principles to the oversight and inspection of aviation operations, in general, and agricultural aviation operations, in specific. In general, the systems safety engineering approach involves understanding the system of interest, identifying unwanted events that are most likely to occur, understanding why those events occur, assessing the risk associated with those events, and determining how to best control those risks. These basic steps can be applied to any system. In the context of the SASO project, the approach must be tailored to work within a genre of sociotechnical systems and a specific set of systems in particular (i.e., 14 CFR Part 137 operations). As such, a large portion of the methodologies developed for this project is transportable to other domains of aviation, with tailoring required for any given area in aviation. Thus, the first goal is to develop methodologies to apply systems safety engineering to FAA-regulated aviation systems and document the rationale and application of these approaches.

The goal of the 14 CFR Part 137 work in particular is to develop a system safety measurement model that can assess risk at the certificate holder level. Such a measurement model has two main components. The first is a basic risk-modeling framework that provides a theoretical and practical basis for risk measurement. The second is 14 CFR Part 137-specific data that can be used to quantify risk. These data include a baseline assessment of risk, risk indicators, risk controls, and risk factor weights. The basic framework for system safety measurement is transportable across segments of aviation, but the specific risk indicators and weights are segment specific and require in-depth research.

The main product generated by the 14 CFR Part 137 research will be the system safety measurement model. The goal of the current phase of work is to present the theory and rationale behind the collection of hazard chain and risk analysis data. This report will also document the results of the data collection effort in detail. This information is presented in detail so that the reader can critically evaluate the methodologies in the abstract as well as the implementation and results of the methodologies in practice.

This report is structured into two major sections. The first section details the methodologies used to extract unwanted event information, construct hazard chains, and assess risk. The second section deals with the implementation of these methodologies during a meeting with subject matter experts (SME) and the results of that meeting. Conclusions and statements for future work are then offered.

3. DATA COLLECTION APPROACH.

The data collection methodologies were designed to support the development of the system safety measurement model. The premise of this model is that a variety of factors influence the level of safety with which a given certificate holder operates. That is, agricultural aviation operations entail a certain amount of risk in general, but certain risk factors associated with any given operator moves this risk up or down. This approach to risk estimation is similar to prediction based on general linear models where prediction for a specific entity begins with an overall average value that is adjusted up or down based on the presence or absence of certain predictor factors. This approach is also similar to that used by insurance underwriters where the presence or absence of certain factors are used to add and subtract risk points, providing a relative index of risk against which premiums can be assessed.

Identification of these risk factors requires a thorough understanding of the chain of events that lead to unwanted events, as well as the likelihood of occurrence for each of these chains. Thus, risk assessment is conducted within the context of hazard chains, and hazard chains are used to map unwanted events, as well as identify risk indicators and risk control measures. A major practical concern is that any number of unwanted events could occur during Title 14 CFR Part 137 operations, meaning that there are theoretically an infinite number of hazard chains. Practicality dictates that the number of unwanted events subject to investigation be limited. To this end, data from the FAA Accident Incident Database System (AIDS) were used to identify the most common accidents and incidents in agricultural aviation. This finite listing of unwanted events was used to set the stage for hazard identification and risk assessment.

AIDS was used for this portion of the data collection effort because of its structure and format. AIDS is an FAA database that uses key identifiers commonly used across other FAA databases. The information contained in AIDS documents accidents and incidents reported to the FAA as investigated by FAA field investigators. This database is very similar to National Transportation Safety Board's (NTSB) accident investigation database. Even though the NTSB's database houses more information about a given event, the information contained in AIDS (namely type of event, phase of flight in which the event occurred, and event severity) was sufficient for this purpose. The degree of overlap across the two databases was also examined to ensure that AIDS and the NTSB database contained information on the same events. Results of this examination revealed that the two databases overlapped for 3133 accidents and incidents. AIDS contained records for 192 accident and 776 incident events that were not included in the NTSB database and the NTSB database contained records for 303 accident and 1 incident events that were not included in AIDS.

This section documents the three components of the hazard chain construction and risk assessment process: unwanted event identification, hazard chain construction, and risk assessment. Section 3.1 provides a detailed account of the event identification process and the

results of that process, while sections 3.2 and 3.3 provide a description of the hazard chain construction and risk assessment methodologies, respectively. The hazard chain construction and risk assessment results are presented in section 4.

3.1 UNWANTED EVENT IDENTIFICATION.

The term "unwanted event" is used to describe any accident or incident that causes damage to property and/or injury or death to people. The FAA uses the terms "incident" and "accident" to distinguish between unwanted events of varying severity. The AIDS database contains a data field to categorize each event as either an accident or incident. Both types of unwanted events, accidents and incidents, where included for analysis and are collectively referred to as "unwanted events" or "events" (i.e., these two phrases are synonymous and used interchangeably).

This section describes the process through which unwanted safety-related events in Title 14 CFR Part 137 operations were identified. The unwanted safety events serve as the basis for the hazard chain construction. This section also provides a detailed description of how empirical data from the FAA AIDS were used to identify the most common event scenarios across the various phases of flight.

3.1.1 Background.

A key component in systems safety engineering is identifying hazards within a system and the quantification of the risks associated with those hazards. In the context of 14 CFR Part 137 operations, hazards begin with some root cause and propagate through 14 CFR Part 137 functions, potentially reaching the flight operations stage where they may result in an unwanted event. These hazards can be logically linked to form a chain of events, known as a hazard chain. In general, there are two ways to construct those chains: inductive and deductive construction. The inductive construction process entails defining a root cause or the beginning of a chain and generating a list of potential intermediate and proximate hazards that stem from that starting point. One version of this process is known as Event Tree Analysis. The deductive construction process begins with a specific outcome of interest. Then, possible causes are identified by moving backward in the sequence of events until one or more root causes are identified. A common application of this technique is known as Fault Tree Analysis (FTA).

The deductive approach to hazard chain construction is a logical choice when the outcomes of interest are known, such as when risk analysis is being conducted on an intact system. In the case of 14 CFR Part 137 operations, event data are readily available in the FAA AIDS, providing valuable information about the types and number of events that have occurred in the past. By generating a finite list of unwanted events, the tasks of hazard chain construction and risk analysis becomes manageable.

The AIDS data will be used for several specific purposes. First, the data will be used to quantify the number of unwanted events and compute the mean severity of each event type within each phase of flight to assess the relative risk posed by each phase of flight (Risk = Severity * Likelihood). Second, events will be grouped using the event description codes from the database within the various phases of flight. This will facilitate the computation of relative likelihood and average severity for each event type within each phase of flight. This information will be used to

compute the risk associated with each event type allowing for the rank ordering of event type according to risk posed.

3.1.2 Data Manipulation.

3.1.2.1 Data Extraction and Screening.

Data from the AIDS were obtained from the FAA in the form of a complete Microsoft® Access® database. The database included all accidents and incidents investigated by the FAA from 1979 to 2004. Only fixed-wing aircraft accidents and incidents were considered for this analysis. The analysis was restricted to fixed-winged operations to simplify the model construction process. Records associated with specific manufacturers, such as Sikorsky and Bell, were removed from the analysis as those companies primarily manufacturer helicopters. Additionally, AIDS records that failed to indicate the type of aircraft involved in the accident/incident were removed from analysis. The event codes were also scrutinized to identify accident and incident cases that obviously involved helicopters and those cases were removed. If the aircraft manufacturer field was blank, that record was removed. Records that did not contain an event description code, contained the event code "unknown," or did not contain a phase of flight code were removed from the analysis. The original database contained 5507 records, of which 1667 were removed, resulting in 3840 records for analysis.

3.1.2.2 Event Description.

Each record in the AIDS provides a field for an event description code to record a high-level summary of the accident/incident. In most cases, this description falls short of explaining why the event occurred. For example, one event listing is called "hard landing." Given this description, and the fact that the event was recorded in the AIDS, it can be deduced that the aircraft in question landed hard enough to cause some sort of damage to the aircraft and/or to the occupants. What cannot be discerned is the cause of the hard landing, such as an engine failure, pilot error, or weather conditions. Most records in the AIDS have an accompanying primary cause data field for an elaboration on the cause of an event. Unfortunately, this information is often redundant. For example, one of the most common events across all of the 14 CFR Part 137 records is the striking of an object (e.g., power lines, power pole, fence) during dispensing. The primary cause listed for the vast majority of those cases was "failure to avoid objects or obstructions," which does little to clarify the cause of the event. As a result, it was decided that only the event description listing (with corresponding information about event severity and phase of flight) would be extracted, since only this information was deemed to be at the appropriate level to serve as the unwanted outcome of interest for the upcoming hazard chain construction process.

3.1.2.3 Phase of Flight.

The phase of flight data field in the AIDS indicates when the initiating cause of the event occurred relative to the flight operations being conducted. There are 26 unique phases of flight listed in the AIDS records along with an "unknown" listing. Most of these phases are elaborations within commonly regarded phases of flight, such as takeoff, cruise, approach, and landing. For example, there are five unique phases listed under the heading of cruise. Of these

listings, three typically refer to dispensing operations, one to the climb-to-cruise operation, and one to normal cruise. For the purposes of this analysis, the unique subphases were combined into main phases. For example, the analysis includes the phases of ground including taxi, takeoff, cruise, dispensing (which is a set of subphases within cruise in the AIDS), descent, approach, and landing. Other phases, such as scud and unauthorized low-level buzz, are categorized as other.

3.1.2.4 Phase of Flight and Event Definitions.

The hazard chain construction process was arranged so that hazard chains were constructed for each unwanted event within the context of a specific phase of flight. The process was structured this way for two reasons. First, identical unwanted events may have different hazard chains depending on the context within which that unwanted event occurs. For example, the series of events that lead to a collision with an object are different for the dispensing phase of flight than they are for the takeoff phase of flight. Second, by organizing the events by phase of flight, the construction process can be segmented so events associated with the more dangerous phases of flight can be addressed first.

As discussed later in section 3.1.3, the majority of events recorded in the AIDS occurred during the dispensing, takeoff, and landing phases of flight. Within each phase, the events were sorted by risk in descending order, and the top ranked events that accounted for 80% of the events were chosen for the hazard chain construction.

Table 1 presents the three phases of flight that were used for this report and defines each phase of flight in terms of activities that are included within each phase. The goal of presenting these definitions is to address any ambiguity about specific activities that are encompassed in a particular phase of flight.

Table 1. Phases of Flight and Definitions

Phase of Flight	Includes
Takeoff	Operations associated with transitioning the aircraft from the ground to the air. This phase begins with the application of takeoff power on the runway and ends when climb-to-cruise is established.
Dispensing	All operations associated with dispensing agent on the target, including reconnaissance.
Landing	The portion of flight where the aircraft is put on the runway surface. Landing begins with the flare and ends when the aircraft reaches taxi speed.

Table 2 presents a description of each unwanted event that was identified during event identification. The events are described within the context of a specific phase of flight.

Table 2. Event Definitions for Each Phase of Flight

Phase of Flight	Event	Description
Dispensing	Collision w/wires-poles	A collision with wires or poles during dispensing-related operations.
	Controlled collision w/ground	Controlled flight into terrain, usually the result of a loss of situation awareness.
	Stall	An unintended stall.
	Collision w/trees	A collision with trees during dispensing operations.
	Engine malfunction	Any situation involving an unwanted loss of power.
	Nose-up-and-over	A condition in which an aircraft ends up in this state (usually the result of a forced landing on soft terrain).
	Collision w/other	A collision with any object other than another aircraft, animal, fence, airport hazard, building, or pole. Common examples in dispensing are collisions with irrigation pipes, levies, and vehicles.
Takeoff	Nose-up-and-over	Aircraft toppling over onto nose during ground operations. Includes incidents related to misapplication of brakes or soft terrain.
	Controlled collision w/ground	Any incident that occurs during the takeoff phase that results in the aircraft contacting the ground while under the direct control of the pilot (i.e., no spins/stalls).
	Collision w/other	A collision with any object other than another aircraft, animal, fence, airport hazard, building, or pole. Examples include collision with a vehicle or person.
	Engine malfunction	Any situation involving an unwanted loss of power.
	Collision w/trees	A collision with trees during takeoff. Usually the result of a loss of engine power, aircraft overloading, or downwind takeoff.
	Stall	An unintended stall.
	Collision w/fence	A collision with a fence during takeoff. Usually, the fence in question lies at the perimeter of the operating facility.
	Loss of directional control-ground loop	Loss of directional control that leads to a ground loop during the takeoff roll.
Landing	Nose-up-and-over	Aircraft toppling over onto nose during operations. Includes incidents related to misapplication of brakes or soft terrain.
	Loss of directional control-ground loop	Loss of directional control that leads to a ground loop during the takeoff roll.
	Loss of directional control	Loss of directional control during landing, resulting in an unintended exiting of the runway
	Collision w/other	A collision with any object other than another aircraft, animal, fence, airport hazard, building, or pole. Examples include collision with a vehicle or person.

3.1.2.5 Severity Computation.

Most event records included data fields noting the extent of damage to the aircraft and the number of persons injured or killed as a direct result of the event. Aircraft damage is categorized as either "none," "minor," "substantial," or "demolished." These categories were assigned values of 0 to 3, respectively. The fatality and injury data are expressed as quantities (i.e., number injured and number killed). To compute an overall severity score for a given record, the numerical value assigned for damage is used as the base number and one point is added to that number if any injuries were noted. Thus, a demolished aircraft (3) and an accompanying injury (+1) resulted in a severity score of four. If any fatalities were associated with a record, the severity score was automatically scored as a five, regardless of aircraft damage. The result was a severity rating scale that ranges from 0 to 5. This scale was chosen because it is similar to the scales often used when SMEs evaluate hazard likelihood and severity in the context of a risk assessment matrix. The severity rating scale is summarized in table 3.

Table 3. Severity Ratings Based on AIDS Data

Aircraft Damage	No Fatalities/Injuries	Injuries Present	Fatalities Present
0—None	0	1	5
1—Minor	1	2	5
2—Substantial	2	3	5
3—Demolished	3	4	5

While severity ratings are computed at the record level, records are aggregated by event type within phase of flight. The severity ratings are also aggregated, providing an average severity score for a given type of event within a given phase of flight. Severity scores are a critical part of the risk computation process because risk is defined as the product of severity and likelihood.

3.1.2.6 Event Likelihood Computation.

In most risk assessment situations, likelihood is computed as a function of the number of unwanted events per unit of usage or operation. For example, the likelihood of engine failure is commonly computed in terms of the number of failures per hour of operation, or even as the number of failures per passenger mile. Unfortunately, AIDS records do not facilitate such calculations. Instead, the likelihood of events can be computed relative to the occurrence of all events. For example, the likelihood of an unwanted event occurring during dispensing operations can be computed by dividing the number of events observed during dispensing operations by the total number of events that have occurred. In this case, that number would be 2320 divided by 3840, which equals 0.604 or 60.4%. This value refers to the probability that any given event will occur during the dispensing phase of flight and does not represent the probability that any given flight will terminate in an accident or incident during dispensing operations. This is why the term relative probability is used, as opposed to true probability.

There are multiple levels at which likelihood values can be computed. The example presented above shows the computation at the phase of flight level, but similar computations can be made within each phase of flight. For example, the likelihood of an aircraft colliding with wires or poles during the dispensing phase of flight can be computed by taking the observed number of

collisions with wires or poles (467) and dividing by the observed number events during dispensing operations (2320), which equals 0.201 or 20.1%. Again, this value does not represent the probability of an aircraft colliding with wires or poles during dispensing operations; instead, this value represents the probability of an accident or incident occurring during dispensing operations will involve a collision with wires or poles.

Both likelihood examples demonstrate the relative nature of the computed likelihood values. If data were available about the number of events per mission flown (i.e., the observed number of events divided by the observed number of missions flown), event likelihood values at the individual flight level could be computed. This value would be the best index of safety and would be on par with safety data compiled for other areas of aviation (i.e., 14 CFR Part 121 operations).

3.1.2.7 Risk Computation.

A risk value is a numerical expression based on the product of event severity and event likelihood. Thus, events that are more likely to occur pose more risk to the system, with severity being equal. Similarly, events that lead to more severe consequences pose more risk to the system, with likelihood being equal. Risk values are pragmatic in that they provide a way to simultaneously consider the likelihood and severity of an unwanted event. This is an important concept when resources for hazard mitigation programs are finite and only a portion of unwanted events can be addressed. In such circumstances, it may be tempting to focus on unwanted events that are more likely to occur with the goal of reducing the overall number of unwanted events, but the folly of such a strategy is easy to see, should a less common, but severe unwanted event occurs.

In many circumstances, hazards and unwanted events are assessed in terms of whether the risk posed by the hazard or unwanted event is "acceptable." The definition of acceptable must be provided by the organization, but the concept of acceptable risk requires knowing how likely an unwanted event is relative to some metric of operation (i.e., hours of operation, cycles). As noted earlier, such data are not available for 14 CFR Part 137 operations. While relative risk data (i.e., how often one type of unwanted event occurs relative to all types of unwanted events) will not support the categorization of risk as acceptable or unacceptable, it can be used to prioritize efforts to address hazards, especially when resources are limited.

3.1.2.8 Selection of Unwanted Events for Hazard Chain Construction.

Given the large number of accidents and incidents recorded in AIDS and the relatively large number of unique unwanted event descriptions, it is not feasible to construct hazard chains for each unique unwanted event. Instead, hazard chains are constructed for events that have the highest level of risk and represent the majority of the accidents and incidents. Since the sequence of steps that lead to unwanted events are likely to differ by phase of flight, unique hazard chains must be constructed for identical events that occur during different phases of flight. Thus, if the "stall" event is recorded for the takeoff and dispensing phases of flight, two separate hazard chains must be constructed. Similarly, each hazard chain must have a risk value associated with it because each chain represents an unwanted event occurring within a specific

phase of flight. The likelihood and severity values for the stall event will likely differ as a function of the phase of flight.

The selection process for unwanted event hazard chain construction began by selecting the phases of flight that account for the majority of events in the AIDS. The risk associated with each unwanted event category was calculated within its respective phase of flight and the unwanted events were rank-ordered (in descending order) by risk within that phase of flight. The top-ranked event categories that account for 80% of the events within that phase of flight were transitioned to the hazard chain construction phase for further analysis.

3.1.3 Results.

3.1.3.1 Summary Statistics.

A total of 3840 records were used for analysis. Table 4 presents vital summary information about the records, such as the number of records per phase of flight and the average severity of the events memorialized in the records. As seen in the table, events most frequently occurred during the dispensing phase of flight operations, with the majority of those events resulting in a severity outcome of 2 to 3 on the 0- to 5-point scale. The risk values by phase of flight follow the same trend as the count values, meaning that those phases that had the most events also had the highest risk numbers. This is not surprising, given the uneven distribution of events across the phases of flight. Over 84% of all events occurred during the dispensing and takeoff phases of flight and almost 95% were accounted for when the landing phase was included. Given these data, three phases of flight warranted further interest: dispensing, takeoff, and landing.

Table 4. Overall Summary of Records and Severity by Phase of Flight

Phase of Flight	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Dispensing	2320	60.4	60.4	0	5	2.26	1.04	1.37
Takeoff	908	23.6	84.1	0	5	2.13	.70	0.50
Landing	409	10.7	94.7	0	5	1.78	.58	0.19
Approach	86	2.2	97.0	0	5	2.12	.95	0.05
Ground	59	1.5	98.5	0	5	1.59	1.04	0.02
Cruise	37	1.0	99.5	0	5	1.86	1.46	0.02
Other	12	0.3	99.8	1	5	2.50	1.00	0.01
Descent	9	0.2	100.0	0	5	2.44	1.67	0.01
Total	3840	100.0	-	0	5	2.17	.95	0.27

SD = Standard deviation

Another perspective of the event data is presented in table 5. The highest risk event was "collision with wires-poles" and the most frequent event was "nose-up-and-over." It is important to note for an event to be classified as "nose-up-and-over," it must meet one of the following two criteria: (1) an aircraft that flips because it has a brake lockup during landing or (2) a mechanical problem that results in a forced landing on soft terrain that causes the aircraft to flip over. In any event, 9 separate unwanted events accounted for over 80% of 14 CFR 137 events.

Table 5. Event Listings and Frequencies Across all Phases of Flight (sorted by risk)

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Collision w/wires-poles	516	13.44	13.44	0	5	2.39	1.19	0.32
Nose-up-and-over	536	13.96	27.40	1	5	2.1	0.58	0.29
Controlled collision w/ground	459	11.95	39.35	1	5	2.19	0.65	0.26
Stall	308	8.02	47.37	1	5	2.7	0.87	0.22
Engine malfunction	422	10.99	58.36	0	5	1.7	0.96	0.19
Collision w/trees	267	6.95	65.31	1	5	2.68	0.9	0.19
Collision w/other	299	7.79	73.10	0	5	2.1	0.85	0.16
Forced landing	225	5.86	78.96	0	3	1.66	0.68	0.1
Loss of directional control-ground loop	164	4.27	83.23	0	4	1.79	0.58	0.08
Uncontrolled collision w/ground	69	1.80	85.03	1	5	3.17	1.11	0.06
Collision w/fence	89	2.32	87.34	1	5	2.06	0.76	0.05
Loss of directional control	69	1.80	89.14	1	5	1.93	0.88	0.03
Gear collapse	69	1.80	90.94	1	3	1.57	0.56	0.03
Midair collision	31	0.81	91.74	1	5	3.45	1.29	0.03
Propeller malfunction/failure	43	1.12	92.86	0	3	1.7	0.83	0.02
Loss of directional control-drag wing	36	0.94	93.80	1	5	2.28	0.78	0.02
Fire/explosion in flight	30	0.78	94.58	1	5	2.7	1.02	0.02
Spin	18	0.47	95.05	2	5	3.44	0.92	0.02
Other	35	0.91	95.96	0	5	1.03	1.1	0.01
Overshoot landing	29	0.76	96.72	0	3	1.69	0.66	0.01
Hard landing	25	0.65	97.37	0	3	1.76	0.72	0.01
Fire/explosion on ground	14	0.36	97.73	1	3	2.71	0.61	0.01
Undershoot landing	12	0.31	98.05	1	3	1.92	0.67	0.01
Collision w/tower	10	0.26	98.31	2	5	3	0.94	0.01
Propeller to person	2	0.05	98.36	5	5	5	0	0.01
System failure	16	0.42	98.78	0	3	1.19	0.75	0
Collision w/aircraft (one up in air)	7	0.18	98.96	1	2	1.86	0.38	0
Collision w/aircraft on the ground	7	0.18	99.14	1	2	1.71	0.49	0
Airframe failure on ground	4	0.10	99.24	1	1	1	0	0
Collision w/building	4	0.10	99.35	1	3	2	0.82	0
Wake turbulence	4	0.10	99.45	1	3	1.75	0.96	0
Blown over	3	0.08	99.53	1	2	1.33	0.58	0
Collision w/airport hazard	3	0.08	99.61	2	3	2.33	0.58	0
Collision w/birds	3	0.08	99.69	1	3	2	1	0

Table 5. Event Listings and Frequencies Across all Phases of Flight (sorted by risk) (Continued)

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Propeller blade	3	0.08	99.77	2	2	2	0	0
Airframe failure in flight	2	0.05	99.82	4	5	4.5	0.71	0
Controlled collision w/water	2	0.05	99.87	3	5	4	1.41	0
Gear retracted during ground operations	2	0.05	99.92	1	1	1	0	0
Collision w/animal	1	0.03	99.95	2	2	2	-	0
Uncontrolled collision w/water	1	0.03	99.97	4	4	4	-	0
Wheels-up landing	1	0.03	100.00	1	1	1	-	0
Total	3840	100	-	0	5	2.17	0.95	0.05

SD = Standard Deviation

3.1.3.2 Event Summaries by Phase of Flight.

The next level of analysis involves grouping the events according to phase of flight. The number of records falling into each event code was counted. As described earlier, some event codes were collapsed into a single code to consolidate unique but similar events.

