FIRE WATER SYSTEM RELIABILITY IN INDUSTRIAL APPLICATIONS

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ABSTRACT

Reliability of fire protection systems is often discussed, written about, and even put into codes and standards. However, reliability is seldom considered for the fire protection system as a whole. Why does this happen and why should the designer consider the system as a whole?

Existing codes and standards incorporate the concept of reliability usually in the form of key component redundancy for some parts of a system. The "Fire Safety Concepts Tree" presented in the National Fire Protection Association Guide 550, Guide to the Fire Safety Concepts Tree, provides a starting point for considering the performance of a water based fire suppression system.

Considering fire protection objectives for water based fire suppression systems, means of evaluating system reliability can be developed. This development requires identification of system components that are significant to the overall system reliability.

INTRODUCTION

Fire experience shows examples of failure in fire protection systems causing a fire to be ineffectively controlled. Even though there are examples of system reliability being a factor causing damage to a greater extent than acceptable, there is not sound data to clearly point to the need for specific actions in achieving a more reliable installation.

Existing codes and standards incorporate the concept of reliability usually in the form of key component redundancy for some parts of a system. Such standards include National Fire Protection Association in the United States, British Standards from Great Britain and Korean Fire Regulations.

NFPA 13, Standard for the Installation of Sprinkler Systems, Paragraph 2-1.1[1] states,

> "All materials and devices essential to successful system operation shall be listed."

This requirement is common throughout the standards of the National Fire Protection Association. By requiring materials and devices which are evaluated by an independent organization to an identified standard or is found suitable for a specified purpose, the standard implies an increased reliability. However, this does not guarantee increased reliability or indicate the degree of change in the reliability. The individual component reliability will be dependent on the criteria applied in the organization's evaluation. And the reliability of the final installation will be dependent on design layout and workmanship during the installation.

In NFPA 20, Standard for Fire Pumps, Paragraph 6-2.3.1 [2] states the following regarding electric power supplies.

> "For pump(s) driven by electric motor(s) where reliable power cannot be obtained from a private power station or utility service, one or more of the following shall also be provided:
>
> a) A secondary private power station or utility service,
> b) An on-site generator (see Section 6-2.4.2),
> c) A redundant diesel engine driven fire pump complying with Chapter 8, or
> d) A redundant steam turbine driven fire pump complying with Chapter 10."

In Paragraph A-6-2.3 a reliable source is identified as possessing identified characteristics, one of which is infrequent power disruptions from environmental or man-made conditions. Obviously, the user or authority having jurisdiction must determine the acceptable frequency of power disruptions.

In BS 5306:Part 2, Rules for Automatic Sprinkler Installations,[3] water supply reliability is addressed in Section 12.1 as follows:

> 12.1 Reliability
> 12.1.1 All practical steps shall be taken to ensure the continuity and reliability of water supplies.

Reliability is not defined and is subject to interpretation of the user and the authority implementing the standard. In these examples the concept of reliability is qualitatively addressed.

An example of a more specific approach to reliability is the following requirement from NFPA 20, Standard on Centrifugal Fire Pumps.[2]

> 8-2.5.1 Starting Devices. Engines shall be equipped with a reliable starting device.
> 8-2.5.2.1 Number and Capacity of Batteries. Each engine shall be provided with two storage battery units. ....
> 8-2.5.2.3 Battery Recharging. Two means for recharging storage batteries shall be provided. One shall be the generator or alternator furnished with the engine. The other shall be an automatically controlled charger taking power from an alternating current power source.

SYSTEM EVALUATION TOOLS

Many hazard evaluation tools are available to identify the sequence of events that can lead to an undesirable event, an accident. These tools include process/system checklists, fault tree analysis (FTA), success tree analysis and Event Tree Analysis (ETA).

System checklists provide a means of comparing a system to a standard set of requirements. The standard might be a government or enforcing body regulation. It also might be an association or company guide. It is fairly simple to implement and provides an indication of compliance with some minimum set of criteria as incorporated by the authors of the checklist. The checklist can identify basic deficiencies such as presented in the code requirements given above. It will not address individual configuration hazards which were not considered by the developers of the checklist.

