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**Application of Probabilistic Risk Analysis Techniques
to Evaluate the Role of Fire Dampers
in a Cascaded Ventilation System**

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ABSTRACT

The design of chemical processing or nuclear facilities requires the control of toxic chemical or radioactive gases to prevent their release into the atmosphere. For safety, all contaminated room air must pass through absorbent filters before being released to the outside environment. For the medium to large facility, large air supply and exhaust systems are designed to move air through the facility. Because of the resulting negative pressure of the cascaded ventilation system, the building structure and the internal system must be designed to meet many accident conditions. Safety design features are required to prevent accidents and mitigate accident severity. Choosing capital spending alternatives to provide design safety features should depend on the accident conditions, occurrence rate, and accident severity. Traditionally, accident analysis only focuses on severities.

A probabilistic risk analysis (PRA) is proposed to supplement the traditional problem assessing methods. This paper assesses fire damper closures using risk analysis in evaluating the various design alternatives. The consequences of fire damper closure in a large cascaded ventilation system depend on both the facility's wall structure and the ventilation system size. There are always a variety of design alternatives to mitigate hazards and several design alternatives are illustrated. The proposed evaluation methodology can be applied to help in managerial decision.

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I. INTRODUCTION

Because of the cascade design requirement, facility areas are separated by dividing walls having HVAC ducts penetrations for air passage. Unless there are special design requirements, the dividing walls are made of conventional panels that can only handle a 5-lb/ft² differential pressure. According to NFPA 90A, when HVAC ducts pass through fire walls, fire dampers must be added to prevent propagation of fires to adjacent rooms through the HVAC ducts. These fire dampers are closed automatically on fire detection or they can be closed inadvertently. When fire dampers are closed suddenly, the cascaded ventilation system response can cause excess negative pressure on the exhaust side of some walls. If the force is large enough, the walls can deflect, or a partial wall or even a building's exterior face can collapse. Similarly, the air supply system can cause positive pressures in the upstream side rooms. In contaminated parts of the plant, the positive room pressure can cause dangerous gases to leak from control led environments.

In a design, two safety feature approaches can be assessed: one approach is to reduce the probability of fire damper closure; the second is to mitigate the hazard due to the fire damper closure. To provide a safety feature having the least hazard and cost impact requires a thorough analysis. Factors considered are causes of the fire damper closure, occurrence frequency, room pressure changes, and structural tolerance.

The hardy-cross algorithm is used to assess the airflow rate and room pressure changes under the accident conditions, and the PRA technique is used to determine the fire closure occurrence frequencies due to fires or inadvertent actuation. From the analysis results, design recommendations can be provided on an objective and cost-effective basis.

II. METHODOLOGY

The measurement of a risk associated with a fire damper closure consists of two major elements:

- (1) the consequences of the fire damper closure accident scenarios in terms of the degree of building damage.
- (2) the probability of a fire damper closure.

Four steps are recommended for performing the risk analysis: preparation, risk identification, consequence/ probability assessment, and risk management (see figure 1). A brief description on each step is presented herein.

A. PREPARATION

This step consists of the following three tasks:

- (1) **System Familiarization:** Information is acquired on facility layout, airflow rates and room pressures, fire damper locations, P&IDs, and other items that are important to the consequence severity assessment. These include structural design of walls and windows, inventory of hazardous material, and contamination zoning. The functional requirements and the safety features are identified. Information on the supporting systems, including control logics, electrical power supplies, and fire protection system, etc., is also obtained.
- (2) **Initiating Event Identification:** An initiating event is any event that causes perturbation to the normal cascaded ventilation operation and could result in a severe accident. The initiating events to the operation of the system can be identified from a master logic diagram, which uses the results of a failure mode and effects analysis (FMEA), preliminary hazard assessment (PHA), and sound engineering judgment.