The events that account for at least 80% of the events within the dispensing, takeoff, and landing phases of flight will be transferred to the hazard chain construction phase. The events associated with the other phases of flight are also presented, but will not be a part of the hazard construction phase.

3.1.3.2.1 Ground Phase Results.

Eight event types account for over 80% of events during the ground phase of operations. As shown in table 6, gear collapse accounted for the majority of the events and also posed the most risk to ground operations. Further investigation of several gear collapse incidents revealed that some of the incidents occurred during taxi operations, while others were the result of a hard landing. Unfortunately, the coding of the investigating inspectors appears to be somewhat variable, producing multiple event codes for similar events.

Table 6. Frequency and Severity of Most Common Events During Ground Phase

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Gear collapse	16	27.12	27.12	1	2	1.31	0.48	0.36
Fire/explosion on ground	6	10.17	37.29	1	3	2.50	0.84	0.25
Collision w/other	11	18.64	55.93	0	2	1.27	0.79	0.24
Propeller to person	2	3.39	59.32	5	5	5.00	0.00	0.17
Other	3	5.08	64.41	1	5	2.33	2.31	0.12
Collision w/aircraft on the ground	4	6.78	71.19	1	2	1.50	0.58	0.10
Loss of directional control-ground loop	3	5.08	76.27	1	2	1.67	0.58	0.08
Blown over	3	5.08	81.36	1	2	1.33	0.58	0.07
Nose-up-and-over	3	5.08	86.44	1	1	1.00	0.00	0.05
Collision w/fence	2	3.39	89.83	1	1	1.00	0.00	0.03
Engine malfunction	2	3.39	93.22	1	1	1.00	0.00	0.03
Collision w/wires-poles	1	1.69	94.92	2	2	2.00	-	0.03
Airframe failure on ground	1	1.69	96.61	1	1	1.00	-	0.02
Fire/explosion in flight	1	1.69	98.31	1	1	1.00	-	0.02
Gear retracted during ground operations	1	1.69	100.00	1	1	1.00	-	0.02
Total	59	100	-	0	5	1.66	0.56	0.11

SD = Standard deviation

3.1.3.2.2 Takeoff Phase Results.

Eight event types account for over 80% of the events during the takeoff phase of operations. As shown in table 7, nose-up-and-over and controlled collisions with ground account for the majority of events followed by collision with various objects. AIDS data were reviewed to obtain more information on the possible causes leading to a nose-up-and-over event. Narratives associated with such events point to several qualitatively different causes, such as mud puddles on the runway to various incidents resulting in a forced landing in a soft field. Ideally, only the former scenarios would be classified as up and over, while the latter would be classified as forced landings, or even as mechanical or engine failures. (The first eight events listed in table 7 will be transferred to the hazard chain construction phase.)

Table 7. Frequency and Severity of Most Common Events During Takeoff

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Nose-up-and-over	169	18.61	18.61	1	5	2.20	0.64	0.41
Controlled collision w/ground	133	14.65	33.26	1	5	2.20	0.58	0.32
Collision w/other	113	12.44	45.70	1	4	2.14	0.65	0.27
Engine malfunction	85	9.36	55.07	0	4	1.92	0.86	0.18
Collision w/trees	63	6.94	62.00	2	4	2.44	0.56	0.17
Stall	63	6.94	68.94	1	4	2.33	0.60	0.16
Collision w/fence	53	5.84	74.78	1	5	2.25	0.81	0.13
Loss of directional control-ground loop	53	5.84	80.62	1	4	1.77	0.67	0.10
Collision w/wires-poles	27	2.97	83.59	1	4	2.41	0.69	0.07
Forced landing	27	2.97	86.56	1	3	2.00	0.55	0.06
Loss of directional control	27	2.97	89.54	1	4	1.96	0.76	0.06
Gear collapse	21	2.31	91.85	1	3	1.86	0.48	0.04
Loss of directional control-drag wing	16	1.76	93.61	2	3	2.13	0.34	0.04
Overshoot landing	10	1.10	94.71	0	3	1.90	0.88	0.02
Fire/explosion on ground	6	0.66	95.37	2	3	2.83	0.41	0.02
Propeller malfunction/failure	9	0.99	96.37	1	3	1.44	0.73	0.01
Uncontrolled collision w/ground	5	0.55	96.92	2	4	2.40	0.89	0.01
Hard landing	4	0.44	97.36	2	3	2.50	0.58	0.01
Fire/explosion in flight	2	0.22	97.58	3	3	3.00	0.00	0.01
Spin	2	0.22	97.80	2	3	2.50	0.71	0.01
Other	6	0.66	98.46	0	1	0.83	0.41	0.01
Midair collision	1	0.11	98.57	4	4	4.00	-	0.00
Collision w/aircraft on the ground	2	0.22	98.79	2	2	2.00	0.00	0.00
Collision w/building	1	0.11	98.90	3	3	3.00	-	0.00
Airframe failure on ground	3	0.33	99.23	1	1	1.00	0.00	0.00
System failure	3	0.33	99.56	1	1	1.00	0.00	0.00
Collision w/aircraft (one up in air)	1	0.11	99.67	2	2	2.00	-	0.00
Propeller blade	1	0.11	99.78	2	2	2.00	-	0.00
Gear retracted during ground operations	1	0.11	99.89	1	1	1.00	-	0.00
Wake turbulence	1	0.11	100.00	1	1	1.00	-	0.00
Total	908	100	-	0	5	2.07	0.53	0.07

SD = Standard deviation

3.1.3.2.3 Cruise Phase Results.

Five event types account for over 80% of events in the cruise phase of flight, as shown in table 8. The most common event type in this phase was forced landing, which occur as a result of several causes, such as fuel exhaustion, engine failure, or some other type of mechanical failure.

Table 8. Frequency and Severity of Most Common Events During Cruise

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Forced landing	17	45.95	45.95	0	3	1.18	0.88	0.54
Engine malfunction	6	16.22	62.16	0	4	1.67	1.37	0.27
Midair collision	2	5.41	67.57	5	5	5.00	0.00	0.27
Collision w/wires-poles	4	10.81	78.38	1	3	2.25	0.96	0.24
Spin	2	5.41	83.78	3	5	4.00	1.41	0.22
Airframe failure in flight	1	2.70	86.49	5	5	5.00	-	0.14
Collision w/other	1	2.70	89.19	2	2	2.00	-	0.05
Propeller malfunction/failure	1	2.70	91.89	2	2	2.00	-	0.05
Controlled collision w/ground	1	2.70	94.59	1	1	1.00	-	0.03
Collision w/fence	1	2.70	97.30	1	1	1.00	-	0.03
Fire/explosion in flight	1	2.70	100.00	1	1	1.00	-	0.03
Total	37	100	-	0	5	2.37	0.92	0.17

SD = Standard deviation

3.1.3.2.4 Dispensing Phase Results.

Table 9 presents the results of the dispensing operations phase of flight analysis. Six events account for over 80% of the events in the dispensing phase of flight. In this context, the nose-up-and-over event does more to describe the final position of the aircraft, as compared to describing the actual unwanted event that occurred. Several different events, most likely linked with a forced landing, could occur during dispensing operations to result in a nose-up-and-over event. A nose-up-and-over event is also possible during dispensing if the aircraft, specifically its landing gear, comes in contact with the ground or an object during dispensing. A review of the event narratives indicated in many cases that the nose-up-and-over event description is used primarily to describe the final status of the aircraft as compared to what occurred during flight. As such, the "collision w/other" event will also be transferred to the hazard chain construction process along with the other top seven events.

Table 9. Frequency and Severity of Most Common Events During Dispensing

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Collision w/wires-poles	467	20.13	20.13	0	5	2.41	1.22	0.49
Controlled collision w/ground	315	13.58	33.71	1	5	2.20	0.68	0.30
Stall	233	10.04	43.75	1	5	2.83	0.92	0.28
Collision w/trees	197	8.49	52.24	1	5	2.76	0.97	0.23
Engine malfunction	320	13.79	66.03	0	5	1.64	0.97	0.23
Nose-up-and-over	231	9.96	75.99	1	4	2.13	0.52	0.21
Collision w/other	132	5.69	81.68	0	5	2.23	1.02	0.13
Forced landing	163	7.03	88.71	0	3	1.63	0.65	0.11

Table 9. Frequency and Severity of Most Common Events During Dispensing (Continued)

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Uncontrolled collision w/ground	57	2.46	91.16	1	5	3.16	1.08	0.08
Midair collision	22	0.95	92.11	1	5	3.55	1.14	0.03
Fire/explosion in flight	26	1.12	93.23	1	5	2.81	0.98	0.03
Propeller malfunction/failure	32	1.38	94.61	0	3	1.78	0.87	0.02
Spin	13	0.56	95.17	3	5	3.54	0.88	0.02
Collision w/fence	25	1.08	96.25	1	3	1.84	0.55	0.02
Collision w/tower	10	0.43	96.68	2	5	3.00	0.94	0.01
Loss of directional control-drag wing	9	0.39	97.07	2	5	3.00	1.12	0.01
Other	22	0.95	98.02	0	5	0.95	1.05	0.01
Hard landing	8	0.34	98.36	1	3	2.00	0.53	0.01
System failure	10	0.43	98.79	0	3	1.30	0.95	0.01
Loss of directional control	3	0.13	98.92	2	5	3.67	1.53	0.00
Loss of directional control-ground loop	4	0.17	99.09	2	2	2.00	0.00	0.00
Controlled collision w/water	2	0.09	99.18	3	5	4.00	1.41	0.00
Collision w/birds	3	0.13	99.31	1	3	2.00	1.00	0.00
Wake turbulence	3	0.13	99.44	1	3	2.00	1.00	0.00
Gear collapse	3	0.13	99.57	1	2	1.67	0.58	0.00
Airframe failure in flight	1	0.04	99.61	4	4	4.00	-	0.00
Uncontrolled collision w/water	1	0.04	99.66	4	4	4.00	-	0.00
Collision w/building	2	0.09	99.74	1	2	1.50	0.71	0.00
Fire/explosion on ground	1	0.04	99.78	3	3	3.00	-	0.00
Overshoot landing	2	0.09	99.87	1	1	1.00	0.00	0.00
Collision w/animal	1	0.04	99.91	2	2	2.00	-	0.00
Collision w/aircraft (one up in air)	1	0.04	99.96	2	2	2.00	-	0.00
Propeller blade	1	0.04	100.00	2	2	2.00	-	0.00
Total	2320	100	-	0	5	2.41	0.86	0.07

SD = Standard deviation

3.1.3.2.5 Descent Phase Results.

As shown in table 10, seven events were associated with descent phase events covering nine separate incidents/accidents. The relatively small number of events in this phase of flight makes interpretation of event frequency difficult.

Table 10. Frequency and Severity of Most Common Events During Descent

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Uncontrolled collision w/ground	2	22.22	22.22	4	5	4.5	0.71	1.00
Controlled collision w/ground	2	22.22	44.44	2	3	2.5	0.71	0.56
Collision w/trees	1	11.11	55.56	4	4	4	-	0.44
Nose-up-and-over	1	11.11	66.67	2	2	2	-	0.22
Engine malfunction	1	11.11	77.78	1	1	1	-	0.11
Forced landing	1	11.11	88.89	1	1	1	-	0.11
Collision w/wires-poles	1	11.11	100.00	0	0	0	-	0.00
Total	9	100	-	0	5	2.14	0.71	0.35

SD = Standard deviation

3.1.3.2.6 Approach Phase Results.

Ten events accounted for over 80% of events during the approach phase of flight, as shown in table 11. The most frequent, and most hazardous, event was a collision with wires-poles. The nose-up-and-over event is also listed in this phase and potentially may cause difficulty in the hazard chain construction phase, because it does more to describe the final state of the aircraft as compared to identifying the actual type of event that occurred.

Table 11. Frequency and Severity of Most Common Events During Approach

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Collision w/wires-poles	11	12.79	12.79	0	4	2.00	1.18	0.26
Nose-up-and-over	9	10.47	23.26	1	3	2.00	0.50	0.21
Stall	7	8.14	31.40	2	3	2.29	0.49	0.19
Forced landing	9	10.47	41.86	0	3	1.78	0.83	0.19
Undershoot landing	9	10.47	52.33	1	3	1.78	0.67	0.19
Midair collision	6	6.98	59.30	1	5	2.50	1.52	0.17
Collision w/other	7	8.14	67.44	1	3	2.00	0.82	0.16
Uncontrolled collision w/ground	3	3.49	70.93	3	5	3.67	1.15	0.13
Engine malfunction	6	6.98	77.91	0	3	1.83	1.17	0.13
Controlled collision w/ground	5	5.81	83.72	2	2	2.00	0.00	0.12
Collision w/trees	4	4.65	88.37	1	3	2.00	0.82	0.09

Table 11. Frequency and Severity of Most Common Events During Approach (Continued)

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Collision w/fence	3	3.49	91.86	2	2	2.00	0.00	0.07
Loss of directional control—drag wing	2	2.33	94.19	2	3	2.50	0.71	0.06
Loss of directional control	1	1.16	95.35	5	5	5.00	-	0.06
Collision w/airport hazard	1	1.16	96.51	3	3	3.00	-	0.03
Fire/explosion on ground	1	1.16	97.67	3	3	3.00	-	0.03
Hard landing	1	1.16	98.84	2	2	2.00	-	0.02
Propeller malfunction/failure	1	1.16	100.00	1	1	1.00	-	0.01
Total	86	100	-	0	5	2.35	0.76	0.12

SD = Standard deviation

3.1.3.2.7 Landing Phase Results.

As shown in table 12, five events accounted for over 80% of the events in the landing phase of flight. The nose-up-and-over event was the most frequent, but unlike some of the other phases, the nose-up-and-over event is a possible direct outcome due to improper landing techniques. (The top five events will be transferred to the hazard construction phase.)

Table 12. Frequency and Severity of Most Common Events During Landing

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Nose-up-and-over	123	30.07	30.07	1	5	1.94	0.58	0.58
Loss of directional control-ground loop	104	25.43	55.50	0	3	1.79	0.55	0.46
Loss of directional control	38	9.29	64.79	1	3	1.68	0.57	0.16
Collision w/other	35	8.56	73.35	1	3	1.77	0.55	0.15
Gear collapse	29	7.09	80.44	1	3	1.48	0.57	0.10
Overshoot landing	17	4.16	84.60	1	2	1.65	0.49	0.07
Loss of directional control-drag wing	9	2.20	86.80	1	2	1.78	0.44	0.04
Forced landing	8	1.96	88.75	1	3	2	0.53	0.04
Hard landing	12	2.93	91.69	0	2	1.33	0.65	0.04
Collision w/aircraft (one up in air)	5	1.22	92.91	1	2	1.8	0.45	0.02
Stall	4	0.98	93.89	2	2	2	0	0.02
Collision w/fence	4	0.98	94.87	1	3	1.75	0.96	0.02
Undershoot landing	3	0.73	95.60	2	3	2.33	0.58	0.02
Controlled collision w/ground	2	0.49	96.09	2	2	2	0	0.01
Collision w/airport hazard	2	0.49	96.58	2	2	2	0	0.01

Table 12. Frequency and Severity of Most Common Events During Landing (Continued)

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Other	4	0.98	97.56	0	1	0.75	0.5	0.01
System failure	3	0.73	98.29	1	1	1	0	0.01
Collision w/building	1	0.24	98.53	2	2	2	-	0.00
Collision w/wires-poles	1	0.24	98.78	2	2	2	-	0.00
Collision w/aircraft on the ground	1	0.24	99.02	2	2	2	-	0.00
Propeller blade	1	0.24	99.27	2	2	2	-	0.00
Uncontrolled collision w/ground	1	0.24	99.51	2	2	2	-	0.00
Engine malfunction	1	0.24	99.76	1	1	1	-	0.00
Wheels-up landing	1	0.24	100.00	1	1	1	-	0.00
Total	409	100	-	0	5	1.71	0.44	0.07

SD = Standard deviation

3.1.3.2.8 Other Phase Results.

The "other" phase of flight refers to events that occurred during phases denoted by the FAA as either "unauthorized low level flight" (11 events) or "scud running" (one event). Six events account for over 80% of the events associated with the other phase of flight, as shown in table 13. The most frequent event was collision with wires-poles.

Table 13. Frequency and Severity of Most Common Events During "Other" Phases

Event	Count	Percent	Cumulative Percent	Severity				Risk Value
				Min.	Max.	Mean	SD	
Collision w/wires-poles	4	33.33	33.33	1	3	2	0.82	0.67
Collision w/trees	2	16.67	50.00	3	3	3	0	0.50
Uncontrolled collision w/ground	1	8.33	58.33	5	5	5	-	0.42
Spin	1	8.33	66.67	3	3	3	-	0.25
Controlled collision w/ground	1	8.33	75.00	2	2	2	-	0.17
Collision w/fence	1	8.33	83.33	2	2	2	-	0.17
Engine malfunction	1	8.33	91.67	2	2	2	-	0.17
Stall	1	8.33	100.00	2	2	2	-	0.17
Total	12	100	-	1	5	2.63	0.41	0.31

SD = Standard deviation

3.1.4 Summary.

AIDS data were examined to determine the most frequent unwanted events for all 14 CFR Part 137 operations and for each phase of flight. The vast majority of events occurred during the dispensing, takeoff, and landing phases of flights. The resulting list of unwanted events from those three phases will serve as the starting point for the hazard construction phase of this project.

A total of 3840 accidents and incidents listed in the AIDS were reviewed. Several key conclusions can be drawn based on this analysis. First, more events occur during the dispensing phase of 14 CFR Part 137 operations than all other phases combined. These data clearly indicate that dispensing operations warrant top priority in the hazard chain identification process. Second, five to ten event types account for over 80% of events across the various phases of flight. The isolation of those events that account for the most events allows for the effective and efficient concentration of resources during the hazard construction phase. From a systems safety perspective, there is no way to institute controls for all hazards within a system; instead, the goal is to focus on those hazards that pose the greatest level of risk to the system. The identified events served as the starting point for hazard chain construction. The event types that account for at least 80% of the events in the dispensing, takeoff, and landing phases of flight are identified in table 14. In all, 19 separate events identified across three phases of flight were selected for further research.

Table 14. Events Transferred to Hazard Chain Construction for Each Phase of Flight

Phase of Flight	Event
Dispensing	Collision w/wires-poles
	Controlled collision w/ground
	Stall
	Collision w/trees
	Engine malfunction
	Nose-up-and-over
Takeoff	Nose-up-and-over
	Controlled collision w/ground
	Collision w/other
	Engine malfunction
	Collision w/trees
	Stall
	Collision w/fence
	Loss of directional control-ground loop
Landing	Nose-up-and-over
	Loss of directional control-ground loop
	Loss of directional control
	Collision w/other
	Gear collapse

Pilot testing of the subsequent hazard chain construction and risk analysis procedures indicated that the length of time required to complete the analysis for a given unwanted event would make it very difficult for the SME groups to complete the hazard chain construction and risk analysis processes on all 19 events over the period of a two-day meeting. Due to limited time resources, the 19 events had to be prioritized relative to one another to ensure that the SME groups evaluated the potentially highest risk unwanted events at the expense of attention to the lower risk events. Thus, new risk values were computed for the 19 events. Likelihood values were based on the frequency of the event relative to the total number of events (3840), while severity values were based on AIDS severity information. The revised, prioritized listing of the 19 events is given in table 15.

Table 15. Prioritized List of Events for Further Research Ordered by Risk Value

Phase of Flight	Event	Count	Percent	Cumulative Percent	Severity				Risk Value
					Min.	Max.	Mean	SD	
Dispensing	Collision w/wires-poles	467	12.16	12.16	0	5	2.41	1.22	0.29
Dispensing	Controlled collision w/ground	315	8.20	20.36	1	5	2.2	0.68	0.18
Dispensing	Stall	233	6.07	26.43	1	5	2.83	0.92	0.17
Dispensing	Collision w/trees	197	5.13	31.56	1	5	2.76	0.97	0.14
Dispensing	Engine malfunction	320	8.33	39.90	0	5	1.64	0.97	0.14
Dispensing	Nose-up-and-over	231	6.02	45.91	1	4	2.13	0.52	0.13
Takeoff	Nose-up-and-over	169	4.40	50.31	1	5	2.2	0.64	0.10
Dispensing	Collision w/other	132	3.44	53.75	0	5	2.23	1.02	0.08
Takeoff	Controlled collision w/ground	133	3.46	57.21	1	5	2.2	0.58	0.08
Takeoff	Collision w/other	113	2.94	60.16	1	4	2.14	0.65	0.06
Landing	Nose-up-and-over	123	3.20	63.36	1	5	1.94	0.58	0.06
Landing	Loss of directional control-ground loop	104	2.71	66.07	0	3	1.79	0.55	0.05
Takeoff	Engine malfunction	85	2.21	68.28	0	4	1.92	0.86	0.04
Takeoff	Collision w/trees	63	1.64	69.92	2	4	2.44	0.56	0.04
Takeoff	Stall	63	1.64	71.56	1	4	2.33	0.6	0.04
Takeoff	Collision w/fence	53	1.38	72.94	1	5	2.25	0.81	0.03
Takeoff	Loss of directional control-ground loop	53	1.38	74.32	1	4	1.77	0.67	0.02
Landing	Loss of directional control	38	0.99	75.31	1	3	1.68	0.57	0.02
Landing	Collision w/other	35	0.91	76.22	1	3	1.77	0.55	0.02
Landing	Gear collapse	29	0.76	76.98	1	3	1.48	0.57	0.10

SD = Standard deviation

3.2 HAZARD CHAIN CONSTRUCTION.

3.2.1 Background.

The identification of accident and incident events served as the major data input for the construction of hazard chains. By identifying the most common unwanted events, a limited number of hazard chains could be constructed to explain the majority of events. The fundamental purpose of the hazard chains was to provide a context within which key risk indicators and risk controls could be identified. That is, by understanding how events develop, factors associated with the events and potential risk controls could be identified. Once these factors and controls were identified, they were used to create a safety measurement model to adjust event likelihood estimates based on the presence or absence of various risk factors and risk controls.

3.2.2 Hazard Chain Theory.

Most, if not all, accidents and incidents are the result of a series of events. The event immediately before the final outcome is usually the most salient and is often called the proximate cause of the unwanted event. Usually, the proximate cause of an unwanted event does not materialize on its own, meaning that one or more intermediate causes are responsible for the occurrence of the proximate cause. For example, an engine malfunction may be the proximate cause of an unwanted event, but there are many possible reasons why the engine malfunction occurred. These reasons would be labeled as intermediate causes. But intermediate causes are not the true cause of an unwanted event as they also require the presence of some precipitating cause, referred to as the root cause. In the case of the engine malfunction, intermediate causes may involve improper maintenance, which is caused by deeper issues, such as poor maintenance protocols, lack of funding for maintenance activities, or improperly trained personnel. Most root causes for events are located in management functions of the certificate holder's operation.

