System Safety Analysis of the Opelika Fire Department's Crawling Simulator

by

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Abstract

Firefighters have among the most physically and psychologically challenging jobs in the world, incurring more than 80,000 injuries each year. Firefighter training is crucial, as higher knowledge and experience levels are inversely proportional to their risk of injury or work-related illness. However, a paradox is created in that the training itself is the third highest cause of firefighter injury. Therefore, enhancing training safety is paramount to creating a safer overall work and training environment for firefighters. This study focused on a particular training facility, a crawling training device used by the East Alabama Fire Departments. The simulator is built into a cargo trailer and is located in Lee County, Alabama. A system safety analysis was performed incorporating the use of tools such as a preliminary hazard list (PHL), preliminary hazard analysis (PHA), risk assessment matrix, fault tree analysis (FTA), and failure mode and effect analysis (FMEA). Through the analysis, several hazards were identified and assessed, and recommendations for abating these hazards were proposed, specifically for hazards resulting from the lack of an evacuation plan and absence of an occupant monitoring system.

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List of Abbreviations

AS/NZS	Australian and New Zealand Standards
C	Celsius
CAD	Computer-Aided Drawing
CFR	Code of Federal Regulations
CPAT	Candidate Physical Ability Test
CPR	Cardiopulmonary Resuscitation
DC	Direct Current
DVR	Digital Video Recorder
FMEA	Failure Mode and Effects Analysis
F	Fahrenheit
FTA	Fault Tree Analysis
GPS	Global Positioning System
HR	Heart Rate
IR	Infrared
ISTA	International Safe Transit Association
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PHA	Preliminary Hazard Analysis

PHL	Preliminary Hazard List
PPE	Personal Protective Equipment
RPN	Risk Priority Number
SCBA	Self-Contained Breathing Apparatus
STF	Slips, Trips, and Falls
VO_2 Max	Maximal oxygen consumption
WBT	Wet Bulb Temperature

CHAPTER ONE

1.1 INTRODUCTION

Amongst the wide variety of firefighting training mechanisms, one of the most common is a confined restricted space exercise. The Opelika Fire Department has created a self-contained, confined restricted space simulator made from a converted freight trailer (tractor-trailer), located at the Opelika Fire Department Training Center in Opelika, AL. Designed by a retired fire department officer, the dimensions of the trailer are 45’ (length) x 8’ (width) x 8’ (height), and it is made primarily of framing lumber (2” x 6”) and plywood (Davis, Tang, Sesek, Gallagher, 2014). Looking inward from the rear overhead roll-up door, there are five openings that allow access to different sections of the maze, as seen in Figure 1. Crawling pathways have the ability to be blocked and diverted throughout the simulator by the use of sliding doors and hinged gates. The centermost door allows access for the trainer to walk inside the interior central hallway of the trailer in order to follow the trainee and provide assistance, if needed. There are some areas of the trailer that could prolong a rescue situation if a trainee is incapacitated or otherwise under duress.

Figure 1. Entrance to the Crawling Simulator

Because this crawling simulator is a unique structure, there are no specific construction standards or guidelines available. In addition, this simulator is intended to present environments that mimic those a firefighter would encounter while performing search and rescue or other firefighting tasks. Therefore, the paths and surfaces that the trainee negotiates in the simulator are, by design, not compliant with typical walking and working surfaces one might encounter in a manufacturing setting. As a result, some of the hazards identified in this trailer are unique and were not formally evaluated. Likewise, commercially available simulators do not have an Occupational Safety and Health Administration (OSHA) specified 'safety protocol' governing them. However, despite a lack of regulatory mandate, some newer commercial units, such as Draeger's Mobile Training Gallery, do have advanced safety features like air conditioning, ventilation capabilities, shortened evacuation routes, and video monitoring (Draeger, 2015).

1.2 OBJECTIVE

The objective of this study was to perform a system safety analysis of the Opelika Fire Department's crawling and restricted space simulator. Some of the physical obstacles encountered within the simulator include rafters, slides, stairs, tight corners, and limited mobility pathways. In addition to the aforementioned physical obstacles, the environment inside the trailer includes extreme summer temperatures, complete darkness, and some indications of mold. Upon completion of the system safety analysis, hazards were to be identified along with accompanying failure modes. Abatements for the identified hazards are proposed to reduce the severity, and/or probability of occurrence, and increase the detectability of said hazards and failure modes.

A second objective was to provide a highly monitored environment for the trainees. An infrared camera system was installed to provide an external trainer with constant visual observation of the trainee. Additionally, the trainees were provided with a biometric vest that recorded and monitored physiological vital functions in real-time.

1.3 SCOPE

1.3.1 Application

The crawling simulator is used primarily by East Alabama Fire Departments to introduce firefighting trainees and new graduates of the 16-week training program to restricted space environments. The 16-week training program consists of rigorous physical training, search and rescue operations, and equipment information sessions. Trainees are sent through the crawling simulator no earlier than the twelfth week, only after they have passed the Candidate Physical Ability Test, a physical test administered by the Alabama Fire College. Particular aspects of the

CPAT directly correlate to restricted space simulation. Specifically, Event 6 of the CPAT involves a search mission that tests “aerobic capacity, upper body muscular strength and endurance, agility, balance, anaerobic endurance, and kinesthetic awareness” (IAFF, 2015). The crawling simulator helps trainees overcome psychological conditions, such as claustrophobia, in restricted spaces and manage the limited supply of air in their Self-Contained Breathing Apparatus (SCBA). Due to the demanding nature and restricted configuration of this system, it is important to provide a highly monitored and safe environment for the trainees, while still maintaining a realistic training experience.

1.3.2 Boundaries of the System

This assessment considers the crawling simulator structure, the trainers as facilitators, and the trainees as occupants along with their associated gear. As described in the introduction, the simulator is constructed entirely from wood. The firefighting gear consists of turnout pants and coat, SCBA and associated components, hood, helmet, boots, and gloves. The number of occupants is typically limited to one trainee plus one or more trainers depending on class size.

The crawling simulator is built into a 1977 Great Dane freight trailer that is approximately 45’ (length) x 8’ (width) x 8’ (height). The drivetrain of the trailer is completely dilapidated, in that all the tires are dry rotted or flat, and the trailer is stabilized by blocks under the axles. The trailer lacks a stable foundation, such as a concrete pad, and as a result, some uneven settling of the support blocks in the grass and soil has occurred. A 3D computer-aided drawing (CAD) representation of the trailer was created to illustrate the multiple possible pathway configurations (Figures 2 and 3). Figure 2 shows the CAD simulation of the internal structure of the crawling simulator, as seen from the posterior, or back side of the simulator furthest from the entrance, without the surrounding walls of the trailer present. Similarly, Figure 3 shows the internal structure viewed from the front side entrance, where the roll-up door is located.

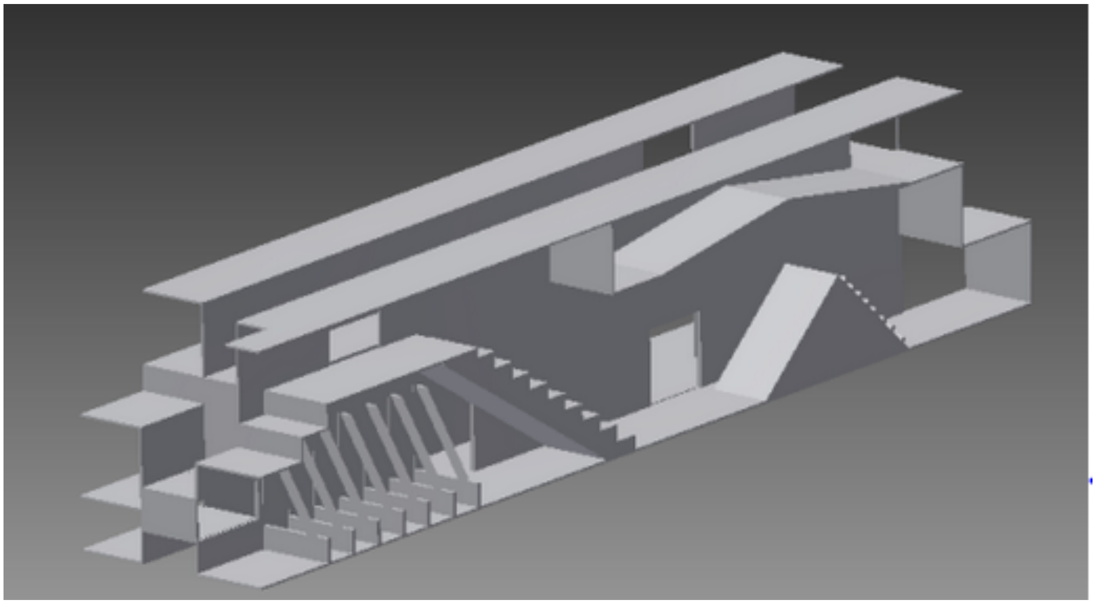


Figure 2. Posterior AutoCAD representation of the internal structure

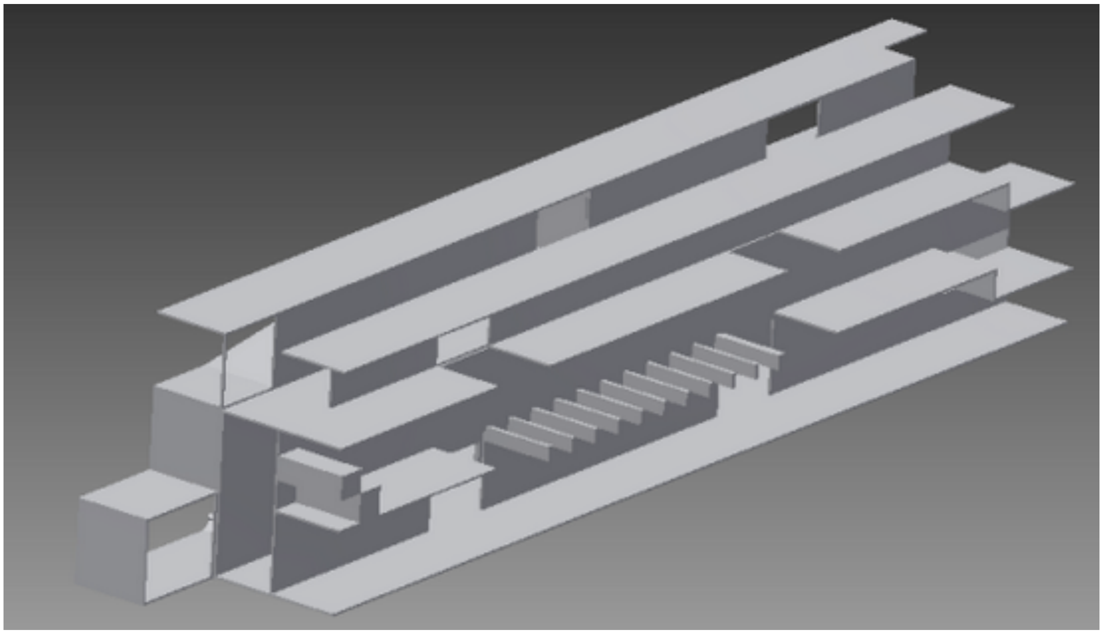


Figure 3. Anterior AutoCAD representation of the internal structure

The internal structure of the simulator is comprised mainly of plywood with framing lumber (2 inch x 6 inch) as the structural supports, and the pathway deviations are made of sliding and hinged plywood doors. Most of the plywood has been worn to a slippery finish from wear and environmental factors over time. The central hallway has several lights to provide visual acuity for the trainer, but the rest of the trailer is devoid of light sources to provide a suitable dark training atmosphere. As shown in Figure 2 and 3, the simulator consists of angled hallways, staircases of varying step size and count, a steep slide portion, and rafters/ceiling joists to mimic obstacles commonly encountered in real-world environments.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Personal Protective Equipment (PPE)