The FTA, first developed in 1961 by Bell Laboratories for missile launch control reliability, is used extensively in nuclear safety analysis and in the chemical process industry. The FTA provides a model for developing quantitative information on the probability of a top event. The following steps are identified in the Guidelines for Chemical Process Quantitative Analysis published by American Institute of Chemical Engineers [4]:

1) system description and choice of system boundary
2) hazard identification and selection of the top event
3) construction of the fault tree
4) qualitative examination of the structure
5) quantitative evaluation of the fault tree

The success tree analysis is similar in concept to the FTA, but the top event is a desired result (success), not an undesired result. The "Fire Safety Concepts Tree" presented in the National Fire Protection Association Guide 550, Guide to the Fire Safety Concepts Tree [5], is a "success tree" based on the principles of fault tree analysis. The Fire Safety Concepts tree can provide a starting point for evaluating the performance of water based fire suppression systems.

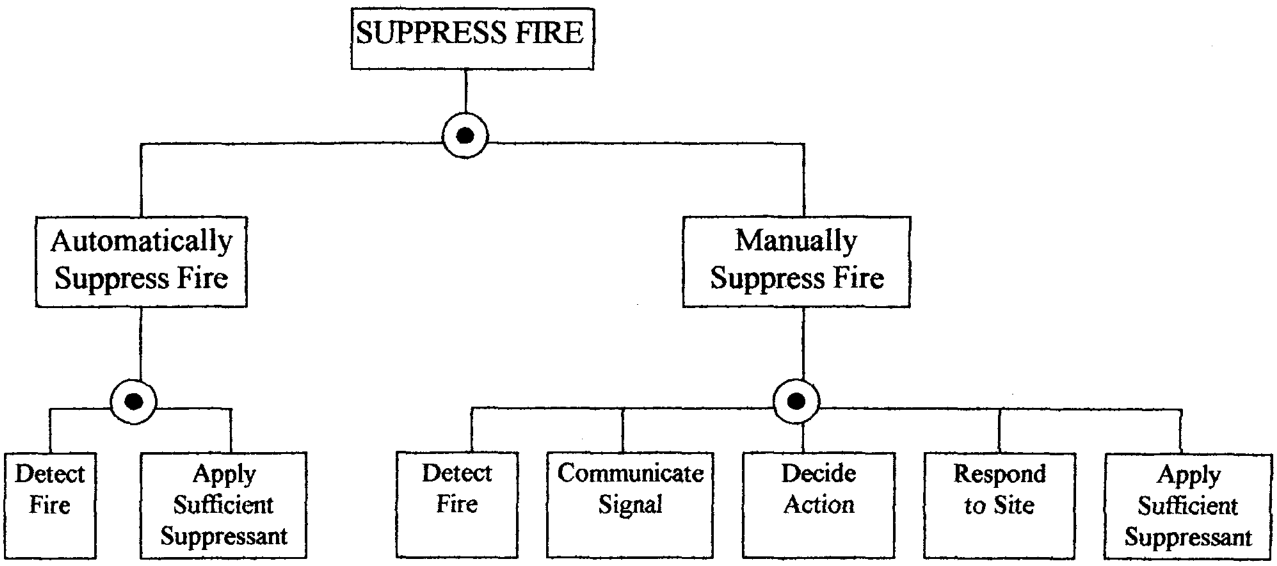

Figure 1 Fire Suppression Branch of Fire Safety Concepts Tree

For water based fire suppression systems, the top event in a fault tree could be 'inadequate water available' or 'water suppression system not available'. In a success tree the top event could be 'suppress fire' or 'system available'. The selection of the top event would be based on the purpose of the evaluation and the system boundaries defined for the evaluation.

The event tree analysis identifies and quantifies possible outcomes following an initiating event. The event tree is used in both the nuclear and chemical industries with two different applications - pre-incident applications and post-incident applications. For hazardous operations, pre-incident application can demonstrate the effectiveness of successive levels of protective measures. For protective systems, post-incident application can identify the results of a protective system component or subsystem failure.

RELIABILITY

There are many tools which are used in evaluating component and system reliability. Conceptually these can be very simple, but in practice they can be very time consuming with difficulty developing quantitative information.

Mohammad Modarres and Yu-Shu Hu give probabilistic and deterministic connotations for reliability in the SFPE Fire Protection Engineering Handbook [6]. Reliability is defined in this reference as the "ability of an item (product, system, etc.) to operate under designated operating conditions for a designated period of time or number of cycles."

The ability can be designated through a probability or designated determistically. The deterministic approach involves an understanding of why and how an item fails and how it can be designed and tested to prevent such failures.