The utility of hazard chains is that they can be used to identify situations that may potentially lead to unwanted events prior to operations taking place. In the context of aviation, unwanted events occur during ground and flight operations, but they are often caused by deficiencies in maintenance, training, and management operations. Hazard chains allow for the assessment and correction of those deficiencies as far in advance as possible, resulting in a safety management system that can construct barriers to hazard propagation at multiple segments of a single chain.

In practice, a single intermediate cause could lead to several different proximate causes, which may be associated with different unwanted events. Similarly, a single root cause may spawn several intermediate causes, which may be associated with several different unwanted events. In some cases, the root causes may be associated with certain aspects of the certificate holder's operations, such as operating in a mountainous region, and may be impossible to eliminate. In other cases, relatively small changes, such as developing and instituting standard operating procedures, may eliminate certain root causes. This is not to say that hazards or risks can be entirely removed from a system, only that certain pathways that lead to unwanted events can be eliminated, resulting in risk reduction.

3.2.3 Components of the Hazard Chain.

There are several distinct components associated with hazard chains, each linked in a specific and definable temporal manner. Thus, not only are the hazards associated with a single chain important, knowing the order in which those hazards occur is also important. For the purposes of this report, a hazard is defined as anything that causes or contributes to the occurrence of an unwanted event. Thus, the hazard chain is comprised of causes and contributory factors, which, under certain circumstances, may lead to unwanted events. A cause is a hazard that is identified as part of the chain of events leading to an unwanted event, while a contributory factor is a hazard that does not directly cause an unwanted event, but the presence of which may influence the likelihood of an unwanted event occurring. Causes are classified as proximate, intermediate, or root.

3.2.4 Unwanted Event.

An unwanted event is any event that occurs during aircraft operations that results in damage to the aircraft, property, or people (excluding events associated with dispersants that have already been dispensed from the aircraft). The unwanted events were identified in section 3.1.

3.2.5 Proximate Cause.

A proximate cause is a hazard that is directly responsible for the unwanted event of interest. At a minimum, a proximate cause has at least one root cause and may have one or more intermediate causes associated with it. Proximate causes always manifest themselves while the aircraft is being operated, either on the ground or in the air. They are also the causes most readily identified by investigators in the field. An example of a proximate cause would be an engine failure during takeoff that results in a forced landing. In such a case, it would not be uncommon to hear the statement, "An engine failure caused the aircraft to crash." While that statement is correct, it does not explain why the engine failed or how to prevent a similar event from occurring in the future.

For the purposes of this report, a proximate cause is defined as any hazard that directly results in the unwanted event of interest.

3.2.6 Intermediate Cause.

An intermediate cause does not directly cause the unwanted event of interest, but facilitates the development or occurrence of additional hazards, which may ultimately cause the event of interest. Consider another engine malfunction example where the root cause may be failure to adequately fund maintenance programs, which leads to the intermediate cause, insufficient maintenance performed. The lack of proper maintenance may ultimately lead to engine failure, causing a forced landing of some type.

For the purposes of this report, an intermediate cause is defined as any hazard that links a root cause with a proximate cause.

3.2.7 Root Cause.

The starting point for all hazard chains is called the root cause and it is usually located in the management function of the overall operation. The root cause is perhaps the most difficult to define since it is easy to identify root causes that are beyond the scope of the certificate holder's domain. For example, the root cause of an engine malfunction may be traced back to poor quality control on behalf of the manufacturer of a specific engine component. One way to phrase such a root cause would be as an uncontrollable/unforeseen event, which would indicate that this root cause is outside the bounds of the certificate holder. The same root cause could be portrayed in terms of poor manufacturing quality control, but the quality control in question is beyond the domain of the certificate holder, and from the certificate holder's perspective, there is little that they can do about the situation.

For the purposes of this report, a root cause is defined as the triggering event for the hazard chain. Given the complex nature of hazard chains, there is no single test that can be used to determine whether or not a given hazard is the root cause. Designation of a hazard as a root cause is more a matter of the specific chain under construction and the need for the SMEs to understand the sequence of events that lead to an unwanted outcome.

3.2.8 Hazard Chain Construction Process.

The goal of the hazard chain is to identify the sequence of events that leads to specific types of events, known as unwanted events. The hazard chain construction process began with the identification of specific unwanted events. SME input was used to identify the proximate cause, intermediate causes, and root causes of each event starting with the known unwanted outcome and working backward. In a sense, this process is very similar to that employed in FTA. The resulting chains can be used for risk assessment and for identifying potential opportunities for hazard mitigation.

Information was collected from the SMEs using a structured interview format wherein the researcher asked a series of standard questions to the SMEs and asked follow-up questions as needed, until the sequence of hazards that lead to a specific unwanted was identified. In most instances, the line of questioning began by identifying the proximate causes for a given unwanted event, and then moved to identifying the intermediate and root causes for each proximate cause.

3.2.9 Step 1—Unwanted Event Presentation.

The first step was to present the SMEs with the unwanted event of interest. The unwanted event was defined within the context of a specific phase of flight; the chain construction process was performed relative to a specific phase of flight and a specific outcome event. SMEs were free to discuss the definition of the unwanted event and changes were made to the definition if clarification was needed.

3.2.10 Step 2—Proximate Cause Identification.

Once the unwanted event was presented and defined, the SMEs were asked to identify possible causes of that event. The causes had to be direct and immediate and had to have occurred during the ground or flight operations proper. Theoretically, there are an infinite number of proximate causes for any given unwanted event, but the emphasis in this process was to identify those proximate causes that could realistically occur during normal operations. In other words, proximate causes linked with gross negligence, extremely rare circumstances, and the like were eliminated at the discretion of the SMEs and facilitators. This is not to say that only proximate causes with an equal or known likelihood of occurrence were listed, only that the nature of the cause and the likelihood of the cause should be realistic possibilities for the majority of 14 CFR Part 137 operators.

3.2.11 Step 3—Intermediate and Root Cause Identification.

Once the proximate causes were identified, the process of constructing the chain of events that could lead to each proximate cause began. This process was centered on the question, "What could cause this to happen?" Using deductive reasoning, the sequence of events leading to a given proximate cause was examined until no further causes could be identified, or additional causes were found to be outside the certificate holder's control. It is important to note that, in many instances, the chain of events leading to a proximate cause often contained multiple branches. Some of these branches converged prior to a root cause being identified and some did not.

Each unique hazard chain originated with a root cause. A single root cause may serve as the starting point for several different chains and may result in multiple unwanted outcome events. A root cause can be located anywhere in the functional model, even in the operations node (e.g., bird strike) and some may not seem to fit in any of the functional nodes (e.g., random human error). Identifying the root cause is a matter of deduction and pragmatism. That is, a root cause must serve as the starting point for a chain of events and must also be linked directly with the certificate holder's operation. Consider the case of a hazard chain associated with human error. There are many possible causes of human error, some of which are clearly beyond the scope of the certificate holder's management of personnel (i.e., random personal events, personal history) and some of which can be monitored by the certificate holder (i.e., hours worked in a day, controlled substance usage). The goal was to determine root causes that identify the origin of hazard chains in sufficient detail so that the certificate holder can identify potential shortcomings in their operations.

3.2.12 Step 4—Creating Graphical Representation of Hazard Chains.

Once the SMEs identified the sequence of hazards related to a single proximate cause, those hazards (e.g., intermediate and root causes) were used to create a graphical representation of the hazard chain. The hazard chain diagrams served several key functions.

- By graphically representing the sequence of events, the researchers were able to confirm the intent of the SMEs.

- The graphical representation of the hazard chain elements made it easier for the SMEs and the researcher to visualize the sequence of events that culminate in proximate causes, enhancing understanding of the events and facilitating revision. The graphical format also made it easier for the SMEs to identify missing hazards or improperly specified relationships.

- The diagrams facilitated the identification of real-world controls that are often used to reduce the likelihood of specific hazards within the sequence of events.

- When the chains were completed, the SMEs had the required context to make risk assessments during the risk assessment phase of the meeting.

3.2.13 Step 5—Identifying Real-World Controls.

The SMEs were asked to identify real-world risk controls that they had either used or observed being used. Risk controls are any mechanisms designed to reduce the likelihood of unwanted or hazardous events. Controls can range from training to specific policies or procedures. As the risk controls were identified, they were inserted into the graphical hazard chain models for SME review. The risk controls will later play a key role in the development of a system safety measurement model.

3.2.14 Step 6—Identifying Contributory Certificate Holder Characteristics.

Similar to risk controls, there are certain certificate holder characteristics that may be linked with event likelihood. As such, these characteristics need to be identified and integrated into the system safety measurement model. The SMEs were asked to think about global factors that might influence the likelihood of a given unwanted event occurring, with an emphasis on factors specific to the certificate holder level of analysis (i.e., not just a global factor like weather or the like). Because these factors will become an integral part of the system safety measurement model, the factors must lend themselves to quantification and measurement using archival data or data collected via a survey or brief interview. All factors were evaluated for their potential use in the system safety measurement model. Those not conducive to quantification were memorialized as a risk indicator rather than a certificate holder characteristic. This concept is discussed in further detail in section 3.3.

3.2.15 Step 7—Hazard Chain Review.

Once the hazard chains were constructed and supporting documentation (i.e., definitions) were organized by the facilitator, the SMEs reviewed the chains to determine if modifications were needed. Changes were made prior to performing risk analysis. The review focused on several specific aspects of each chain.

- Thorough listing of all reasonable proximate causes

- Proper temporal sequence of hazards and controls

- Adequate detail in hazard chain to explain the flow of events

- Plausibility and utility of the identified root causes
- The likelihood that each identified risk control and certificate holder characteristic will have a nontrivial impact on event likelihood

The goal of the review process is to make sure that each chain is general enough to be applicable to most 14 CFR Part 137 operators, yet detailed enough so that the unwanted event associated with the chains is adequately explained.

3.3 RISK ASSESSMENT.

All flight operations, especially 14 CFR Part 137 operations, involve hazardous situations, many of which cannot be completely eliminated. The philosophy of systems safety engineering is based on the notion that hazards can be assessed and controlled so that the risks associated with operations are acceptable to the operator of the system. From the engineering perspective, the goal is to design the hazards out of the systems. Another approach to risk management entails identifying hazards that pose an unacceptable level of risk and controlling those hazards to reduce or eliminate the risk. Emphasis is placed on finding and controlling high-risk hazards first, then moving on to hazards of lesser risk. In any event, risk at the hazard level must be quantified so that rationale risk management decisions can be made.

3.3.1 Defining Risk.

Risk is defined as the product of hazard severity and hazard likelihood. Hazards that result in more severe outcomes (i.e., large amounts of property damage, loss of life, or personal injury) are considered to be of higher risk, all other things being equal. Similarly, hazards that are more likely to result in unwanted outcomes are considered to pose more risk, all other things being equal. From an engineering standpoint, risk is reduced by designing the system so that the likelihood of unwanted events is reduced and the severity of outcomes caused by system failures is mitigated. Clearly, the elimination of hazards and the minimization of likelihood via engineering are limited, both practically and fiscally. Therefore, a basic tenant of systems safety engineering is that different hazards potentially pose different levels of risk to the system. This is an important point to make as hazards that pose a higher level of risk should receive priority when considering hazard control development and implementation. This prioritization makes it possible to reduce risk within a system without causing fiscal strain on the system.

3.3.2 Relating Risk to Safety Measurement.

In the context of systems safety engineering, risk assessment results are often used to prioritize hazard control development activities or even to determine whether certain functions should be continued given their risk level. From a safety measurement perspective, a certificate holder that has taken steps to control high-risk hazards is considered to be safer than a certificate holder that has taken steps to control lower-risk hazards, even if the latter has instituted more controls. That is, the contribution to the operational safety of a specific hazard control effort is dependent on the degree of risk posed by the hazard that has been controlled. Of course, this conclusion must be validated in the context of the system using empirical data. One main use of risk information

is in the construction of an operations safety audit, which serves as the cornerstone of safety measurement.

Another use of risk information is in educating inspectors and certificate holders about the various aspects of aerial application operations that pose the most risk to the safety of the operation. Inspectors can use this information to focus their inspection routines to those aspects of 14 CFR Part 137 operations, while certificate holders can use this information to assess possible safety improvement measures.

3.3.3 Quantifying Risk.

The severity and likelihood components of risk can be quantified using "hard" outcome data (i.e., event probabilities, value of property damage, number of lives lost) or "soft," ordinal-based scales (i.e., 1 = low risk, to 5 = high risk). The former method is preferable to the latter when the required data are available, but such data, especially likelihood data, are typically only available for hard physical systems, such as engines, turbines, and, in some cases, well-choreographed systems, such as power generation and missile launch systems. As discussed in section 3.1, data from the AIDS were used to quantify the relative likelihood of the unwanted events, as well as the average severity of each event type. While these data are useful, they do not provide information about the likelihood of specific proximate causes resulting in unwanted events. The hazard chain construction process identifies multiple proximate causes for each unwanted event, but the AIDS data do not provide information about the likelihood values for each of these proximate causes. Since risk controls address proximate causes, assessing the potential positive impact of a given risk control must be linked with the likelihood of the hazard that the control seeks to mitigate. A risk control that addresses an unlikely hazard has less impact on safety than a risk control that addresses a more likely hazard. Thus, it is necessary to assess likelihood at the proximate cause level. Since quantitative data regarding the likelihood of proximate causes are not available, a qualitative approach to risk assessment was used to estimate proximate cause likelihood values.

3.3.4 Unwanted Event and Proximate Cause Risk Calculations.

For any given unwanted event, there may be several proximate causes, each with a different probability of causing the unwanted event. In other words, the presence of a proximate cause is necessary but not sufficient to cause the unwanted event. Proximate causes can materialize without resulting in an unwanted event. This is an important departure from the traditional approach to fault analysis (e.g., FTA), where the presence of one failure initiates with 100 percent certainty in some subsequent event. To link the concept of proximate cause back to safety measurement, a certificate holder who has taken steps either to reduce the likelihood of proximate causes materializing or to reduce the likelihood of proximate causes resulting in unwanted events is operating at a higher degree of safety than a certificate holder who has not taken such measures. Furthermore, control measures that target high-risk unwanted events do more to enhance safety relative to measures that target infrequent and minor consequence unwanted events. Thus, any measure of safety should weigh the presence of various risk controls in conjunction with the risk associated with the unwanted event of interest and the likelihood of the proximate cause that the risk control is designed to address.

In the present context, the computation of risk requires that two separate likelihood values be estimated in relation to any given unwanted event. First, the likelihood of the proximate cause occurring must be assessed. Second, the likelihood of the proximate cause resulting in the related unwanted event must be assessed. The severity of the related unwanted event will serve as the severity component of the risk calculations.

The process of mathematically combining two probabilities is fairly straightforward. Consider the example of striking a power line during dispensing operations because the pilot failed to see the power line. There is a probability for not seeing a power line given certain conditions, and there is a probability for striking a power line given that the pilot failed to see the line. The likelihood value of interest in the current risk analysis is the combination of these two probabilities. If the probability of not seeing the power line is 0.75 and the probability of hitting the power line given that the pilot fails to see the power line is 0.25, the resulting probability of both events occurring is 0.75 * 0.25 = 0.1875. (Note that these numbers are purely hypothetical.)

The reality of likelihood estimation in most sociotechnical systems is that the empirical data required to generate ratio-scale likelihood calculations are simply not available. As a result, more subjective or qualitative methods must be employed. The results are likelihood estimates that lack mathematical properties and rigor required for computing overall probabilities (see section 4.2 for additional discussion). For example, FTAs of mechanical systems often include empirically based estimates of component failures, which can be algebraically combined to compute the overall likelihood of system failure. This is possible given the mathematical properties of empirical probabilities. These properties are not present in subject evaluations of likelihood and as such, subjective measures of likelihood cannot be mathematically combined to estimate the overall likelihood of system failure.

3.3.5 Likelihood Scale Construction.

When empirical data are not available, SMEs are typically consulted to generate estimates of event likelihood. Usually, SMEs are asked to rate likelihood on a fixed scale that is anchored with qualitative descriptions of likelihood (i.e., remote, possible) and, sometimes, quantitative information (i.e., 1 in 1000 hours). In some cases, SMEs are asked to estimate likelihood in the form of statistical probabilities, but the accuracy and precision of this approach is suspect, and the presentation of such data is likely to give the reader a false sense of accuracy and precision.

3.3.5.1 Subject/Qualitative Likelihood Scales.

The FAA System Safety Handbook [1] provides two sets of standard likelihood scale definitions for qualitative risk assessment. One set of definitions is based on the FAA Acquisition Management System (AMS) procurement process, and the other is based on Military Standard MIL-STD-882. Each approach uses a four- or five-point scale for likelihood, respectively, with the AMS-based FAA scale incorporating both quantitative and qualitative anchors for each category of likelihood. In terms of likelihood, a four-point scale is rather restrictive and may not allow SMEs to adequately categorize likelihood across several proximate causes. Clemens [2] suggested that tailoring the rating scales and category definitions to the project at hand is essential for success and that MIL-STD-882D encourages such customization.

The inherent mathematical limitations associated with quantitative SME rating scales prohibit the calculation of outcome probabilities given some sequence of related events. That is, there is no way to mathematically combine the probabilities associated with each point on the likelihood scale to derive some overall event probability. This is why the SMEs must be instructed to provide a single estimate of likelihood based on two separate likelihood components: the likelihood of the proximate cause occurring, and the likelihood that the unwanted event will occur as a result of the proximate cause.

3.3.5.2 Defining Scale Anchor Points.

Given the examples in the FAA System Safety Handbook and Clemens, a nine-point ordinal likelihood scale was constructed. The qualitative labeling of the nine points along the scale is somewhat arbitrary, but follows those used in MIL-STD-882. The focus of the anchor points is on the certificate holder. The decision to frame likelihood in terms of the certificate holder is consistent with the goal of the project of assessing risk at the certificate holder level. Therefore, the likelihood of events will be assessed in terms of the likelihood of an average certificate holder experiencing a given unwanted event.

The FAA likelihood rating scales presented in the FAA System Safety Handbook anchor the likelihood categories in terms of the number of failures per hours of operation. In adapting this scale for use in the current project, the appropriateness of this failure rate (and the failure rate at the other end of the likelihood scale) must be evaluated in the context of 14 CFR Part 137 operations. Of particular concern is that the AMS-based FAA rating scale was developed for use in risk assessment of mechanical systems and not necessarily for use with sociotechnical systems. Similarly, the FAA Likelihood Rating Scale is typically applied to a fleet of equipment, not just a single unit.

Likelihoods are expressed as the ratio of occurrences to opportunities for occurrences. For example, mechanical failures might be expressed in terms of the number of failures per hour of operation, cycle, year of operation, or mile of operation. To keep the focus of the likelihood estimates on the certificate holder, likelihood will be expressed in terms of certificate holder life cycle. Discussions with SMEs indicate that the typical 14 CFR Part 137 operation has a lifespan of about 20 years. To be more specific, it is estimated that any given single owner is likely to own and operate a business for about 20 years and will likely sell the business to another person at the end of those 20 years.

In addition to specifying the lifespan of the target, it is important to specify whether likelihood estimates should be made at the component level or fleet level. In cases where the risk analysis is performed in the context of a specific operation (e.g., a specific airline), risk evaluations may be done relative to a fleet of specific aircraft (i.e., 15 MD-80 series aircraft) operating over a given number of years. In the context of the current project, most certificate holders operate two aircraft, but some certainly operate more. Those operators who operate more aircraft are exposed to more risk over a given period of time. To produce ratings that can be standardized across all operators, likelihood estimates will be made based on a single operator who operates a single aircraft over the course of 20 years.

The proposed 14 CFR Part 137 Likelihood Rating Scale anchor points reference the number of unwanted event occurrences at the certificate holder level over a 20-year period of operating one aircraft. One end of the scale indicates that the unwanted event will occur five or more times within the career of the operator, while the other end indicates that the unwanted event is likely to occur once to one out of five operators. The center of the scale indicates that the event is likely to occur once to every operator over the course of each operator's career. The frequency values associated with the anchor points along the scale were chosen with SME input.

It is important to note that the purpose of the numerical and text anchors along the scale points was to provide the SMEs with a tangible frame of reference from which they could judge the likelihood of various unwanted events. These anchors need not be used in the computation of risk or the estimation of safety. These frequency values should not be treated as statistical probability values, as is sometimes the case in FTA. Instead, the purpose of the rating scale was to allow the SMEs to evaluate event likelihood in the context of other event likelihood (i.e., this event is more likely than that event). The proposed 14 CFR Part 137 Likelihood Rating Scale is presented in table 16.

Table 16. Proposed 14 CFR Part 137 Likelihood Rating Scale

1	2	3	4	5	6	7	8	9
Extremely Improbable		Extremely Remote		Remote	Somewhat Probable		Frequent	
Once per 5+ operators	Once per 4 operators	Once per 3 operators	Once per 2 operators	Once per operator	2 times per operator	3 times per operator	4 times per operator	5+ times to every operator

Note: The context for the scale is a 20-year 14 CFR Part 137 certificate holder lifespan, assuming that the certificate holder has been operating a minimum of one aircraft.

3.3.6 Risk Assessment Process.

The risk assessment process consisted of evaluating the likelihood of proximate causes that led to specific unwanted events. Empirical data have been used to establish the severity of the unwanted events, but SMEs were needed to evaluate the likelihood of the proximate causes that led to those events. Once a complete hazard chain was constructed for a given unwanted event, the focus of the group was shifted to likelihood assessment of the proximate causes.

3.3.6.1 Other Risk Assessment Methods Considered.

Several different approaches to risk assessment were considered during the risk assessment construction process. The current method was chosen based on theoretical and logistical grounds. Serious consideration was given to having the SMEs estimate likelihood values for each hazard in the hazard chains. These values would then be propagated to determine the overall likelihood of the unwanted event occurring given the sequence of hazards that must take place to cause the outcome. This process is very similar to what is used in FTA, which requires probability values for each event in the tree. When empirical probability data are available for all events in the tree, and as long as the tree is properly specified, the resulting likelihood estimate is very accurate. In the current project, SME judgments would have to be used to generate the event-level probability values, exposing the process to large amounts of error. Not

only would there be error at the individual event level, but this error would be compounded through the propagation process. The resulting likelihood estimate would probably have a larger margin of error associated with it than if the SMEs provided a single estimate at the proximate cause level. From a practical perspective, the process of obtaining the numerous probability estimates is very time consuming and would limit the number unwanted events that the research team could investigate given the limited availability of SMEs.

3.3.6.2 Data Collection Process.

Initially, the research team planned to have the SMEs evaluate likelihood for all unique combinations of certificate holder characteristics and risk controls. The advantage of this approach was that data regarding the interaction effects of controls and characteristics could be collected. During pilot testing, it was determined that SMEs could not adequately distinguish among the various combinations in terms of likelihood. Additionally, limitations on SME time availability precluded the use of any likelihood assessment technique that was excessively time-consuming.

A revised likelihood assessment technique was devised wherein the SMEs would provide a baseline likelihood value for each proximate cause for a given unwanted event, then subsequent likelihood values would be generated given the presence of each risk control and certificate holder characteristic. The logic of this approach was that the SMEs will be able to adjust the likelihood values up or down relative to the baseline values, essentially producing an estimate of the impact on each control and characteristic on likelihood.

This approach takes generic information about what might cause an unwanted event and assesses the likelihood of those events, given information about a specific certificate holder. The utility of this approach is that a generic set of risk information can be applied and customized to reflect the status of a specific certificate holder.

The information contained in each hazard chain graphic was used to construct a matrix similar to that found in table 17. This matrix was presented to the SMEs and likelihood values (based on the FAA Likelihood Rating Scale presented in table 16) were elicited.