2.1.1 Firefighting Garment Characteristics and Requirements

During emergencies, firefighters wear a myriad of personal protective equipment (PPE) along with a self-contained breathing apparatus (SCBA) to protect themselves. Typically, firefighting garments are composed of an outer flame resistant shell, a moisture barrier, and multiple insulating thermal liners. These garments are a firefighter's main line of defense against flame exposure, thermal flux, flashovers, and puncture and abrasion hazards. There are many requirements set forth by the National Fire Protection Agency (NFPA) for firefighting PPE, such as Thermal Protective Performance (TPP), Compressive Conductive Heat Resistance (CCHR), and Total Heat Loss (THL), among many others.

Thermal Protective Performance (TPP) is a rating associated with temperature extremes during flashovers or backdrafts. Generally, thicker and heavier materials will have a higher TPP rating. The National Fire Protection Agency states that firefighting turnout gear must have a 35 TPP rating or higher. This number is what the NFPA considers to be the best balance of thermal protection while maintaining adequate movement capabilities and weight minimization (NFPA, 2014).

The Compressive Conductive Heat Resistance (CCHR) test is designed to test PPE "pinch points," typically the knees and shoulders, where the garments commonly become compressed. The test is a measure of the time it takes for a sample's surface temperature to increase 75.2° F when exposed to a heat source of 536° F. Additionally, the test is conducted with the thermal lining in both a dry and wet condition. TPP and CCHR are linearly related, in that a garment with a higher CCHR rating will also ascertain a higher TPP level.

As the body works hard metabolically, it must exhaust the excess heat produced by the musculoskeletal system. In order to shed this surplus heat, turn out gear must be somewhat breathable while maintaining acceptable outside heat protection. Total Heat Loss (THL) is the NFPA standard measurement for a garments ability to lose heat. The test measures the combined effect of how much heat is exhausted through the material in both conductive and evaporative conditions. As nearly 50% of all firefighter deaths are attributed to cardiac and stroke events, THL is considered one of the most important variables to reduce heat stress and its accompanying effects. As temperatures can regularly surpass 100° F in the simulator, it is of the utmost importance that trainee’s turnout gear meet or exceed the aforementioned standards to alleviate heat stress.

2.1.2 Self-Contained Breathing Apparatus

A Self-Contained Breathing Apparatus (SCBA) is an imperative support line to a firefighter. Open-circuit SCBAs are composed of a full facemask, regulator, air cylinder, pressure gauge, and an adjustable carrying harness. Air cylinders account for the majority of the weight associated with SCBAs, as materials range from steel, to lighter weight aluminum, and even lighter carbon fiber composites. Firefighters use “positive pressure” SCBAs to prevent inward leaking of potentially contaminated air from the environment. The system works by creating a slightly higher than atmospheric pressure inside the mask than that outside the mask. This results in a constant outflow of clean air through any opening created in the facial seal. Figure 4 shows a generic SCBA commonly worn by firefighters.

Figure 4. Example of typical SCBA worn by firefighters
(https://www.scottsafety.com/en/us/DocumentandMedia1/AP75i%20SCBA-w-AV3000-SureSeal.jpg)

2.1.3 Self-Contained Breathing Apparatus Problems

Many SCBA pressure gauges are susceptible to pressure misrepresentations caused by the heating or cooling of the supply cylinder. Pressure and temperature are dependent variables, evident through the Ideal Gas Law, PV = nRT. If a firefighter's tank is charged to 4,500 psi at 80°F (299 K) at the station, but then remains outside on a cold 30°F (272 K) day, the actual pressure inside the tank drops by a factor of 1.102 to only 4,083.5 psi (assuming the tank remained at 4,500 psi). This scenario can also be reversed - pressure gauge readings can increase when entering a significantly higher temperature room from a lower temperature area, as well. While there is an absence of literature regarding this relationship, future research could be conducted to investigate this problem.

A second failure point of SCBAs is the heat exchange from the outside environment to the air inside the tank. In an experiment performed by Michelle Donnelly and Jiann Yang, pressurized SCBA air cylinders were placed into a constant flow oven heated to 212-392° F to conclude whether external heat sources effect internal breathing air temperature. The cylinders were subjected to 392° F for 20 minutes resulting in breathing air repeatedly exceeding 140° F (Donnelly and Yang, 2015). When temperatures in the respiratory tract tissue eclipse 111.2° F, the mucous lining begins to breaks down and tissue damage soon follows (Lv, Liu, Zhang, 2006). If air temperature being inhaled exceeds 212° F, burns to the larynx can occur depending on exposure time (Purser, 2008). However, since recorded cylinder outlet air temperatures still reached above 140° F (measured by placing a thermostat in direct path of the expelled gas from the cylinder air valve), prolonged exposure to inhaled air at these elevated temperatures could potentially cause respiratory damage from the progressive heating of respiratory tract tissue.

Tissue temperatures of the tongue and hard palate have been shown to be directly related to the wet bulb temperature (WBT) of the inspired air (Gallagher, Vercruyssen, Deno, 1985). The results of this study showed that temperatures as low as 93.2° F WBT corresponded to relatively high (scored an eight out of twenty) perceived discomfort in subjects. Also cited in this study, the National Institute for Occupational Safety and Health (NIOSH) guideline for the amount of heat generated by an SCBA is not to exceed 105.8° F when the relative humidity is in the 51-100% range (Gallagher et al., 1985). While certain inspired air temperatures are nonhazardous at lower relative humidity levels, higher relative humidity levels in inspired air can pose a health hazard to the subject over a prolonged period.

2.1.4 Slips, Trips, and Falls (STF) Associated with PPE

Every year, roughly 11,000 firefighters are injured due to slips, trips, and falls (STF) (Park, Rosengren, Horn, Smith, Hsiao-Wecksler, 2011). Since turnout gear can weigh anywhere from

45 pounds to 75 pounds, the added weight is an obvious stability burden. This is especially apparent when considering that the air supply for the SCBA is worn outside the body's center of gravity. Even when a fire is not present in an emergency situation, STF remain a constant hazard to firefighters, as they are required to wear complete turnout gear regardless of the severity of the emergency. Accidents involving STF have observed to account for the longest work absences and highest worker's compensation claims of any incurred injury for firefighters (Cloutier and Champoux, 2000; Walton, Conrad, Fumer, Samo 2003). As material technology continually progresses, lighter weight alternatives can potentially reduce the weight and associated hazards with heavy turnout gear.

2.2 Heat Stress

During the peak summer months, Alabama temperatures can routinely exceed 90°F, often times peaking above 100°F in the afternoons (Chaney, 2013**)**. Once ambient air temperatures reach these levels, the hypothalamus will begin thermoregulatory countermeasures to maintain internal homeostasis. The body regulates temperature by inhibiting an andrenergic, or adrenalinic, response that causes an increase in cutaneous vasodilation, heart rate, and eventually involuntary sweat release (Guyton, 1996). It has been shown that subjects routinely underperform tasks when undergoing heat stress, and the increase in breathing rates consequently causes a faster oxygen consumption than that of a non-heated environment (Axford, McKerrow, Jones, Le Quesne, 1976). In addition to the aforementioned effects, muscular fatigue rates elevate and cognitive performance decrements begins to become apparent even with rudimentary tasks (Rowell, 1974 and Smith, Petruzzello, 1998).

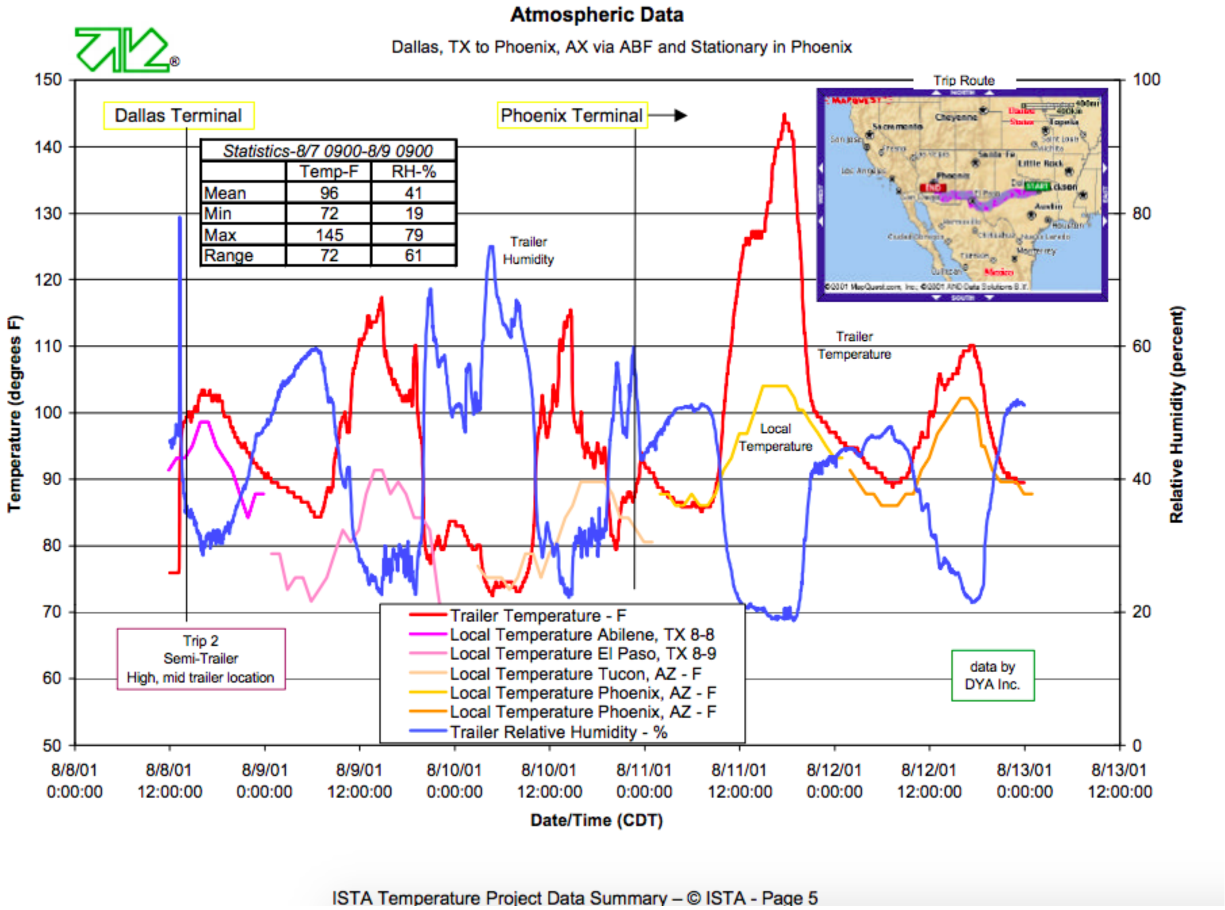
Sweating, the body's most efficient and effective means of exhausting heat, is greatly hindered by a firefighter's turnout gear and clothing requirements. Average core temperature increases from 1.2° C-1.9° C have been shown in live-fire testing with subjects wearing full turnout gear, along with an induced total body weight dehydration average of 1.1% (Fernhall, Fahs, Horn, Rowland, Smith, 2012). Direct corollary effects have been found showing that increased core temperatures in conjunction with dehydration causes STF and balance instability (Smith et al., 1998). Therefore, while turnout gear is a vital support to firefighters, proper acclimation and firefighting training to such elevated core temperature spikes and prolonged exertions are key to survival during emergency situations.