Modarres and Hu give the following representation for the probabilistic approach.

$$R(t) = Pr(T \geq t \,|c_1, c_2, \ldots)$$

where R(t) is the reliability of the item, Pr is the probability, T is the time to failure or cycle to failure of the item, t is the designated period of time or cycles for the item's operation and c_1, c_2, ... are designated conditions. When the conditions are considered in the probability analysis, the above becomes $R(t) = Pr(T \geq t)$.

Probability relationships can then be applied to present component failure probabilities as a function of time. Mechanisms of failure are accounted for through a function called instantaneous failure rate or hazard rate. The hazard rate can be interpreted as the probability of the first and only failure of an item in the next instant of time, given that the item is presently operating. For repairable items the term used is failure rate or the rate of occurrence of failure.

The amount of failure data available will affect the adequacy of the application of data distribution characteristics. Theoretical models using insufficient or inapplicable data will not provide the user with a valid evaluation of the situation under study.

Guidelines for Chemical Process Quantitative Risk Analysis, Center for Chemical Process Safety of the American Institute of Chemical Engineers [4], states the following about the unavailability analysis of protective systems. This states:

> "Protective systems, unlike many other process systems, can fail in two distinct ways:
> 1. Protective systems can fail in a manner such that failure is revealed (e.g., a rupture disk that fails permanently due to cyclic fatigue at the normal operating condition of the process equipment). If the discharge has been designed properly, no hazard will result; but there could be economic implications such as lost and off-spec product, and process downtime.
> 2. Protective systems fail to function on demand allowing design conditions to be exceeded. In this failure pathway, the failure is unrevealed until the demand occurs (e.g., a high pressure switch fails to shut down a pump)."

The unrevealed failure is a very important consideration in performing routine inspections and tests. A parameter used in considering unrevealed features in protective systems is unavailability or probability of failure on demand or Fractional Dead Time (FDT).

If the frequency of a demand on a protective system is known (D) and the FDT of the protective system is known then a resulting “incident rate” (H) can be calculated.

$$H = D \times FDT$$

The FDT is developed from:

$$FDT_T = FDT_C + FDT_t + FDT_{et} + FDT_{er} + FDT_{cc}$$

where:
FDT_T is the total fractional dead time
FDT_C is the fractional dead time for component or system failure
FDT_t fractional dead time for on-line testing
FDT_{et} fractional dead time for human error in proof testing
FDT_{er} fractional dead time for human error in repairing
FDT_{cc} fractional dead time for common cause failure