Table 17. Example Risk Evaluation Matrix for a Single Proximate Cause

	Proximate Cause 1	Proximate Cause 2	Proximate Cause *i*
Baseline			
Characteristic 1			
Characteristic 2			
Characteristic *k*			
Risk control 1			
Risk control 2			
Risk control *j*			

Note: Gray areas indicate that a likelihood rating is not applicable because the risk control only applies to a specific proximate cause.

The difference between each estimate and the baseline value provides an estimate of the impact of each risk control and each characteristic on the likelihood of each proximate cause resulting in the unwanted event. These values provide a basis for establishing weights for the system safety measurement, which is in development. For example, if a given risk control is estimated to have a relatively large impact on likelihood values, that risk control should receive more weight in system safety calculations relative to a control that is deemed to have a relatively small impact. The same logic applies to the certificate holder characteristics.

3.3.6.3 The SME Likelihood Estimation Process.

The SME likelihood estimation process began once a hazard chain for a given unwanted event was completed. Likelihood estimation was completed through group consensus, with the SME group providing a value for each cell in the risk evaluation matrix. Likelihood estimate differences among the SMEs were resolved via discussion. Once a likelihood value was agreed upon, the value was recorded in the matrix.

The following steps explain the SME likelihood estimation process:

- STEP 1: Using a nine-point scale, the likelihood of each proximate cause occurring and resulting in the associated unwanted event was estimated. Likelihood is defined as the probability that a proximate cause will occur and will lead to the unwanted event. It was assumed no controls were in place. This initial evaluation is referred to as the baseline evaluation.

- STEP 2: The likelihood that each proximate cause would occur and lead to the unwanted event was then evaluated with the assumption that the operator had a given certificate holder characteristic, or that a given risk control was in place.

- STEP 3: Using the baseline values for each of the proximate cause, the values were ranked from highest to lowest. Higher values indicated a higher likelihood of occurrence. Validation was completed through discussion of whether the given proximate cause was the most likely reason for the unwanted event to occur, whether the order of events seemed logical and correct, and what impact the certificate holder characteristics had on the likelihood values for each proximate cause. The SMEs then assessed whether the likelihood values associated with each risk control were reasonable. This step is referred to as the likelihood rating validation.

4. THE SME MEETING RESULTS.

4.1 BACKGROUND.

The focus of this project was to develop a system safety metric that would assess certificate holder risk levels using basic information obtained from archival database records and data collected using survey techniques. A systems safety engineering approach was used to construct the metric, focusing on hazard identification and identifying potential proactive risk controls. The underlying premise of this process is similar to that employed by the insurance industry: risk indicators can be identified and used to estimate the amount of risk posed by a given

certificate holder. While insurance companies typically use actuarial data to identify risk indicators, the relatively small amount of 14 CFR Part 137 event data, coupled with fragmented demographic data, renders techniques based on data mining relatively weak. A reasonable alternative to risk model construction in the absence of sufficient event data is to use SME input to identify risk indicators.

This section presents the information gathered during a series of meetings with SMEs. The preparation for the meetings and the methodology for the information-gathering process are described in sections 3.1 through 3.3. The information collected during the current phase of the project will serve as the cornerstone for the development of a system safety metric.

4.2 PROCEDURAL OVERVIEW.

The SME meetings began with a basic introduction of the concept and procedures to the SMEs as well as a discussion of relevant terms and definitions. After addressing the SMEs' questions, the hazard chain was constructed and was immediately followed by a risk evaluation.

The hazard chain construction process began by defining the event of interest. A general discussion of the unwanted event took place. Next, the SMEs were asked to identify all likely proximate causes for the event. Intermediate and root causes were then identified for each proximate cause, thus providing the basic building blocks for the hazard chain. The chains were presented graphically using Microsoft® Visio®, in real time, to aid the SMEs in the identification and construction process. Once hazard chains for all proximate causes within an event were constructed, the SMEs were asked to identify real-world risk controls that would act to reduce the likelihood of the proximate causes. Emphasis was placed on identifying and defining risk controls so that the presence or absence of a given risk control could be identified via a relatively brief survey question. A similar process was followed for the identification of certificate holder characteristics. The main difference between certificate holder characteristics and risk controls is that the influence of the risk controls was limited to a specific or set of specific hazard chains. In contrast, certificate holder characteristics were linked with all proximate causes simultaneously. In some instances, more general and hard-to-define characteristics and risk controls were identified. The vague nature of these items made transforming them into a usable part of a survey instrument unfeasible; thus, these items were listed in the hazard chains as risk indicators. Figure 1 shows a set of sample hazard chains and their labels.

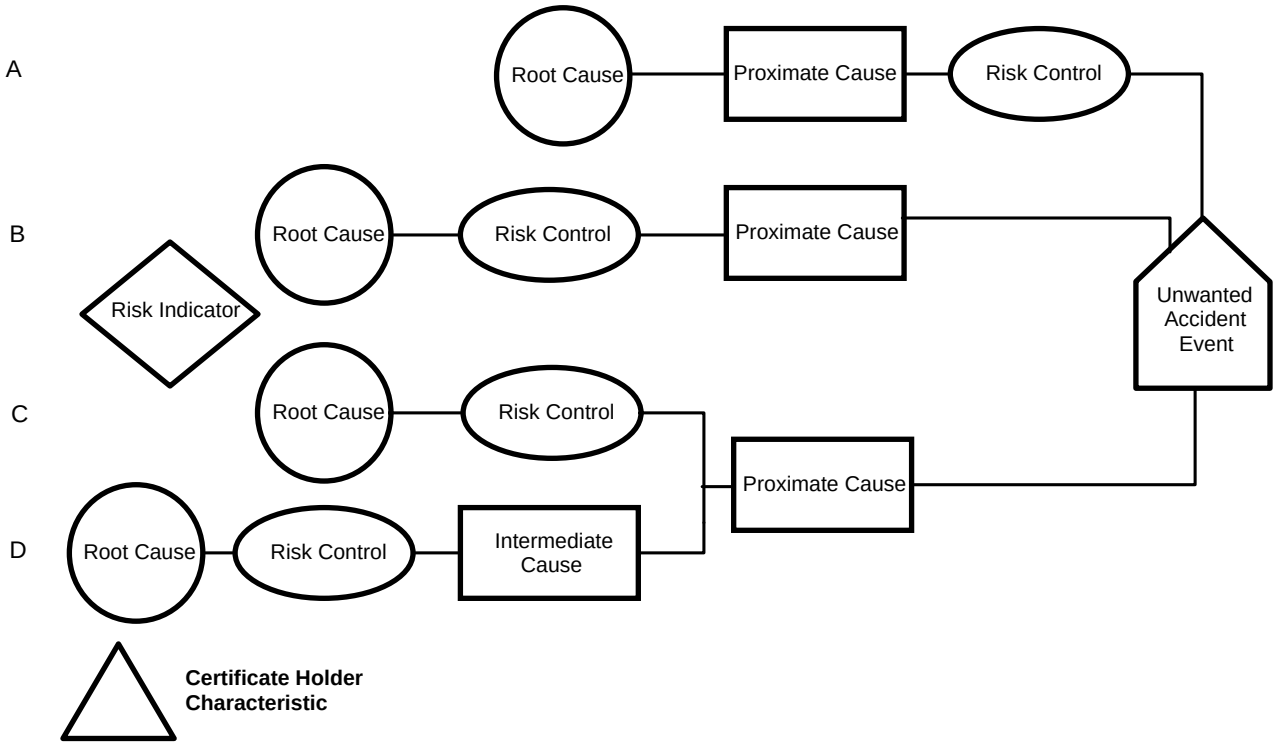

Figure 1. Sample Hazard Chain Diagrams

The risk assessment phase immediately followed the completion of the hazard chain. A matrix was generated for each event. The first step involved assessing baseline risk values for each proximate cause. These baseline values can be interpreted as the likelihood of a given proximate cause occurring and resulting in the unwanted event. Next, likelihood ratings were generated for each identified certificate holder characteristic across all proximate causes. Finally, ratings were generated assuming the presence of each risk control. An example of the risk matrix is presented in table 18.

Table 18. Example Risk Matrix

	Baseline	Proximate Cause 1	Proximate Cause 2	Proximate Cause 3	Proximate Cause 4
Certificate holder characteristics	Characteristic 1				
	Characteristic 2				
Risk controls	Risk control 1				
	Risk control 2				
	Risk control 3				

The likelihood estimates in the risk matrices are based on the proposed 14 CFR Part 137 Likelihood Rating Scale, as shown in table 16.

4.3 MEETING RESULTS.

Initially, several separate SME meetings were planned with inspectors and 14 CFR Part 137 owners/operators. An initial meeting with the owners/operators was held and a great deal of information was collected. Time and resource constraints forced the research team to eliminate plans to meet with FAA inspector SMEs. Fortunately, the data collected during the first meeting was very thorough and covered all the unwanted events of interest.

The meeting with the owners/operators was held in St. Louis, Missouri. Two owners/operators and a representative of the National Association of Agricultural Aviation were present. The SMEs were able to address all 19 events during this meeting, although 3 of the nose-up-and-over events were omitted from evaluation. Thus, a total of 16 events were analyzed. This was the first full-risk evaluation meeting conducted and some key lessons were learned.

The length of time required to analyze any given event progressively decreased as more events were evaluated. This was primarily because certain proximate causes and their respective hazard chains tend to have broad applicability. Thus, a cut-and-paste strategy was used for certain proximate causes once the hazard chain for that proximate cause had been developed. The risk evaluation process followed a pattern similar to the hazard chain construction process, with the ability to cut and paste, reducing the amount of time required to generate the matrices. In most cases, only factors and risk control information was transferred from one matrix to the next; the actual values in the matrices were not transferred. Some of the event categories used in the AIDS were interpreted by the SMEs to be roughly equivalent, at least from a hazard chain construction perspective. For example, various collision events, especially during takeoff and landing, were very similar, as were loss of directional control events.

The SMEs found the nose-up-and-over event categorization quite puzzling. They did not see this as an event; instead, they viewed it more as a description of the final state of the aircraft. As such, these categories were not evaluated.

Post-meeting discussions were held to address specific issues with the data collected during the SME meetings. As the meeting data were used as part of the system safety measurement construction process, some changes to the original structure of the data were made to facilitate model construction.

4.4 PROXIMATE CAUSES.

The proximate causes were the focal point of the hazard chain construction process. A proximate cause was defined as any event that is immediately responsible for an event. Fourteen unique proximate causes were identified across the 16 unwanted events. Several of these proximate causes were present across multiple events, with “lack of attention” named as a proximate cause in 13 of the 16 events. Table 19 presents a list of the proximate causes and their frequency of occurrence.

Table 19. List of Identified Proximate Causes and Frequency of Occurrence

Proximate Cause	Frequency
Lack of attention	13
Downwind ops	10
Misjudgment	9
Loading	8
Maintenance	4
Field layout	3
Crosswind	2
Limited visibility	2
Operator error	2
Unauthorized access to runway	2
Engine malfunction	1
Improper technique	1
Catastrophic failure	1
Weather	1

4.4.1 Lack of Attention.

Lack of attention was a prevalent factor present in 13 of the 16 unwanted events. The hazard chain associated with lack of attention is shown in figure 2. The SMEs emphasized that, in most cases, events and distractions outside the cockpit causes attention problems inside the cockpit. For example, family problems, personal problems, and business issues can occupy the pilot even during flight operations. This division of attention markedly increases the likelihood of most events, putting the pilot and aircraft at increased risk. The SMEs indicated that some organizations are more prone to this problem than others; however, they conceded that identifying exact certificate holder characteristics was very difficult and that a site visit would be required to determine if the risk indicators are present. In general, the SMEs indicated that signs of chaos at the certificate holder's operation are indicators that pilot attention problems are a concern. A possible solution for this problem lies in training the entire staff and crew to monitor pilot behavior and performance, making sure to stop operations if the pilot seems cognitively fragmented. Recent changes in operations, such as new aircraft, new pilots, new equipment, or operations in new fields, are also possible risk indicators.

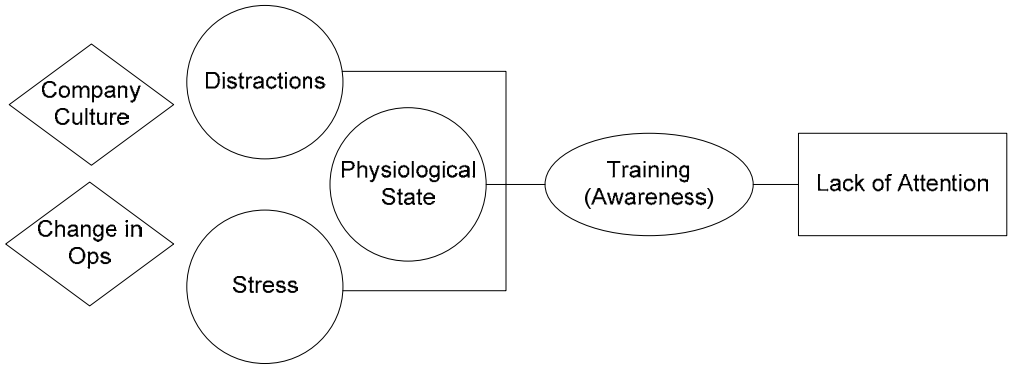

Figure 2. Lack of Attention Hazard Chain

4.4.2 Downwind Operations.

Downwind operations (e.g., takeoff and landing) were listed as a proximate cause for ten unwanted events. Takeoff and landing operations are typically performed into the wind to minimize the ground speed at which the aircraft will transition from ground to flight operations and vice versa. Downwind takeoffs can be extremely dangerous, especially when the aircraft is heavily loaded or terrain or other objects are located at the end of the runway. Downwind operations are usually performed to save time, fuel, or both. In some instances, the layout of the aircraft servicing equipment (i.e., fuel truck, loader) relative to the runway may require a fairly lengthy taxi to set-up the aircraft for an upwind takeoff or landing. In other situations, the layout of the runway relative to terrain features may essentially equalize the risk between downwind operations over favorable terrain and upwind operations into potentially hazardous obstacles. To be sure, downwind operations are not always high-risk endeavors and certain situational factors must be considered prior to executing the operation. On the other hand, the SMEs indicated that such operations should be carefully considered and a great deal of judgment exercised prior to and during downwind operations. To this end, training (especially training geared toward safety attitude formation and judgment) may serve to help pilots more effectively assess the risk associated with downwind operations in a given set of circumstances and forego such operations if the potential risks outweigh the benefits.

4.4.3 Misjudgment.

Misjudgment was identified as a proximate cause in 9 of 16 unwanted events. The term misjudgment was typically used by the SMEs to indicate a situation when the operator is engaged in operations and is attempting to execute the proper action, but makes a mistake with regard to the timing of the operation or the position of other objects relative to the aircraft. Therefore, training efforts were seen by the SMEs as a reasonable way to address this hazard.

4.4.4 Loading.

Aircraft loading was identified as a proximate cause in eight of the unwanted events. Aircraft loading refers to the weight of the aircraft relative to density altitude. Although agricultural aircraft are designed to carry heavy loads, the heavy weight of a dispersant significantly alters the characteristics of the aircraft in flight. The loading factor plays a role in the likelihood of

events during takeoff and the first pass during dispensing, as loading for a given flight tends to be very high at these points. There is an economic advantage to loading the aircraft with as much dispersant as possible so that a maximum amount of acreage can be covered before replenishment is requirement. The economic pressure to operate with maximum loads may encourage some pilots to load the aircraft beyond safe limits, given the environmental conditions. The loading issue is not a simple matter of dispersant weight, aircraft performance, and density altitude; instead, there is a complex interaction between environmental factors, runway conditions, wind speed and variability, and the point-in-time condition of the aircraft that determines the performance envelope of the aircraft at any given point. By increasing the amount of dispersant loaded into the aircraft, the margin of safety in the performance envelope is reduced, and the aircraft may slip outside that performance envelope, even if only briefly, should one or two of many dynamic factors shift in the wrong direction. The SMEs identified training as a mechanism to reduce the likelihood of aircraft loading playing a role in an unwanted event. Knowledge, skills, attitude, and judgment all play a role in the proper management of aircraft-loading information, so training along all of those dimensions should be considered.

4.4.5 Maintenance.

Maintenance was identified in four unwanted events. The hazard chain for maintenance is shown in figure 3. It is important to note that the maintenance proximate cause is not synonymous with the engine malfunction proximate cause, as the maintenance proximate cause covers a wider range of mechanical problems than just power plant problems. The SMEs indicated that there are multiple business pressures, namely financial and time constraints, that tend to dissuade the operator from performing maintenance as needed. There is also the issue that repairs may be performed incorrectly and, hence, contribute to an event. One solution to managing the likelihood of maintenance issues is to institute an on-condition maintenance program, which addresses maintenance problems as soon as they are noticed (as opposed to waiting to fix problems during a time-scheduled inspection period). Another aspect of maintenance is the ability of the operator to properly maintain his or her own aircraft or at least perform some maintenance functions. One indicator that a certificate holder is serious about maintenance is whether he or she owns and maintains maintenance technical publications and updates. Owning these items indicates a commitment to aircraft maintenance and upkeep.

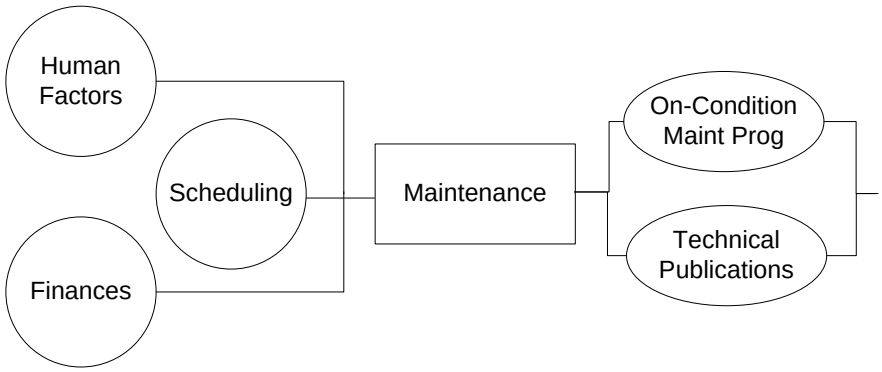

Figure 3. Maintenance Hazard Chain

4.4.6 Field Layout.

Field layout was identified in three unwanted events, as shown in figure 4. The layout of a field can increase the likelihood of aircraft collisions with objects during dispensing. Because unnoticed power lines pose a great threat to the operator, a primary concern is the location and visibility of power lines/poles in a field. A secondary impact of field layout is that the location of power lines, other obstacles, and tree lines can make field entry and exit more dangerous by requiring the pilot to use steeper approach and departure angles during dispensing.

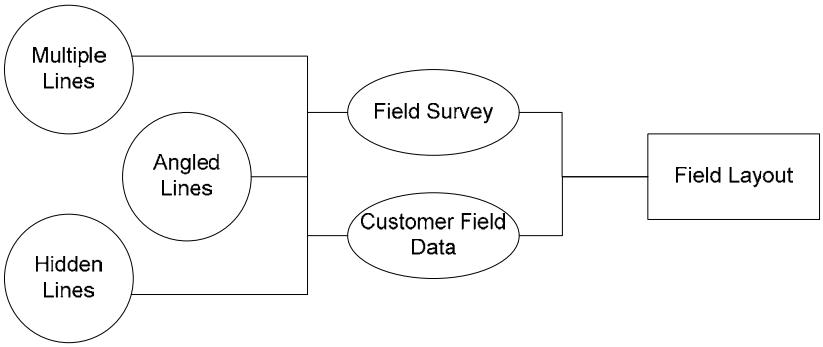

Figure 4. Field Layout Hazard Chain

Ideally, a thorough field survey is conducted prior to operations. Such a survey may include a ground visit to the field and a review of photographs, satellite imagery, and plat surveys. In many instances, a field visit is not practical (i.e., access to the field is limited or not available, time pressures). Therefore, pilots usually perform aerial reconnaissance over a field prior to initial application, but this technique is prone to missing obscure power lines and objects. As a result, customer information about a field can be an invaluable mechanism for identifying potential hazards. This is especially true when fields are irrigated or structures, or "tree islands," are located in the field.

4.4.7 Crosswind.

Crosswind was identified as a proximate cause in two unwanted events. Crosswinds typically play a role during takeoff and landing operations. When crosswinds are within the operational limits of the aircraft, operations can be conducted safely as long as the pilot properly compensates for the crosswind, which is a basic piloting skill. In some instances, crosswind components exceed the limits of the aircraft, but business pressures may encourage the operator to continue with flight operations. The SMEs perceived training as a viable control method, but it is important to note that two types of training are applicable in this situation. First, since there is definitely a skill component involved with crosswind operations, training is one way to address this hazard. Second, there is a judgment component in the decision-making process when deciding to continue operations in the face of hazardous crosswind conditions. Training designed to emphasize the dangers of such operations may encourage operators to put more thought into such operations.

4.4.8 Limited Visibility.

Limited visibility was indicated as a proximate cause in two unwanted events, as shown in figure 5. Visibility limitations arise from several different sources including atmospheric conditions (e.g., smog, fog, smoke, or haze), visual obstructions (e.g., trees, structures), and the position of the sun relative to the aircraft's orientation. The need to perform a field survey is especially important when visibility is limited. A field survey is one way to reduce the likelihood of possible unwanted events. The direction in which swaths are oriented can also help to limit the impact of visibility problems on safety, which is especially important when the sun is low on the horizon. There is also a substantial role for judgment in dealing with limited visibility, specifically being able to identify when changes in operations are needed to maintain safety.

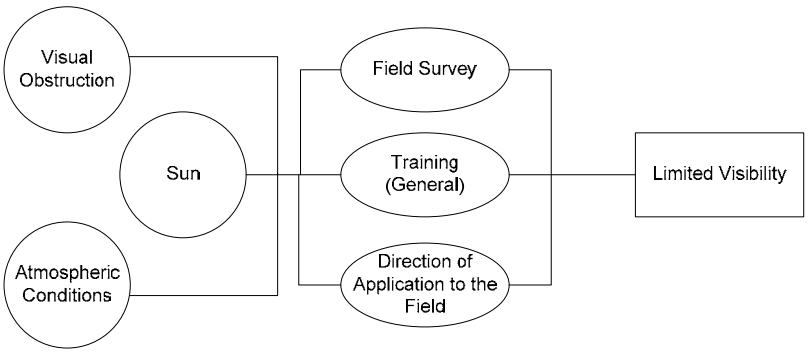

Figure 5. Limited Visibility Hazard Chain

4.4.9 Operator Error.

Operator error was indicated as a proximate cause in two unwanted events. The hazard chain for operator error is presented in figure 6. The operator error proximate cause is associated with engine malfunctions, which are listed as both proximate causes and unwanted events. Pilots may fail to operate equipment properly for several reasons, including lack of knowledge, lack of experience, or a momentary lack of attention. The SMEs indicated training, such as skill or awareness training, may provide a solution. With regard to engine failures as a result of operator error, there are many cases documented in the AIDS where the pilot failed to manage fuel resources properly, usually due to a lack of attention.