Figure 1 Risk Assessment Procedure

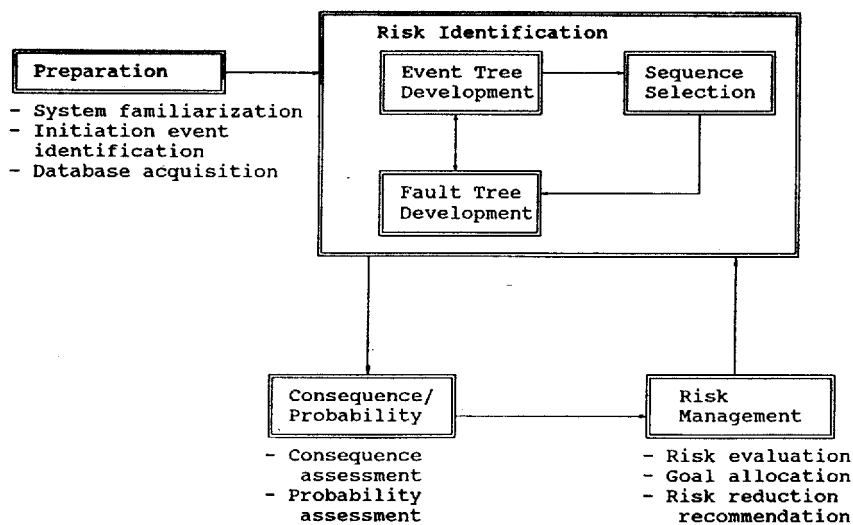


Figure 1 Risk Assessment Procedure

- (3) **Data Acquisition:** Data required to assess the probability of failure includes the component failure rates, repair rates, and testing and maintenance times. This data may be collected from various sources such as WASH-1400 [1] and IEEE-500 [2]. Appropriate error factors can be assigned to model the state-of-the-art uncertainty.

B. RISK IDENTIFICATION

Significant accident scenarios that can result in a fire damper closure accident are identified in this step. This qualitative step is important to the risk assessment because it is impossible to

include all possible accidents in the analysis. Only the significant, conceivable accident scenarios that dominate the risk to the operation are considered. The activities included in this step follow:

- (1) **Event Tree Development:** Event trees are logical diagrams that delineate the progression of accidents caused by the initiating events. The event tree headings are used to model the state of the system operation. These headings can be the barriers, their subsystems, the presence of a physical phenomenon, or the plant state. Accident scenarios are identified by considering the logical combination of the successes and failures of the event tree headings. Each scenario is called an accident sequence.
- (2) **Sequence Screening:** Because numerous sequences can develop in an event tree caused by an initiating event, only those that impose significant risk are evaluated further events with severe consequences and/or relatively high probabilities of occurrence). This sequence screening step requires familiarization of the plant design features, process operation, and engineering judgment.
- (3) **Fault Tree Development:** Fault trees are graphical models that systematically deduce the failure logic of systems or functions modeled by the event tree headings. The events in a fault tree can include different failure modes of the operating system components, failure of the supporting systems, operator errors, and presence of certain physical phenomena (e.g., flooding).

These activities are iterated to refine the analysis to a manageable scale.

C. CONSEQUENCE/PROBABILITY ASSESSMENT

Quantification of the significant accident sequences is performed to provide the basis of the risk of operation. This step consists of two parts:

- (1) **Consequence Assessment:** The consequence of an accident sequence to the facility is determined by the degree of wall damage, which is measured by the damage values defined in Table 1.

Table 1 Wall Damage Values

Wall Damage Severity	$r = \text{Diff P} / \text{Design P}$
I	$r > 3$
II	$3 \geq r > 2$
III	$2 \geq r > 1$
IV	$1 \geq r > 0$

Table I Wall Damage Values

The definition of damage values is a measurement that can be defined by the user for different design safety criteria. The damage values are calculated for each top event of the sequence. The damage value of a system is calculated by wall differential pressure, and the wall differential pressure can be calculated by any of the available computer codes commonly used in the cascaded ventilation system design. The room pressures due to upset conditions created by damper closures are computed based on steady-state incompressible flow assumptions. It is recognized that this involves low air pressures and low airflow velocities in the cascaded ventilation system, and it also involves the compressibility of air. However, because of the inherent low dynamic frequency of wall components versus the pressure wave in air, it is appropriate to assume that the peak surge pressures from a transient analysis due to sudden damper closures will not exceed the final steady-state condition. The steady-state flow in the airflow network can therefore be calculated by the loop-balancing method of Hardy-Cross [3].

