COMMENTS AND SUGGESTED EDITS

After the Alarm Sounds: How We Got Here, Where We Are, and Where We Should Go

Jason D. Averill, Erica D. Kuligowski, and Richard D. Peacock
Engineering Laboratory, National Institute of Standards and Technology

How We Got Here

Soon after the Iroquois Theater Fire (1906), the Rhoades Opera House Fire (1908), and the Triangle Shirtwaist Fire (1911),[1] the engineering and building code community in the United States began to consider the movement of people subsequent to an unwanted fire. As a response, the National Fire Protection Association (NFPA) formed the Committee on Safety to Life in 1913. Among the Committee recommendations at the 1914 NFPA Annual Meeting were building exit and stair requirements, including sufficient stair width that "the entire population could, standing still and as closely packed as possible, fit and take refuge in the stairs,"[2] which explains why the US national model codes design exits for "capacity" and why the capacity is based on the population of a single floor. The exit was sized to "store" people, motionless within the protected exit enclosure, such that the population of one floor will fit within one flight of the stair, with each person in a space 0.6 m (22 in) wide and standing on every other step.[3] By the 1930s, more sophisticated concepts for evacuation (e.g., flow rate for occupants leaving the building) were being developed. These concepts, along with the now-ubiquitous 1.2 m (44 in) stair width, were documented in 1935 by the National Bureau of Standards (NBS, now NIST) report "Design and Construction of Building Exits."[4] The landmark 1935 NBS report substantiates recommendations for exit system design based on surveys distributed to practicing architects, field inspections, citations to previous investigations as far back as 1909, as well as simple observations of exits and exit component usage during rush-hour and fire drill evacuation conditions for contemporary building designs. These recommendations constitute the primary basis for current egress requirements, though modifications have resulted from large-loss incidents, as well as subsequent research (e.g., Templar,[5] Pauls,[6] Predtechenskii and Milinskii,[7] and Fruin[8]).

In addition to stairs, the idea of leveraging the capacity of the elevator system to enhance occupant safety has been long-discussed. Both the aforementioned 1914 NFPA Proceedings and the 1935 Design of Building Exits document discuss the use of elevators for egress from tall buildings, possibly related to the observation that some evacuees in the Triangle Shirtwaist Fire used elevators to evacuate. In 1974, Bazjanac proposed using elevators to evacuate during fire emergencies[9] and presented calculations in 1977.[10] The NFPA Life Safety Code (LSC) considered the issue in the 1970s, including a detailed list of problems with using the elevators as fire exits.[11] The LSC Subcommittee on Means of Egress subsequently passed elevator egress provisions in the late 1970s (Section 5-12 proposal), but the action was overruled by the membership attending the Association's annual meeting.[12] In anticipation of the Americans with Disabilities Act (which required access to buildings but largely neglected consideration of emergency egress for persons with disabilities), a consortium, including NFPA, the American Society of Mechanical Engineers (ASME), and the Council of American Building Officials (CABO) sponsored a symposium on elevators and fire in Baltimore, Maryland in 1991.[12,13] NIST held a workshop in 1992 with the research community and elevator industry.[14] ASME hosted a follow-up workshop in 1995.[15] Recently, significant progress has been made regarding the use of elevators for egress, which will be discussed later in this article.

While verification and validation of behavioral theory lags the development of people movement characteristics, there are links between human behavior and building codes. Assembly occupancies, for example, require 50 percent of the required exit width to be located at the primary entrance since occupants consistently exit buildings preferentially by the exits through which they entered the building. In summary, while building codes, models, and technologies have evolved over many years, current design is not immune from large-loss events or inefficiencies, as we see in the next section.

Where We Are

For 2005, NFPA estimated that the total burden of fire in the United States was estimated at between $267-294 billion, or roughly 2 to 2½% of U.S. gross domestic product.[16] Direct costs, broken out by component:[*]

- Building costs for fire protection, $46 billion;
- Estimated monetary equivalent for the deaths and injuries due to fire, $42 billion;
- Other economic costs, $40 billion;
- The cost of career fire departments, $31 billion
- Net costs of insurance coverage, $16 billion
- Property loss – reported or unreported, direct or indirect, $13 billion.

