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WILDLAND FIREFIGHTER EXPOSURE STUDY:

EVALUATING CORE TEMPERATURE, HEART RATE & HYDRATION

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Table of Contents

Abstract

The Wildfire Research Center at San Diego State University and the Wildfire Program at California State University San Marcos worked in partnership with the United States Department of Agriculture-Forest Service, CAL FIRE, and CAL FIRE Local 2881 to evaluate the physiological and working conditions of wildland firefighters between 2012 and 2015. Funding for this work was provided by the USDA Forest Service.

Conditions dictate that wildland firefighters are often required to work for extended periods in intense heat and brutal environmental conditions. This study will delineate how the regular duties and environmental conditions experienced by wildland firefighters influence key physiological factors including heart rate, respiratory rate, core body temperature, and hydration. Ninety-five CAL FIRE wildland firefighters participated in this study, including personnel at training events, controlled burns, and actual wildland fires. The results reveal that wildland firefighters regularly exceeded safe physiological conditions while performing their duties (regardless of the event type). Nearly 65% of the firefighters had sustained peak heart rates above 200 beats per minute (bpm), while nearly 20% exceeded 220bpm. Virtually every firefighter regularly exceeded the recommended maximum heart rate for work (220bpm minus age). Likewise, measured core body temperatures exceeded 102°F in roughly 70% of the firefighters, with 10% exceeding 103°F. Furthermore, nearly two-thirds of the firefighters started their shifts at or near a level of dehydration. Regardless of their starting status, dehydration rates significantly increased by the end of their duty, with only 25% of the firefighters (that started off at or near dehydration) self-correcting and becoming more hydrated by the end of the shift. Finally, the type of personal protective equipment (PPE) worn by wildland firefighters has a significant influence on their overall physiology. The results suggest that the traditional double-layer PPE produces significantly higher core body temperatures, higher incidence of dehydration, and higher heart rates than single-layer PPE.

1.0 Introduction

Awareness of wildfires as an issue may avoid worldwide focus, but has never been greater in our country's history than now. What were once considered issues of the West are nationally recognized as an increasing threat to all of our communities and ecosystems. As our population continues to grow, decisions on developing and managing the wildland urban interface (WUI) determines our vulnerability and the risks imposed on our firefighters and communities. Given the complexity of land use and natural areas, many firefighters will, at some point in their career, respond to a fire in the wildland and WUI. In the conterminous U.S., the WUI covers approximately 277,668 square miles and has over 45 million housing units.[1] Much of this area is adjacent to the vast areas of federal lands managed by the U.S. Forest Service, Bureau of Land Management, and National Park Service, as well as various state parks, reserves, and open space. The WUI is a modern phenomenon that has become a persistent and permanent presence in the eastern U.S., reaching a maximum of 72% of land area in Connecticut. California, not surprisingly, has the highest number of WUI housing units of any state (5.1 million).

Predictably, as human interaction with our wild areas takes root, we've witnessed an increase in the incidence of fires. On closer inspection the statistics become staggering. Since the 1970s, our nation has endured an increase from an average of three million to an overwhelming seven million acres burned each year – with further increases projected.[2] 2015 was distinguished as the single highest acreage count on record, with over 10 million acres burned in wildland and WUI fires.[3] In California, only about 4% of wildfires are natural events, meaning that well over 95% of our wildfires are the result of human activity.[4] The building and the burning has made the term 'wildland fire'a bit of a misnomer. Large wildfires frequently threaten homes, businesses, and lives, shifting the focus to the urban interface. Further exacerbating the situation, a new paradigm is emerging: we are witnessing a dramatic shift in the frequency and intensity of wild fires due to a variety of factors, again most of which are human-caused.