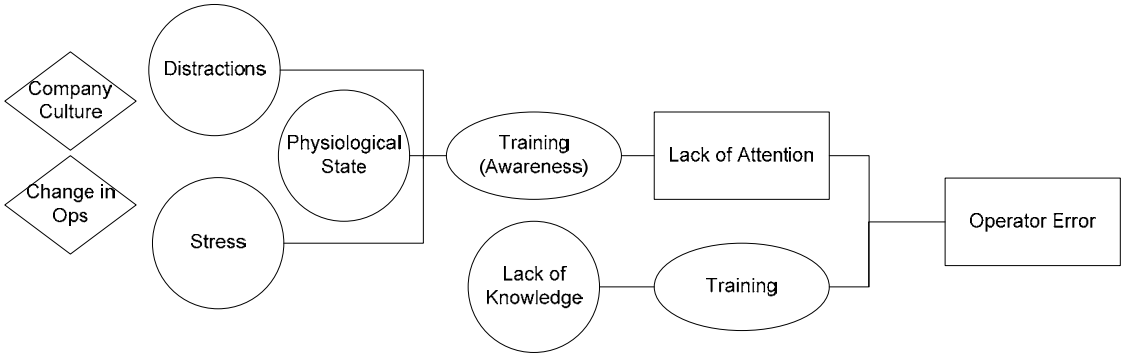

Figure 6. Operator Error Hazard Chain

4.4.10 Unauthorized Access to Runway.

Unauthorized access to runway was indicated as a proximate cause in two unwanted events. This hazard is associated typically with events during takeoff and landing operations where the aircraft strikes a vehicle, person, or animal. Fencing, gates, and warning signs are controls that may reduce the likelihood of hazards on the runway, but the mechanisms may not be feasible for use on secondary fields, such as fields not under the control of the operator.

4.4.11 Engine Malfunction.

Engine malfunction was indicated as a proximate cause in one unwanted event. The hazard chain is shown in figure 7. The engine malfunction hazard chain is made up of the maintenance, operator error, and catastrophic failure chains. The SMEs indicated that some specific power plants are more prone to failure than others. Typically, older engines, even though they are regularly overhauled, may be more likely to fail than newer engines. Similarly, there is an ongoing debate regarding the failure rates of reciprocating engines compared to turbine engines.

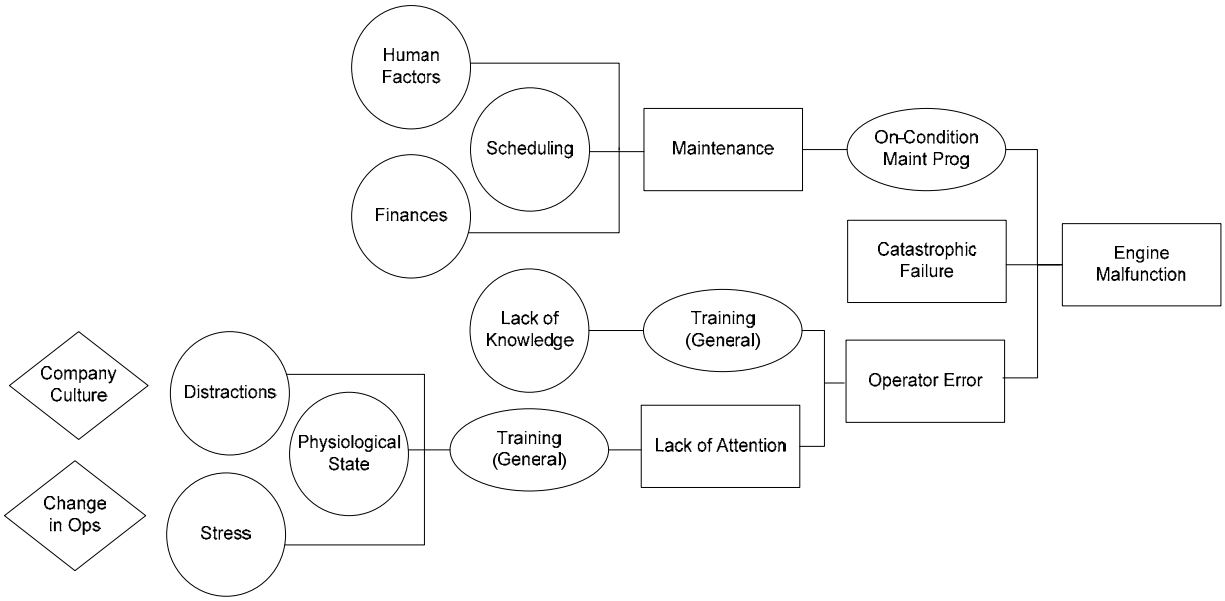

Figure 7. Engine Malfunction Hazard Control

4.4.12 Improper Technique.

Improper technique was indicated as a proximate cause in one unwanted event, as shown in in figure 8. This hazard is associated primarily with stalls during dispensing. A key element in operational efficiency is the ability to turn the aircraft quickly after finishing a spray run. To expedite turns, pilots will often use techniques that put the aircraft into a state close to the edge of the flight envelope. Performing these techniques improperly or poorly can result in the aircraft rapidly exceeding the flight envelope, causing a stall or loss of control.

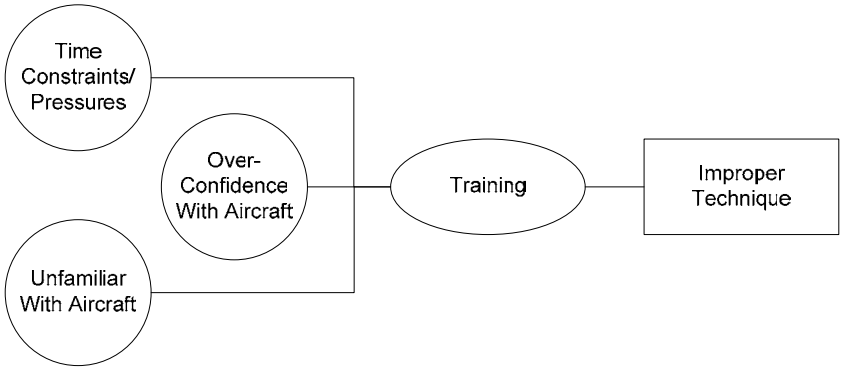

Figure 8. Improper Technique Hazard Chain

4.4.13 Weather.

Weather was indicated as a proximate cause in one unwanted event. The hazard chain is shown in figure 9. The impact of weather on operations safety is broader than this single hazard chain would suggest, but it is important to separate weather as a direct cause of accidents and incidents and as a contributing factor to accidents and incidents. In agricultural operations, the dispersants used are often the limiting factor when it comes to poor weather operations. Some dispersants may require specific conditions (i.e., dry weather) to maintain effectiveness, while many dispersants are simply unsafe for use in strong winds due to drift. Thus, unlike other segments of aviation that function in all weather conditions, agricultural work is limited to very specific weather conditions. For this specific hazard chain, weather was a proximate cause of events. The SMEs indicated that a lack of knowledge about impending weather conditions is usually the actual hazard, as opposed to the weather itself. Some agricultural aircraft cockpits leave little room for dedicated weather avionics, thus restricting the pilot's access to current weather information. Regulations regarding avionics installations can also impact the ability of the operator to install dedicated weather avionics in the aircraft. The methods for dealing with weather conditions primarily are based on obtaining up-to-date weather information, having the knowledge to use that information, and knowing when weather conditions make operations unsafe.

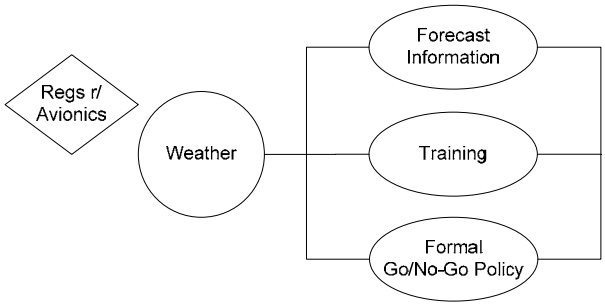

Figure 9. Weather Hazard Chain

4.5 RISK CONTROLS.

The SMEs were asked to identify specific mechanisms to reduce the likelihood of hazards propagating into events. In the context of the hazard chains, risk controls are placed to identify their role in reducing likelihood within the chains. In most cases, risk controls are placed between root causes and proximate causes, but there are several instances when they are placed right before the unwanted event. In some instances, hazard chains involve two or more separate causes linked in a serial fashion so one set of hazard events feeds into another. In such instances, the risk controls associated with the earlier hazard events will have an indirect impact on the likelihood of the latter hazard events and the outcome event. The implication is that a given risk control may have a direct or an indirect impact on the likelihood of the event. A direct impact is where the risk control is linked with either the proximate cause or with the unwanted event, such as in chains A, B, and the top portion of chain C, as shown in figure 1. An indirect association occurs when the risk control has a direct link with an intermediate cause, which is then linked with a primary cause, as in the bottom portion of chain D.

Ten unique risk control mechanisms were identified, as listed in table 20. The most common mechanism was training, which merits additional commentary. The SMEs categorized training into general and awareness training, the former being used as a catchall category, and the latter being associated exclusively with the lack of attention proximate cause. Because the SMEs explicitly discussed only general and awareness training, discussions regarding training efforts are limited to those two categories.

Table 20. List of Risk Control Mechanisms and Frequency of Occurrence

Risk Control Mechanisms	Frequency	
	Direct	Indirect
Training (general)	18	1
Training (awareness)	13	3
On-condition maintenance program	5	0
Technical publications	5	0
Field survey	4	0
Access control	2	0
Customer field data	2	0
Direction of application to the field	2	0
Forecast information	1	0
Formal go/no-go policy	1	0

Note: Direct indicates that the risk control is linked with a proximate cause or the unwanted event. Indirect denotes linkage to an intermediate or root cause within a hazard chain.

4.5.1 Training (General).

In general, training was identified as a viable risk control for many types of hazards. While training is typically associated with skills or knowledge, most training controls identified by the SMEs were aligned with judgment or attitude. That is, many hazardous conditions occur because pilots or crew members choose to engage in risky behavior. In some instances, these choices are calculated and driven by business necessity. In other cases, poor choices seem to be a part of a larger pattern of risky behavior or are driven by personal disposition.

4.5.2 Training (Awareness).

Awareness training was exclusively linked with the lack of attention proximate cause. This type of training is applicable to the entire staff and crew of the operation and is designed to increase awareness about the dangers of external distractions on pilot performance. Issues outside the cockpit, such as personal issues and business pressures, can preoccupy the pilot to the point where performance in the cockpit is impacted. In many cases, the pilot may not be aware of the extent to which their capacities have been undermined, making it more important for crew members and staff to be keen observers and speak out if a situation seems unsafe.

4.5.3 On-Condition Maintenance Program.

Aircraft maintenance issues may serve as a proximate cause for some events. Aircraft maintenance is tightly regulated by the FAA, with regulations prescribing specific service intervals as well as regulations regarding airmen. The business reality of agricultural aviation operations often motivates operators to perform maintenance only at FAA-mandated intervals. Mechanical issues that arise between those intervals are often pushed aside due to time and money pressures. The SMEs indicated that an on-demand maintenance program that addresses all maintenance issues as they arise is one way to limit the likelihood of maintenance problems during operations.

4.5.4 Technical Publications.

Another indicator that a certificate holder may be less likely to experience a maintenance-related event is whether the certificate holder owns and maintains a set of manufacturer technical publications. Proper maintenance of aircraft and power plants requires a large number of technical publications, which are usually provided by the equipment manufacturer. Such publications include original maintenance manuals, periodically published updates, and technical bulletins. Operators that perform some or all their own maintenance should have these publications on hand. Unfortunately, these publications are expensive to obtain and keep current; however, their presence in an operator's shop may be an indicator of solid maintenance practices and a reduced likelihood of maintenance issues.

4.5.5 Field Survey.

One of the greatest threats to agricultural aviation operations is an object in the pathway of the aircraft during dispensing operations. Power lines, trees, terrain, irrigation sprinkler systems, and, more recently, wind-generating towers are just some items that agricultural aircraft might

strike during operations. Ideally, all fields would be flat and free of obstructions, but in reality, this is not the case. Furthermore, many objects located in a field are difficult to see when flying at low altitudes and high speeds. Even if the pilot devotes all his or her attention to spotting hazards, environmental conditions and the physiological limitations of the human visual system make 100 percent detection simply impossible.

The most effective way to deal with this hazard is to perform a field survey prior to commencing operations. The field survey can take on several forms, some of which are more feasible than others, though the logistics of the target field certainly impacts the feasibility of conducting certain types of field surveys. At a minimum, the pilot should fly over the field at a safe altitude prior to dispensing. This approach has limited effectiveness though, because not all objects can be seen from altitude. For example, power lines are often difficult to see from altitude, but objects, such as houses, may provide clues about their possible locations. Field surveys might also be conducted using aerial photographs (such as those used by real estate agents), plat surveys, and even commercially available satellite photos. When the grower/farmer is placing an order for the spraying, that person should be questioned about potential hazards located in or near the field. This information should be clearly marked on the work order for use by the pilot. The most thorough type of field survey is typically an in-person visit to the field to identify, and even mark via global positioning system (GPS), the position of various objects in the field. This last approach is typically not feasible due to the time and cost.

4.5.6 Access Control.

Collisions with objects during takeoff and landing operations are a real possibility. While some events involve a lack of communication between ground and air crews, many involve unauthorized animals, people, and equipment on the runway. This is especially problematic when rural fields are used as a secondary base of operations. Such fields may not be under the direct control or management of the operator (or anyone for that matter) and are easily traversed by unknowing persons and animals. When possible, access should be restricted with fences to minimize the presence of unauthorized objects on the runway.

4.5.7 Customer Field Data.

Similar to the field survey (see section 4.5.5), customer field data can be used to reduce the likelihood of striking objects in a field. In many instances, customers are familiar with objects in their fields, especially sprinkler heads. Whenever possible, operators should ask customers about such objects and request plat surveys, diagrams, or photographs that may help identify objects.

4.5.8 Direction of Application to the Field.

The likelihood of some events, such as controlled collision with terrain or collision with objects in the field, increases if the aircraft is pointed toward a setting sun, put into turbulent air, or forced to fly close to power lines or tree lines. Thorough preflight planning can keep the aircraft in an optimal position relative to hazards in the field. It is often the case that the pilot will need to alter the application direction to compensate for the time of day or various environmental conditions.

4.5.9 Forecast Information.

14 CFR Part 137 operations should be performed in favorable weather conditions, primarily because most dispersants require specific conditions for effective use and because drift is a major concern (i.e., high winds will spread dispersant for an unpredictable distance downwind). As such, weather usually becomes a factor when poor or outdated forecast information is used to plan activities and the pilot encounters unexpected weather events. This is particularly problematic if the target field is a long distance from the base of operations. The use of instant, accurate, and current forecast data obtained via the Internet or other service will reduce the likelihood of encountering rapid-moving weather systems and unexpected weather events.

4.5.10 Formal Go/No-Go Policy.

Another mechanism for dealing with weather-related hazards is to develop a formal go/no-go policy that sets clear criteria for minimum weather conditions. By establishing these policies in advance and following them in practice, operators remove some of the burden (i.e., scheduling, time, money) associated with deciding whether or not to fly a mission. The decision to fly (relative to weather) should be based on objective information and safety guidelines rather than financial concerns or other business pressures.

4.6 CERTIFICATE HOLDER CHARACTERISTICS.

The likelihood of hazard chains is obviously impacted by the presence of risk controls, but likelihood values may also be impacted by specific certificate holder characteristics, such as the type of aircraft operated or the location of operations. While risk controls apply to specific components within a hazard chain, certificate holder characteristics have a much broader impact. They are aligned with more global aspects of the operator and tend to be linked with business practices and philosophies. These characteristics will be a key component of the resulting system safety measure.

Table 21 presents certificate holder characteristics that were identified across the 16 unwanted events and the number of times that each characteristic was noted. The pilot experience and unimproved runway operations were rather common certificate holder characteristics.

Table 21. Certificate Holder Characteristics and Frequency of Characteristics

Characteristics	Frequency
Lack of experience	13
Poor runway conditions	10
All turbine/piston fleet	2
Rough terrain operations	2
Geographic characteristics	1
Group operations	1
Irrigated field operations	1
Minimal equipment	1
Technical publications	1

4.6.1 Pilot Experience.

Pilot experience, or lack of experience, was commonly identified as having an impact on operational safety. The industry generally uses a 1000 hour criteria to distinguish between experienced and inexperienced pilots. Pilots with less than 1000 14 CFR Part 137 hours are generally considered to pose a high level of risk. As a certificate holder characteristic, the risk associated with inexperienced pilots increases as the proportion of operations conducted by inexperienced pilots (i.e., those pilots with less than 1000 14 CFR Part 137 hours) increases. Unfortunately, the only way to gain experience is to work in the field, but doing so puts the certificate holder at risk. The SMEs indicated that some pilots who are new in the agricultural aviation arena sometimes buy or lease their own aircraft and work under contract for a certificate holder until they have gained adequate flight time to get hired on a full-time basis. In some situations, the need to keep operating costs down may lead some certificate holders to hire pilots with minimal agricultural aviation experience. Training was identified as a method of controlling the risk associated with inexperience. In this instance, training across knowledge, skill, judgment, and attitude domains is warranted. Also, the certificate holder could assign a more experienced pilot to assist in decision-making and to supervise the new pilot before sending him or her into the field unaccompanied.

4.6.2 Unimproved Runway Operations.

Many operators use several different airfields during the course of their operations. Some airfields are actually dirt roads, grass fields, or paved roads, but usually these facilities are not under the direct control of the operator and may not be in proper repair. Unimproved runways pose a greater risk to operational safety than those that are properly maintained and regulated. By way of business necessity, some operators must integrate these unimproved airstrips into their routine operations, even though doing so exposes them to a higher level of operational risk. It is up to the operator to evaluate the condition of the secondary facility and to assess whether the risks associated with using the facility outweigh the benefits. To that end, training that addresses the potential risks associated with using secondary facilities may reduce the likelihood of poor runway conditions that lead to unwanted events.

4.6.3 All Turbine/Piston Fleet.

The composition of an operator's fleet may have an impact on safety. The SMEs suggested that operators with an all-turbine fleet experience fewer mechanical failures, although this perspective is a matter of debate among operators. The use of an all-turbine fleet (1) impacts safety beyond the link to mechanical failures, (2) indicates that the operator has much more invested in his or her operation, and (3) may signal that the operator is more fiscally stable (or at least has greater resources). Turbine aircraft tend to outperform piston aircraft due to the copious power provided by the turbine. This translates into higher load capacity and the potential for greater operational efficiency.

4.6.4 Rough Terrain Operations.

The type of terrain encountered by the operator was perceived to have an impact on safety, primarily because emergency landings in rough terrain are much more likely to cause injury and

damage than emergency landings in smooth terrain. Rough terrain also increases the likelihood of the aircraft striking terrain features during application.

4.6.5 Geographic Characteristics.

Geographic features, such as hills, valleys, and tree lines, can impact operational safety through several mechanisms. These features increase the danger associated with emergency landings and increase the possibility of aircraft collisions during operations. Perhaps the greatest risk posed by geographic features is that they can cause unpredictable wind patterns to form in proximity to swath paths, resulting in unexpected turbulence.

4.6.6 Group Operations.

It is common for several aircraft to perform operations over the same field or adjacent fields simultaneously. It was noted by one SME that group operations occasionally lead to pilots competing with each other. Unfortunately, this competition can lead to a pilot exceeding the envelope of the aircraft, resulting in an unwanted event (e.g., stall during dispensing).

4.6.7 Irrigated Field Operations.

Irrigated fields pose a hazard to operations due to irrigation systems that could be struck by the aircraft during dispensing operations. This is especially problematic when the stands are buried within taller crops, like corn. It is common practice for the aircraft to fly with the wheels right at the top of the crops, and natural variations in the flight path or ground elevation may put the wheels into the crops.

4.6.8 Minimal Equipment.

There are a host of new technologies that can aid operators in safe operations. GPS and weather-monitoring equipment can keep operators informed and help them plan the safest and most efficient application runs possible. Operators with minimal equipment may be more at risk for some events, especially weather-related events. The downside to having advanced technology in the cockpit is that it can distract pilots from their tasks. Training pilots to use and manage advanced technologies in the cockpit is necessary to achieve the safety benefits of these technologies.

4.7 RISK INDICATORS.

Hazard chain and risk data collected from the SMEs will serve as the foundation of a system safety measure designed to assess the risk of a given certificate holder based on specific pieces of information. The safety measure will use both archival FAA certificate holder data and information collected directly from the certificate via a phone call, mail survey, or site visit. The key to making the system metric feasible is to use data that are relatively simple to obtain, are linked with specific outcomes of interest (e.g., safety), and are unambiguous. At this point, the research team envisions using a survey or questionnaire to obtain pertinent data that are not available via the FAA data archives. Thus, certificate holders will be asked to voluntarily provide specific pieces of information about their operation. The goal is to present questions that

have obvious meanings and responses (e.g., how many aircraft do you operate?). Such questions tend to be answered dichotomously or with concrete numbers. During the course of the SME meeting, some factors were identified as being linked with operational safety that were not easily defined, nor easily quantified.

The research team did not want to discard this type of information, but it was obvious that such information did not cleanly fall into any of the existing features of the hazard chain models. Thus, a category called risk indicators was created to document less tangible factors that might provide information about system safety at the operator level, but are not easily quantified and would not be practical for inclusion in a survey-based data collection process. Table 22 provides a list of the identified risk indicators and the number of times that each appears in the hazard chains.

Table 22. Risk Indicators and Frequency of Risk

Risk Indicator	Frequency
Company culture	26
Change in operations	16
Regulations regarding avionics	1

4.7.1 Company Culture.

Company culture is a universal risk indicator that is commonly used in multiple safety domains to describe the orientation of an organization with regard to safety and safety practices. This term is similar to the term safety culture, which is commonly used in the aviation industry. The basis of this risk indicator is the notion that some operators are methodical and well-scripted in their operations, making decisions based on information, and planning out events in advance. Other operators are more haphazard, responding to business demands and making decisions to put out fires. In addition to the manner in which the business is run, company culture also refers to the emphasis placed on safety by the administrators of the organization. Some operators have a very strong safety-first mentality, where safety concerns are placed ahead of business concerns. Other operators are much more lax when it comes to safety and place little, if any, emphasis on making safety concerns an integral part of decision making.

The overall concept of company culture and its impact on safety has a great deal of intuitive appeal and empirical support. The drawback is that at the present time, there are no known measures of company culture that would be suitable, and feasible, for use with 14 CFR Part 137 operators (i.e., relatively small aviation organizations) that might serve as a predictor of safety outcomes. Current work being done by the 14 CFR Part 121 research team examines methods to assess the safety culture of an airline operator and its relationship with safety outcomes.

4.7.2 Change in Operations.

The SMEs considered the risk associated with operations to increase if operations in unfamiliar areas were undertaken. For example, it is not uncommon for operators to perform contract work at locations quite some distance from their home base of operations. These remote operations

can impact safety in several different ways. First, the fact that the area of operations is unfamiliar to the operator's staff puts the operator at risk. Unique features and hazards near the target field must be learned and accommodated, as well as any unique weather patterns. The airfield will be unfamiliar to the operator and may hold certain hazards that are not readily apparent. Second, operations away from the main base may put a strain on the pilots and the operator as they adjust to the new surroundings, distance from family, and unfamiliar living quarters. The adjustments may have physical and mental consequences, such as fatigue and distraction. Finally, working in a new, remote locale may cause chaos or uncertainty in an otherwise calm and stable operating environment. Procedures and decision-making processes may be disrupted with negative consequences.