2.2.1 Heat Stress in Overweight Subjects

Firefighters have been shown to reach near-maximal heart rates in as little as a few minutes, especially when coupled with heat stress (Geibe et al., 2008). It has been hypothesized that fatal cardiac events are triggered by elevated cardiovascular demands, thermal extremes, and the psychological demands encountered during firefighting activities (Barr, Gregson, Reilly, 2010). Prolonged exercise in overweight individuals has been shown to have an increased strain on cardiac functionality, as certain studies report nearly 80% of firefighters are overweight and have an average BMI of over 30 (Soteriades et al., 2005; Geibe et al., 2008). Although a direct link has not been established, its estimated that 20-30% of firefighters are hypertensive, inevitably contributing to cardiac complications in high stress and heat situations (Kales, Soteriades, Christophi, Christiani 2007).

2.2.2 Heat Trends Inside Enclosed Trailers

The International Safe Transit Association (ISTA) performed a study that showed there is a heating effect, or an increase in the internal trailer temperature over that of the outside temperature, with enclosed tractor-trailers. ISTA found that this heating effect is present throughout a broad range of ambient outside temperatures, ranging from a few degree increase at mild temperatures to a 41°F increase when the outside temperature was 104°F (ISTA, 2002). An interesting facet to note is that the temperature inside the trailer is inversely correlated with the relative humidity inside the trailer, as well. As relative humidity decreases inside the trailer, the inside temperature rises in accordance, as shown in Figure 5. Since heat stress represents a significant concern to the profession, steps are continually being taken to improve turnout gear to alleviate the associated bodily stresses.



Statistics-8/7 0900-8/9 0900

	Temp-F	RH-%
Mean	96	41
Min	72	19
Max	145	79
Range	72	61

ISTA Temperature Project Data Summary – © ISTA - Page 5

Figure 5. Inside Trailer Temperature vs. Outside Ambient Temperature (www.ista.org/forms/ISTA_Temperature_Report-2002.pdf)

2.3 Oxygen Deficiency Effects

Another prevalent cause of morbidity and mortality in the firefighting profession is hypoxia (Prien and Traber, 1988). According to the Occupational Safety and Health Administration (OSHA), if ambient oxygen levels decrease below 19.5%, the space is considered inadequate to sustain normal life and the entrant may start to notice adverse biological effects from the lack of oxygen (Riaz, Arslan, Khalid, 2014). Low oxygenation of the blood can cause heart and breathing rates to increase as the cardiac system tries to compensate for the oxygen deprivation

(Riaz et al, 2014). Hypoxic effects can, however, be observed in a normally oxygenated environment by hypoventilation during strenuous exercise (Woorons, 2014).

CHAPTER THREE

3. METHODOLOGY

3.1 RESEARCH PLAN

During the initial site visit, an outside walk around the trailer allowed preliminary observations of the trailer, and an initial safety consensus of the trailer's internal structure and layout. In order to create a safer environment for trainees in the simulator, a monitoring system was proposed to allow trainers to maintain constant visual contact with trainees. Once the plan to develop the monitoring system was in place, an ensuing Preliminary Hazard List (PHL) was compiled to begin the system safety analysis. Upon completion of the analysis, abatements were proposed for the observed hazards, as well as a statistical analysis performed to estimate the probabilities for the initiators of all said hazards.

3.2 DATA COLLECTION

A 3D model of the internal structure to the simulator was developed. Through firsthand measurements, Figure 1 and 2 allowed a complete perspective of the system. Given a set number of fourteen IR cameras, the AutoCAD rendering was used to map where each camera could be placed to eliminate blind spots. After several mockup configurations were considered, a layout was decided upon and installed.

Preliminary hazards were noted from initial site visits, but subsequent visits allowed for a more in depth evaluation of the previously noted hazards. Firefighters from the Opelika Fire Department were on site for assistance and to re-configure the simulator to demonstrate the complexity of the maze. Training officers report that the trainee time to crawl through the maze can be adjusted between 5 and 25 minutes. Through interactions with trainees and officers, appropriate firsthand probabilities associated with certain hazards were estimated, and further group collaborations provided feedback on the efficacy of proposed hazard solutions.

3.3 SYSTEM SAFETY ANALYSIS PROCEDURE

To complete the safety analysis, a team was devised to “divide and conquer” the process. The team consisted of Abishek Rao, Menekse Salar, and Claire Schmidt from the Auburn University Occupational Safety and Ergonomics Graduate Program. The team collaborated and discussed on every step of the process to ascertain the most accurate analysis.

The first step used in the safety analysis was to generate a Preliminary Hazard List (PHL), which was used to identify as many potential hazards in the system as possible. The PHL includes potential hazards that were both observationally collected from site visits and acquired from firefighter’s experiences through interviews. Using the PHL as a basis, a Preliminary Hazard Analysis (PHA) was then conducted, where each hazard was analyzed for a possible abatement to both ameliorate the risk and reduce the severity associated with each outcome. From the findings in the PHA, the team developed a Fault Tree Analysis (FTA) to highlight common/basic events worst/top case events and analytically derive the probability of each event occurring. Finally, the team performed a Failure Mode and Effect Analysis (FMEA) on the current system, and then reevaluated this analysis by including interventions and recommendations.

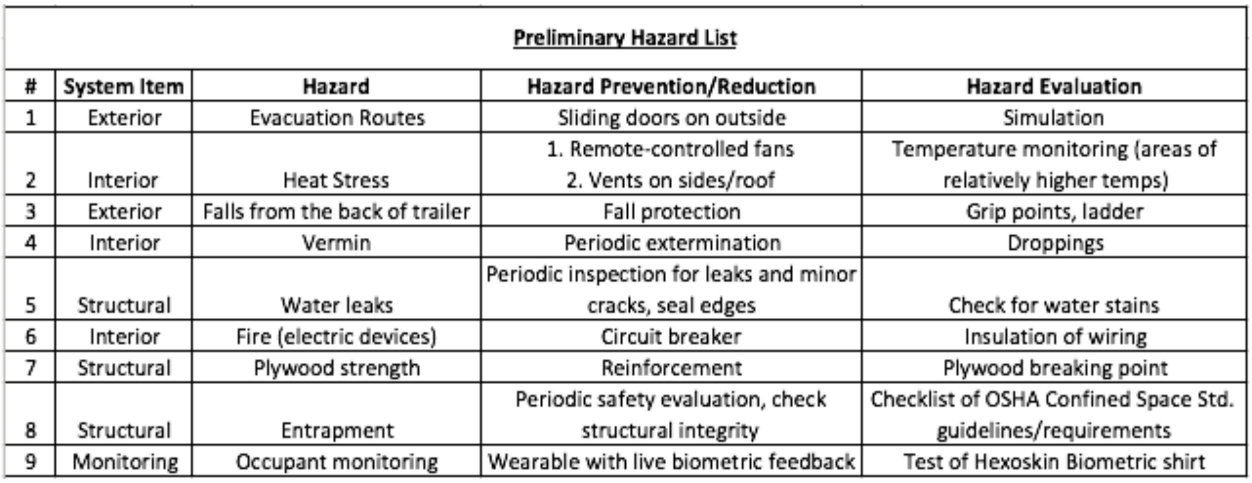
CHAPTER FOUR

4. SYSTEM SAFETY ANALYSIS

4.1 Preliminary Hazard List (PHL)

A PHL provided a simple overview of all the known hazards present in the current system. Typically, the PHL will consist of the hazard itself, initial prevention strategies, and general initiators. The simulator was divided into four subsystems (Exterior, Interior, Structural, and Monitoring) to allocate hazards into more specific categories. Within each of these subsystems, hazards were identified and compiled below in Table 1. A primary analysis provided ways to lower the risk of the hazard and specify ways to further investigate end effects.