Recent research suggests that the fire season is much longer than historically observed.[5] In an analysis of the western United States, the numbers and intensity of wildfires have significantly increased since the mid-1980s. Shifting climatic conditions and land use change have combined to produce more frequent wild fires while also increasing the overall annual wildfire season.[6] Even more disconcerting is that recent research suggests that regional temperatures in places like California may increase from 1.7 C to 5.8 C by 2100, depending on the climate model used and the emissions scenarios assumed.[7] If these trends continue, and the concomitant problems associated with drought and climate change suggest the trend is inexorable, it is conservatively predicted that large fires (defined as 500 acres or more) will increase nearly 35% by 2050 and an

1 Radeloff, V., R. Hammer, S. Stewart, J. Fried, S. Holcomb, and J. McKeefry. 2005. The Wildland-Urban Interface in the United States. Ecological Applications 15:799-805.

2 Headwater-Economics. 2011. U.S. Communities Dealing with WUI Fire Fact Sheet. (ICC) 1.1.2011.

3 National Interagency Fire Center. 2016. https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html (last accessed 6/10/16)

4 Rahn, M. 2009. Wildfire Impact Analysis: 2003 Wildfires in Retrospect. http:// re.sdsu.edu. San Diego State University. Wildfire Research Report No. 1. Montezuma Press. San Diego, CA.

5 Running, S.W. 2006. Is Global Warming Causing More, Larger Wildfires? Science 313: 927-928.

6 Westerling, A., H. Hidalgo, D. Cayan, and T. Swetnam. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. Science 940.

7 D. Cayan, A. L. Luers, M. Hanemann, G. Franco, and B. Croes, Scenario of Climate Change in California: Overview. CEC-500-2005-186-SF (2006).

alarming 55% by the end of this century.[8] Future decisions on development and management of the WUI are critical in determining future vulnerability and risks.

The more we gather data the portrait for firefighters darkens. These changing conditions have a direct and negative impact on firefighter exposure as the frequency of high or extreme fire-risk days increases. What this means for the "traditional" concept of wildland firefighting is that the regularity, intensity, and complexity of wildland firefighting is increasing, resulting in associated increases in the risks to firefighters responding to these incidents. The ability to effectively combat wildfires is inextricably linked to firefighter health and safety.

The firefighters response to a wildland or WUI fire, demands strenuous physical work over rugged terrain, often in hot, dry, smokey conditions. Incidents can last hours or weeks, usually requiring consecutive working days and shifts of up to 24 hours long.[9,10,11] While the general impression of wildland firefighting is that the firefighters are working in near constant presence of actual fire, in many incidents a majority of tasks performed during wildfire suppression occur away from the fire or after the fire has been put out (e.g. mop-up). Consequently, it is vital that we understand the physiological conditions of firefighters across a diversity of duties and tasks, and across a range of environmental conditions.

Even a cursory glance forces us to appreciate that the physical demands of wildland firefighting are executed while wearing personal protective equipment (PPE). This can create a highly insulating environment, in addition to individuals carrying an additional 10- to 20-kg (or more) of food, water, safety gear, and equipment. This combination of exertion, psychological stress, weighted personal equipment and hostile environmental conditions creates a demanding work environment that can affect nearly every system of the body. As a result, wildland firefighters

8 Westerling, et al. 2006.

9 Aisbett, B., A. Wolkow, M. Sprajcer, and S. Ferguson. 2012. Awake, Smoky, and Hot: Providing an Evidence-base for Managing the Risks Associated with Occupational Stressors Encountered by Wildland Firefighters. Applied Ergonomics 43: 916–925.

10 Rodríguez-Marroyo J., J. Villa, J. López-Satue, R. Pernía, B. Carballo, J. García-López, et al. 2011. Physical and Thermal Strain of Firefighters According to the Firefighting Tactics Used to Suppress Wildfires. Ergonomics 54: 1101–1108.

11 Cater H., D. Clancy, K. Duffy, A. Holgate, B. Wilison, and J. Wood. 2007. Fatigue on the Fireground: The DPI Experience. Hobart, Australia.

experience the limits of what the human body was meant to endure. Repeated exposure to these conditions can lead to injuries, long-term health effects, and increased morbidity and mortality.

