Review

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SFPE classic paper review: Interim guide for goal oriented systems approach to building fire safety by Harold E. 'Bud' Nelson

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Introduction

Harold E. 'Bud' Nelson has made many important contributions to the fire protection engineering profession. These include his development of Fire Safety Evaluation Systems [1], the Fire Form set of fire safety calculations [2], FPETOOL software [3], and the Available Safe Egress Time concept [4], just to name a few. However, in my opinion, Bud's development of the General Services Administration's (GSA) Goal-Oriented Systems Approach in 1972 represented a turning point in the progress and evolution of fire protection as an engineering discipline. In addition, it represented Bud's initial foray into the business of pushing the profession toward systematic, engineering-based solutions for fire safety. This milestone initiated a 30-year labor of love for Bud – a determined effort to direct the profession into a new era whereby fire safety would become more of an engineering discipline.

Background

In the late 1960s and early 1970s, a flurry of activity occurred with the intent of introducing a more 'systematic' approach to building fire safety [5]. The genesis of this activity rested with the application of systems analysis for decision making in the US Department of Defense in the 1950s and 1960s. Harold E. 'Bud' Nelson was at the center of this transfer of technology to the fire safety community and was largely responsible for the development of the GSA 'Goal-Oriented' Systems Approach to Building Fire safety. There have been a number of general discussion

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papers and technical reviews published regarding this methodology [6–9]. The most detailed account of the method itself was prepared by Bud and included as Appendix D of the GSA 5920.9, Building Firesafety Criteria [6,10,11]. The published Appendix D provides a detailed description of the methodology along with the technical rationale, quantitative goals and objectives, probability estimates, and example applications.

Appendix D, more formally referred to as the 'GSA Systems Approach to Building Firesafety,' represented a major departure from code-based prescriptive fire safety requirements. For the first time, building fire protection design could be based on a systematic evaluation of the building occupancy and the performance of fire protection features and compared to stated quantitative goals and objectives (i.e., acceptable level of risk). The concepts outlined in Appendix D represented a significant beginning for today's performance-based design. The review provided here focuses on key elements of the methodology and its influence on the fire protection community. A comprehensive technical review of the methodology, the probability assignments, and areas for further development were performed by Watts [6], which includes a complete copy of GSA's Appendix D. The reader is referred to this study for a more detailed analysis of the method as well as the original document.

Methodology

The underlying structure of the Goal-Oriented Firesafety Systems Approach is a conventional decision/logic tree. The GSA tree was designed by Nelson and his colleagues at GSA to represent all available means of providing fire safety for office buildings. Therefore, at a minimum, the tree could be used as a tool for examining alternative possible means of providing fire safety and identifying interdependences. Figure 1 provides a general view of the very top of the GSA decision tree. The tree actually consisted of many more detailed branches. The level of detail associated with these branches was determined by the available knowledge needed to populate each of the branch elements with quantitative values.

Two types of logic gates were used to show hierarchical relationships among the parameters in the tree. 'OR' gates, represented by a circle with a plus sign (+) in it, were used to indicate that any one of the elements below the gate would assure the successful outcome of the element located above the gate. This is illustrated in Figure 1 where successful prevention 'OR' control of fire characteristics 'OR' protection of life and property would lead to successful attainment of the fire safety objectives. The other convention used in the decision tree was the 'AND' gate, represented by a circle with a dot (•) in it. This convention is also illustrated in Figure 1, and represents a condition in the tree where *all* of the elements below the gate are required in order to assure the successful outcome of the element above the gate. For example, in order to achieve acceptable 'PROTECTION,' both the [Life] and [Property] elements must be satisfied.