Table 1. Preliminary Hazard List



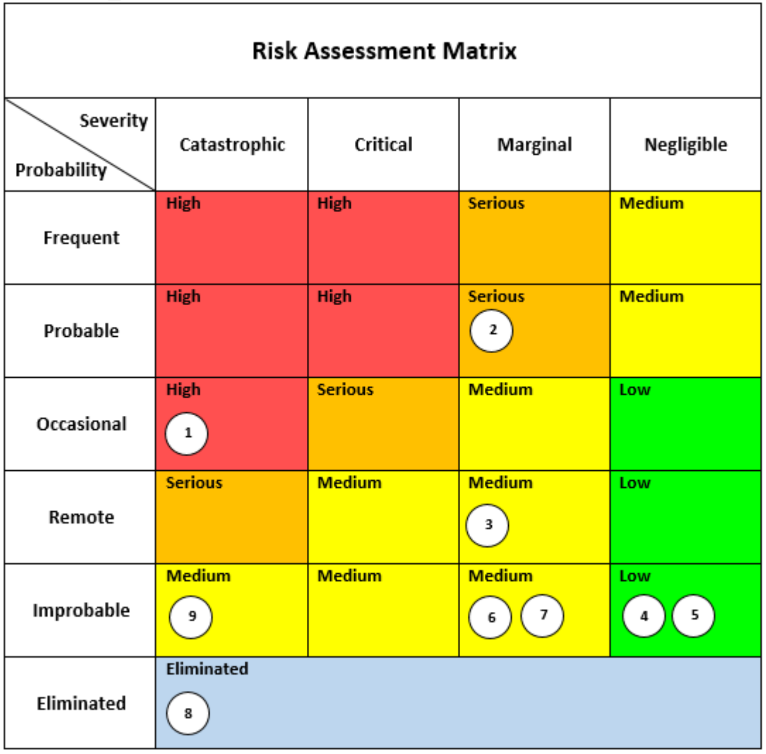
Preliminary Hazard List

#	System Item	Hazard	Hazard Prevention/Reduction	Hazard Evaluation
1	Exterior	Evacuation Routes	Sliding doors on outside	Simulation
2	Interior	Heat Stress	1. Remote-controlled fans 2. Vents on sides/roof	Temperature monitoring (areas of relatively higher temps)
3	Exterior	Falls from the back of trailer	Fall protection	Grip points, ladder
4	Interior	Vermin	Periodic extermination	Droppings
5	Structural	Water leaks	Periodic inspection for leaks and minor cracks, seal edges	Check for water stains
6	Interior	Fire (electric devices)	Circuit breaker	Insulation of wiring
7	Structural	Plywood strength	Reinforcement	Plywood breaking point
8	Structural	Entrapment	Periodic safety evaluation, check structural integrity	Checklist of OSHA Confined Space Std. guidelines/requirements
9	Monitoring	Occupant monitoring	Wearable with live biometric feedback	Test of Hexoskin Biometric shirt

4.2 Preliminary Hazard Analysis (PHA)

The Preliminary Hazard Analysis (PHA) identifies hazards in a system at the design level. A PHA also brings causal factors, consequences, and a quantified risk to fruition. The PHA was developed using the four subsystems identified in the previous section. Preliminary failure modes were established for each of the nine system hazards that were identified. Since there is no governing standard for a training simulator of this type, similar standards were associated independently for multiple hazards. Once the PHA was thoroughly analyzed, hazards were composed into a more visually effective table called the Risk Assessment Matrix. The table is structured so that the worst credible outcomes are in the top left cell, while minimal risk hazards are structured to the bottom right. A complete Risk Assessment Matrix can be seen in Table 2, along with the accompanying PHA in Table 3.

Table 2. Preliminary Hazard Analysis



Risk Assessment Matrix

Severity / Probability	Catastrophic	Critical	Marginal	Negligible
Frequent	High	High	Serious	Medium
Probable	High	High	Serious ②	Medium
Occasional	High ①	Serious	Medium	Low
Remote	Serious	Medium	Medium ③	Low
Improbable	Medium ⑨	Medium	Medium ⑥ ⑦	Low ④ ⑤
Eliminated	Eliminated ⑧			

(http://www.advanceddivingsystems.com/Images/Learning/RiskAssessmentMatrix.png)

1. Evacuation failure
    - Trainee is unable to be evacuated due to incapacitation and trailer layout design
2. Heat stress
    - Trainer or trainee suffer from heat stress/exhaustion and become incapacitated
3. Fall from back of trailer
    - Unguarded falls from back of the trailer
4. Bacteria, ants, rats, and associated droppings
    - Extermination of vermin
5. Water leaks
    - Exterior inspection for areas of wear
6. Fire hazard
    - AC power strip overloading
7. Plywood breaking
    - Plywood wear from weight stress and abrasion
8. Adherence to OSHA standards
9. Occupant monitoring failure
    - Trainer incapacitation and/or video system failure

Table 3. Preliminary Hazard Analysis (PHA)

PRELIMINARY HAZARD ANALYSIS			
EXTERIOR			
Trailer Layout	Evacuation failure	29 CFR 1910.36	Sliding doors on outside
		29 CFR 1910.37	
		29 CFR 1910.38	
		115 CMR 7.08(3)(b)	
Fall protection	Falls from back of trailer	ANSI B11	Secure harness
		29 CFR 1910.212	
INTERIOR			
Ventilation	Heat stress	BCA	Remote control fan
		AS 1668 Ventilation	Vents on sides/roof
Biological Materials	Bacteria, viruses, ants,	BCA Requirements	Ventilation isolation
	snakes, rats	Dangerous goods	requirements
	Hazardous substances	legistlation and guidance	Periodic examination
		AS 2982 Surfaces	
Wood breaks	Water leaks	29 CFR 1910.22-30	Housekeeping -
Water leaks		ANSI A1264.2-2012	Sanitation
Loss of grip - rafters			Periodic inspection of
			trailer
Dangerous goods	Fire (electric devices,	BCA Requirements	Ventilation
	combustible dust)	Dangerous good	Eliminate transport of
		legistlation and guidance	gases or liquids
		AS 2430 Hazardous	
		area classification	
		AS 2430 Classification	
		and Hazardous areas	
		NFPA-70	
STRUCTURAL			
	Plywood breaking	APA PRP - 108	
		ANSI/AF&PA NDS-2005	
	Entrapment	29 CFR 1910.146	Use OSHA Standards
MONITORING			
Emergency control	Occupant Monitoring failure		Occupant's oxygen level

4.3 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a deductive failure analysis, stemming from the top down analytic technique, to identify the potential ways to reduce risk in a system. A fault tree uses Boolean logic to link together failure events that may ultimately lead to the undesirable top event. Fault trees are formed by identifying a top undesirable event, and then further breaking down intermediate causal events that end in initiators or basic events. Basic events propagate through Boolean logic gates, such as “AND” and “OR” gates, to terminate into the top undesirable event.

The numerical outcome of the FTA provides the probability of occurrence of top undesirable event. This is calculated by summing the probabilities of each individual cut set. A cut set is a group of basic events, which, if all were to occur, would result in the occurrence of the top undesired event. Probabilities for all twenty basic events were computed using statistics from industry, estimation, trainee feedback, firefighter officer interviews, and literary research.

The rationale for attaining all of the probabilities is listed in Appendix B, along with corresponding citations.

*The Fault Tree is attached to the end of this document in APPENDIX A
*The corresponding analysis is attached to the end of this document in APPENDIX B

4.4 Failure Mode and Effects Analysis (FMEA)

A Failure Mode and Effects Analysis (FMEA) is an inductive reasoning analysis to identify single point failures in a system. FMEAs take most of the undesirable intermediate events from the FTA, and rank them using a Risk Priority Number (RPN). There are three factors, Occurrence, Detectability and Severity, which contribute to the calculation of the RPN. Each factor is scored on a 1-10 scale. The failure modes are ranked based on RPN score and events with the highest scores are chosen for further evaluation. The goal of the FMEA is to formulate and implement engineering or administrative controls to reduce one or more of the three contributing factors in the RPN score. Once appropriate controls are identified and implemented, the high-ranking scores are reexamined and compared to their original RPN.

*The FMEA is attached to the end of this document in APPENDIX C

CHAPTER FIVE

5. RESULTS AND DISCUSSION

5.1 PHL & PHA

Each hazard was analyzed for improvements by breaking the hazards into subsystems (Exterior, Interior, Structural, and Monitoring). As shown in Table 1, the hazards from the PHL (no significant order) show the main concerns regarding the simulator. Some of the identified hazards are nearly impossible to completely ameliorate, as they would entail substantial redesigning and/or rebuilding the trailer. For instance, installing sliding doors or ventilation fans into the exterior might compromise the structural integrity of the trailer and place excessive stress on surrounding cross members where the cutouts were made.

As far as monitoring the occupants, the IR camera system provided live video feed of the trainees, in the event of entrapment or a medical emergency, and provided trainee feedback on crawling performance. Furthermore, a biometric vest, known as a Hexoskin, was proposed to remotely monitor a trainee's cardiovascular exertion. The biometrics measured from the vest include VO_2 MAX, breathing rate, liters of air/minute consumed, HR max and average, g-forces, and a pedometer. While the pedometer is accelerometer-based and not GPS, it gives a close estimate of a trainee's path length compared to the average of all the trainees who completed the same maze configuration.

Ventilation was a debated factor, especially when interviewing the officers and trainees. The overall consensus of the trainees "liking" the heat was overwhelming. The team proposed a theoretical ventilation system to circulate outside air into the trailer, but the reduction in air temperature would fail to simulate a real emergency situation. A ventilation system would, however, greatly reduce heat stress hazards during the simulation.

5.2 FAULT TREE ANALYSIS (FTA)

As explained above in section 4.4, cut sets were determined from the fault tree. Cut sets were used to determine the overall probability of the top undesirable event. As shown in Appendix B, the probability of occurrence of a Severe Injury, the top undesired event, is approximately 4.6%. Individual trainee exposure in the simulator is highly variable based on the firefighter turnover each year, which in turn affects recruiting schedules. For instance, the Auburn Fire Department typically holds recruiting sessions that coincide with Auburn University's academic calendar. This is not the case with the Opelika Fire Department; they recruit on an as-needed basis and therefore have a greater variance on trainee exposure.

The cut sets were ranked from highest to lowest, and the top three cut sets are discussed below:

- **Cut Set #22** => (**3**,**7**): The most likely scenario encountered by this cut set is the trainee suffers from dehydration effects (becoming incapacitated) and can't be seen by the camera system. The probability of this cut set is 0.018 or 1.8%. The two basic events that can directly result in the occurrence of the top undesirable event are: (**3**) Blind spot and (**7**) Excessive perspiration. Especially during the summer, perspiration is a major concern. The trainees have an unregulated administrative control in place wherein trainers only encourage trainees to hydrate themselves with 7-8 liters of water throughout the course of the day, instead of mandating a set amount of water to consume. A hard control would involve drinking a liter of water with rehydrating solution before using engaging the simulator. At present, there is a three-foot section of blind spot unable to be covered by the camera system. It is up to the trainer monitoring the video system to look for the trainee in the next frame.

- **Cut Set #24 =>** (**5,7**): The most likely problem occurring with this cut set is the trainee suffers from dehydration (becoming incapacitated) and the camera system fails to return video feedback or the camera position has been displaced by the trainee. The probability of this cut set is 1.04%. The two basic events that can directly result in the occurrence of the top undesirable event are: (**5**) Camera failure and (**7**) Excessive perspiration. Camera failure, in this case, is defined as a hardware failure or a displacement of the camera from trainee movements.