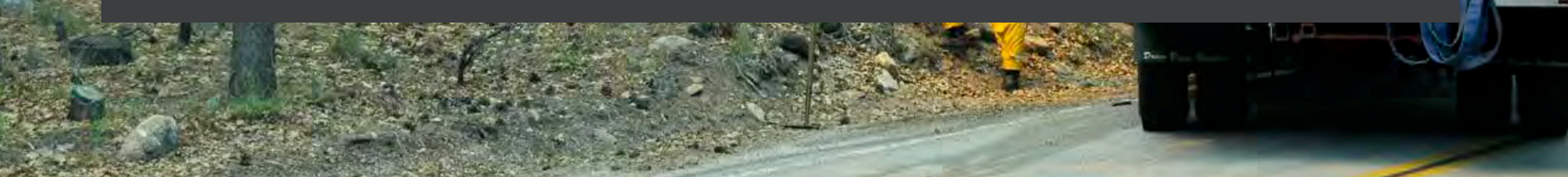
Unfortunately, the majority of the research describing the effects of firefighting have investigated relatively short bouts of activity, or simulated events in controlled or simulated environments. This stands in stark contrast to the often long hours worked on extended attack incidents with chaotic and diverse environmental conditions. These studies certainly provide valuable information about relationships between the working environment and the effects on the human body, but it is likely that the results obtained under these controlled conditions are not necessarily analogous to actual working conditions. They may in fact underestimate the physiological stresses that occur during an actual incident. What is more concerning is that a vast majority of the work on firefighter health and safety tends to focus on urban, structure, and high-rise incidents. As a result, experts in the industry generally agree that wildland firefighting is, in many respects, at least a generation behind with regard to fundamental research and understanding health effects.[12]

The magnitude of physiological strain, cardiovascular impact, and thermal stress experienced by a wildland firefighter are the result of diverse and complex variables including environmental (e.g. work performed, duration, protective equipment, and ambient environmental conditions) and personal factors (e.g. individual characteristics, hydration, physical fitness, and health condition). This project was designed to improve our understanding and provide recommendations to improve the health and safety for those working on wildland and WUI fires.

1.1 Core Body Temperature

Thousands of occupational heat related illnesses (HRI) are documented annually, and hundreds of duty-related civilian causalities that result from environmental heat exposure.[13] In 1986, the National Institute for Occupational Safety and Health (NIOSH) estimated that roughly 5 to 10 million workers in the U.S. experience excessively hot working conditions that may impact health and safety.[14] Higher temperature working conditions and thermal loading of an individual is not only physically dangerous, it also decreases an individual's productivity, decreases their ability to perform tasks, and can lead to a higher incidence of injury.[15,16,17] Once on notice policymakers recognize staffing and liability concerns. This is of particular importance to wildland firefighting

12 Rahn, M. and T. McHale. 2015. A Comprehensive View on the Future of Fighting Wildfires by a Team of Experts. CAL FIRE Local 2881 Symposium. Sacramento, CA.
13 Bureau of Labor Statistics. Last accessed: May 14, 2016. Injuries, Illnesses, and Fatalities databases. 2014 Available at: http://www.bls.gov/iif/
14 National Institutes for Occupational Safety and Health (NIOSH). 1986. Criteria for a recommended standard…Occupational Exposure to Hot Environments Revised Criteria 1986. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, NIOSH, and Division of Standards Development and Technology Transfer. Full report available at: www.cdc.gov/niosh/docs/86-113/86-113.pdf.
15 Lin, R. and C. Chan. 2009. Effects of Heat on Workers' Health and Productivity in Taiwan. Glob Health Action. doi: 10.3402/gha.v2i0.2024.
16 Ramsey, J. 1995. Task Performance in Heat: a Review. Ergonomics. 38(1):154–65.
17 Park, E., K. Hannaford-Turner, and H. Lee. 2009. Use of Personal Protective Equipment in Agricultural Workers Under Hot and Humid Conditions. Ind Health. 47(2):200–1.



given the complex and hazardous working environment that regularly requires rapid response and decision-making.