EXAMPLE

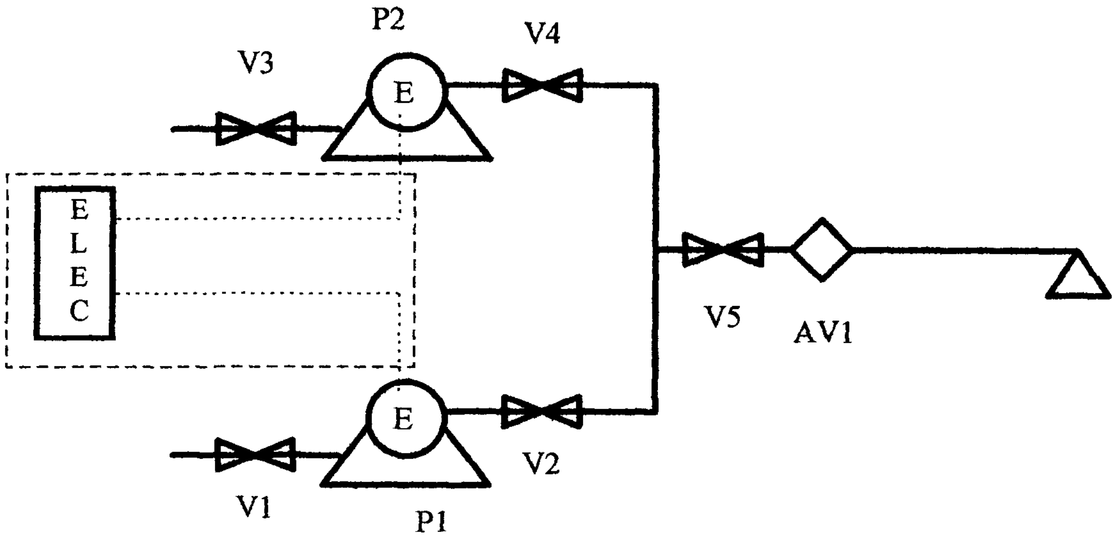

Fig. 2 Typical Water Supply Arrangement

The most common water supply for fire protection systems in Korea is provided using pumps taking suction from a water tank. Fig. 2 is a schematic diagram of this water supply arrangement. The first step is to define the boundaries of the system. Often the electrical supply to the fire pumps is not considered when designing or evaluating the fire water supply. When the electrical supply is considered, common practice is to look at only the source of electricity and not the distribution system between the source and the fire pump motors. In Figure 1 this is the area inside the dashed line. An electric generator may be provided for a plant in the event of loss of main electric power. However, this generator often supplies a piece of switchgear that supplies the fire pump motors through electrical cabling that are routed in the same path to the fire pump room.

For this example I will consider the electrical distribution system, the fire pump, and the water distribution system up to the alarm valve. Other components that could be considered are the electric motor, the pump control system including pressure switch and motor controller, the water storage tank and the pressure tank. It is important to keep the analysis as simple as possible.

The performance of the water supply system in relationship to the water suppression system controlled by AV1 can be evaluated. A fault tree for 'no water available to AV1' could be developed as shown in Fig. 3.

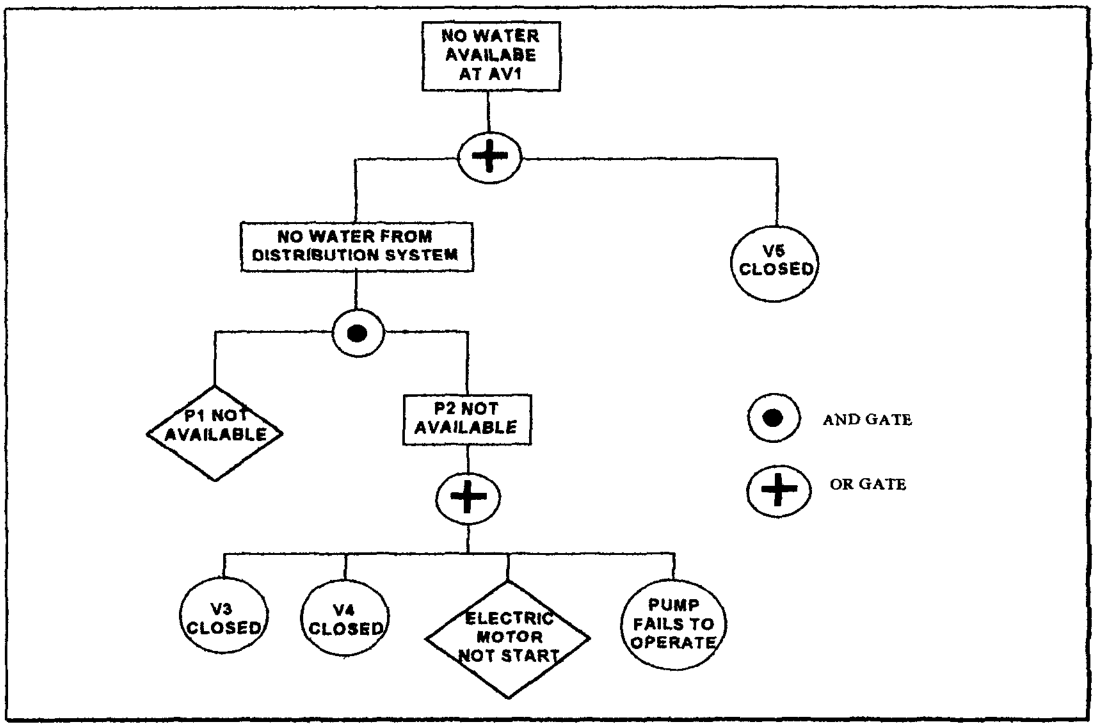

Fig. 3 Simple Fault Tree for Fire Water Distribution

In Figure 3 the development of 'P1 not available' would be the same as that shown under 'P2 not available'. The 'Electric motor not start' could be developed further considering the pressure switch, the motor controller, the electrical distribution system and the electric power supply. Probabilities, appropriate for a particular installation, can be applied to each of the stages to develop a probability for the unavailability of water to AV1. This number would only apply to the water distribution system and not to the fire suppression system itself.