- (2) Probability Assessment: The selected accident sequences described by the event trees and the related fault trees are quantified according to the approach described in NUREG/2300 [4]. Minimal cut sets are generated for the sequence fault trees. A cut set is called minimal if the system will no Longer fail when any one of the component failures in the set is restored to success. The conditional probability of occurrence of the selected sequences is then calculated from the minimal cut sets. The total (unconditional) probability of an accident sequence is the product of the frequency of the initiating event and the conditional probability of the sequence. The risk identification step and the consequence/probability assessment step are usually iterated to refine the analysis.

D. RISK MANAGEMENT

At this point of the assessment, the risk of the system reaching an accident status is quantified with the probabilities, the corresponding wall damage values, and chances of the damage values due to the failure of each safety barrier in the sequences selected. These results can be applied to the following evaluations:

- (1) **Quantitative Evaluation of Systems Risk:** The probability of failure, wall damage, and impacts to system confinement due to failure of each safety barrier are assessed, along with the total risk of the occurrence of system accidents. These quantified properties are then compared to a goal set by the design objectives. If necessary, reevaluation of facility safety features or improvement of operational procedures can be initiated to reduce the identified risk. Thus, well defined criteria can be specified effectively to evaluate the adequacy of the safety barriers incorporated into the systems design.
- (2) **Comparative Evaluation of Different Designs:** Because a quantitative basis is obtained using the PRA methodology, the risk of different designs of a cascaded ventilation system to reduce or eliminate damage due to fire damper closure can be compared on a tangible basis. The better design can be judged on the risk level and the manageability of wall damage, as well as the potential failure rates of various key components in a system design.
- (3) **Goal Allocation:** The PRA provides a common measure to determine the risk associated with different systems. With the knowledge of the wall damage values and the probability values, different systems within a facility can be compared in terms of the risk and factors that are important to air release prevention. The results can be used to prioritize the different plant systems in terms of wall damage category in order to develop plant design and maintenance schedules, allocate resources for plant improvement (e.g., the system with the highest damage risk will be investigated first), etc. The PRA can also be used in cost/benefit analyses to evaluate the justification of design changes in terms of wall damage reduction and investment requirements.

The goal allocation usually depends on the safety requirements and the capital investment. A risk assessment code (RAC) matrix is prepared for the safety design criteria. The RAC value is determined by the severity category (Table 1) and the frequency category (Table 2). Table 3 correlates the occurrence frequency and severity, and it determines the system's RAC value. A system that has a RAC of 1 or 2 is normally not acceptable and requires a design modification to reduce the RAC value to 3 or 4.

Table 2 Occurrence Frequency

Qualitative Frequency	Occurrence (event/yr)
A (frequent)	$A \geq 1.0$
B (probable)	$1.0 > B \geq 1 \times 10^{-1}$
C (occasional)	$1 \times 10^{-1} > C \geq 1 \times 10^{-2}$
D (remote)	$1 \times 10^{-2} > D \geq 1 \times 10^{-3}$
E (improbable)	$1 \times 10^{-3} > E \geq 1 \times 10^{-6}$
F (not credible)	$1 \times 10^{-6} > F$

Table 2 Occurrence Frequency

III. DEMONSTRATION OF METHODOLOGY

Figure 2 illustrates a sample application of the proposed methodology.

A. PREPARATION

- (1) **System Familiarization:** Four rooms are serially connected in a cascaded ventilation system. The air flows from Room A to Room D, exhausts through the air exhaust filtration unit, and releases at the stack. The cascaded ventilation system maintains each room in negative pressure. The requirement of the air change rate determines the airflow volume through the system. Air blowers for the air handling unit and the induced (ID) fans for the air exhaust filtration unit work together to move the air through the system. A programmable Logic control (PLC) system controls the fan speed at both the air handling units and the air exhaust filtration units to provide the airflow volume and the air filter pressure drop.