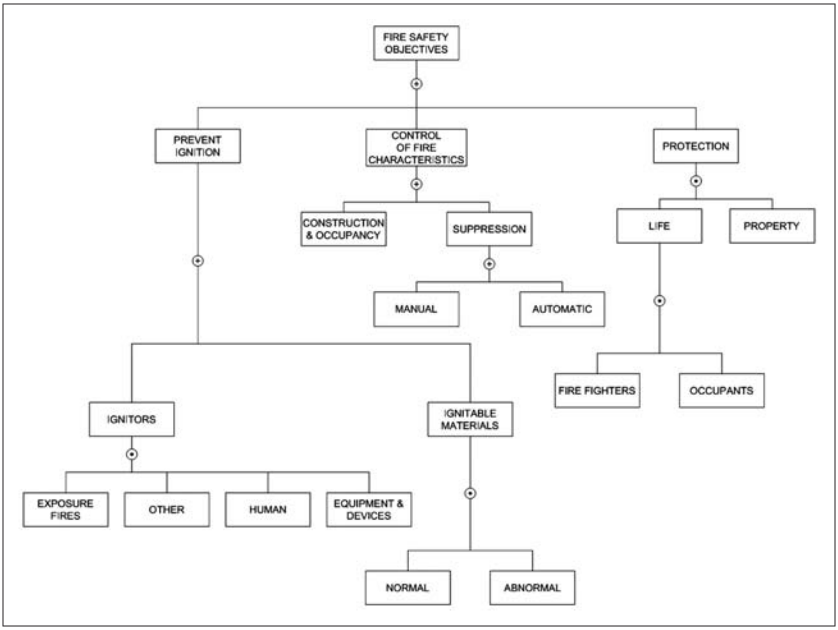

Figure 1. Primary branches of GSA 5920.9 Appendix D fire safety decision tree. Contribution of the National Institute of Standards and Technology [6].

An important component of the GSA method was the revision of GSA's policy statement on fire safety, using probabilistic criteria for mission-focused goals. Figure 2 illustrates the GSA mission critical goals for either general or critical operations in buildings. The criteria were expressed in terms of the probability of limiting fire development to each of successive spatial or structural modules within a building. Using the tree structure, probability calculations were performed for each workstation, room, and floor, based on the proposed or existing fire protection features. Where the calculated probabilities were higher than those associated with the GSA goal probabilities (i.e., values lie below the 'general' or 'critical operations' curves in Figure 2), the required safety objectives were considered met. This approach was an early attempt to develop explicit quantified fire safety goals and objectives, an element recognized by Nelson to be crucial for successful application of risk based methods.

Implementation

The GSA method has both qualitative and quantitative aspects. The qualitative component was associated with use of the decision tree as an overall guide for fire protection planning. The quantitative component relies on

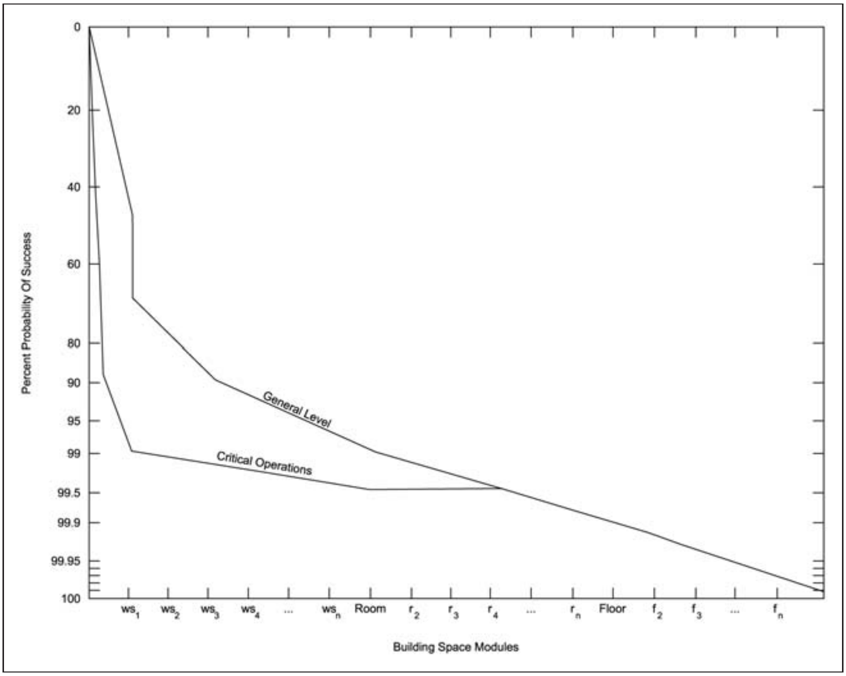

Figure 2. GSA mission focused goals (ws = workstation, r = room, and f = floor. Contribution of the National Institute of Standards and Technology [6].