- **Cut Set #23 =>** (**4**,**7**): The most likely scenario regarding this cut set is the trainee suffers from dehydration (becoming incapacitated) and the wireless video connection is obstructed by the trainee, rendering a loss of video for the effected camera. The probability of this cut set is 0.94%. The two basic events that can directly result in the occurrence of the top undesirable event are: (**4**) Wireless feed disconnection and (**7**) Excessive perspiration. In the event of a signal loss, the video stream from the camera may become fragmented or incur a complete video loss.

5.4 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

The top three failure modes that were identified in the FMEA were: panic attack, helmet fault and loss of communication. The RPN scores of these were 252, 196 and 144, respectively. Panic attacks were found to be the highest occurring event because most of the interviewed trainees viewed the simulator as an introduction to a highly confined restricted spaces. The best way to control this outcome is to have trainees gradually work their way into simulator by means of external smaller confined restricted space training setups or shortening the path taken through the simulator. Helmet faults are usually caused by two main events. Either the trainee's helmet makes contact with a wall or barrier and becomes dislodged, or the helmet is not initially secured properly by tightening the chin strap. The consequences of a helmet fault can be very detrimental, as the breathing mask can get displaced, potentially leading to outside air inhalation. If this happens, the trainees mentioned that it is very hard to readjust the mask and once the positive pressure seal is broken, air leaks out very quickly. Loss of communication can have significant effects if the trainee loses consciousness or the trainer is not paying attention. Although the SCBAs being used have an accelerometer based auditory alarm system, known as a Personal Alert Safety System (PASS), to detect motionless users, the only way a trainer knows whether a trainee is under duress is if the trainee himself knocks on the side of the trailer or the trainer hears the auditory PASS alarm.

5.5 COMPARISON OF STANDARDS IN THE PHA

The most notable standard referred to in the PHA is 29 CFR 1910.36, design and construction requirements for exit routes. This standard calls for an adequate number of evacuation routes in any area of the workplace. At present, the trailer has only one way of entering and exiting at the front and it is not in compliance with the standard. Similarly, 29 CFR 1910.146 deals with confined-space entry and requires a permit for a confined restricted space meeting the specifications enumerated in the standard. There is currently no permit necessary for entering the simulator. Although, since there are no governing standards for restricted space simulators, compliance to the previously stated standards is not mandatory.

The AS/NZS 1668 standard regulates ventilation in spaces for the purpose of removing toxic fumes, dusts, and vapors and rids the area of them. The tunnels of the simulator have very low air circulation; however, the trainees wear a SCBA throughout the simulation to provide clean air. 29 CFR 1926.510 specifies having fall protection on working surfaces over 4’ off the ground. The simulators rear deck is above 4 feet, yet provides no fall protection along the edge of the entrance. Since the AS/NZS standards are only applicable in Australia and New Zealand, confined restricted space simulators outside said countries are not mandated to comply with these standards.

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 TRAINEE MONITORING

A common finding between all the analyses is that remote monitoring can ameliorate a few of the hazards present in the current system, including occupant evacuation/monitoring and limiting excessive perspiration. By incorporating the IR camera system into the simulator and a biometric wearable onto the trainee, both the trainee and trainer will have greater safety reassurance with reliable technology. Allowing the trainer to constantly monitor the trainee's vitals is a constant assurance that overexertion thresholds are not being eclipsed. The particular biometric vest proposed, the Hexoskin, is able to estimate the amount of air being consumed on a one-minute average basis. This metric, in conjunction with the vibratory/auditory alarms already in the trainee's SCBA PASS, should provide not only a tertiary oxygen monitoring system, but also a training tool to show the trainee how to more appropriately manage their oxygen supply. Figures 6 and 7 show the Hexoskin application and the biometrics being recorded.

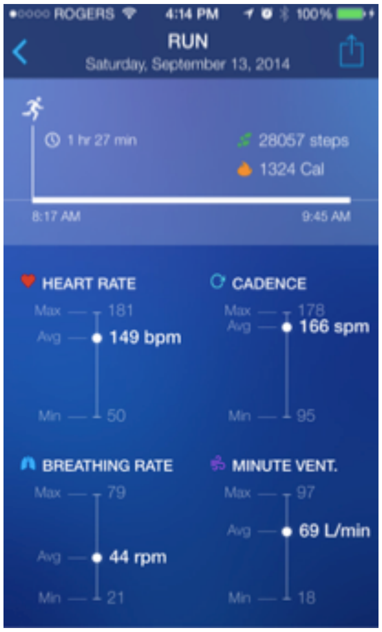


Figure 6. Hexoskin Application Displaying Live Data

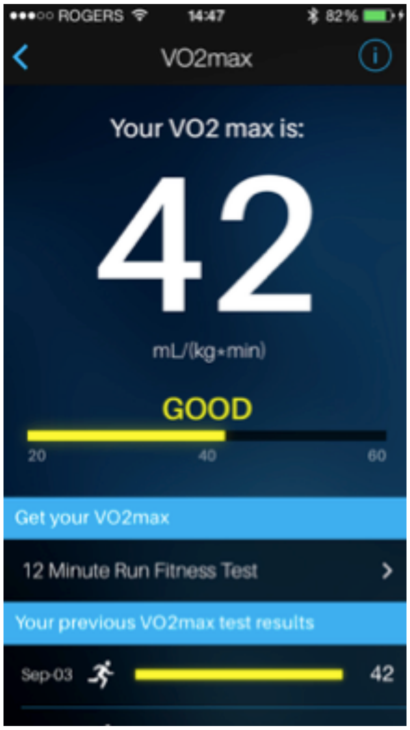


Figure 7. $VO_{2\ MAX}$ Estimation in Hexoskin Application

From the Fault Tree, there are two events that have to take place for the top undesirable event to occur: ‘Medical Emergency’ and ‘Unable to Evacuate.’ They are connected by an “AND” gate. All the cut sets feature at least one element from the ‘Unable to Evacuate’ branch. If the trainees were to wear the Hexoskin, it would act as a failsafe and essentially change the gate from an “OR” gate to an “AND” gate. This change is depicted in Figure 8, below.

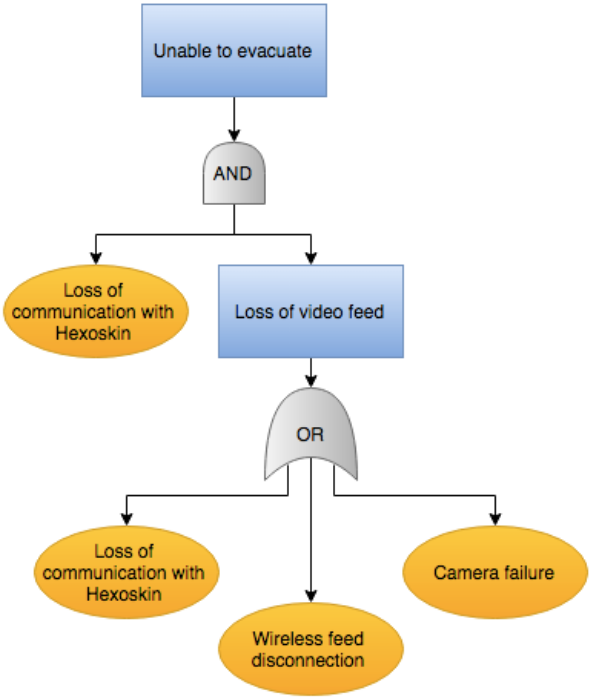


Figure 8. Updated Loss of Communication Branch

As seen in section 5.2, each of the 3 highest cut sets feature an element from the ‘Unable to Evacuate’ branch. In Figure 8, the gate was changed from the existing “OR” gate to an “AND” gate, and thus, there will now be two elements from this branch in each of those cut sets. This will add another multiplier further reducing the probability of occurrence and accordingly reduce the overall probability of the top undesirable event.

Including the HEXOSKIN, in conjunction with the IR cameras, reduces the FMEA detection score to a 4, which in turn reduces the RPN from 144 to 72.

In the future, it may be possible to set up a mobile command center for a secondary trainer outside the trailer. This mobile command center could include all of the live IR camera feeds and the biometric data in real time from the Hexoskin device. Through data analytics, fire departments could see individual trainee strengths and areas in need of improvement, all the while providing a safer simulator experience.

6.2 EVACUATION

Exiting the trailer in the event of an emergency is the second-most imminent issue regarding the risk associated with the trailer. Adding an evacuation route will greatly improve the overall safety of the simulator while keeping the simulation of a real fire scenario intact. Based on firsthand experience as well as officers' recommendations, suggested locations for evacuation doors are highlighted in Figure 9, below.

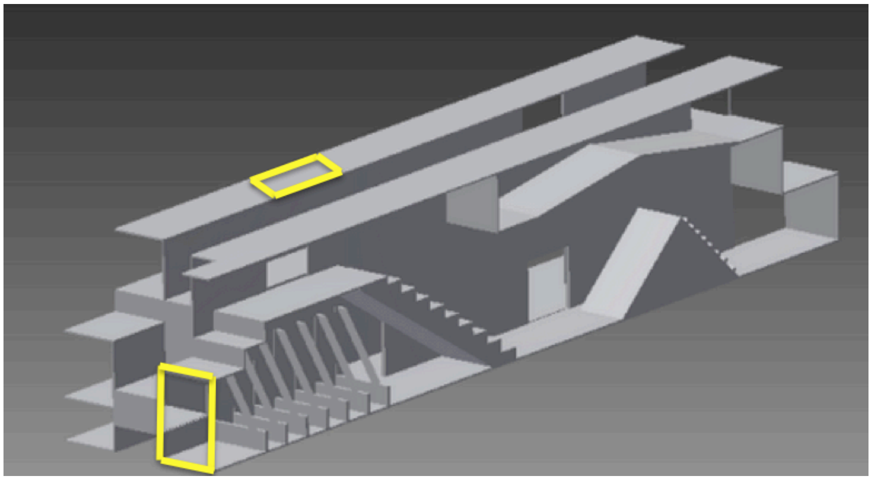


Figure 9. Proposed Evacuation Doors

The two proposed evacuation doors are positioned in the areas where the interviewed trainees felt most fatigued or would be prone to becoming incapacitated. The first evacuation door is located at the end of the rafters in the back of the simulator on the first level. Access to this corner is very limited due to the rafters and remote location from the central tunnel. Also, this location was chosen as a consequence of a trainee previously experiencing a panic attack and kicking a hole through the simulator wall in an attempt to escape. From this evacuation door, the instructor can gain access to an incapacitated trainee in the rafters as well as in the descent landings from the second level very quickly. The second proposed evacuation door would be in the floor of the third level central crawl space. Adding this extra exit door would allow access into the trainer's central tunnel below. Fatigue at this point in the maze is extremely high because the trainee has ascended both levels and is in an extremely narrow crawl space. The door could be hinged into the floor, allowing it to be opened only from below in the central tunnel. Once the trainee is lowered through this evacuation door, the trainer has an unobstructed exit path leaving the simulator.