Provision of adequate egress provisions (or failure to) contributes directly to the two largest direct costs: installed fire protection and deaths and injuries. Indeed, at first glance, egress is a life safety problem. Of all victims of structural fires in the United States (roughly 2,800 per annum[17]), Hall indicates that one-fourth perish during evacuation.[18] Therefore, as many as 700 persons could be saved by egress design improvements. Of these, approximately 150 would be in non-residential buildings, nearly 100 would be in apartment houses and the remainder would be in one- or two-family residences.

In order to improve the outcomes of residential fire scenarios by improving the time to escape, the design of a typical one- and two-family residence's egress system should be considered. The configuration of common two- or three-story residences requires occupants to egress down to the first floor (often the origin of fatal fires) via an unprotected path. Even in a single-story home, the configuration of the sleeping areas is often such that occupants must egress through the area of fire origin due to a dead-end corridor arrangement serving the bedrooms. However, fire fatalities may be more cost-effectively better addressed by reducing the number of fires and the resulting fire growth and spread.

[*] As an exclusively indirect cost (an opportunity cost of work not performed), the monetary value of donated time from volunteer firefighters - $80-107 billion was not reported in the bulleted list.

Egress design technologies could significantly reduce the annual life loss in non-residential buildings. Improvements in signage, markings, and lighting led to great reductions in egress time from One World Trade Center on September 11, 2001 compared to the 1993 bombing and subsequent evacuation of the same building. On September 11, 2001, self-evacuation and the use of elevators in World Trade Center Building Two (before it was struck by an airplane) led to several thousand saved lives.[19] Validated egress models which accurately convey the expected range of evacuation times are on the critical path to performance-based design (PBD); however, the present dearth of usable input or validation data renders model output highly uncertain. If validated egress and fire models with a broad range of appropriate input data were available, an Australian study estimated of the potential impact of PBD at 0.5% of the total cost of construction.[20] This could translate to national savings of roughly $5B in the United States.

While there are reasons to believe that egress research and implementation will achieve significant reductions in the national fire burden, there are also reasons to wonder whether the problem is increasing. Aggressive building designs, changing occupant demographics (an aging population and an obesity epidemic in the US and other developed countries), and consumer demand for higher-performing and more energy-efficient systems have pushed egress designs beyond the traditional stairwell-based approaches. While precious little underlying data exists for traditional stair-based egress systems, there is virtually no technical foundation for performance and economics of emerging systems such as occupant evacuation elevators, active direction egress signage, or mass notification technologies.

Egress Modeling

Evacuation calculations are increasingly becoming a part of life safety analyses. In some cases, engineers are using back-of-the-envelope (hand) calculations to assess life safety, and in others, computational evacuation models are being used. Hand calculations usually follow the equations given in the Society of Fire Protection Engineers (SFPE) Handbook[21] to calculate mass flow evacuation from any location within the building. The occupants are assumed to be standing at the doorway to the egress component on each floor as soon as the evacuation begins. The calculation focuses mainly on points of constriction throughout the building (commonly the door to the outside, transitions between egress components, or where different paths merge together) and calculates the time for the occupants to move past these points and to the outside. To achieve a more realistic evacuation calculation, or a more efficient solution, engineers have been looking to evacuation computer models to help assess key egress design aspects. Currently, there are dozens of evacuation models to choose from, with various underlying bases, interfaces, characteristics, and applications. These models can range from a numerical implementation of the hand calculations (thus having the same limitations as the hand calculations) to models that have complex equations and occupants with simulated decision-making.