Rooms A through D are protected by a fire protection system with a photoelectric smoke detector. According to NFPA 90.A, an automatic fire damper must be installed in the ventilation duct where the duct penetrates a fire-rated wall.

Fire dampers installed between rooms prevent fire propagation from one room to another in the event of a fire accident and can also cause oxygen starvation in the room air to help extinguish the fire. The fire damper is closed automatically when a fire detection system detects a fire. The fire damper can also be closed because of a system malfunction or human error.

Table 3 Risk Assessment Code (RAC) Matrix^a

Qualitative Frequency	Severity Level			
	I	II	III	IV
A (frequent)	1	1	1	3
B (probable)	1	1	2	3
C (occasional)	1	2	3	4
D (remote)	2	2	3	4
E (improbable)	3	3	3	4
F (not credible)	4	4	4	4

^aAcceptability criteria:

<u>RAC</u>	<u>Description</u>
1	Unacceptable
2	Undesirable
3	Acceptable with controls
4	Acceptable

Table 3 Risk Assessment Code (RAC) Matrix^a

Figure 2 Sample Application of Cascaded Ventilation System

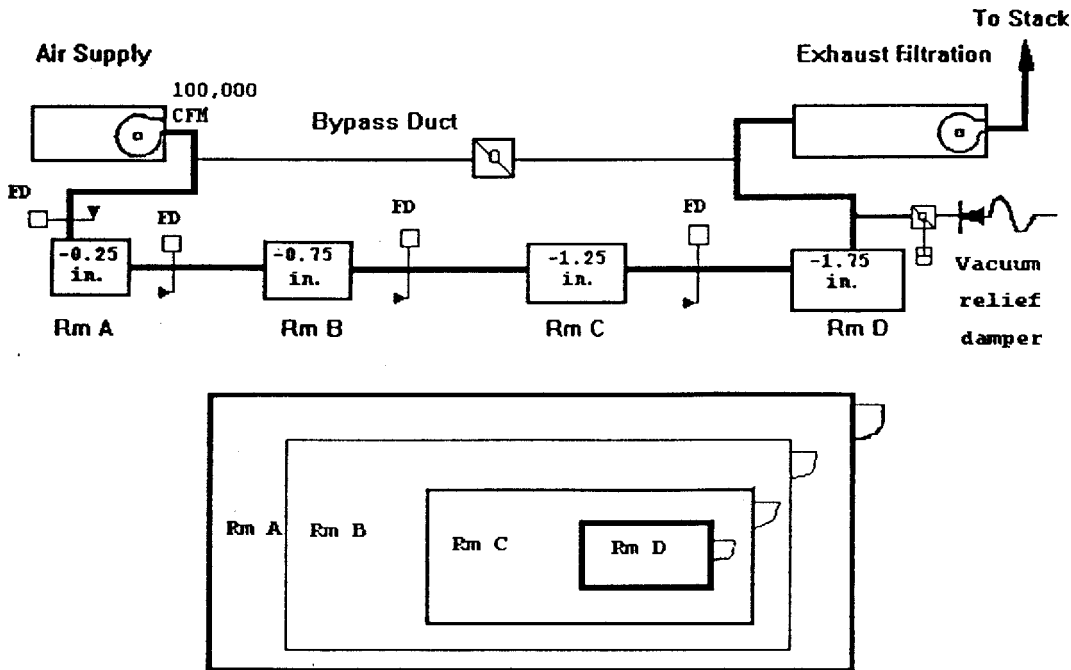


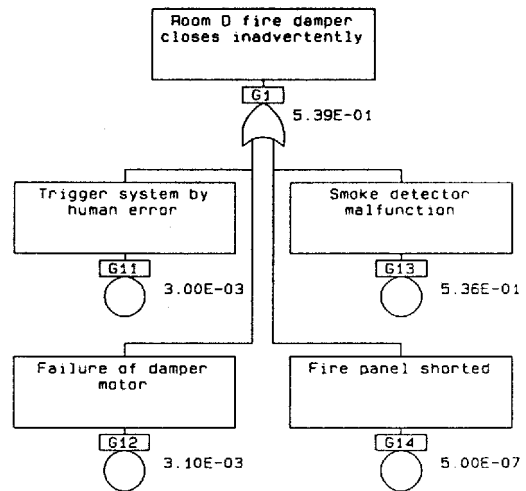
Figure 2 Sample Application of Cascaded Ventilation System

- (2) **Initiating Event Identification:** In Figure 2, two initiating events are identified as causing fire damper closure, which is caused either by a fire in a room or by an inadvertent closing of the dampers.
- (3) **Database Compilation:** The fire occurrence frequency is evaluated by using historical similar facility data. The fire damper's inadvertent closure is calculated by a constructed fault tree (see Figure 3). The fault tree shows that a fire damper can be closed by human error, fire damper motor failure, fire detection false actuation, or a fire panel's shorted circuit. The failure rate data used in the fault tree is collected from IEEE-500 [2] and DuPont [5].