6.3 FUTURE RESEARCH AREAS

6.3.1 COOLING VEST

One main hazard for almost all trainees entering the crawling simulator is excessive perspiration. The team devised an idea to incorporate a cooling jacket, made of cloth and ice packs, for trainees to wear under their turnout gear. This idea would, however, be exclusive to simulator use only, as real fire scenarios would cause the liquids inside the vest to eventually act as heat sinks for external heat sources. While most interviewed trainees thought the cooling jacket would be a great tool, it was unanimously decided the jacket would degrade the overall training experience represented by the trailer, as temperature extremes would be minimized.

6.3.1 TEMPERATURE EFFECT ON SCBA AIR CYLINDER PRESSURE

Another area of research could confirm whether the Ideal Gas Law is applicable to air cylinder tanks, as discussed in the literature review section 2.1.3. Relatively simple tests could prove whether pressure differences occur with prolonged outside temperature changes. More definitively, the length of exposure to an ambient temperature change required to effect air cylinder pressure could be experimentally quantified and assessed.

REFERENCES

American Society of Safety Engineers. “ANSI ANSI/ASSE A1264.2-2012 Standard for the Provision of Slip Resistance on Walking/Working Surfaces.” *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 2007. Web. 19 April 2015. <http://www.asse.org/assets/1/7/A1264.2TechBrief4-2012.pdf >.

"AS/NZS 1668 Seminar Notes." *iMIS 15*. AIRAH, n.d. Web. 19 Apr. 2015. <http://www.airah.org.au/imis15_prod/Divisionmeetingpresentations/AS1668_Seminar_Notes/AS_1668_Overview.aspx>.

Axford, A. T., McKerrow, C.B., Jones, A.P., Le Quesne, P.M. "Accidental exposure to isocyanate fumes in a group of firemen." *British Journal of Industrial Medicine* 33.2 (1976): 65-71.

Barr, D., Gregson, W., Reilly, T. “The thermal ergonomics of firefighting reviewed.” *Applied Ergonomics* 41(1) (2010): 161-72.

Chaney, Philip L. “Climate.” *Encyclopedia of Alabama.* Alabama Humanities Foundation, 13 June 2013. Web. 10 June 2015. <http://www.encyclopediaofalabama.org/article/h-1283>.

Cloutier, E., Champoux, D. “Injury risk profile and aging among Quebec firefighters.” *International Journal of Industrial Ergonomics* 25 (2000): 513-23.

Code of Massachusetts Regulations. “115 CMR 7.08(3)(b) Standards for all Services and Supports: Safety Plan.” *Department of Developmental Services*. CMR, 2009. Web. 19 April 2015. <www.mass.gov/eohhs/docs/docs/dmr/regs/reg-115cmr007.pdf>.

"CPR Statistics." *CPR Statistics.* American Heart Association, 2014. Web. 10 June 2015. <http://www.heart.org/HEARTORG/CPRAndECC/WhatisCPR/CPRFactsandStats/CPR-Statistics_UCM_307542_Article.jsp>.

Davis, J., Tang, R., Sesek, R., Gallagher, S. "Evaluating Firefighter Crawling Performance in a Controlled Environment." *Advances in Safety Management and Human Factors* 10 (2014): 3.

Donnelly, M., Yang, J. “Experimental and modeling study of thermal exposure of a self-contained breathing apparatus (SCBA).” *Burns* 41 (2015): 1017-27.

"Draeger Fire Simulation Trailer (mobile)." *Home*. Draeger, n.d. Web. 19 Apr. 2015. <http: //www.draeger.com/sites/en_aunz/Pages/Fire-Services/Fire-simulation-trailer-mobile.aspx>.

Fernhall, B., Fahs, C.A., Horn, G., Rowland, T., Smith, D. “Acute effects of firefighting on cardiac performance.” *European Journal of Applied Physiology* 112 (2012): 735-41.

Geibe, J. R., Holder, J., Peeples, L., Kinney, A. M., Burress, J. W., & Kales, S. N. “Predictors of on-duty coronary events in male firefighters in the United States.” *The American Journal of Cardiology* 101(5) (2008): 585-9.

Guyton, A.C. “Body temperature, temperature regulation and fever.” *Textbook of Medical Physiology* (1996): 911-22.

"IAFF: Wellness-Fitness Initiative." *IAFF Main*. IAFF FireFighters, n.d. Web. 19 Apr. 2015. <http://www.iaff.org/HS/CPAT/cpat_index.html>.

ISTA. “ISTA Temperature Project – Data Summary.” *International Safe Transit Association,* 2002. Web. 19 April 2015. < http://www.ista.org/forms/ISTA_Temperature_Report-2002.pdf>.

Kales, S.N., Soteriades, E.S., Christophi, C.A., Christiani, D.C. “Emergency duties and deaths from heart disease among firefighters in the United States.” *New England Journal of Medicine* 356 (2007): 1207-15.

Lv, Y., Liu, J., Zhang, J. “Theoretical evaluation of burns to the human respiratory tract due to inhalation of hot gas in the early stage of fires.” *Burns* 32 (2006): 436-46.

Manning, J., Griggs, T.R. "Heart rates in fire fighters using light and heavy breathing equipment: similar near-maximal exertion in response to multiple work load conditions." *Journal of Occupational and Environmental Medicine* 25.3 (1983): 215-8.

NFPA. “Standard on selection, care, and maintenance of protective ensembles for structural fire fighting and proximity fire fighting.” *National Fire Protection Agency*, 2014. Web. 19 April 2015. < http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=1851>.

Occupational Safety and Health Administration. “ANSI Z359.1 Safety Requirements for Personal Fall Arrest Systems, Subsystems, and Components.” *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 2007. Web. 19 April 2015. <https://www.millerfallprotection.com/pdfs/ANSI-Z359Standard/Understanding%20ANSI%20Z359.pdf>.

Occupational Safety and Health Administration. “29 CFR 1910.22 General Requirements: Walking-Working Surfaces.” *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 2011. Web. 19 April 2015. <https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9714>.

Occupational Safety and Health Administration. “29 CFR 1910.36 Design and construction requirements of exit routes.” *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 2011. Web. 19 April 2015. <https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9724>.

Occupational Safety and Health Administration. “29 CFR 1910.37 Maintenance, safeguards, and operational features for exit routes.” *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 2011. Web. 19 April 2015.

<https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9725>.

Occupational Safety and Health Administration. "29 CFR 1910.38 Emergency action plans." *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 2011. Web. 19 April 2015. <https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9726>.

Occupational Safety and Health Administration. "29 CFR 1910.146 Permit-Required Confined restriced spaces." *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 2011. Web. 19 April 2015. <https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9797>.

Occupational Safety and Health Administration. "29 CFR 1910.212 Machinery and Machine Guarding." *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 2011. Web. 19 April 2015. <https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9836>.

Occupational Safety and Health Administration. "29 CFR 1926.501 Duty to have fall protection." *U.S. Department of Labor, Occupational Safety and Health Administration.* OSHA, 1995. Web. 19 April 2015. <https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_id=10757&p_table=STANDARDS>.

Park, K., Rosengren, K.S., Horn, G.P., Smith, D.L., Hsiao-Wecksler, E.T. "Assessing gait changes in firefighters due to fatigue and protective clothing." *Safety Science* 49 (2011): 719-26.

Prien, T., Traber, D.L. "Toxic smoke compounds and inhalation injury—a review." *Burns* 14.6 (1988): 451-60.

Purser, D.A. "Assessment of hazards to occupants from smoke, toxic gases and heat." *The SFPE Handbook of Fire Protection Engineering* 4th Ed (2008).

Riaz, Z., Arslan, M., Khalid, A. "CoSMoS: A BIM and wireless sensor based integrated solution for worker safety in confined restriced spaces." *Automation in Construction* 45 (2014): 96-106.

Rowell, L.B. "Human cardiovascular adjustments to exercise and thermal stress." *Physiological Reviews* 54 (1974): 75-159.

Standards Australia. "AS 1668.2-2002 The use of ventilation and airconditioning in buildings – Ventilation design for indoor air containment control." *Standards Australia.* AS, 2002. Web. 19 April 2015. <http://www.airah.org.au/iMIS15_Prod/Content_Files/Divisionmeetingpresentations/ACTNSW/Simon-Hill-1.pdf>.

Smith DL, Dyer K, Petruzzello SJ. “Blood chemistry and immune cell changes during one week of intensive firefighting training.” J *Thermal Biology* 29 (2004): 725-9.

Smith D., Petruzzello S.J. “Selected physiological and psychological responses to live-fire drills in different configurations of firefighting gear.” *Ergonomics* 41 (1998): 1141-54.