deterministic knowledge and probability estimates to propagate probabilistic estimates of success through selected branches of the tree where such knowledge can be estimated.

Qualitative applications

The decision tree provided a relatively complete, simple, qualitative picture of the critical elements to be considered in developing fire safety strategies for office buildings. The designer or the authority could use the decision tree to identify interdependencies as well as candidate tradeoffs. Alternative strategies or 'tradeoffs' could be established among elements below any 'or' gate in the tree. For example, the desired success in 'CONTROL OF FIRE CHARACTERISTICS' could be achieved by successful implementation of [Construction and Occupancy] and/or [Suppression] elements (Figure 1).

This qualitative aspect of the decision tree has been used extensively in fire hazard and fire risk analyses over the years. The NFPA's Fire Safety Concepts Tree, first published in 1980 [12], is a direct evolution of the GSA decision tree and is routinely used to guide fire safety analyses.

Quantitative applications

Quantitative implementation of the Goal-Oriented Firesafety Systems Approach involved the development of a series of probability curves similar in form to that shown in Figure 2. The curves were characterized by an x-axis that represented a series of increasing fire sizes (i.e., fire spread) and a y-axis composed of the cumulative probability of success in limiting the fire size (i.e., probability of limiting the fire size to one work station, multiple work stations, one room, multiple rooms, the floor of fire origin, or beyond). The curves were based on available probability data, with refinements based on state-of-the-art knowledge regarding fire growth and spread, barrier performance, and similar input associated with each of the primary elements in the branch of the decision tree involved with fire spread. Rashbash et al. [8] includes a discussion of the lack of functional relationships associated with the probability curves due to the discrete series of fire sizes represented on the x-axis. However, the general form of the curves clearly have value in providing a means for stakeholders to envision the relative risk impact of changes in design features in the decision tree. This was one of Nelson's primary early objectives in developing this methodology.

A good illustration of the quantitative application of the GSA method involves compartment of origin calculations. In order to determine the probability of success in limiting a fire to the compartment of fire origin, the impact of the fuel source itself (i.e., likelihood of self termination) as well as the role of automatic and/or manual fire suppression needs to be determined. Nelson developed a series of probability curves, referred to as I-curves, that provides estimates of the probability of success in limiting fire growth to the compartment due to self termination. The I-curves, illustrated in Figure 3, were developed for several fuel packages expected to be present in GSA's typical office building.

Nelson also developed probability estimates regarding the expected performance of automatic sprinklers and manual fire fighting, which were provided in Appendix D. Using the 'compartment of origin' branch of the decision tree (Figure 4), the probability of success in limiting a fire to some state smaller than the compartment of origin can be calculated based on the simple 'OR' gate expression:

$$P(L_i) = 1 - (1 - P(I_i))(1 - P(A_i))(1 - P(M_i)) \quad (1)$$

where i is the designated state of maximum fire size (e.g., $1 - n$ workstations, etc.), $P(I_i)$ the probability of self termination at extent i, $P(A_i)$ the probability of automatic suppression at extent i, and $P(M_i)$ the probability of manual suppression at extent i.

The values for I_i, A_i, and M_i are obtained from individual probability curves for any building space module. The resultant value is the probability of success associated with limiting the spread of fire to a particular module within the compartment of origin.