The fault tree in Fig. 3 does not show that the failure of the electric motor to start could result from loss of power due to electrical distribution system that would affect both P1 and P2. A careful review of the fault tree and development of the fault tree in sufficient depth is required. Even with further development there would need to be clear equipment identification which would show that the same piece of switchgear or the same electrical raceway was connected to both pumps. A basic fault tree will not identify this type of failure which is known as a common cause failure.

Fig. 4 shows an event tree developed for this same water distribution system. 'P1 does not operate' is the initiating event. The event tree allows evaluation of key features that influence the results of P1 not operating. Here loss of electric power as a significant feature is more readily apparent. However, it is still not clearly identified as a common failure.

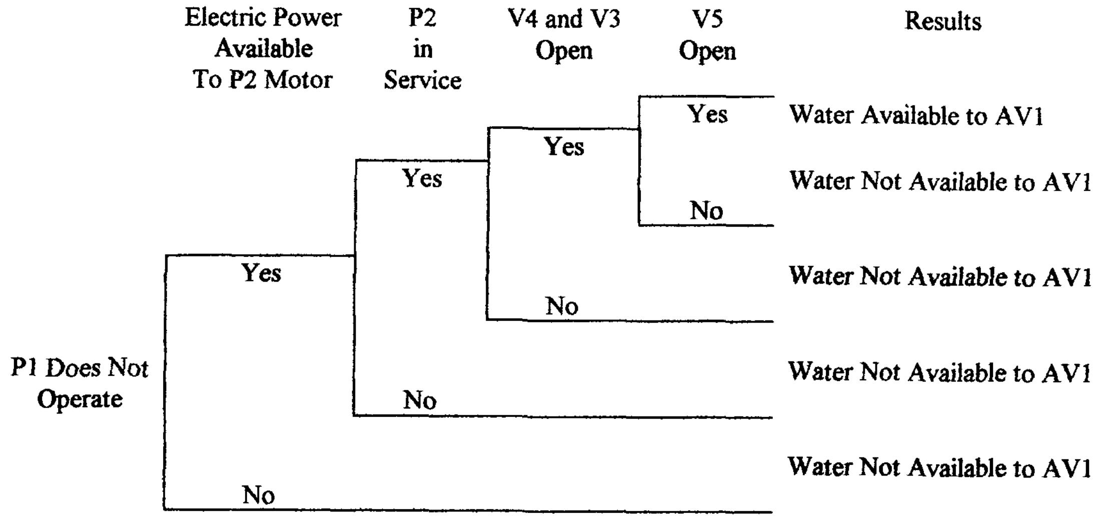

Fig. 4 Example Event Tree for Water Distribution System

When applying quantitative analysis to this event tree, the probability of P1 not operating on demand would be the start point for calculating the probability of water being available to AV1.
From Reliability Engineering and Risk Assessment by Ernest J. Henley and Hiromitsu Kumamoto [7], probabilities of failure per demand for various classes of plant hardware are presented as follows:

Class of Equipment	Range of Probability per Demand
Major Mechanical (diesel gen., etc.)	$1 X 10^{-1}$ to $1 X 10^{-2}$
Electro-mechanical (motors, clutches, etc.)	$1 X 10^{-2}$ to $1 X 10^{-4}$
Mechanical (pumps, valves, etc.)	$8 X 10^{-2}$ to $1 X 10^{-5}$
Electrical (relays, switches, etc)	$8 X 10^{-2}$ to $8 X 10^{-5}$

The ranges of data for each class has a significant variation. If the reason for developing quantitative analysis is to measure performance against an acceptable level of performance, the input data can be managed to create a predetermined result. Using quantitative analysis to evaluate comparison of alternative arrangements will be better. The quantitative results can still be misleading due to inaccuracy of input data.
However, use of quantitative data can be difficult to develop and even misleading. Sufficient plant specific information will not be available. General probability data may reflect conditions that are not fully presented in the data. Information for non-emergency systems will have different operating conditions.

The most useful application is documentation of the qualitative analyis. It is a clearer presentation of the concepts used, factors considered and, relationship between components. Such documentation is a help in future decision making for budgeting purposes and design changes.

CONCLUSION

For fire suppression water systems in industrial facilities, much of the information developed through application of systematic use of a logic method may be readily understood by the plant engineering and plant safety staff without going through this exercise. However, this understanding may not be sufficient to demonstrate to management the importance of investing in projects dealing with improved reliability.

Presentation of problems in a simple and easily understood diagram may be very important in selling management on the need to improve reliability of a particular installation. For quantitative anlaysis reasonable data supported by local and industry wide experience is needed.

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