4.7.3 Regulations Regarding Avionics.

FAA regulations are designed to enhance aviation safety, but sometimes these regulations have unintended consequences. In the case of agricultural aviation, new technologies have been developed to aid operators in the precise and safe placement of dispersants, but avionics regulations may impede the ability of an operator to legally place such avionics in aircraft. The needs of the agricultural aviator are markedly different from those of commercial operators and private pilots, but the regulations regarding avionics are not tailored to suite the 14 CFR Part 137 operator. As a result, avionics designed to enhance safety and efficiency in agricultural aviation are sometimes kept out of the cockpit by FAA regulations and may increase the risk associated with these operations.

4.8 EVENT DATA.

The information shown thus far converges to form hazard chains associated with specific events. As shown in table 7, 19 events of interest were selected, with 3 nose-up-and-over events eliminated, as described in section 4.3. The events and the FAA AIDS data regarding the events provide a context within which the hazard chains can be developed and interpreted. Each chain has empirical AIDS data associated with it that provide information about relative frequency and severity. Each event is precipitated by proximate causes, and each cause has its own likelihood of occurrence. The SMEs' role in this process was to identify the proximate causes associated with each unwanted event, deduce the intermediate and root causes associated with each proximate cause, and assess the extent to which certain factors (i.e., risk controls, certificate holder characteristics, risk indicators) increase or decrease the baseline likelihood of a given proximate cause that result in a specific event.

The event data provide the context within which SMEs evaluated event likelihood, risk control effectiveness, and the implications of certificate holder characteristics on event likelihood. These data will be subsequently used in the construction and weighting of factors for the system safety measure.

The hazard chain diagrams in this section use a basic set of symbols to present information pertinent to each event. The legend for the hazard chain graphics is shown in figure 10. The use of color in the diagrams is designed to aid the reader in distinguishing between separate hazard chains within a single event.

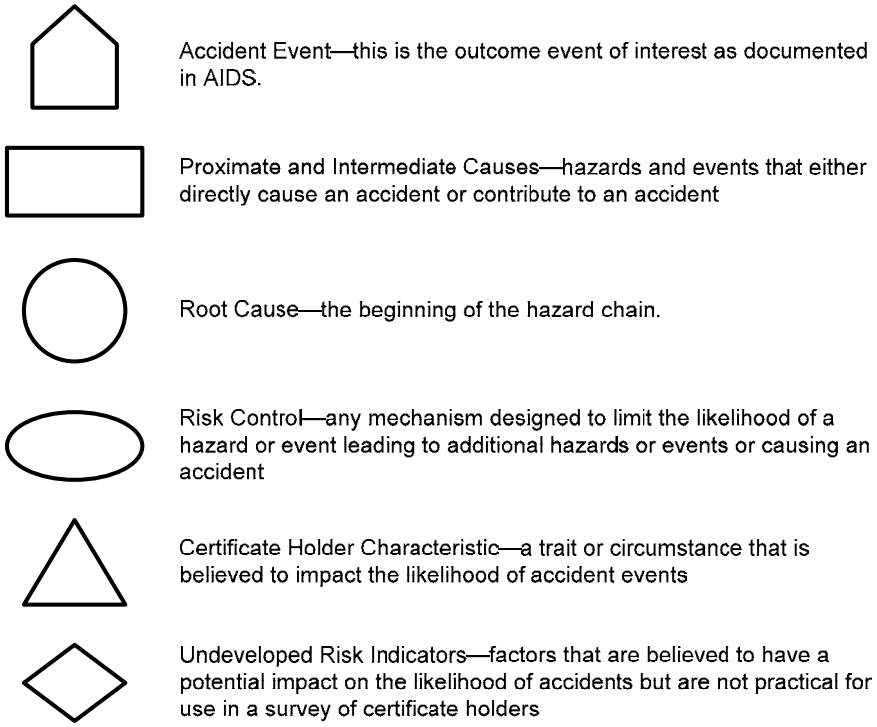

Figure 10. Hazard Chain Diagram Legend

4.8.1 Collision With Lines or Poles During Dispensing.

As shown in table 23 and figure 11, three proximate causes and five unique risk control measures were identified for this event. The risk matrix in table 23 lists the risk controls, proximate causes, baseline, and resulting likelihood values. Lack of attention was identified as the most likely proximate cause. The likelihood values provided by the SMEs are relatively high, which correlates with the fact that the collision with lines or poles event was the most frequent event in AIDS. The SMEs identified the field survey and direction of application to the field risk controls as the most effective methods of reducing the likelihood of this event. Safety during the dispensing is linked with pilot attentiveness, experience, and careful planning of field application. Of course, there is no substitute for field survey information, which can identify hazards in the field prior to application and can aid the operator in properly planning an application mission.

Table 23. Collision With Lines or Poles Risk Matrix

	Factor	Proximate Cause		
		Lack of Attention	Field Layout	Limited Visibility
	Baseline	7	6	6
Certificate holder characteristics	Pilot experience (less)	9	8	8
Risk controls	Awareness training	5	-	-
	Training	-	-	4
	Field survey	-	3	3
	Customer field data	-	4	-
	Direction of application to the field	-	5	3

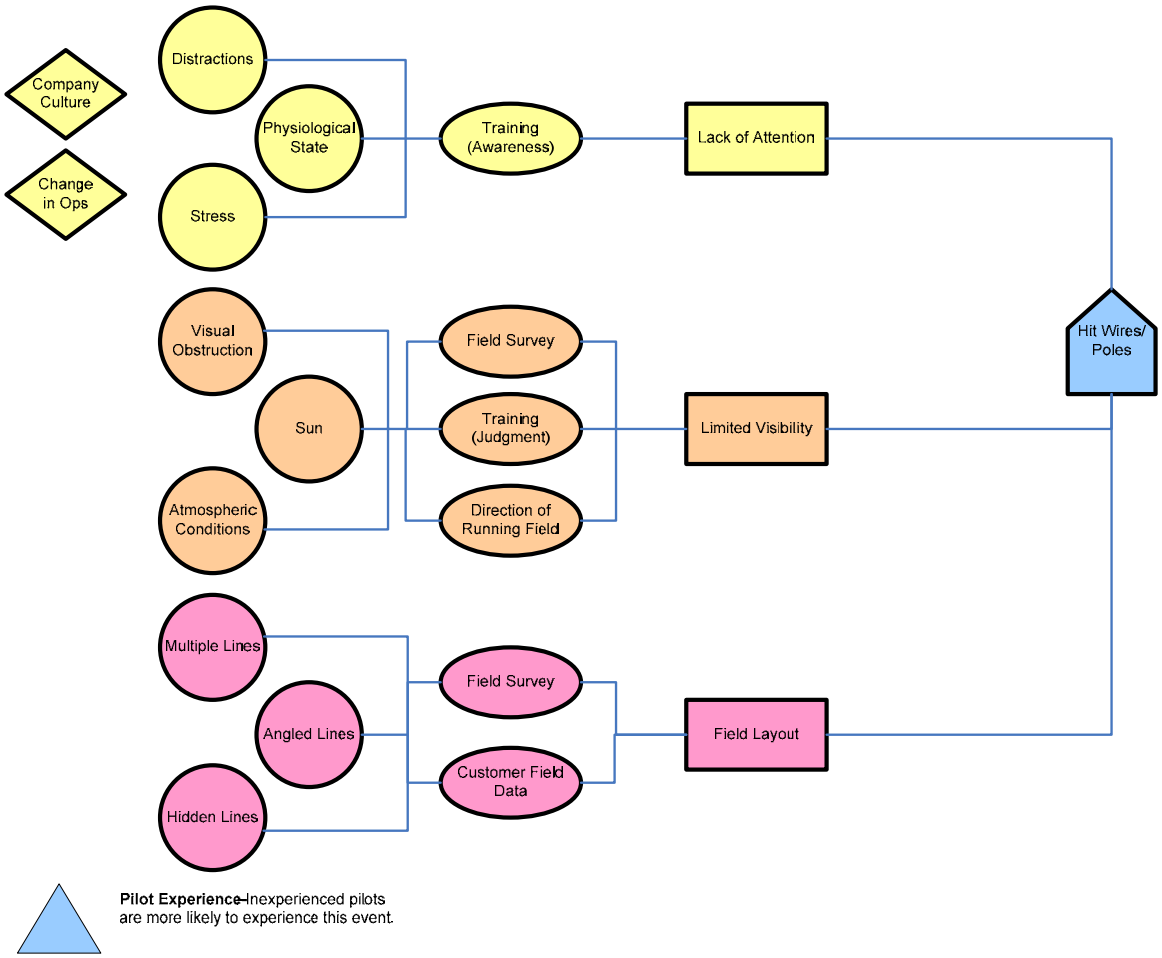

Figure 11. Collision With Wires or Poles During Dispensing

4.8.2 Controlled Collision With Ground During Dispensing.

Four proximate causes and five unique risk control measures were identified for this event, as shown in table 24 and figure 12. Lack of attention was listed as the most likely proximate cause, and power problems and weather were listed as least likely. Three certificate holder characteristics, geographic characteristics, pilot experience, and minimal equipment were also identified as having an influence on the likelihood of this event. The SMEs made a point to link geographic characteristics with environmental phenomena, such as updrafts and wind shear, noting that rough terrain (i.e., sudden changes in elevation) or tree lines often cause areas of turbulence and inconsistent wind patterns. The minimal equipment characteristic was linked with this event under the logic that those operators with limited access to weather forecast and environmental data are more likely to suffer losses due to weather phenomena compared to those using modern sources of weather information both in and out of the cockpit. Also, minimal equipment may be linked with the operation of older or less reliable (e.g., reciprocating power plant) equipment, increasing the likelihood of power problems. The link between minimal equipment and field layout (i.e., field layout is more likely to cause unwanted events when minimal equipment is involved) was based on the logic that modern GPS displays can aid operators in swath planning, thereby avoiding the need for sharp descents into the field. The consensus of the SMEs with regard to this event was that pilots are most likely to fly into the ground when the aircraft is heavily loaded. It is important to note that aircraft loading is more complex than the weight of the dispersant loaded into the aircraft and is intertwined with several atmospheric variables, which are subject to change without notice. Fields surrounded by vertical obstructions (i.e., lines or trees) often require a relatively steep entry, which can prove quite difficult to judge and perform when the aircraft loading is high. The result can be that the aircraft is flown into the ground because the pilot attempted to break the descent too late.

Table 24. Controlled Collision With Ground During Dispensing Risk Matrix

	Factor	Lack of Attention	Field Layout	Weather	Power Problems
	Baseline	4	3	2	2
Certificate holder characteristics	Geographic characteristics	5	3	5	4
	Minimal equipment	4	5	6	3
	Pilot experience	5	4	3	3
Risk controls	Awareness training	2	-	-	-
	Training	-	2	1	1
	On-condition maintenance program	-	-	-	1
	Weather forecast resources	-	-	1	-
	Formal go/no-go policy	-	-	1	-

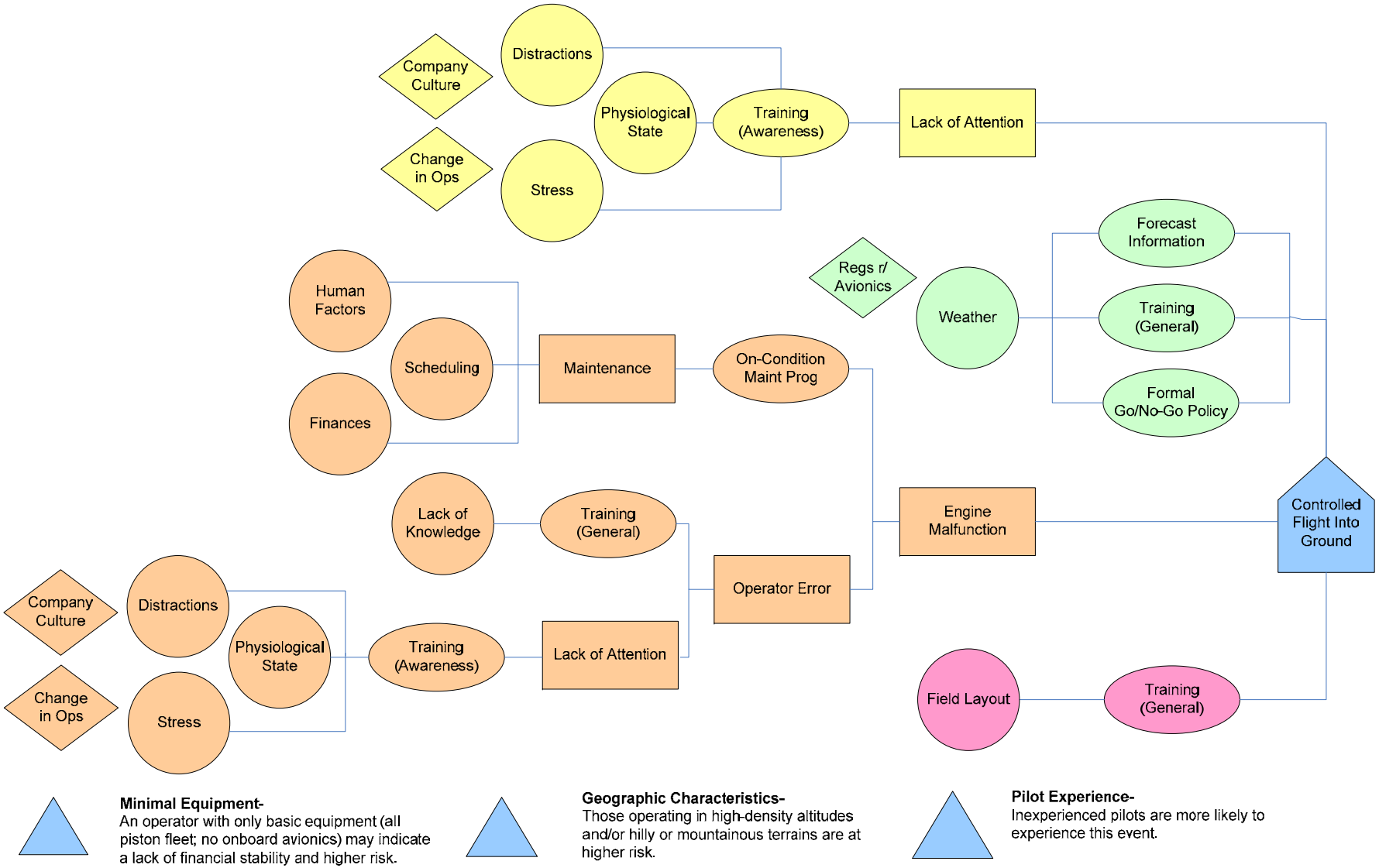

Figure 12. Controlled Collision With Ground During Dispensing

4.8.3 Aircraft Stall During Dispensing.

Stalls during dispensing were linked with turns made at the end of an application run. When the aircraft reaches the edge of the field, dispensing is ceased and the aircraft must be turned around and set-up for the next swath. The longer the aircraft spends turning, the less efficient the application operation. Therefore, operators tend to emphasize the need to turn the aircraft as quickly as possible, but the physics of flight limit the rate at which the aircraft can be turned. This limit changes dynamically with multiple atmospheric variables and the state of aircraft (fuel load and dispersant load). If the pilot attempts to exceed the capability of the aircraft to turn, given these factors, the aircraft will stall and likely crash. The SMEs attributed this event to improper technique and noted that pilots may be more prone to push the envelope of the aircraft if they are engaged in group operations. The rationale for this linkage was that group operations sometimes encourage competition among pilots. See table 25 and figure 13 for more information.

Table 25. Aircraft Stall During Dispensing Risk Matrix

	Factor	Improper Technique
	Baseline	3
Certificate holder characteristics	Group operations	4
Risk controls	Training	2

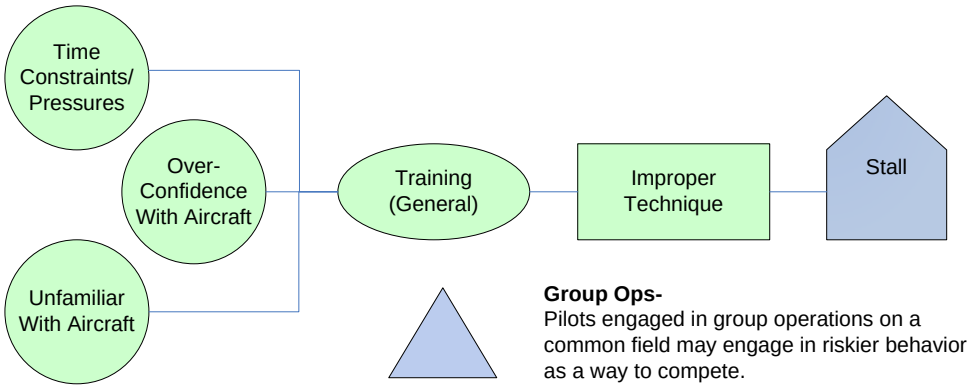

Figure 13. Aircraft Stall During Dispensing

4.8.4 Collision With Trees During Dispensing.

There are two main scenarios where trees pose a hazard to dispensing operations. Trees can be located as an island in the middle of a field or along the perimeter of the field. SMEs indicated that trees in the middle of a field are surprisingly difficult to judge, and trees at the edges of the field might be hit during entry or exit. Risk controls for this type of hazard are similar to other situations involving the aircraft hitting objects. Awareness, experience, field surveys, and mission planning are very important for mission safety. Table 26 and figure 14 contain additional information.

Table 26. Collision With Trees During Dispensing Risk Matrix

	Factor	Lack of Attention	Field Layout	Limited Visibility	Misjudgment
	Baseline	4	3	3	4
Certificate holder characteristics	Pilot experience	5	5	5	6
	Rough terrain	6	5	4	5
Risk controls	Awareness training	3	-	-	-
	Training	-	2	2	3
	Field survey	-	2	2	-
	Direction of running field	-	2	2	-

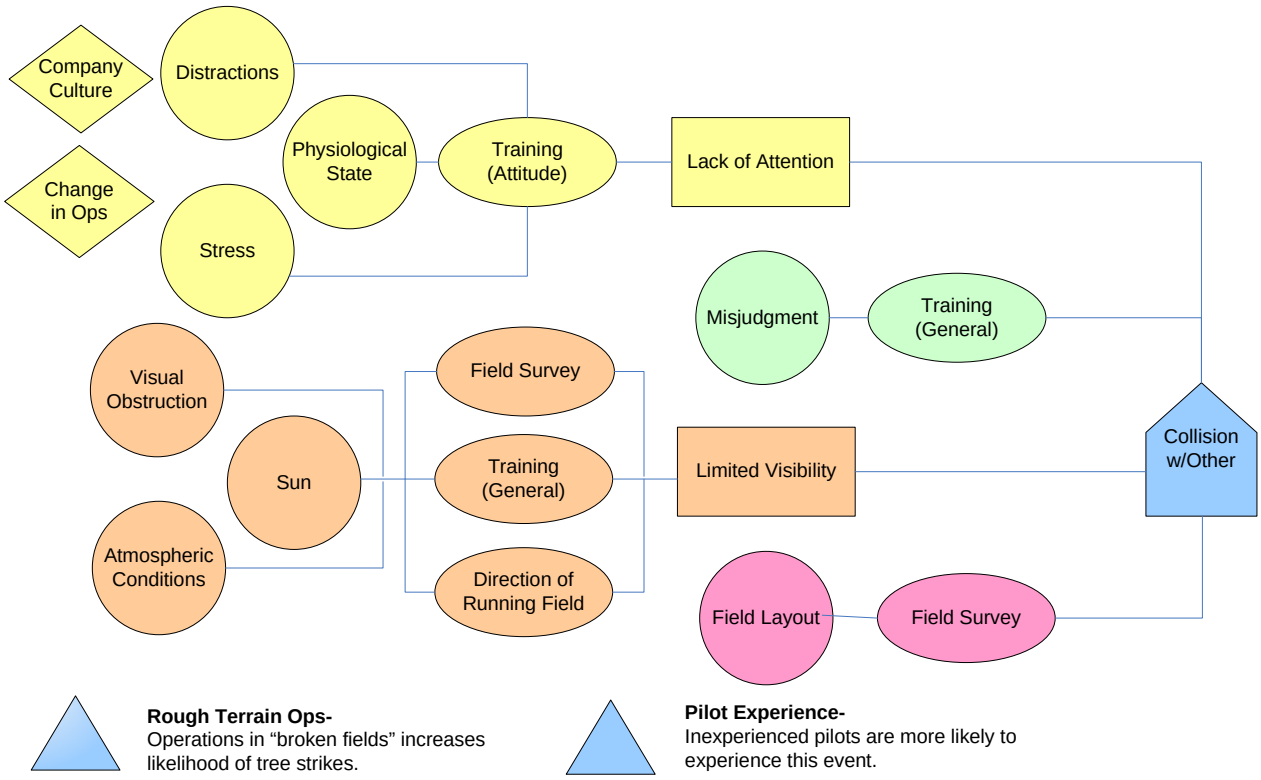

Figure 14. Collision With Trees During Dispensing

4.8.5 Engine Malfunction During Dispensing.

Engine malfunctions and failures are especially problematic during the dispensing phase of operations because the aircraft is being operated at a very low altitude or is in a very tight turn. There is so little time for the pilot to react and plan that the outcome of the situation is often a function of the scenario and the surrounding terrain. Complete engine failures are relatively rare compared to a partial loss of power. In the latter case, quick action by the pilot (i.e., jettison of dispersant) can usually save the aircraft. The SMEs indicated that turbine aircraft may be less

likely to suffer engine malfunctions during operations, but they also noted that this opinion is subject to debate. Table 27 and figure 15 contain additional information.

Table 27. Engine Malfunction During Dispensing Risk Matrix

	Factor	Maintenance	Operator Error	Catastrophic Failure	Lack of Attention
	Baseline	3	4	2	4
Certificate holder characteristics	Rough terrain	4	5	4	5
	Pilot experience	4	5	2	5
	All turbine fleet	2	3	1	3
Risk controls	Awareness training	-	-	-	2
	Training	-	2	-	-
	On-condition maintenance program	2	-	-	-
	Technical publications	2	-	-	-

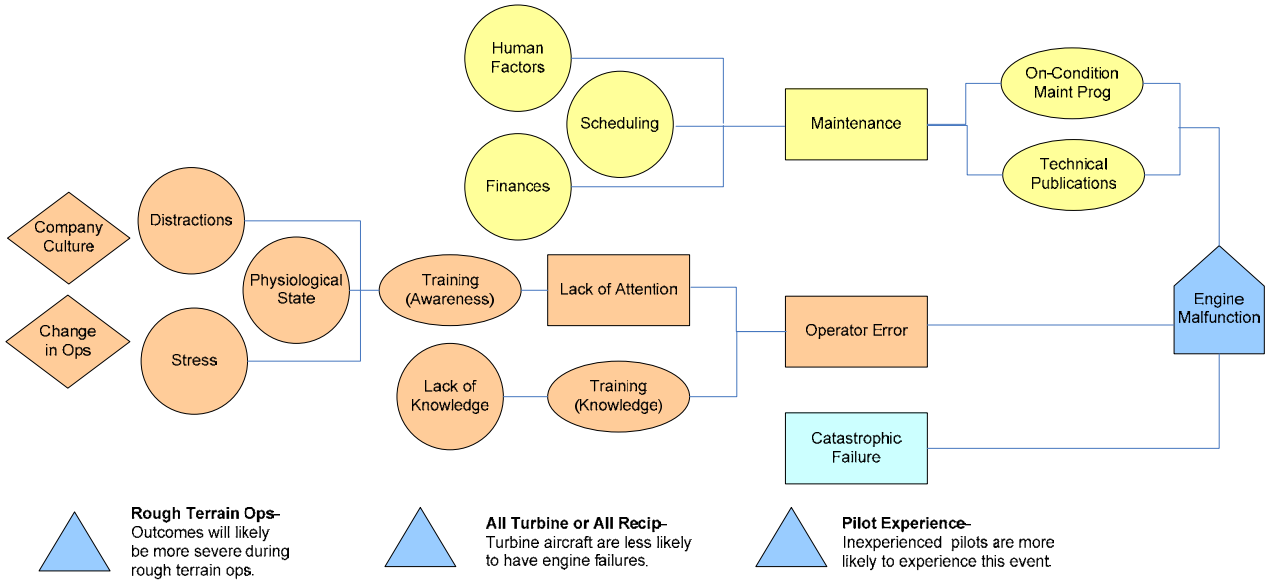

Figure 15. Engine Malfunction During Dispensing

4.8.6 Collision With Other Objects During Dispensing.

The FAA AIDS specifically documents collisions between aircraft and power lines, trees, buildings, and other aircraft. Collisions with other objects are simply noted as "other." There are a variety of objects that an aircraft might hit during dispensing, including sprinklers, vehicles, people, animals, and almost anything else that might be in its path. The SMEs indicated that operating in irrigated fields is a definite risk factor that increases the likelihood of an unwanted event. When operations are being conducted in irrigated fields, safety can be improved with pilot awareness, a field survey, and proper swath planning. Table 28 and figure 16 contain additional information.