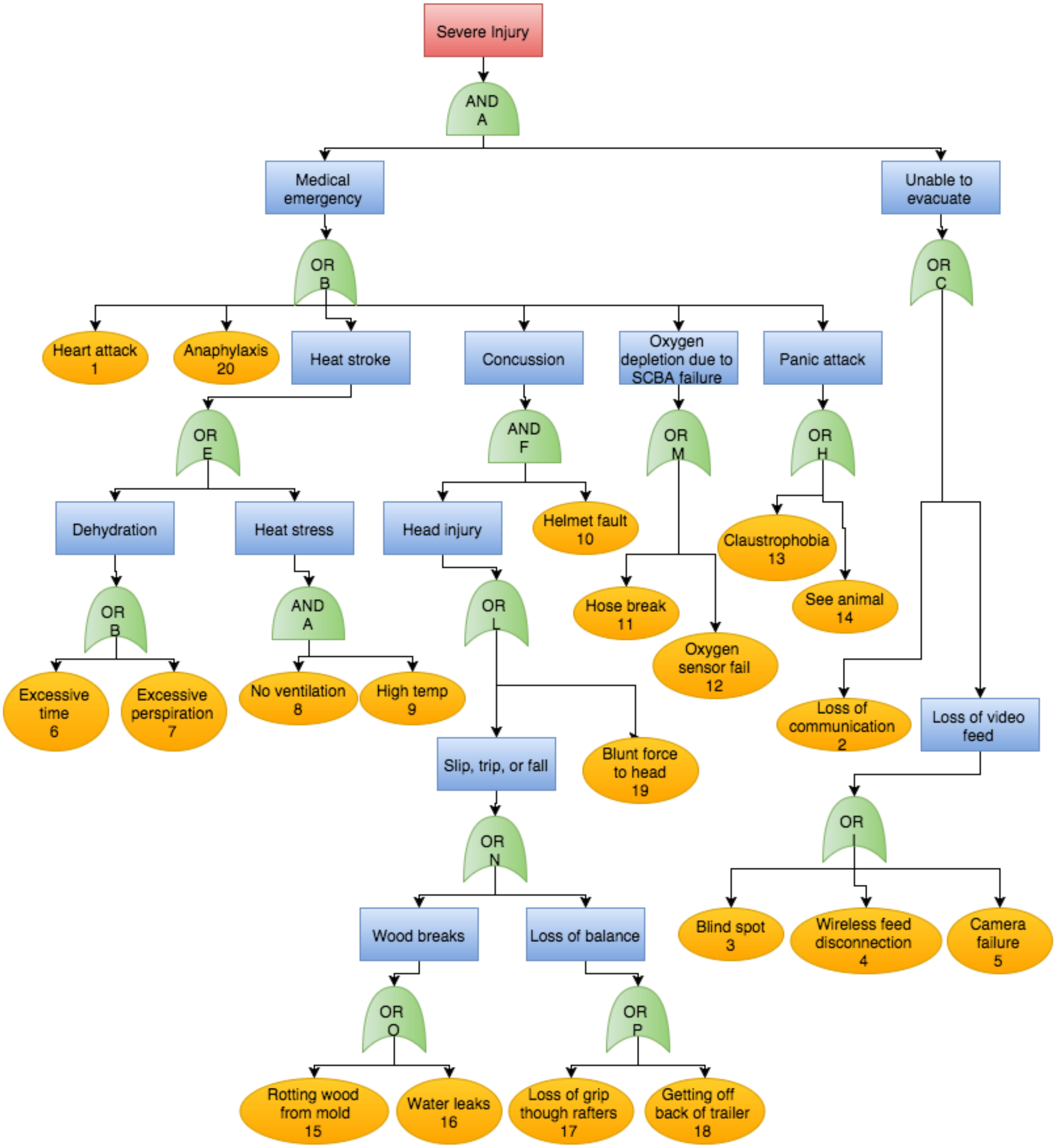
Soteriades, E.S., Hauser, R., Kawachi, I., Liarokapis, D., Christiani, D.C., Kales, S.N. “Obesity and cardiovascular disease risk factors in firefighters: a perspective cohort study.” *Obes Res* 13 (2005): 1756-63.
Standards Australia. “AS/NZS 2982:2010 Laboratory design and construction.” *Standards Australia.* AS, 2010. Web. 19 April 2015. < http://www.freestd.us/soft/255449.htm>.

Walton, S.M, Conrad, K.M., Fumer, S.E., Samo, D.G. “Cause, type, and workers’ compensation costs of injury to firefighters.” *American Journal of Industrial Medicine* 43 (2003): 454-8.

Woorons, X. “Hypoventilation training, push your limits!” *Arpeh* (2014): 164.

APPENDICES

APPENDIX A: COMPLETE FAULT TREE



APPENDIX B: FAULT TREE ANALYSIS

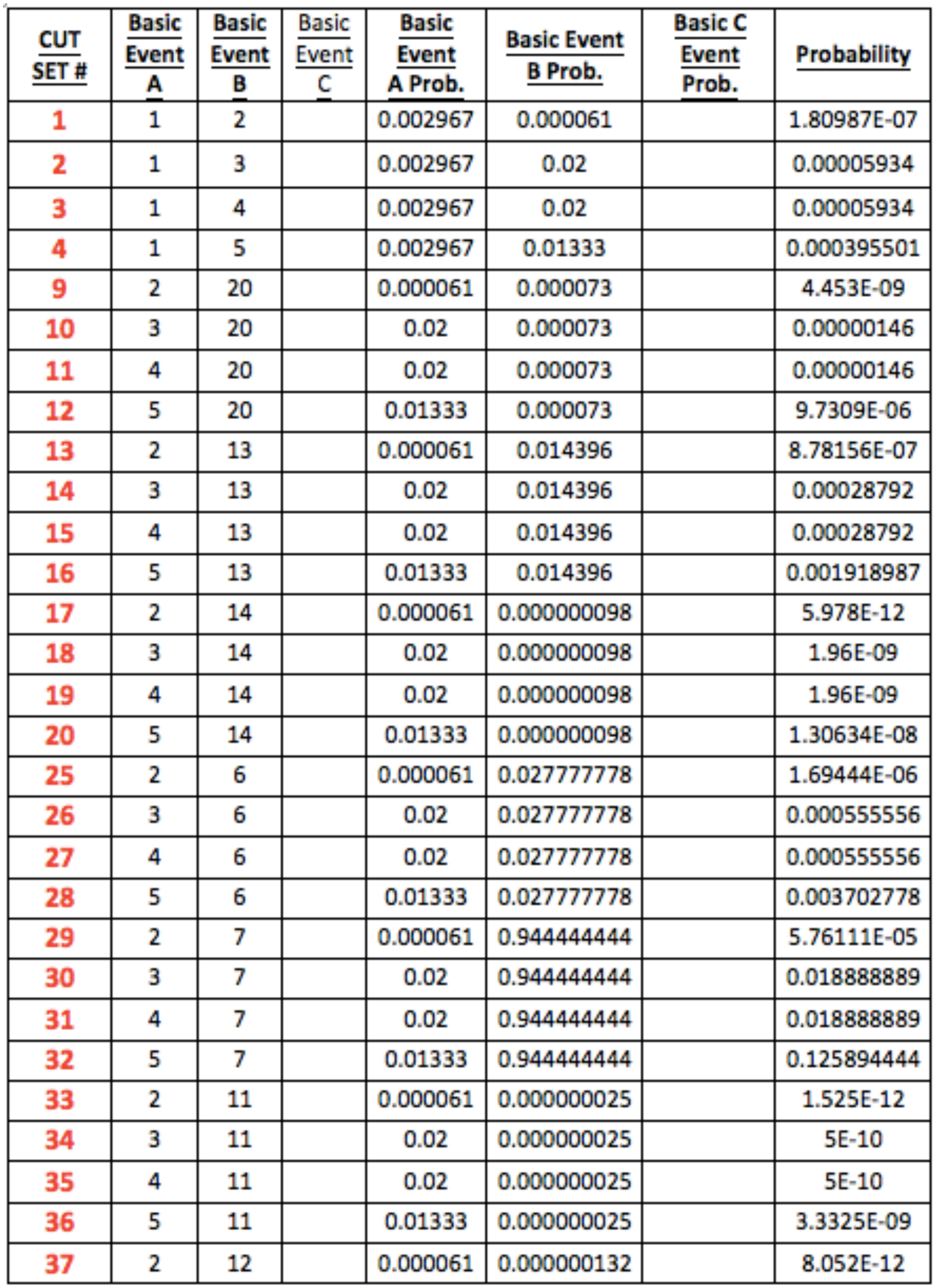
#	Basic Event	Rationale	Equation	Probability	Reference
1	Heart attack	(663 of 1821 firefighters had heart attack) * (24% of firefighters are 16-29 years old) * 1,129,250 of 332,583,006 Americans are firefighters)	(663/1821)*(0.24*1129250/332583006)	0.2967	http://apps.usfa.fema.gov/firefighter-fatalities/fatalityData/statistics
2	Loss of communication	Happens as a cause of trainer/trainee incapacitated -> 2 * (probability of heart attack) + 2 * (probability of anaphylactic shock)	2*(0.002967) + 2*(0.00007349)	0.00608	http://apps.usfa.fema.gov/firefighter-fatalities/fatalityData/statistics, http://www.mayoclinic.org/diseases-conditions/anaphylaxis/basics/definition/con-20014324
3	Blind Spot	No camera system monitoring specific area	1000 sqft of trailer with 20 sqft of blind spot = 20/1000	2	Firefighter feedback
4	Wireless feed disconnection	Power cables being tripped on, based on firefighter feedback	Prob of STF, 1/50	2	Firefighter feedback
5	Camera failure	Faulty camera equipment or cables being disrupted	Prob of camera failing = 1 fault/7.5 min avg	13.33	http://bensoftware.com/forum/discussion/641/camera-loses-connection-and-reconnecting-every-minute/p1

6	Excessive time	According to interview with firefighters ,1 out of 36 said they spent longer than expected in the simulator	1 of 36	2.777	Firefighter feedback
7	Excessive perspiration	According to interview with firefighters, 34 out of 36 perspired excessively	34 of 36	94.444	Firefighter feedback
8	No ventilation	Front of trailer is open so it can be used to ventilate. 1 out of 4 walls	Area of one panel / area of all panels	0.0754	Firefighter feedback
9	High temperature	(39 of 365 days were >= 90 degrees F WBT) * (5 of 1821 deaths were due to heat exhaustion)	(39/365)*(5/1821)	0.029	http://www.ncdc.noaa.gov/
10	Helmet Fault	Helmet being faulty	29% faulty helmets	0.29	http://www.cyclehelmets.org/1139.html
11	Hose break	Hose in SCBA is faulty * hose is snagged in trailer ; (1 out of 4 SCBA hoses doesn't meet NIOSH flow rate requirements) * (0.001% that a hose can snag, based on firefighter feedback)	(.25)*(0.00001)	0.0000025	http://www.usfa.fema.gov/downloads/pdf/publications/tr-088.pdf
12	Oxygen sensor fail	((5*10^-6 compressor leak failures in SCBA/hour) * (7.5 min in trailer avg / 60 min/hr)) OR ((1*10^-4 electrical power failures in SCBA/hr) * (7.5 min avg in trailer / 60 min/hr)) OR ((5*10^-7 fluid line leaks failures in SCBA/hour) * (7.5 min avg in trailer / 60 min/hr))	((5*10^-6)*(7.5/60))+((1*10^-4)*(7.5/60))+((5*10^-7)*(7.5/60))	1.31187E-05	http://esh-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=387

13	Claustrophobia	Interview with firefighters AND (6% of Americans have claustrophobia) * (24% of firefighters are 16-29) * (Total number of firefighters in USA) = 16,528/Total number of firefighters	(0.24*(1.129/332.583)*0.06*332,583,006)/1,129,250	0.014396	Phobias: A Handbook of Theory, Research, and Treatment. Chichester; New York: Wiley, 1997
14	See animal	(24% firefighters ages 16-29) * (Total number of firefighters in USA) * (Number of bites in US annually / Total US population)	(0.24*(1.129/332.583)*(4,000,000/332,583,006)	0.0000098	http://healthofchildren.com/A/Animal-Bite-Infections.html
15	Rotting wood due to mold	Prob of exterior wood equilibrated with air	0.14	0.14	http://failures.wikispaces.com/Assessment+and+Remediation+of+Wood+Defects
16	Water leaks	(108 rainy days / 365 days) * (100% of holes in trailer)	(108/365)*1.0	0.29589	http://www.currentresults.com/Weather/Alabama/average-yearly-precipitation.php
17	Loss of grip while moving through rafters	(60 sqft of trailer is rafters) / (1000 sqft of total area)	60/1000	0.06	Davis et al., 2014. Evaluating Firefighter Crawling Performance in a Controlled Environment, AHFE, Krakow Poland