There have been several recent trends in egress model features which have increased the complexity of the evacuation models overall.[22]

1. More models are including behaviors and decision-making capabilities for the simulated occupants.

2. The attributes and decisions of the occupants are often defined in a probabilistic fashion which requires multiple iterations of each simulation to determine the range of expected occupant evacuation times and movement speeds.
3. The majority of the available models simulate movement on a continuous grid. The continuous grid is more complex since occupants are not assigned to a specific cell but can instead be located anywhere in the building.
4. Modeling input is now more complex, including incorporation of fire effects into the simulation and CAD drawings import features.
5. Nearly all current models provide three-dimensional visualization of people movement and building geometry. While this change does not improve the underlying quality of the numerical results, it better enables insight into the evacuation process.

While egress models continue to develop more complex features and formulations, the underlying technical basis for modeling (which includes both rigorous, science-based theory and publicly available, well-documented datasets) has progressed substantially more slowly. The root basis for many models continues to be a handful of historic datasets.[23] As a result, rigorous verification and validation of egress models is typically lacking and is well behind the reliability of fire modeling predictions.

Human Behavior and Emergency Management

Traditionally, evacuation models and users have often made assumptions and simplifications about occupant behavior (i.e., what people do during evacuations) that can be unrealistic and are likely to produce inaccurate results. Behavioral research in the fire community has been previously conducted, including development of theory (e.g., Sime[24] and Bryan[25]) and data (e.g., Paulsen,[26] Keating and Loftus,[27] and Proulx[28]).

Kuligowski is developing a comprehensive conceptual model of occupant behavior during building fires by describing the current state of evacuation modeling of human behavior in fire, identifying gaps in current behavioral techniques, and outlining a general process model for occupant response to physical and social cues in a building fire event.[29] A theory should predict the variety of behaviors performed by occupants in a building fire (e.g., seek information, warn, rescue, and prepare). Since occupants' actions vary based on their interpretations of and interactions with their physical and social environments, it is crucial to develop a theory of occupant behavior in building fires based on social, psychological and group behavioral processes.[30]

Social scientific theory has acknowledged for over 70 years that human action or response is the result of a process. Instead of actions based on random chance or even actions resulting directly from a change in the environment, an individual's actions are frequently the result of a decision-making process.[31] Research in disasters, based on social scientific theory, has led to the development of social-psychological process models for public warning response (e.g., Mileti and Sorensen[32] and Perry, et. al[33]). These models specify that people go through a process of specific phases, including receiving the warning, perceiving a threat, personalizing the risk, and deciding upon a plan of action to protect people and property in response to a disaster.[31] Additionally, researchers of fire evacuations (e.g., Bryan,[34] Feinberg and Johnson,[35] and Breaux, et. al[36]) have shown that a process involving the phases of recognition and interpretation of the environment influence occupant actions. In these process models, there are specific cue- and occupant-related factors that influence the outcome of each phase of the process (e.g., whether the person hears the warning or interprets the situation correctly). Cue-related factors are described later in this paper and occupant-related factors include previous experiences, knowledge about disasters, and training. Research remains inconclusive about the direct effects of demographics (e.g., gender, age, income, education, race, and marital status) on the decision-making process. An understanding of the decision-making process and its influential factors can be developed into a conceptual model to predict the types of individual behaviors that are likely to occur in building fires.

People Movement Data

As part of a program to better understand occupant movement and behavior during building emergencies, NIST has been collecting stairwell movement data during fire drill evacuations of multi-story buildings. These data collections are intended to provide a better understanding of this principal building egress feature and develop a technical foundation for codes and standards requirements. To date, NIST has collected fire drill evacuation data in eleven office, municipal, and residential building occupancies ranging from six to 62 stories in height that have included a range of stairwell widths and occupant densities. The goal is to provide a solid technical basis for the required number and width of stairs in tall buildings. As the data are converted to spreadsheet and quality control is completed, it is being made available on a public website[†] for use by the fire protection and egress communities.

Additionally, to support standardization of egress datasets, Gwynne has developed a standardized format for archive data.[37] In addition to improving the ability of the user to parse and understand the dataset, standardization will enhance the quality of future data collections. By reviewing the standard data reporting and storage format prior to data collection, researchers are provided with a checklist of data collection elements which may increase the number and quality of the collected data elements.