B. RISK IDENTIFICATION

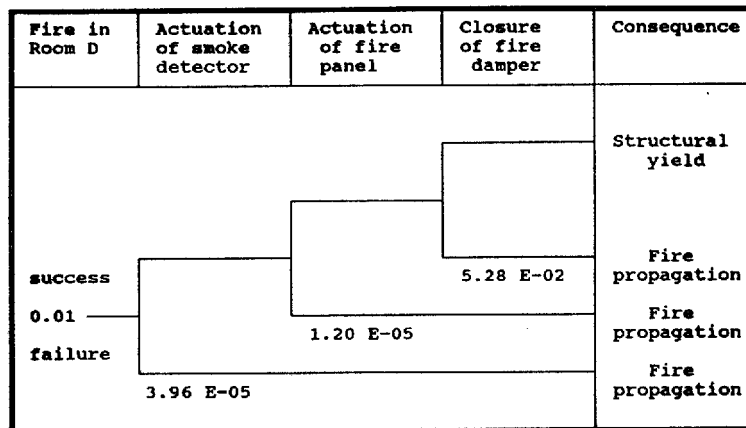
- (1) **Event Tree Development:** An event tree of a fire in Room D is demonstrated in Figure 4. The sequences of an initiating event will depend on the success and failure of the top events. The consequence of a fire damper closure to prevent fire propagation is the structural yield. However, the consequence of a fire damper not closing is the fire damage in the adjacent rooms when the fire propagates to those rooms.

Figure 3 Fault Tree for Inadvertent Fire Damper Closure



**Figure 3 Fault Tree for Inadvertent
Fire Damper Closure**

Figure 4 Event tree of Fire Damper Closure Following a Fire in Room D



**Figure 4 Event tree of Fire Damper Closure
Following a Fire in Room D**

- (2) Sequence Screening: Four accident sequences are depicted in the event tree and one sequence is investigated as a demonstration of the analysis. The sequence of a fire damper closure due to a fire accident is an important sequence to be investigated. The fire damper closure due to an inadvertent closure is a sequence event.
- (3) Fault Tree Development: As indicated in A.(3) (above), a fault tree is constructed to evaluate the probability of inadvertent fire damper closure. The major contributor of the actuation is identified clearly in the fault tree and is due to a false fire detection by the smoke detector. The fault tree of a fire occurring in a room and the fault tree of a fire suppression system failure are not shown in this sample demonstration because design specific information is required in order to have a meaningful demonstration; therefore, generic data is used for the system failure rate evaluation.