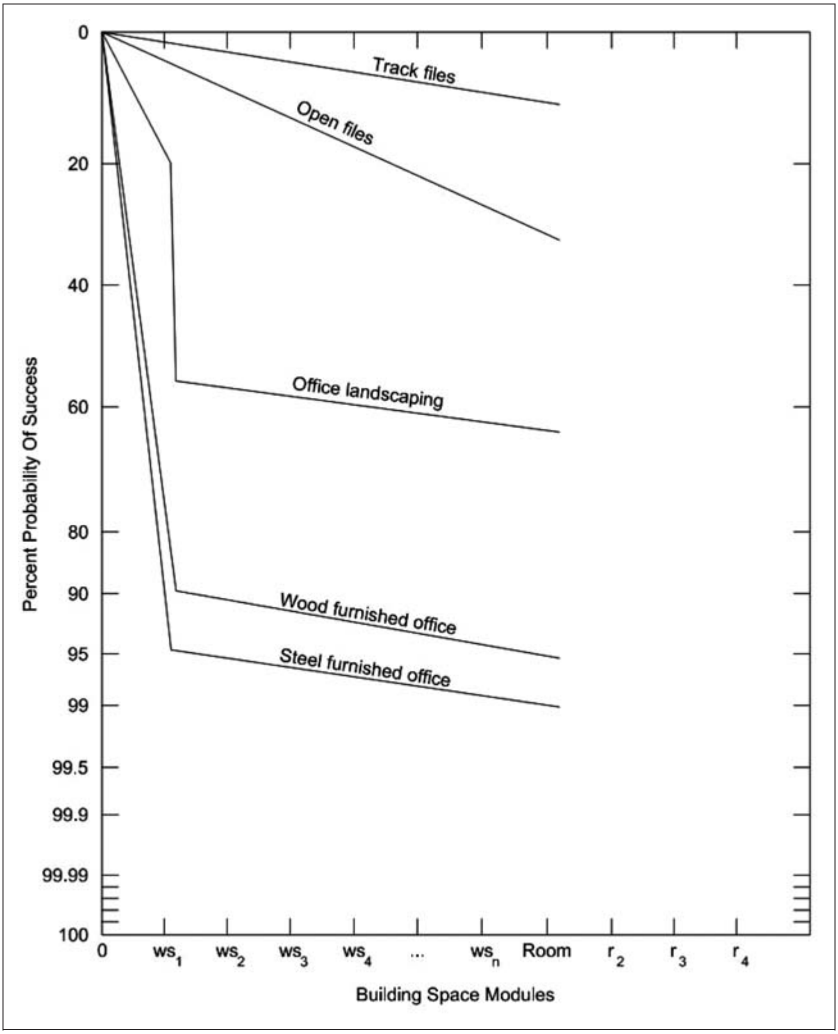

Figure 3. GSA I-curves (ws = workstation and r = room). Contribution of the National Institute of Standards and Technology [6].

Similar calculations can be performed for other branches of the decision tree, including compartment barriers. Rather than relying solely on barrier fire resistance ratings as prescribed in the applicable building codes, probability curves are developed in order to estimate the likelihood that barriers would limit the spread of a fire beyond the compartment. In this case, the key elements are (1) extent of openings, (2) thermal resistance, and (3) the structural integrity of the barrier(s). The relationship of these three elements to barrier integrity in the decision