Studies addressing HRI often focus on physical exertion; those working in an outdoor environment are at particularly high risk, especially for those jobs that require significant exertion and/or endurance.[18] Seasonal wildland firefighters, short duration employees, and those in the early stages of their training (e.g. military) are identified as a relatively susceptible population for HRI.[19,20] Studies on heat exposure have been a key priority for the military since the 1950's when guidelines at training facilities were established to help reduce heat causalities.[21] Additional research with the military also identified that heat stroke is more commonly associated with overweight individuals, and often occurs (regardless of fitness level) within the first two hours of activity.[22] This basic research has helped us understand the human response to stressful working environments. The bad news is that a singular focus and body of literature on wildland and WUI firefighters is lacking. This is unacceptable given the modern dynamic of wildland firefighting.

What we do know, is that the onset of heat stress occurs when a person has either been overexposed to high thermal conditions or has exerted themselves beyond a safe level for the existing thermal environment.[23] This is unfortunately a common scenario for most wildland firefighters.[24] It is well documented that the use of PPE can exacerbate the risk of HRI, even when the subject is operating in conditions that are not considered particularly hot.[25] Studies on firefighters found that PPE profoundly influenced an increase in HRI, with incidence of injury occurring at significantly lower ambient temperatures when compared with the general civilian workforce (~79°F versus ~89°F respectively).[26] Further confounding the situation, dehydration can significantly influence HRI, even in individuals that are generally physically fit and acclimated to the heat.[27] Suitable understanding of the relationships between heat related illnesses and the implications for wildland/WUI firefighters remains limited.

1.2 Heart Rate

Take a moment to consider that heart or cardiovascular disease accounts for almost half of all duty-related fatalities among U.S. firefighters.[28,29] Additionally, it is estimated that for every heart-related fatality, there are an estimated seventeen non-fatal, line-of-duty cardiovascular disease events that occur in the U.S. fire service.[30] The number of cardiac events has been relatively stable since 2005.[31] Many of these fatalities are related to sudden cardiac death during fire

18 Nelson, N., C. Collins, R. Comstock, and L. McKenzie. 2011. Exertional Heat-Related Injuries Treated in Emergency Departments in the U.S., 1997–2006. Am J Prev Med. 40(1):54–60.
19 Maeda, T., S. Kaneko, M. Ohta, K. Tanaka, A. Sasaki, and T. Fukushima. 2006. Risk Factors for Heatstroke Among Japanese Forestry Workers. J Occup Health. 48(4):223–9.
20 Epstein, Y., D. Moran, Y. Shapiro, E. Sohar, and J. Shemer. 1993. Exertional heat stroke: a case series. Med Sci Sports Exerc. 31(2):224–8.
21 Minard, D., H. Belding, and J. Kingston. 1957. Prevention of heat casualties. J Am Med Assoc. 165(14):1813–8.
22 Esptein et al. 1999.
23 National Oceanic and Atmospheric Administration (NOAA). 2005. Heat wave: a major summer killer. Last Accessed 5/10/2016.: www.nws.noaa.gov/om/brochures/heat_wave.shtml
24 Rodríguez-Marroyo et al. 2001.
25 Crockford, G. 1999. Protective Clothing and Heat Stress: Introduction. Ann Occup Hyg. 43(5):287–8.
26 Bonauto, D., E. Rauser, and L. Lim. 2010. Occupational Heat Illness in Washington State, 2000–2009. Washington State Department of Labor & Statistics. Technical Report Number 59-2-2010.
27 Ekbom, B., J. Greenleaf, and L. Hermansen. 1970. Temperature Regulation During Exercise Dehydration in Man. Acta Physiol Scand. 79:475–483.
28 Fahy, R., R. LeBlanc, and J. Molis. 2009. Firefighter Fatalities in the United States – 2008. Quincy, MA: National Fire Protection Association.
29 Kales, S., E. Soteriades, C. Christophi, et al. 2007. Emergency duties and deaths from heart disease among firefighters in the United States. N Engl J Med. 356:1207–1215.
30 Karter M. and J. Molis. 2005. Firefighter Injuries. National Fire Protection Association. Quincy, MA.
31 Fahy, R. 2010. U.S. Fire Service Fatalities in Structure Fires, 1977-2009. NFPA.

ground activities and when responding to, or returning from fires.[32,33]