Table 28. Collision With Other Objects During Dispensing Risk Matrix

	Factor	Lack of Attention	Field Layout	Limited Visibility	Misjudgment
	Baseline	3	2	2	3
Certificate holder characteristics	Pilot experience	5	4	4	5
	Irrigated field operations	5	4	3	4
Risk controls	Awareness training	2	-	-	-
	Training	-	1	1	2
	Field survey	-	1	1	-
	Direction of running field	-	1	1	-
	Customer field data	-	1	-	-

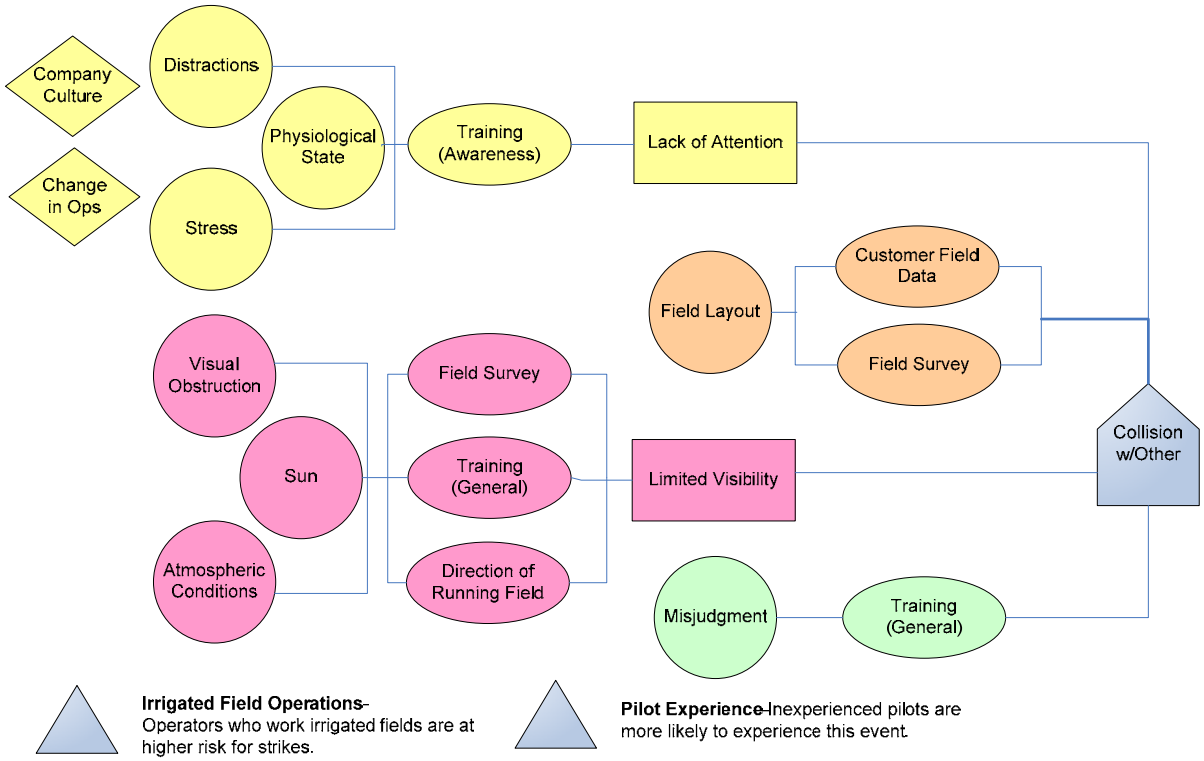

Figure 16. Collision With Other Objects During Dispensing

4.8.7 Controlled Collision With Ground During Takeoff.

Takeoff can be a precarious phase of flight under certain conditions. For example, high loadings and unimproved runways can make the takeoff phase very dangerous. There are a host of factors that interact with one another to alter the performance of the aircraft. Thus, the same aircraft with the same payload might perform differently at different times of the day. This fact, coupled with a short runway, downwind operations, or a tree line at the end of the runway, can result in an event. Combating this hazard is a matter of awareness, experience, and training. Table 29 and figure 17 contain additional information.

Table 29. Controlled Collision With Ground During Takeoff Risk Matrix

	Factor	Lack of Attention	Misjudgment	Loading	Downwind Takeoff
	Baseline	3	3	4	4
Certificate holder characteristics	Pilot experience	5	5	6	6
	Unimproved runway operations	5	5	5	5
Risk controls	Awareness training	2	-	–	–
	Training	–	2	3	3

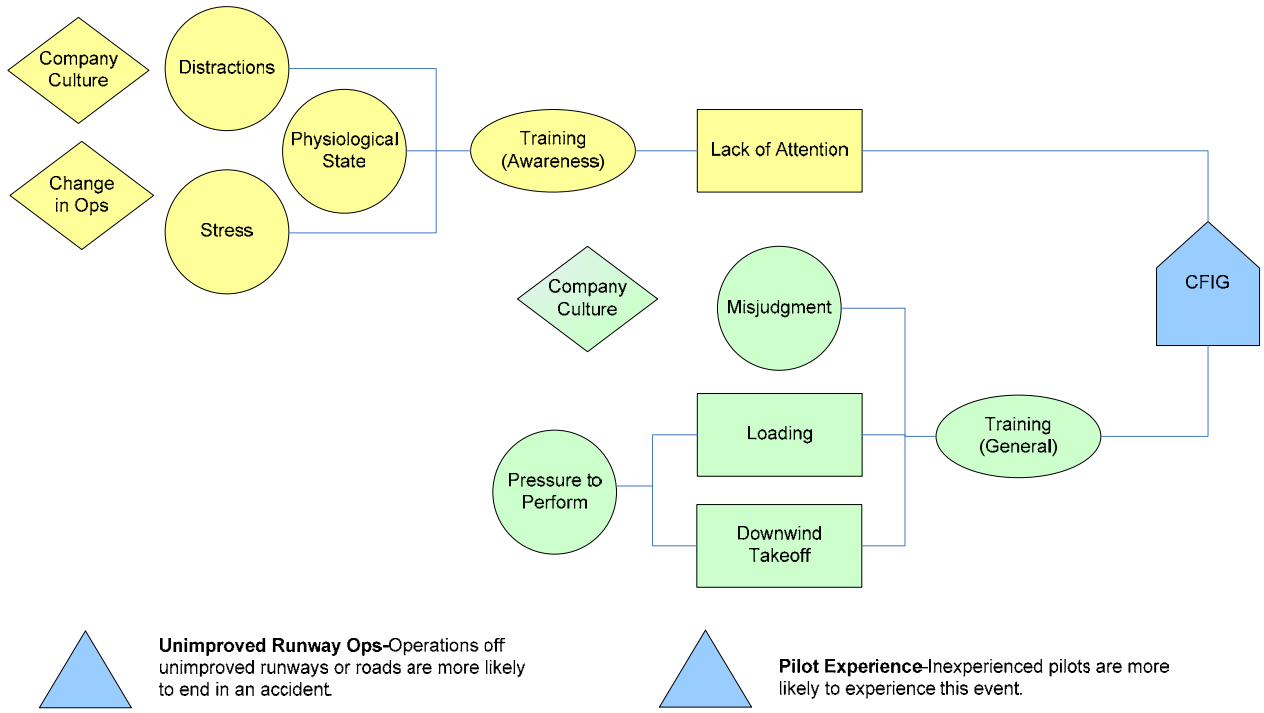

Figure 17. Controlled Collision With Ground During Takeoff

4.8.8 Collision With Other Objects During Takeoff.

In addition to the hazards noted in section 4.8.7, the takeoff phase of flight can be complicated by a variety of other objects on the runway, such as vehicles, people, and animals. Because the aircraft is usually fully loaded during takeoff, evasive maneuvers are difficult to execute and the aircraft is difficult to stop. Also, the nose-up attitude of tail-wheel aircraft obscures the vision of the pilot during the early stages of takeoff. It is important that crew members are aware of ongoing operations and that all vehicles and equipment are kept clear of the runway. In some instances, especially when remote secondary airstrips are used, unsuspecting persons may inadvertently cross the airstrip at inopportune times. Animals are also known to encroach on runways. Access control mechanisms are probably the most effective at dealing with these latter hazards. Full fencing may be required if there is a consistent problem with animal

encroachment, but posted signage may be sufficient to keep humans clear of the runway. Table 30 and figure 18 contain additional information.

Table 30. Collision With Other Objects During Takeoff Risk Matrix

	Factor	Lack of Attention	Misjudgment	Loading	Downwind Takeoff	Unauthorized Runway Access
	Baseline	2	2	2	2	3
Certificate holder characteristics	Unimproved runway operations	2	2	2	2	4
Risk controls	Awareness training	1	–	–	–	–
	Training	–	1	1	1	–
	Access control	–	–	–	–	2

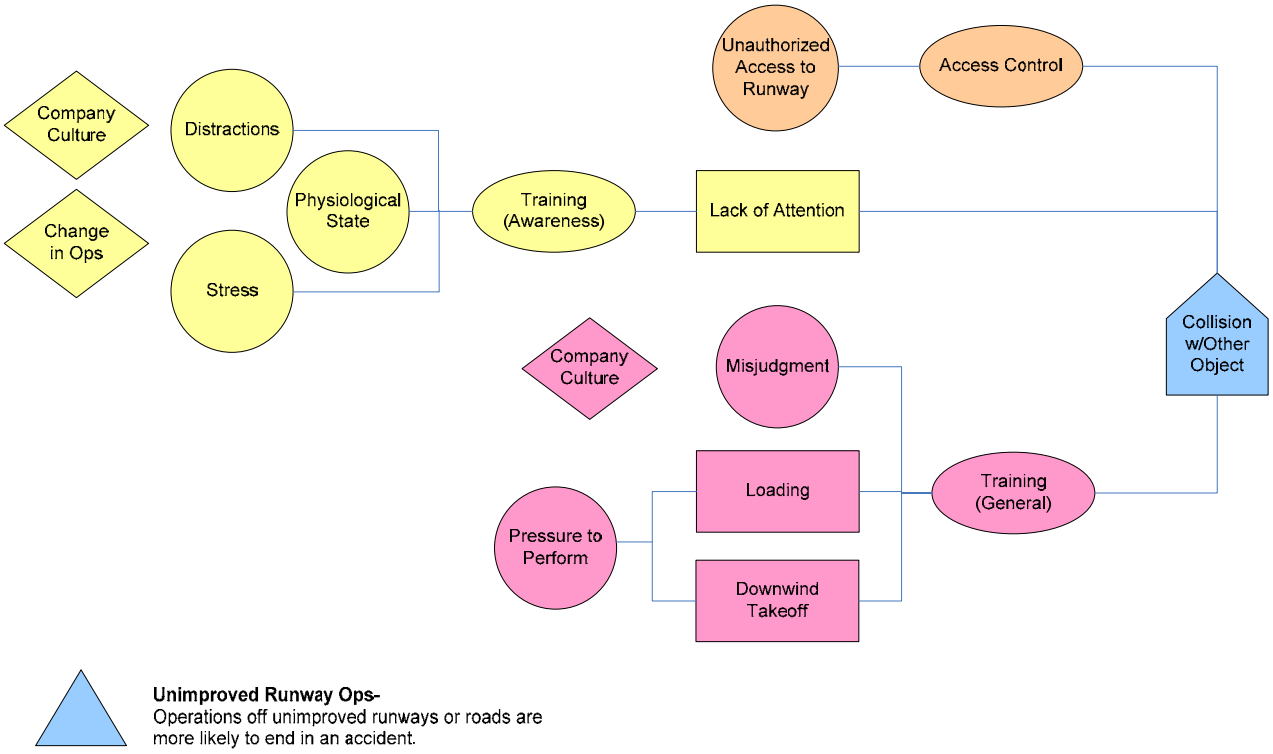

Figure 18. Collision With Other Objects During Takeoff

4.8.9 Ground Loop During Landing.

Four proximate causes and four risk control measures were identified for this event, as shown in table 31 and figure 19. The risk matrix in table 15 provides a list of the risk controls, proximate causes, baseline, and resulting likelihood values. A ground loop is when the aircraft quickly turns, usually in excess of 180 degrees, during ground operations. This maneuver is

unintentional and often results in damage to the aircraft. Crosswind was identified as the most likely proximate cause. Combating this problem is mostly a function of training and experience.

Table 31. Ground Loop During Landing Risk Matrix

	Factor	Lack of Attention	Maintenance	Crosswind	Downwind Landing
	Baseline	2	2	3	2
Certificate holder characteristics	Pilot experience	3	2	4	3
	Unimproved runway operations	3	2	4	3
Risk Controls	Awareness training	1	–	–	–
	Training	–	–	2	1
	On-condition maintenance program	–	1	–	–
	Technical publications	–	1	–	–

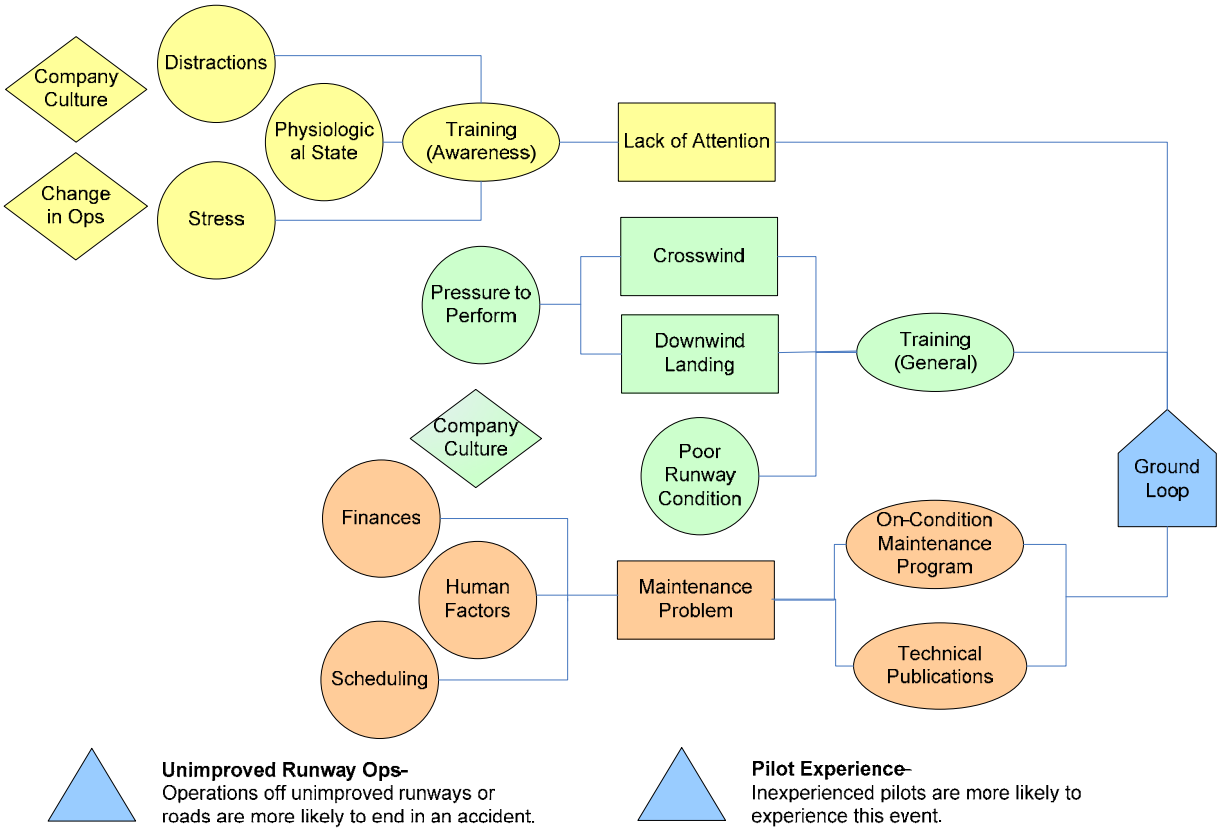

Figure 19. Ground Loop During Landing

4.8.10 Engine Malfunction During Takeoff.

During takeoff, the aircraft tends to be heavily loaded and maximum power is needed. While complete engine failures are rare, a loss in power, even a minor loss, poses great risk at takeoff. As with engine malfunctions during dispensing, the outcome of these events is somewhat

determined by the layout of the surrounding areas (i.e., terrain, trees, fencing). Avoiding engine malfunctions is a matter of proper operation and vigilant maintenance. Table 32 and figure 20 contain additional information.

Table 32. Engine Malfunction During Takeoff Risk Matrix

	Factor	Maintenance	Operator Error	Catastrophic Failure
	Baseline	3	4	2
Certificate holder characteristics	Rough terrain	4	5	4
	Pilot experience	4	5	2
	All turbine fleet	2	3	1
Risk controls	Training	–	2	–
	On-condition maintenance program	2	–	–
	Technical publications	2	–	–

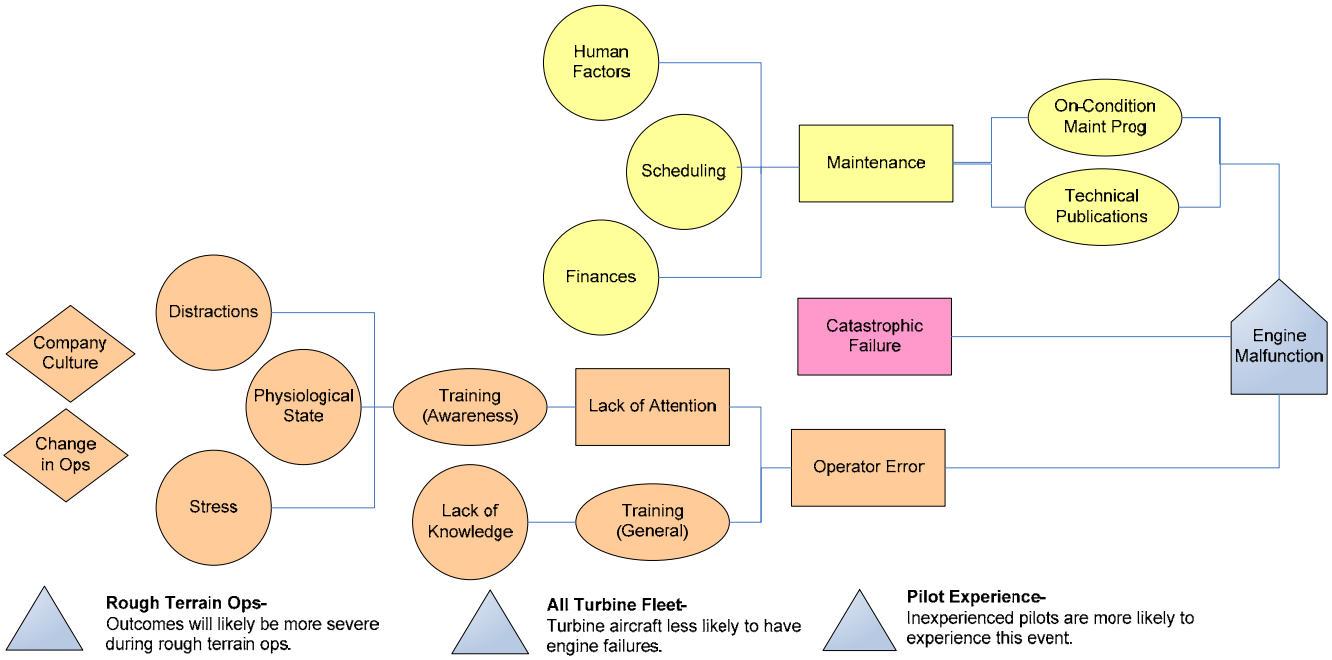

Figure 20. Engine Malfunction During Takeoff

4.8.11 Collision With Trees During Takeoff.

A collision with a tree line during takeoff is usually the result of the aircraft not having enough speed to gain sufficient altitude in a given distance. This might result from a variety of factors, all of which reduce aircraft acceleration, including overloading, downwind operations, misjudgment of the amount of runway needed, or poor runway conditions. It is up to the pilot to assess the likelihood of success early in the takeoff and to execute an abort if needed. Slow decision making or misjudgment can result in a failed takeoff attempt. Table 33 and figure 21 contain additional information.

Table 33. Collision With Trees During Takeoff Risk Matrix

	Factor	Lack of Attention	Misjudgment	Loading	Downwind Takeoff
	Baseline	2	2	2	2
Certificate holder characteristics	Pilot experience	3	3	3	3
	Unimproved runway operations	3	3	3	3
Risk controls	Awareness training	1	–	–	–
	Training	–	1	1	1

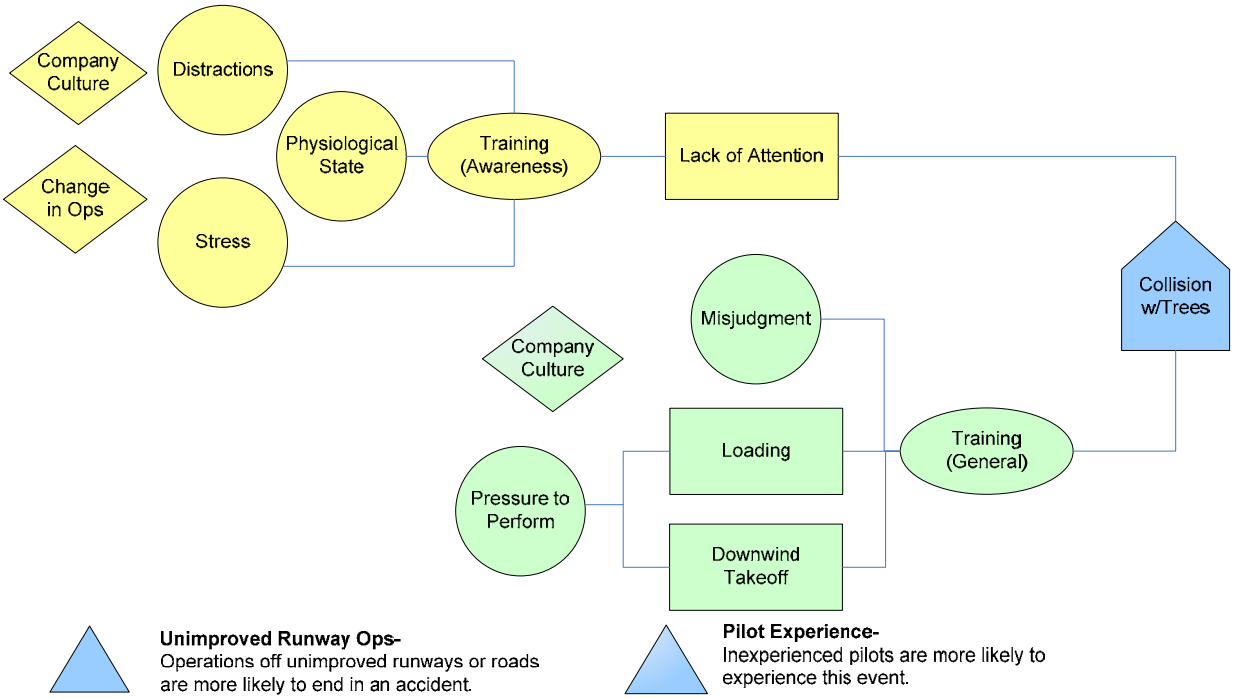

Figure 21. Collision With Trees During Takeoff

4.8.12 Aircraft Stall During Takeoff.

This event is very similar to the collision with trees during takeoff described in section 4.8.11. The major difference is that a stall is usually due to improper control inputs by the pilot, perhaps in an attempt to get the aircraft off the ground before it has sufficient airspeed or attempting to establish a high rate of climb without sufficient airspeed. These scenarios are typically predicated by inadequate runway length, downwind operations, aircraft loading, or poor runway conditions. Table 34 and figure 22 contain additional information.