Elevators

Elevators may become a significant component of evacuation from tall buildings in the near future and should dramatically reduce the overall building evacuation time for high-rise buildings when used in conjunction with stairs. Recent code provisions were included in both the International Code Council (ICC) International Building Code (IBC) and the NFPA Life Safety Code. Subsequent to the World Trade Center disaster in 2001, a collaborative effort between ASME, NIST, International Code Council (ICC), NFPA, U.S. Access Board, and the International Association of Firefighters (IAFF) was launched to reexamine the use of elevators.[38] This resulted in quarterly task group meetings to develop technical requirements for occupant and firefighter use of elevators during fire emergencies. Primary findings from the task groups were recently presented in December 2010 in Orlando, FL.

A recent economic analysis examined the first- and life-cycle costs for two prototypical office buildings using the IBC alternatives. For new high-rise buildings over 128 m (420 ft) high: (1) an additional exit stair is a cost-effective alternative to the installation of occupant evacuation elevators on a first-cost

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[†] http://www.nist.gov/el/fire_research/egress.cfm

basis; and (2) occupant evacuation elevators are a cost-effective alternative to the installation of an additional exit stair on a life-cycle cost basis when rental rates are high and discount rates are low.[39] Public policy should then balance the economic considerations of stairs versus elevators in the context of potentially significant egress performance benefits afforded by use of occupant evacuation elevators.

Egress Research Priorities

1 A general human behavior model with a theoretical foundation and numerical validity;

2 A database archiving actual building emergency evacuations;

3 Methods to embrace the stochastic nature of inputs and outcomes in building evacuation;

4 A validated method to integrate distributions of egress calculations with fire hazard calculations;

5 Adoption of technology for people movement, data collection, and within modeling constructs; and

6 Round-robin assessment of egress model and user capabilities.

Where Should We Go?

A Consensus Research Agenda

In order to maximize the effectiveness of limited resources, the egress community would benefit greatly from a prioritized, consensus-based research agenda. The first five proposed research initiatives discussed here were initially presented at the 5th International Conference on Pedestrian and Evacuation Dynamics in Gaithersburg, MD in March 2010.[40] By marshalling limited resources towards collectively or systematically addressing significant issues, the field can mature more rapidly and maximize the impact of future efforts. A consensus research agenda approach has been successful in other disciplines at guiding both researchers during the proposal development stage, as well as agencies or organizations which fund research. If a research proposal has the magnitude of the problem validated by an objective, traceable publication linked to the consensus of disciplinary experts, confidence in successful outcomes is increased in both funding and receiving parties. One example of a successful consensus research agenda is the Firefighter Life Safety Initiatives.[41] A representative cross-section of fire service leaders gathered and achieved consensus on sixteen priority research needs. The document subsequently guided grant applications and awards from agencies of the U.S. Federal Government. A second example of a research agenda includes the six research priorities identified in “Grand Challenges for Disaster Reduction,”[42] a document developed by the U.S. National Science and Technology Council’s Subcommittee on Disaster Research. Finally, while the “Rethinking Egress” workshop in 2008 did not produce a consensus research agenda, the proceedings document several hundred ideas for innovative technologies which may improve building evacuation.[43]

1: Develop and validate a comprehensive theory which predicts human behavior during pedestrian or evacuation movement.

Ball bearing and other physics-based models are inadequate to predict the full range of possibilities for evacuation scenarios. People make predictable, though varied, decisions when confronted with evolving information and conditions, rather than behaving like robots or inanimate objects responding to fixed laws of nature. The first step will require theoretical models, several variants of which already exist. The second step will be to develop methods (beyond observational) which can validate the components of the theoretical models. The final step is to integrate the theoretical models into the egress models.

2: Create a comprehensive database of actual emergency data.