In an investigation of on-duty cardiac-related fatalities, NIOSH reports "*Firefighting activities are strenuous and often require firefighters to work at near maximal heart rates for long periods. The increase in heart rate has been shown to begin with responding to the initial alarm and to persist through the course of fire suppression activities.*"[34] Additional studies suggest that the risk of dying from coronary heart disease (and related factors) is 10 to 100 times higher during firefighting activities than during non-emergency fire department duties.[35]

Studies within the fire services have documented that typical duties and training activities can often result in near maximal heart rates that are often reached early and maintained for prolonged periods after peak activities. These rigorous duties can trigger heart events in firefighters, especially those with existing or undiagnosed heart problems.[36,37,38] Researchers at the University of Illinois conducted a structure fire study, observing that it was not uncommon for firefighters to reach nearly 190 beats per minute (reaching age-predicted maximal heart rates).[39] Similar studies have documented analogous results during training and active fire scenarios,[40,41,42] while other studies found less than maximal heart rates during firefighter training events.[43]

A paucity of research specific to wildland and WUI firefighting, especially in the areas of cumulative effects and extended duty is unfortunate and likely consequential. One of the limitations of existing studies is that they focus on structure fire incidents that typically have limited durations of less than an hour. Further, some studies that collected real-time data have screeched to a halt once physiological parameters reached advanced levels (e.g. high core temperatures or heart rates). While the safety of the participant is obviously of paramount concern, halting these studies limits insight into actual fire scenarios and the wildland firefighter, where individuals often work for extended periods of time under extreme conditions.

32 Fahy, R. P. LeBlanc, and J. Molis. 2007. What□s Changed Over the Past 30 Years? NFPA.
33 Fahy, R. 2005. U.S. Firefighter Fatalities Due to Sudden Cardiac Death. NFPA.
34 NIOSH. 2004. Report Number FACE-F2004-46. http://www.cdc.gov/niosh/face200446.html.
35 Kales, S. E. Soteriades, C. Christophi, and D. Christiani. 2007. Emergency Duties and Deaths from Heart Disease among Firefighters in the United States. New England Journal of Medicine 356(12): 1207-1215.
36 Kales SN, Soteriades ES, Christoudias SG, et al. 2003. Firefighters and on-duty deaths from coronary heart disease: a case control study. Environ Health. 2003; 2:14.
37 Holder, J., L. Stallings, L. Peeples, et al. 2006. Firefighter Heart Presumption Retirements in Massachusetts 1997–2004. J Occup Environ Med. 48:1047–1053.
38 Kales, S., E. Soteriades, C. Christophi, et al. 2007. Emergency Duties and Deaths from Heart Disease Among Firefighters in the United States. N Engl J Med. 356:1207–1215.
39 Smith, D., T. Manning, and S. Petruzzello. 2001. Effect of Strenuous Live-Fire Drills on Cardiovascular and Psychological Responses of Recruit Firefighters. Ergonomics. 44(3): 244-254.
40 Manning, J. and T. Griggs. 1983. 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 Medicine. 25(3): 215–218.
41 Duncan, H., G. Gardner, and R. Barnard. 1979. Physiological Responses of Men Working in Fire Fighting Equipment in the Heat. Ergonomics. 22(5): 521-527.
42 Sothmann, M., K. Saupe, D. Jasenof, and J. Blaney, 1992. Heart Rate Response of Fire Fighters to Actual Emergencies: Implications for Cardiorespiratory Fitness. Journal of Occupational Medicine. 34(8): 797-800.
43 Romet, T. and J. Frim. 1987. Physiological Responses to Fire Fighting Activities. Eur J Appl Physiol Occup Physiol. 56(6):633-8.

1.3 Hydration

It is well documented as well as common sense that maintaining healthy levels of hydration is critical to the safety and performance of an individual. Despite the fact that the National Fire Protection Agency (NFPA) has promulgated multiple standards that address hydration, there is a general lack of guidance on how to effectively monitor and maintain healthy levels of hydration, especially during prolonged wildfire incidents where firefighters are exposed to extreme environmental conditions. Although several studies (discussed in Section 4.3) address the methods of hydration, exhaustive protocols do not currently exist and ad libitum hydration seems to dominate the recommended strategies.