Table 34. Aircraft Stall During Takeoff Risk Matrix

	Factor	Lack of Attention	Misjudgment	Loading	Downwind Takeoff
	Baseline	1	1	2	2
Certificate holder characteristics	Pilot experience	2	2	3	3
	Unimproved runway operations	2	2	3	3
Risk controls	Awareness training	1	–	–	–
	Training	–	1	1	1

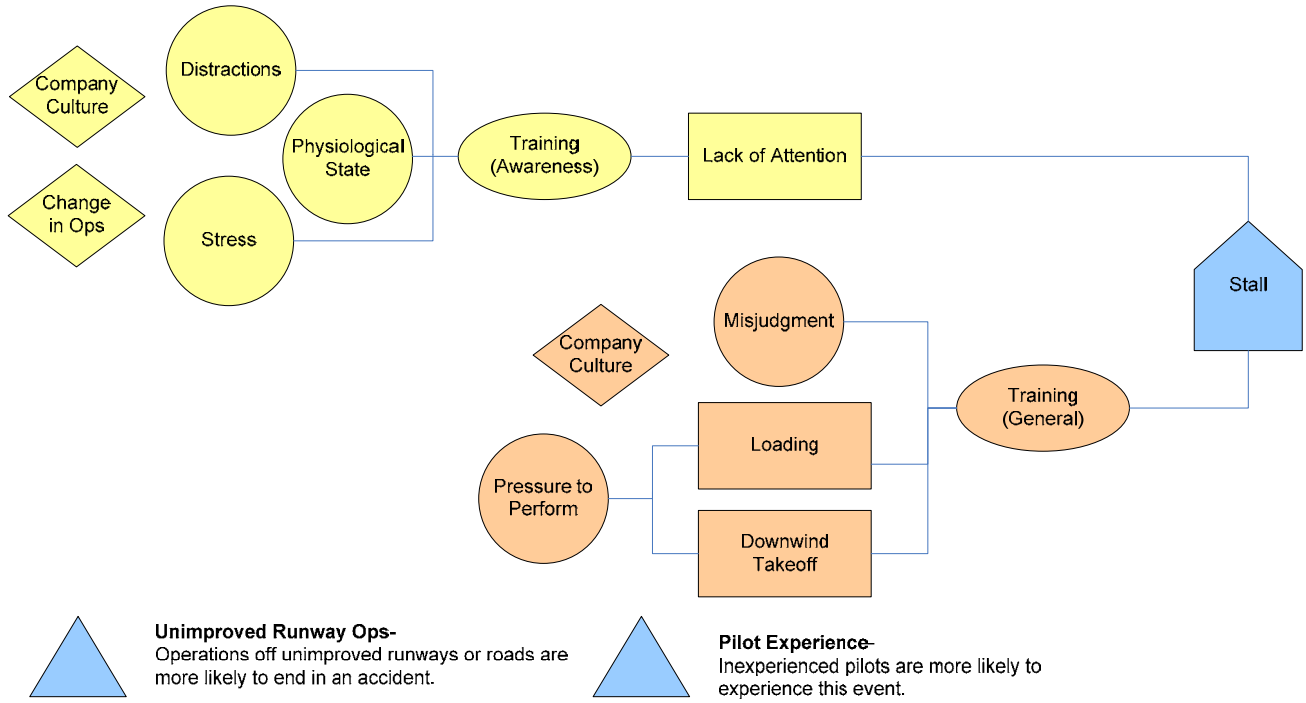

Figure 22. Aircraft Stall During Takeoff

4.8.13 Collision With Fence During Takeoff.

This event is very similar to the collision with trees during a takeoff event (see section 4.8.11). A collision with a fence during takeoff is usually the result of the aircraft not having enough speed to gain sufficient altitude in a given distance. This might result from a variety of factors, all of which reduce aircraft acceleration including overloading, downwind operations, misjudgment of the amount of runway needed, or poor runway conditions.. Another factor to consider is that a heavy aircraft is difficult to stop, meaning that any delay in deciding to abort a takeoff can result in the aircraft running out of runway prior to takeoff. Table 35 and figure 23 contain additional information.

Table 35. Collision With Fence During Takeoff Risk Matrix

	Factor	Lack of Attention	Misjudgment	Loading	Downwind Takeoff
	Baseline	2	2	2	2
Certificate holder characteristics	Pilot experience	3	3	3	3
	Unimproved runway operations	3	3	3	3
Risk controls	Awareness training	1	–	–	–
	Training	–	1	1	1

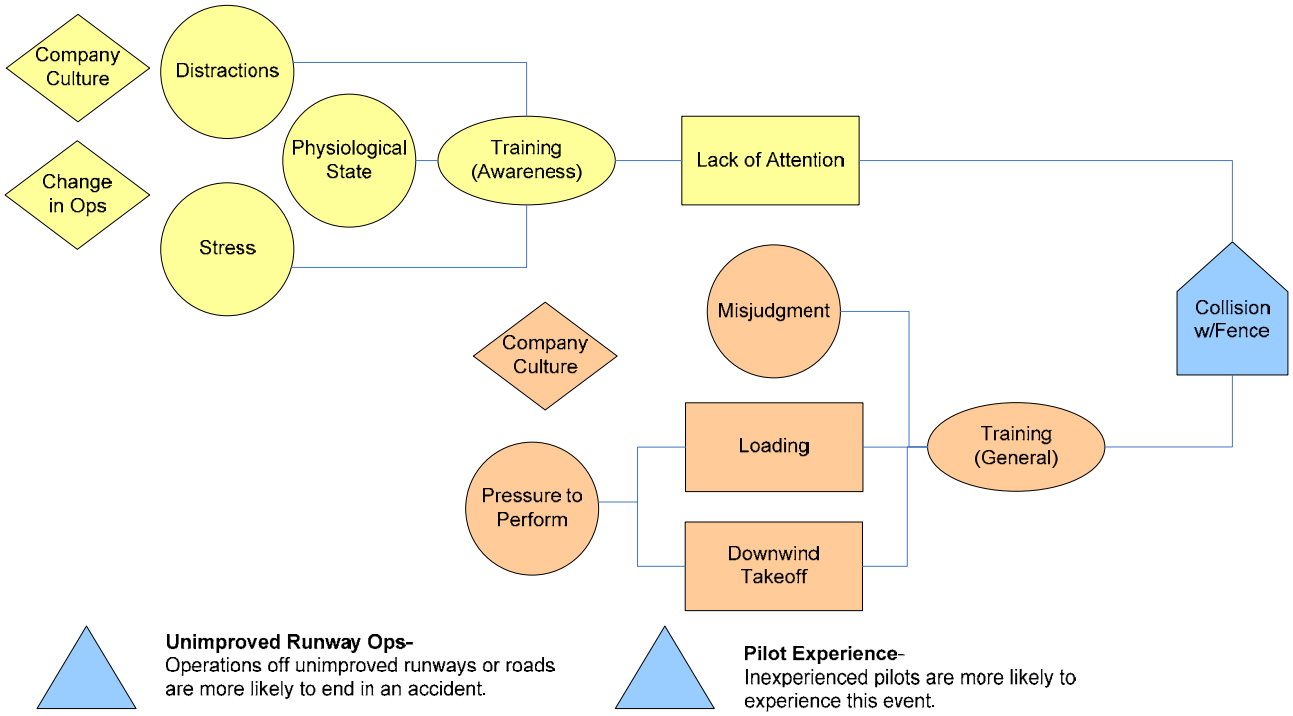

Figure 23. Collision With Fence During Takeoff

4.8.14 Ground Loop During Takeoff.

Ground loops during takeoff are similar to those during landing (see section 4.8.9). However, ground loops during takeoffs are less likely, probably because a loaded aircraft is more stable due to inertia. Table 36 and figure 24 contain additional information.

Table 36. Ground Loop During Takeoff Risk Matrix

	Factor	Lack of Attention	Maintenance	Crosswind	Downwind Takeoff
	Baseline	2	2	3	2
Certificate holder characteristics	Pilot experience	3	3	4	2
	Unimproved runway operations	3	3	4	2
Risk controls	Awareness training	1	–	–	–
	Training	–	1	2	1

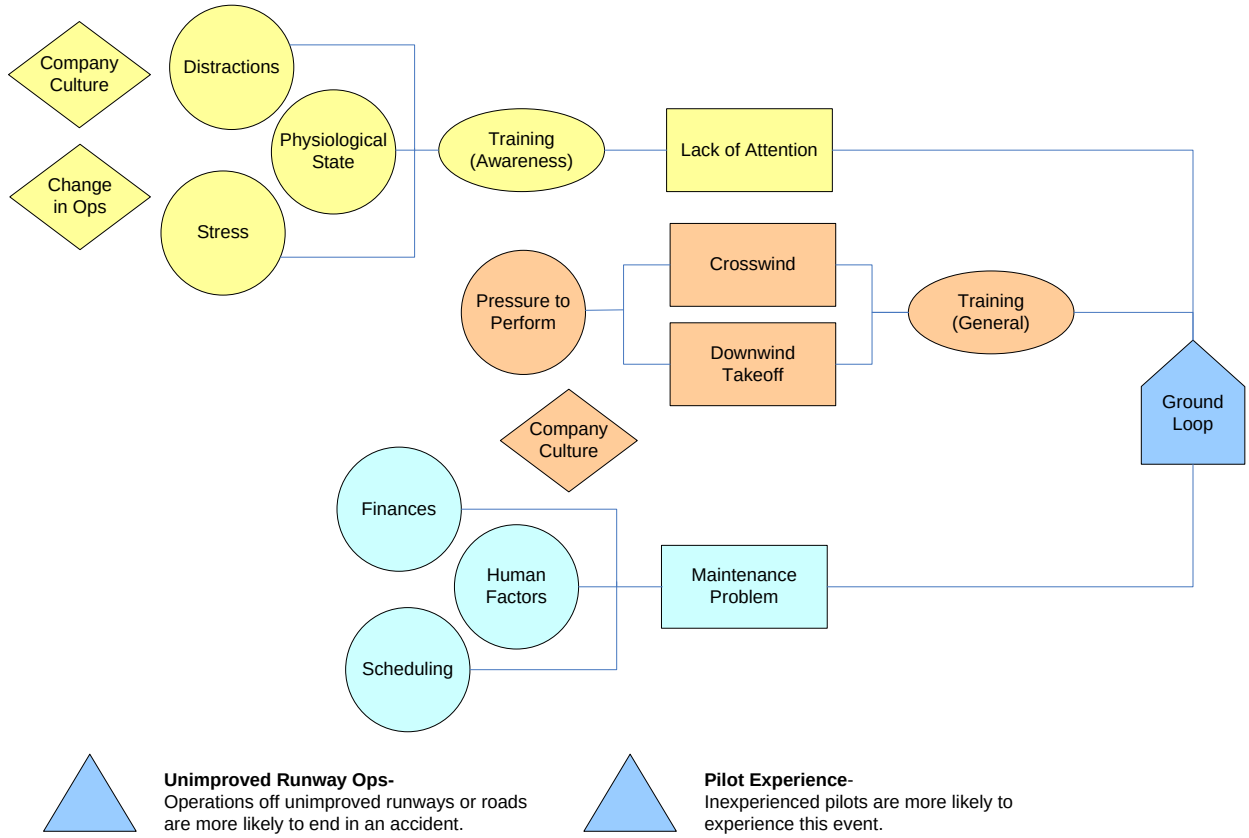

Figure 24. Ground Loop During Takeoff

4.8.15 Loss of Directional Control During Landing.

A loss of directional control on landing involves the aircraft running off the side of the runway. There are several causes for this type of event, including a strong crosswind, maintenance issues, runway problems, or incorrect control inputs by the pilot. To some extent, tail-wheel aircraft are difficult to control during landing and takeoffs due to the inherent directional instability of tail-wheel aircraft. Table 37 and figure 25 contain additional information.

Table 37. Loss of Directional Control During Landing Risk Matrix

	Factor	Lack of Attention	Maintenance	Crosswind	Downwind Takeoff
	Baseline	1	1	2	1
Certificate holder characteristics	Pilot experience	2	1	3	2
	Unimproved runway operations	2	2	3	2
Risk controls	On-condition maintenance program	–	1	–	–
	Technical publications	–	1	–	–
	Awareness training	1	–	–	–
	Training	–	–	2	1

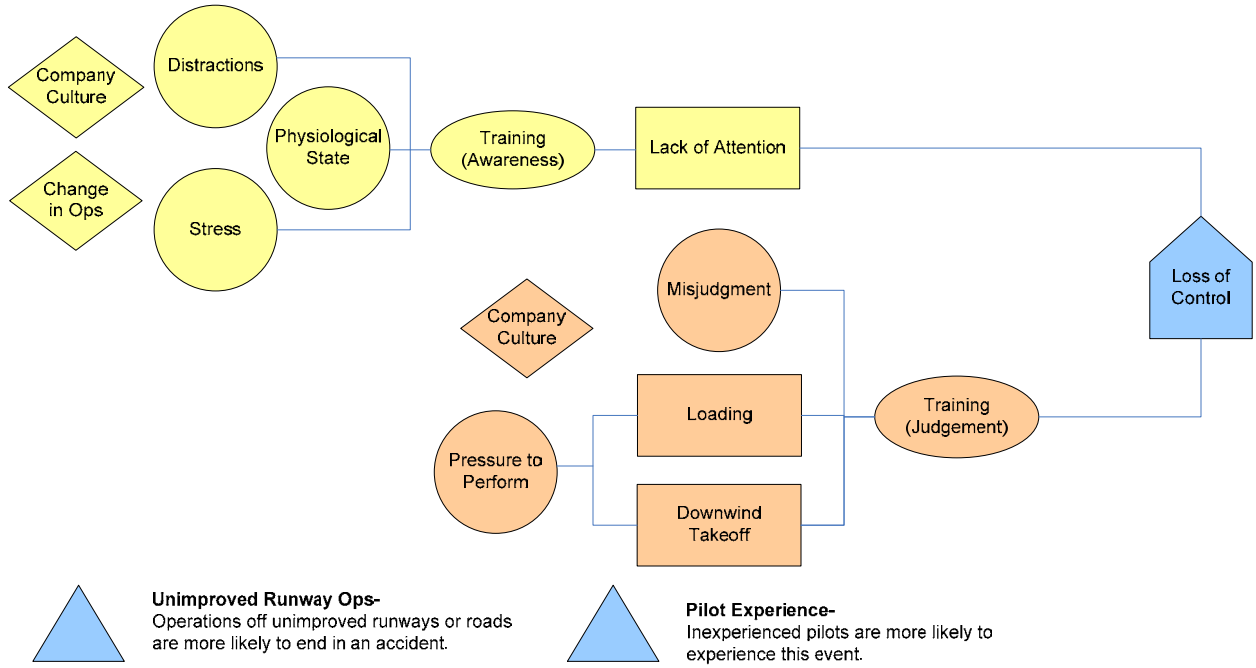

Figure 25. Loss of Directional Control During Landing

4.8.16 Collision With Other Objects During Landing.

The collision with other objects during landing is similar to collision with other objects during takeoff, as described in section 4.8.8. The main difference between these two events is that the pilot can observe objects on the runway, usually in sufficient time to perform a go-around. Similarly, personnel on the ground might have more opportunity to see an aircraft on approach and remove themselves from the runway. Table 38 and figure 26 contain additional information.

Table 38. Collision With Other Objects During Landing Risk Matrix

	Factor	Lack of Attention	Misjudgment	Loading	Downwind Takeoff	Unauthorized Runway Access
	Baseline	2	2	2	2	3
Certificate holder characteristics	Unimproved runway operations	2	2	2	2	4
Risk controls	Awareness training	1	–	–	–	–
	Training	–	1	1	1	–
	Access control	–	–	–	–	2

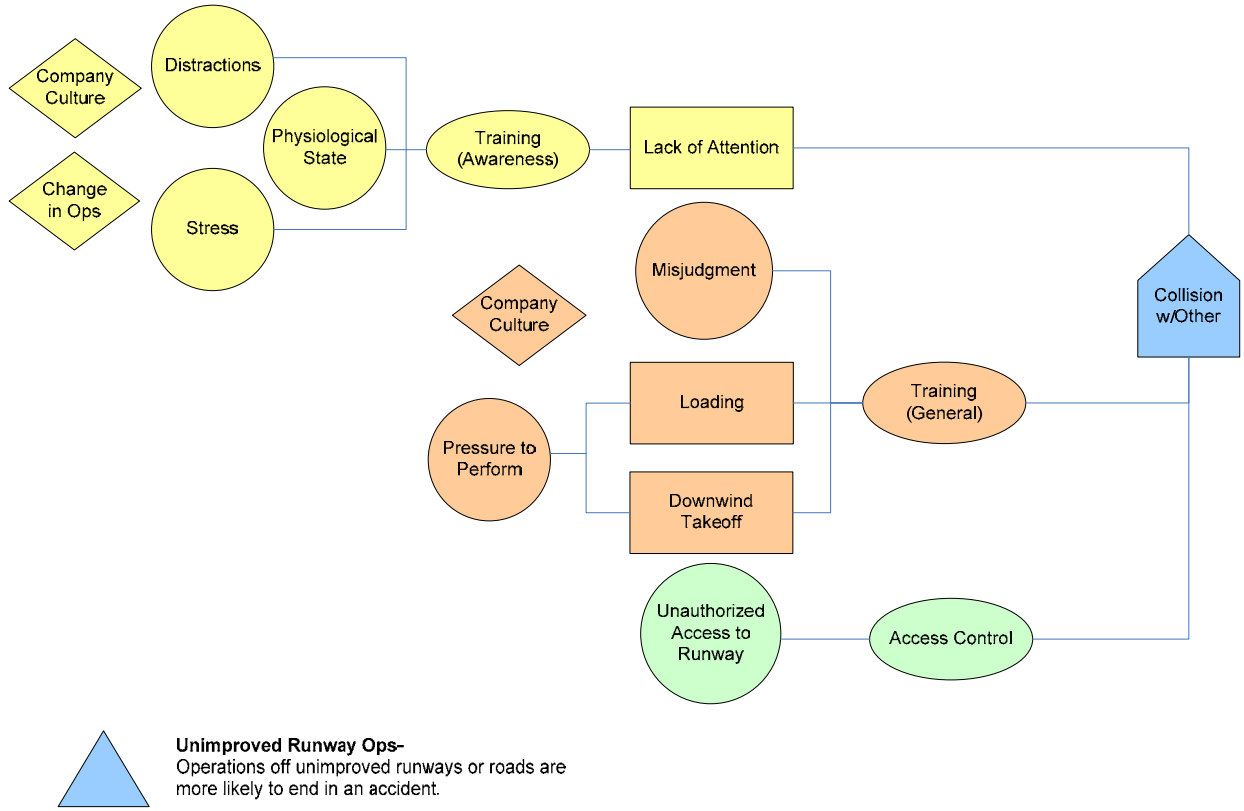

Figure 26. Collision With Other Objects During Landing

4.9 SUMMARY.

The SME meeting in St. Louis, Missouri was a success, and the data collected during that meeting set the stage for the development of the system safety metric. This completed data collection effort was based on a systematic approach to identifying and understanding hazards and unwanted events in 14 CFR Part 137 operations. This approach was not intended to identify every possible event and proximate cause. Instead, the focus was on the unwanted events that constitute the majority of events recorded in the FAA AIDS. This approach was pragmatic, as it recognizes the fact that limited resources are available to operators and the FAA to alter operations and behavior.

5. CONCLUSION.

The overall goal of the System Approach for Safety Oversight (SASO) project was to develop a system safety metric that will aid the Federal Aviation Administration (FAA) inspectors and certificate holders in the assessment of operations safety. It is anticipated that the metric will be used as a high-level screening device to identify certificate holders with potential safety problems. At the certificate holder level, the metric will be used to identify specific problem areas within the operation, providing specific feedback about ways to improve operational safety.

The general approach for the system safety metric development was rooted in general systems safety engineering practices and concepts. In brief, these practices and concepts focus on the identification of hazards within a system, the quantification of risk associated with those hazards, and the investigation of how hazards propagate through a system to cause unwanted events. Once this information is gathered, risk control mechanisms can be placed strategically within the system to reduce the likelihood of unwanted events. In essence, this report provides the bulk of this information. The data collection strategy used for the current work was designed to provide maximum information for the construction of a system safety metric, which, in and of itself, is not a typical application of systems safety engineering concepts.

Traditional applications of systems safety engineering concepts focused on a specific set of operations within a specific context. The SASO work generally falls into the realm of research because it emphasizes the application of systems safety engineering concepts across multiple organizations, each performing somewhat different functions and operating in different environments. Furthermore, unlike traditional systems safety efforts, the goal of SASO is not to directly fix system problems, but to quantify the level of safety within a given system and provide high-level feedback regarding potential system safety problems. These applications represent a unique use of systems safety engineering technologies. As such, there is a need for continued research and development of these technologies, with the measure of success defined as the extent to which the application of this work helps the FAA perform its oversight and inspection duties more effectively and efficiently, and the extent to which this work provides usable feedback to certificate holders.

6. FUTURE WORK.

The completion of the hazard identification and risk analysis phase of this project represents a major milestone, and these data will serve as the foundation for the system safety measurement model. The next phase of this project will be the development and validation of the model.

7. REFERENCES.

1. *System Safety Handbook*, Federal Aviation Administration, 2000. Available from http://www.faa.gov/library/manuals/aviation/risk%5Fmanagement/ss%5Fhandbook/

2. Clemens, P.L., *Fault Tree Analysis*, 4th ed., Sverdrup Technology, Inc., Lecture presentation, February 2002. Available from http://www.estaca.fr/bde/lev/Cours/SDF//ARBRE%20DEFAI/arbre%20defaillance%2094%20pages%20tr%E8s%20bon.pdf