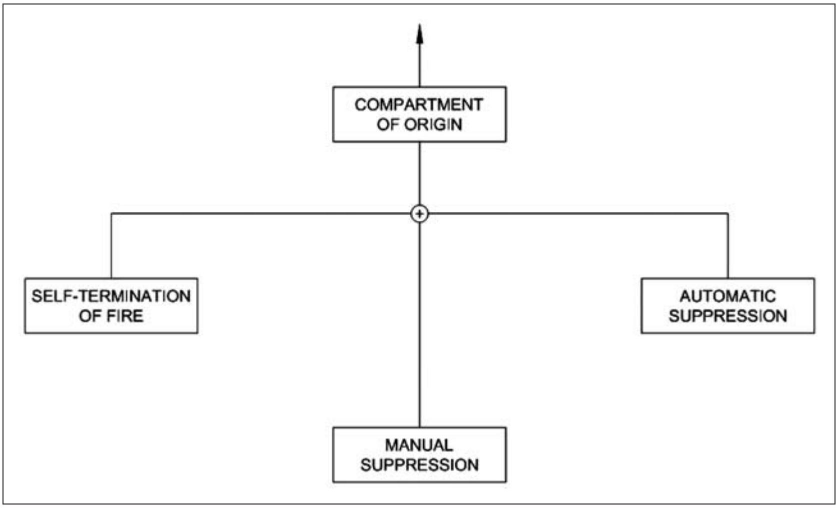

Figure 4. Compartment of Fire Origin Branch of GSA Fire Safety Tree. Contribution of the National Institute of Standards and Technology [6].

tree involves the probability of success of barrier j based on the 'AND' gate expression:

$$P(F_j) = P(O_j \cdot T_j \cdot D_j) = P(O_j)P(T_j)P(D_j) \tag{2}$$

where $P(O_j)$ is the probability of success of barrier j completeness, $P(T_j)$ the probability of success of barrier j thermal resistance, and $P(D_j)$ the probability of success of barrier j structural integrity.

Typical results

Based on a series of probability calculations for key branches in the decision tree, a final measure of fire safety, referred to by Nelson as an *L*-Curve, is determined. The '*L*-curve' for a building represents the cumulative probability of limiting fire spread at each spatial module (e.g., workstation, room, floor, and multiple floors). The *L*-curve is developed based on calculation of the cumulative probability at each module and at each barrier. An example *L*-curve is provided in Figure 5. It is the result of connecting points '*a*' through '*q*,' which represent the cumulative probabilities calculated at each point relative to the space modules. In order for the design alternative to be considered acceptable, the *L*-curve has to lie below the GSA goal curve (i.e., equal or greater probability of success). In Figure 5, the design option fails to meet the GSA goal criteria and, therefore, would not be considered viable.

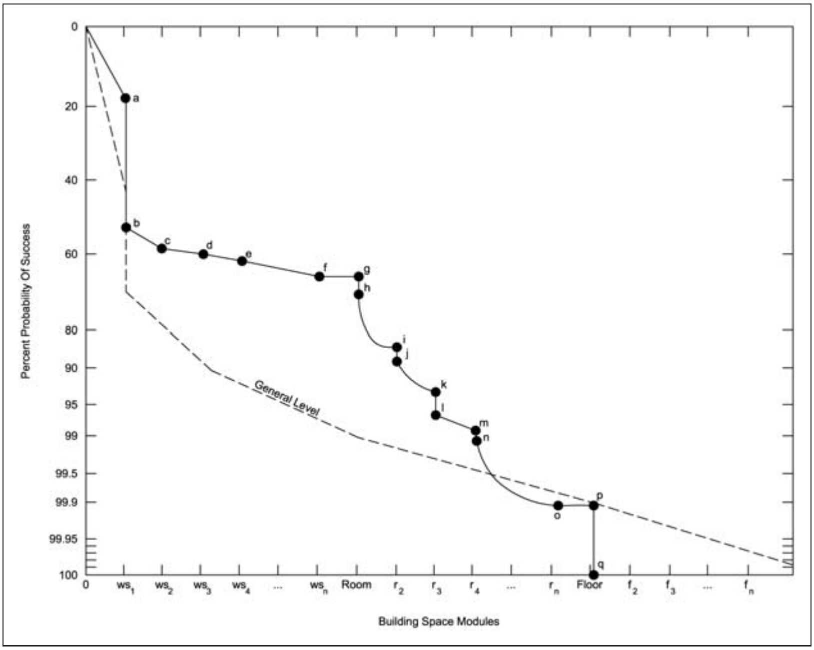

Figure 5. GSA L-curve (ws = workstation, r = room, f = floor). Contribution of the National Institute of Standards and Technology [6].