The impact to our wildland firefighters is real. Sports medicine research has demonstrated that a loss of fluids (and even minor losses in body mass) is correlated with a decrease in physical ability, concentration, alertness, and performance.[44,45,46] The cumulative effects from excessive heart rates, environmental exposures, and excessive core body temperatures is of genuine concern for wildland and WUI firefighting. It is estimated that the average 200 pound structure firefighter can lose two percent of their body mass within 30 to 60 minutes (depending on work intensity and environmental conditions), causing significant physiological issues.[47] It is not clear however, how extended duty, high levels of activity, and excessive temperatures influence the mental or physiological capabilities of wildland firefighters. Using a sports metaphor, we better understand the sprinter, yet find the marathoner a mystery.

1.4 Personal Protective Equipment (PPE)

Personal protective equipment (PPE) is necessary to protect firefighters from burn and inhalation injuries. That is the good news. The most immediate problem is that the PPE adds to the weight of an already burdened firefighter, adding friction and unwanted heat generation with fabrics that interfere with the body's natural thermoregulation processes (sweating and evaporation). Heat dissipation is significantly impaired by PPE, largely due to the encapsulation of the individual.[48] This can add strain on an individual's respiratory and cardiovascular system. Past studies demonstrate that simply wearing structure PPE (and SCBA) while walking can heighten core temperature and heart rates. The type of PPE (e.g. fully encapsulating versus lesser PPE) can also affect physiological response to work, depending on the level of insulation produced.[49]

FEMA training guidelines recommend that structural firefighters wear lighter weight PPE and limit their turnout use to very short durations to minimize heat stress injuries.[50] No such option exists for the wildland firefighter. It is recognized that the typical urban or structural firefighting

44 Rodrigues, R., B. Baroni, M. Pompermayer, et al. 2014. Effects of Acute Dehydration on Neuromuscular Responses of Exercised and Nonexercised Muscles After Exercise in the Heat. J Strength Cond Res. 28:3531–3536.
45 Maughan, R. 2003. Impact of Mild Dehydration on Wellness and on Exercise Performance. Eur J Clin Nutr. 57: Suppl 2, S19–S23.
46 Pompermayer, M., R. Rodrigues, B. Baroni, et al. 2014. Rehydration During Exercise in the Heat Reduces Physiological Strain Index in Healthy Adults. Rev Bras Cineantropom Desempenho Hum. 16:629637.
47 McEvoy, M. and D. Rhodes. 2015. Hydration and Firefighter Performance. Fire Engineering. 168(4).
48 Smith, D., G. Horn, E. Goldstein, S. Petruzzello, et al. 2008. Firefighter Fatalities and Injuries: The Role of Heat Stress and PPE. Firefighter Life Safety Research Center, Illinois Fire Service Institute. University of Illinois and Urbana-Champaign.
49 Smith, D., S. Petruzzello, J. Kramer, S. Warner, B. Bone, and J. Misner. 1995. Selected Physiological and Psycho-Biological Responses to Physical Activity in Different Configurations of Firefighting Gear. Ergonomics. 38(10): 2065-2077.
50 FEMA. 2002. Introduction to Wildland/Urban Interface Firefighting for the Structural Company Officer. Training Manual, 2002.

companies are more frequently responding to wildland and WUI fires.[51] Unfortunately, many of these companies do not have the resources to carry the lighter weight PPE specifically for WUI firefighting. Understanding the effect PPE has on firefighters, and having flexible, configurable, and adaptive PPE is becoming more important as the incidents of wildland and WUI fires increases across the U.S.

1.5 Goals and Objectives

The goal of our study is to understand the relationship between the wildland and WUI working environment and firefighter health and safety. We will identify areas where tactics, equipment, protocols, or policy can be amended to improve the health and safety of our wildland firefighters. Our aim is to understand the relationship between diverse environmental factors, core body temperature, heat exposure, heart rate, respiration rate, activity, dehydration, and PPE.