C. CONSEQUENCE/PROBABILITY ASSESSMENT

- (1) Consequence Assessment: In the case of fire damper closure, the airflow will be stopped immediately. After the fire damper closure, the ID fans of the exhaust unit cannot pull enough air out of the system, and the PLC of the system will accelerate the fan in order to meet the flow volume. At the same time, the air handling unit cannot push enough air through the system. The PLC will also increase the supply fan speed to provide more air. The increased air supply would cause pressurization of the rooms upstream of the fire damper.

If the fire damper in Room D is closed, the pressure reduces from -1.75-in. wc to -4-in. wc. The upstream room pressure increases due to the fire damper blockage. The Room C pressure increases to 2-in. wc. At this point, the wall between Room C and Room D has a differential pressure of 6-in. wc or 30 lb./ft². The material of a typical

dividing wall can withstand a 5-Lb./ft² force with 50% over design. The ratio of the pressure difference in the accident condition to the design pressure difference (1.0-in. wc) is greater than 3. The dividing wall would fail under this circumstance. Hence, the severity of the wall damage is a Category I.

- (2) Probability Assessment: The probability of a smoke detector's false detection is evaluated at 0.53. The probability of a large fire is 0.01. The frequency of an inadvertent fire damper closure is 0.54, and the frequency category is probable. The frequency of a fire damper closure due to a fire is 0.01, which is occasional.

D. RISK MANAGEMENT

From the sequence occurrence frequency and the consequence severity, the RAC value can be determined from Table 3. Current design will have a RAC value of 1 for both inadvertent actuation and fire accident. Therefore, design recommendations are required.

E. RECOMMENDATIONS

To reduce the damage severity and the occurrence frequencies of fire damper closure, the alternatives of the design are analyzed in order to avoid the fire damper closure. Risk mitigation methods are recommended to reduce risk. The following corrective measures are considered:

- (1) Provide a bypass air duct from the main supply air to an outside intake damper on the main exhaust air duct. This provision will reduce the facility damage due to excess negative pressure. The severity Level after implementing this recommendation is IV. Hence, the RAC of events are 3 and 4, respectively.
- (2) Reduce the frequency of false actuation of fire detectors by cross-zoned or confirmation design and reduce the fire occurrence rate by administrative control on the ignition source and combustible loading. This provision will reduce the fire damper closure frequency by at least two orders of magnitude. The frequency of fire damper closure becomes remote and improbable. The RAC of both events becomes 2 and 3, respectively.
- (3) Revise the automatic control system to cover all accident scenarios in which the operator can readjust the airflow to control the fan's speed and prevent a high differential pressure condition. Instead of increasing the fan speed, the system can use excess negative pressure to slow down the fan speed. After implementing the recommendation, the severity becomes III and the RAC becomes 2 and 3, respectively.
- (4) Increase the minimum design pressure for the panel or partition walls. If cost-effective, the roof and walls can be reinforced by using concrete or stronger structural material. The severity will be IV and the RAC for these events becomes 3 and 4, respectively.

- (5) Provide a vacuum-relief damper on the HVAC exhaust duct. The effect of this recommendation will be the same as (1) to reduce the severity of the consequence. The RAC value after implementing the recommendation becomes 3 and 4, respectively.

IV. CONCLUDING REMARKS

The methodology of combining current cascaded ventilation design technology and PRA technology was demonstrated to provide a very important design methodology that will ensure a safer design without excessive expenses. This methodology will also provide a quantitative basis to assist facility designers in the choice of a cascaded ventilation system that has the lowest risk among alternatives. The information generated includes the probability, wall damages, and importance measures of various key design features and components. After the system is selected, the same methodology can be used to determine the number of barriers required in order to reduce the risk to a predetermined safety margin. From a design viewpoint, the risk level is determined by the component failure rates. The proposed methodology also allows a designer to know which component plays a critical role in the overall system safety so that the designer can prescribe the necessary high-quality component and/or redundancy to improve safety.

One important application of the proposed method is the evaluation of the consequence, which will help designers and plant operators identify the consequence of the top event occurrence. This analysis will bring forth the physical design parameters that cause the top event occurrence and, hence, provides the information to assist a designer/risk analyst in mitigating the top event failure.

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