Limitations

The Goal-Oriented Firesafety Systems Approach has been successfully applied to GSA buildings. However, it is highly dependent on the accuracy of the input data for the elements that make up the key branches of the decision tree. In addition, Watts [6,7] identified several conceptual and structural limitations, including (1) limited variability in selection of fire spread scenarios, (2) the absence of a means to calculate the 'most likely' fire development scenario, (3) the extensive use of professional judgment to compensate for gaps in needed technical information, and (4) a lack of consideration for time dependencies. Beyond these issues, Watts also identified the unconventional portrayal of the probability scale (i.e., the *Y*-axis) as well as the potential failure of the decimal probability calculations to properly convey very real differences in estimated levels of fire safety [8].

Nelson did not consider the method to be complete. He knew that a number of elements in the decision tree did not lend themselves to quantitative evaluation. Due to the subjective nature of many of the elements, an exact, quantitative analysis was not expected. However, the use of the method (i.e., decision tree) and assignment of discrete values led to higher reliability and greater flexibility in fire safety design. Also, having a means to systematically document decision logic significantly extended the state of the art beyond compliance with prescriptive code requirements for a number of fire safety features, including fire resistance, compartmentation, fire alarm, and fire suppression.

Continued development activities

The GSA decision analysis framework has been broadly relied upon in the fire protection community in the development of more refined methods. As noted earlier, NFPA developed and refined the Fire Safety Concepts Tree so it could be applied. Professor Robert Fitzgerald led a significant effort over a number of years at Worcester Polytechnic Institute that resulted in the development of probability-based engineering procedures to evaluate the expected performance of building fire safety features [13,14]. In addition, SFPE developed a methodology for implementation of performance-based fire protection design [15]. These efforts, as well as others, relied on the initial work done by Nelson and his colleagues at GSA.

A quote from Watts [6] best summarizes the scope and importance of Bud's effort, documented in GSA's Appendix D:

> The distinct contribution of the Goal-Oriented Systems Approach is in the systematic consideration of fire safety. At the time of its development, it was the most inclusive systematic approach to building fire safety ever issued in the United States. It served to spur interest in systems approaches and is recognized in the United States as the principal motivational effort in the development of the application of systems concepts to fire protection engineering.

Final comments/personal notes

I met Bud Nelson (Figure 6) for the first time while I was an undergraduate student at the University of Maryland. I found his energy and vision to be boundless. This was a man on a mission. I later worked under Bud's supervision at GSA, and observed firsthand the development efforts associated with what was initially Bud's concept of systematic implementation of building fire safety concepts.

The GSA Systems Approach was the first broad-based attempt in the USA fire safety community to move from prescriptive-based codes to rational, engineering based fire safety in buildings. The efforts associated with development and implementation of this method were both challenging and rewarding. Many of the top minds in the fire safety community joined with Bud to help in the development efforts, as evidenced by the international conferences that were held to develop and refine both the framework and the input data for the GSA method [9,11,16,17].

Over the next 30 years, I observed the continual evolution on Bud's part as he moved the community from this basic systems model approach to more quantitative engineering methods. Much of what we find ourselves doing today can be attributed at least in part to Bud's vision and efforts. It has been a privilege to know Bud for all these years.

Figure 6. Harold ‘Bud’ Nelson.

In conclusion, it is only fitting to share the following comments from Dr. Jack Watts, after he read a draft of this article:

> I went from a degree in Fire Protection Engineering to Operations Research in graduate school. Subsequently I worked part time for Bud at NBS. I was amazed to see how he had intuited so many fundamental concepts of Operations Research and applied them to fire safety. I was a vehicle to get his work at GSA published for a wider audience [6] but was so taken by his insights that I focused my doctoral dissertation on his work [7]. In my mind there has never been another person who so changed thinking about Fire Protection Engineering and I believe the ramifications of his ideas will continue well into the future.

We learned of Bud’s passing on 21 July 2011 with great sadness. His passion for the profession of fire protection engineering will be sorely missed.

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