2.0 Methods

Employing a cooperative agreement funded by the USDA Forest Service, our research team was embedded with CAL FIRE and had real-world access to trainings, controlled burns, and actual wildfire incidents to collect data on environmental factors and firefighter physiology. We assessed firefighters while they were actually conducting training activities that generally occurred on extended hoselays of 2,000 feet, controlled burns (of both grasslands and mixed shrub), and on actual wildfire incidents. A primary objective was to ensure that we had no operational impact on wildfire incidents, underscoring that data collection would occur as a byproduct of normal activities. Another objective was to collect data across a diverse cross section of CAL FIRE firefighters with regard to gender, age, experience, and physical condition. We were technically constrained by the additional requirement that we work only with individuals who were willing to volunteer to participate in the experiment. This did not prove to be inhibiting since so many were willing to step forward that candidates were then selected based on a random draw of those firefighters available for each day of the experiment.

A biological use authorization approval was provided through

51 Rahn and McHale, 2015.

San Diego State University by the Institutional Biosafety Committee and Institutional Review Board (IRB) in accordance with 45 CFR 46 and 21 CFR 50. All subjects included in the study were on-duty CAL FIRE firefighters who voluntarily signed a comprehensive research consent form (approved by the IRB). During all phases of the research involving firefighters, the highest level of care and concern was given to the safety and health of the participants. All information collected was protected to ensure the privacy of study participants per human subject protocol requirements. Firefighters involved in the study were identified only by a unique number rather than by name.

This study was designed to be consistent with the methods being used by the U.S. Forest Service in related studies on firefighter exposure. A key goal is that meaningful comparisons can be made. Variables were monitored every second and included: heart rate, respiratory rate, skin temperature, and core body temperature. The BioHarness™ (designed by Zyphr Technology) was used to monitor heart rate, activity, and respiratory rate. This device is generally regarded as a robust and reliable field-based tool for measuring these factors, [52] including use by firefighters during duty and in hot environments.[53,54]

Maximum heart rate for each individual was estimated using the formula HRmax = 220bpm – age,[55] and was calculated based on data collected by the BioHarness. The BioHarness provides a quantifiable measure of activity through use of a tri-axial accelerometer and piezoelectric technology. This estimate of activity, measured in vector magnitude units by the BioHarness, is considered a reliable metric for monitoring personal activity and exertion.[56]

Core body temperature (T_c) was recorded every ten seconds using a CorTemp® Ingestible Core Body Temperature Sensor (designed by HQInc.) that wirelessly transmits core body temperature as it travels through the digestive tract. The sensor's signal passes harmlessly through the body to the CorTemp Data Recorder worn on the outside of the body. Ambient temperature was measured every ten seconds using a USB temperature probe with external high temperature thermistor (Lascar EL-USB) that was attached to the front of the web gear on the firefighter to monitor ambient temperature and radiant heat exposure. Additional ambient conditions and heat stress were recorded every 15 minutes with a Extech HT30 Heat Stress WBGT meter, logging wet blub globe temperature, ambient air temperature, and relative humidity.

Additional data collected on the individual firefighter included rank, shift duration, age, gender, height, weight, Body Mass Index (BMI), hydration levels, nutritional information, PPE (double or single layer), fitness level, and nicotine use. For hydration, we measured urine specific gravity (U_{sg}) before and after the activity period being monitored.[57] A urine sample was collected in the morning before shift and at the end of the monitoring period with a hand-held refractometer used to estimate U_{sg}. For our purposes, a U_{sg} of less than 1.020 was generally considered the

52 Hallstone, J. and A. Kilding. 2011. Reliability and Validity of the Zephyr BioHarness to Measure Respiratory Response to Exercise. Measurement in Physical Education and Exercise Science. 25(4): 293-300.

53 Smith, D., J. Haller, B. Dolezal, C. Cooper, and P. Fehling. 2014. Evaluation of a Wearable Physiological Status Monitor During Simulated Fire Fighting Activities. J. of Occup. And Env. Hyg. 11(7): 427-433.