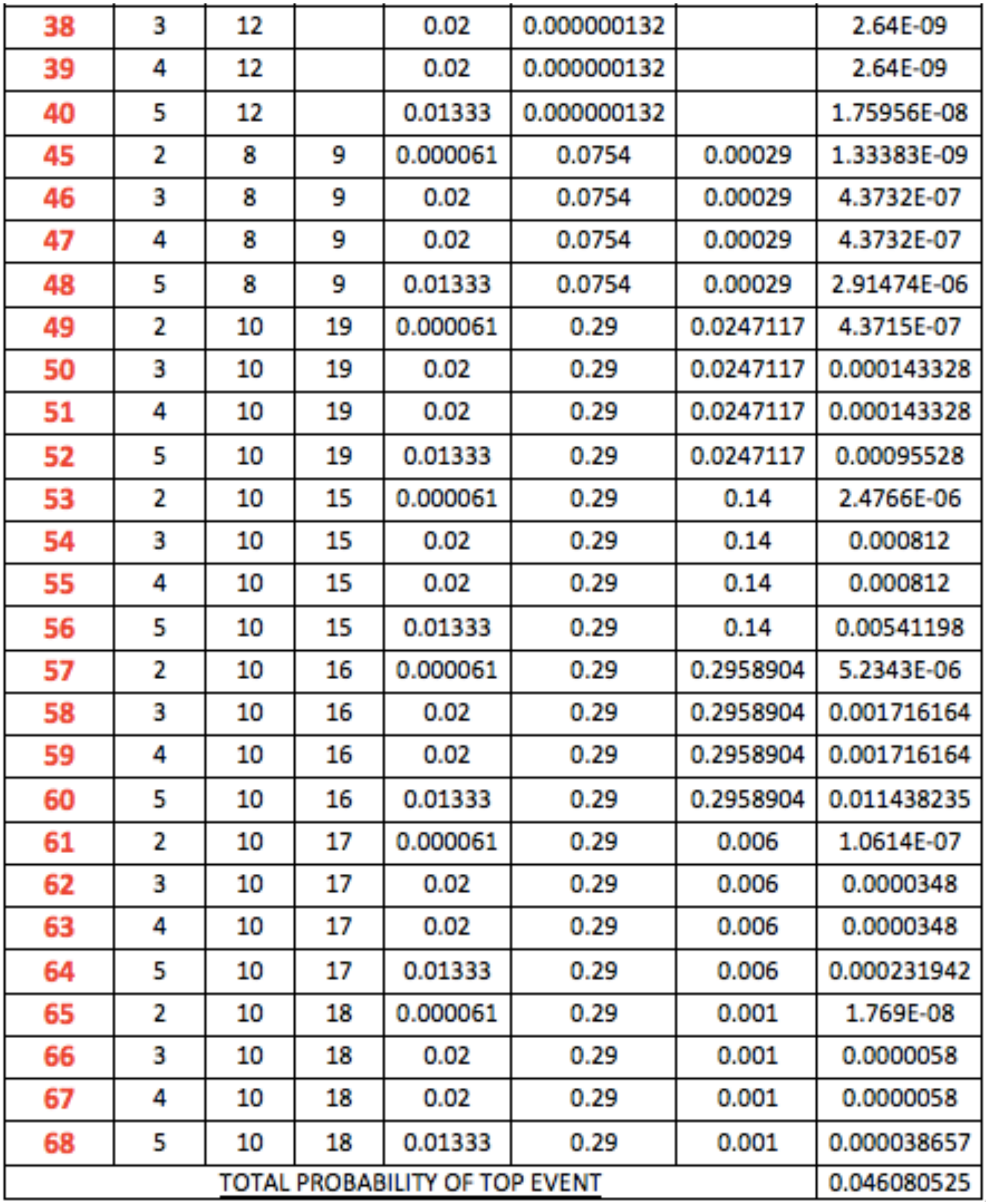
18	Getting off back of trailer	Never happened per interview with firefighters. Line of sight, heavy object restriction -> 1/1000 chance of occurance	(1/1000)	0.1	Firefighter feedback
19	Blunt force to head	(Porobability of helmet being faulty) * (Probability of helmet impact with object leading to cuts, concussions)	(0.29)*(45/1821)	0.7166	http://apps.usfa.fema.gov/firefighter-fatalities/fatalityData/statistics
20	Anaphylactic reaction	(3 million cases of analphylactic shock in US) * (24% firefighters aged 16-29) * (Total number of firefighters in USA)	(3,000,000/332,583,006) *(0.24*(1,129,000/332,583,009))	0.007349	http://www.mayoclinic.org/diseases-conditions/anaphylaxis/basics/definition/con-20014324

CUTSET PROBABILITIES AND PATHSETS



CUT SET #	Basic Event A	Basic Event B	Basic Event C	Basic Event A Prob.	Basic Event B Prob.	Basic C Event Prob.	Probability
1	1	2		0.002967	0.000061		1.80987E-07
2	1	3		0.002967	0.02		0.00005934
3	1	4		0.002967	0.02		0.00005934
4	1	5		0.002967	0.01333		0.000395501
9	2	20		0.000061	0.000073		4.453E-09
10	3	20		0.02	0.000073		0.00000146
11	4	20		0.02	0.000073		0.00000146
12	5	20		0.01333	0.000073		9.7309E-06
13	2	13		0.000061	0.014396		8.78156E-07
14	3	13		0.02	0.014396		0.00028792
15	4	13		0.02	0.014396		0.00028792
16	5	13		0.01333	0.014396		0.001918987
17	2	14		0.000061	0.000000098		5.978E-12
18	3	14		0.02	0.000000098		1.96E-09
19	4	14		0.02	0.000000098		1.96E-09
20	5	14		0.01333	0.000000098		1.30634E-08
25	2	6		0.000061	0.027777778		1.69444E-06
26	3	6		0.02	0.027777778		0.000555556
27	4	6		0.02	0.027777778		0.000555556
28	5	6		0.01333	0.027777778		0.003702778
29	2	7		0.000061	0.944444444		5.76111E-05
30	3	7		0.02	0.944444444		0.018888889
31	4	7		0.02	0.944444444		0.018888889
32	5	7		0.01333	0.944444444		0.125894444
33	2	11		0.000061	0.000000025		1.525E-12
34	3	11		0.02	0.000000025		5E-10
35	4	11		0.02	0.000000025		5E-10
36	5	11		0.01333	0.000000025		3.3325E-09
37	2	12		0.000061	0.000000132		8.052E-12

CUTSET PROBABILITIES AND PATHSETS



38	3	12		0.02	0.000000132		2.64E-09
39	4	12		0.02	0.000000132		2.64E-09
40	5	12		0.01333	0.000000132		1.75956E-08
45	2	8	9	0.000061	0.0754	0.00029	1.33383E-09
46	3	8	9	0.02	0.0754	0.00029	4.3732E-07
47	4	8	9	0.02	0.0754	0.00029	4.3732E-07
48	5	8	9	0.01333	0.0754	0.00029	2.91474E-06
49	2	10	19	0.000061	0.29	0.0247117	4.3715E-07
50	3	10	19	0.02	0.29	0.0247117	0.000143328
51	4	10	19	0.02	0.29	0.0247117	0.000143328
52	5	10	19	0.01333	0.29	0.0247117	0.00095528
53	2	10	15	0.000061	0.29	0.14	2.4766E-06
54	3	10	15	0.02	0.29	0.14	0.000812
55	4	10	15	0.02	0.29	0.14	0.000812
56	5	10	15	0.01333	0.29	0.14	0.00541198
57	2	10	16	0.000061	0.29	0.2958904	5.2343E-06
58	3	10	16	0.02	0.29	0.2958904	0.001716164
59	4	10	16	0.02	0.29	0.2958904	0.001716164
60	5	10	16	0.01333	0.29	0.2958904	0.011438235
61	2	10	17	0.000061	0.29	0.006	1.0614E-07
62	3	10	17	0.02	0.29	0.006	0.0000348
63	4	10	17	0.02	0.29	0.006	0.0000348
64	5	10	17	0.01333	0.29	0.006	0.000231942
65	2	10	18	0.000061	0.29	0.001	1.769E-08
66	3	10	18	0.02	0.29	0.001	0.0000058
67	4	10	18	0.02	0.29	0.001	0.0000058
68	5	10	18	0.01333	0.29	0.001	0.000038657
TOTAL PROBABILITY OF TOP EVENT							0.046080525

PATH SET #1	2	3	4	5										
PATH SET #2	1	6	7	8	10	11	12	13	14	20				
PATH SET #3	1	6	7	9	10	11	12	13	14	20				
PATH SET #4	1	6	7	8	11	12	13	14	15	16	17	18	19	20
PATH SET #5	1	6	7	9	11	12	13	14	15	16	17	18	19	20

APPENDIX C: FAILURE MODE AND EFFECTS ANALYSIS

Process Function	Failure Mode	Effects of Failure	Severity	Causes of Failure	Occurrence	Control	Detection	RPN	Recommended Actions
Physiological	Panic Attack	Hysteria	6	Claustrophobia/Medical history	6	Visual	7	**252**	Medical history check/CPAT
PPE	Helmet fault	Displaced mask -> Limits vision/oxygen depletion	7	Helmet knocks mask	7	Manual	4	**196**	Tighten face mask strap
Physiological	Panic attack	Hysteria	6	Vibration to warn trainee about oxygen level	6	Visual	4	**144**	Training
Administrative	Loss of communication	Inability to get emergency notifications	9	Trainer/trainee incapacitated	2	Manual	8	**144**	3rd party present to communicate
Physiological	Allergic reaction	Inability to breathe	7	Contact w/ allergen	2	Manual	9	126	Pest control/Epi pen on hand
Physiological	Heart attack	Medical emergency	10	Medical history	1	Manual	9	90	Trained EMS defibrillator
Administrative	Loss of video feed	Inability to track the occupants	3	Blind spot/wireless camera disconnection	5	Manual	6	90	Periodic maintenance of cameras
PPE	Supply air hose breaks	Oxygen depletion	8	Snagging of the supply line	1	Visual	8	64	Clear debris and obstacles from simulator
PPE	Oxygen sensor failure	Oxygen depletion	8	Manufacturer defect/maintenance	1	Manual	8	64	Regular inspection and testing
PPE	Helmet fault	Concussion	7	Improper use or care	1	Manual	9	63	Regular inspection and testing
Physiological	Heat stroke	Overheating	7	Dehydration	1	Visual	5	35	Ventilation/ hydration
Administrative	Slip, trip, fall	Injury/incidents	4	Loss of balance/wood break	1	Visual	6	24	Fall protection/ inspections