The field of evacuation has developed largely on the foundation of a small number of (30+ year old) data sets. The data are routinely extrapolated far beyond the scope of the original data. Virtually no information exists which examines the applicability of the existing data for real emergency scenarios. A comprehensive database which catalogues the progress and outcomes for real emergency incidents (the crucible in which theory and drills are tested) is a necessary condition for acceptance and validation of all knowledge in the field. Establishment of the database will require methods to document initial conditions, incident environmental conditions, and occupant information and responses, both during the incident and post-incident. Even if the researchers knew when and where an event would occur, the infrastructure to collect, analyze, and archive the data has not yet been developed.

3: Embrace variance.

The vast majority of current generation models are deterministic. Building evacuations are highly stochastic processes. Evacuate the same building with the same people starting in the same places on consecutive days and the answers could vary significantly. In addition, the number of people present within a building (and the mobility performance of individuals) can vary day-to-day or within a day. The egress community must move away from terms such as average and evacuation time, and adopt tools and techniques which manage distributions of inputs and outputs. Probabilities should be attached to the distributions and a discussion of acceptable risk should take place in every nation and community.

4: Integrate results of evacuation models with fire models to enable accurate and reliable performance-based design

The calculation of Available Safe Egress Time (ASET) is well ahead of any reliable and validated prediction of Required Safe Egress Time (RSET). The interaction of the occupants with the constraints imposed by the emergency (e.g., people evacuating through smoke) has implications for a host of disciplinary contributions (toxicology, psychology, sociology, architecture, engineering, mathematics, to name a few). Scenarios equivalent to the SFPE performance-based fire safety design scenarios should be developed for building evacuation. In addition, both of these concepts are distributions (as discussed in Grand Challenge No. 3), and methods for combining the outcome distributions in a meaningful way that can be understood by the design and regulatory communities for safe and cost-effective building design must be developed prior to realization of the full potential for performance-based design.

5: Embrace technology.

Given the paucity of data on simple concepts (such as stairs), it should not surprise anyone that virtually no data exist for use of technology to improve building evacuation effectiveness. Technologies exist and are being developed based on integration of building sensor information, communication technologies, active signage, and movement technologies, such as elevators, escalators, and alterative escape devices. For these technologies, there are virtually no experimental data, incident data, theoretical models, or computational algorithms to encourage adoption of more effective strategies. The egress community must lead the way in enabling the enhancements by proactively seeking and developing technologies through data and models.

6. Model Validation

In addition to conducting research to establish a strong technical foundation for egress, the fire protection engineering community (a primary user of egress models), should establish a formal round-robin assessment of egress models. Validation efforts are few and largely undertaken using proprietary datasets (not in the public domain) by model developers who are familiar with the validation data, including the outcome. The round-robin should be conducted using several types of models (assuming that the model is applicable to the scenario), across several different scenarios, and by general (though knowledgeable) users, as well as expert users (possibly including developers). Ideally, the process would be consistent with a model validation standard.[‡] A round-robin assessment of egress models meeting these criteria will establish several key outcomes:

1. Variance of model output given identical inputs for several models.
2. Variance of model output for different users of the same model given similar initial information.
3. Benefits of underlying formulation and various sub-models relative to accuracy and simulation time.

Though it represents a significant community investment, given the significant life-safety and economic considerations which result from egress model simulations, it would seem prudent to have an objective assessment of inter-model and inter-user capabilities and outcomes.

Conclusion

Much work remains to enable accurate and computationally efficient simulation of the egress process. However, building evacuation and occupant safety presents the fire protection engineering and egress research communities with exciting opportunities to improve the efficiency and safety of the built environment. Embracing both disruptive technologies and the inherent variance of the egress phenomena, as well as committing to the establishment of a strong technical foundation through rigorous data collection, analysis, and validation, will achieve a “win-win” scenario: a measurable decrease in deaths and injuries through reduced capital investment in egress and fire protection solutions.

[‡] Currently, there is no standard for validation of egress models, though ASTM is considering whether to create such a standard.

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