54 Kim, J. R. Roberge, J. Powell, A. Schafer, and W. Williams. 2013. Measurement Accuracy of Heart Rate and Respiratory Rate during Graded Exercise and Sustained Exercise in the Heat Using the Zephyr BioHarness. Int. J. Sports. Med. 34(6): 497-501.

55 Miller et al. 1993. Predicting max HR. Medicine & Science in Sports & Exercise. 25(9): 1077-1081.

56 Johnstone, J., P. Ford, G. Hiughes, T. Watson, A. Mitchell, and A. Garrett. 2012. Field Based Reliability and Validity of the Bioharness Multivariable Monitoring Device. J. Sports. Sci. Med. 11(4): 643-652.

57 Urinalysis has been shown to be the most valid and reliable method for determining moderate changes in fluid balance. See generally: Armstrong, L.E., Soto, J.A., Hacker, F.T., Casa, D.J., Kavouras, S.A., Maresh, C.M. 1998. Urinary indices during dehydration, exercise, and rehydration." Int. J. Sport Nutr. 8: 345-355.

lowest acceptable level of hydration for firefighters.[58,59] Nutritional information was recorded from each volunteer, documenting food and fluid intake during the 12-hour period prior to the activity, as self-reported by the study participant. Where practical, we collected data on the current fitness of each firefighter using the USFS step test.[60,61] These tests were generally conducted on the volunteers the day before the event when logistically possible.

Once all the data was downloaded, collected, and collated, a "data cleaning" protocol was used to remove any extraneous or anomalous data and gross errors that were a byproduct of sensor faults or other technical errors. This vastly improves the data analysis and subsequent reliability and validity of statistics across all variables. The basic statistics for heart rate, activity, respiration and core temperature was calculated for each minute of the study. A maximum sustained value for heart rate, respiratory rate, and activity was identified during each minute interval as the peak value that was sustained for at least 10 seconds during any given minute. Maximum core temperature was identified during each minute as the peak value sustained for 30 seconds during each minute interval. All data were then combined into a complete time-series spreadsheet and exported into Microsoft Excel (v15), MiniTab (v16), and R (v3.2.5) for analysis.

58 Sawka MN, Burke LM, Eichner ER, et al. American College of Sports Medicine Position Stand: Exercise and Fluid Replacement. Med Sci Sports Exerc. 2007; 39:377390.
59 McEvoy and Rhodes, 2015.
60 Sharkey, B.J. 1979. Physiology of Fitness: Prescribing Exercise for Fitness Weight Control and Health, Human Kinetics Publishers.
61 Sharkey, B. 2003. Work capacity test: administrator's guide. NWCG PMS 307 NFES 1109. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 28 p.

3.0 Results

Between April 2013 and June 2015, we were able to collect data on 95 firefighters: 25 firefighters at three training events; 30 firefighters at four controlled burns; and 40 firefighters at five wildfire incidents. Of the firefighters monitored, 93 were male and two were female; 26 were wearing double layer PPE while the rest wore single layer; 72 were a rank of Firefighter 1 or 2, 11 were Engineers, and 12 were Captains. Additional summary statistics on the firefighters are provided in Table 1. The average age of the firefighters was 29 years old, with an average height of 5'10" and average weight of 188 pounds. Fifteen firefighters self-identified as using nicotine.

Table 1. Summary Statistics for Firefighters Included in the Study (field instrumentation was limited to a minimum U_{sg} of 1.01 and a maximum of 1.04*).**

Variable	Mean	SE Mean	StDev	Median	Min	Max
Start Hydration (urine specific gravity)*	1.020	0.000692	0.00675	1.02	1.01	1.04
End Hydration (urine specific gravity)*	1.023	0.000802	0.00782	1.024	1.01	1.04
Age (years)	28.71	0.691	6.736	26	21	50
Height (inches)	70.61	0.288	2.807	70	65	79
Weight (lbs)	187.71	2.46	23.94	185	150	265
BMI	26.45	0.294	2.862	25.8	20	37
Max Heart Rate (beats per minute)	199.27	2.13	20.8	202	126	238
Max Core Temperature (Fahrenheit)	102.00	0.0897	0.874	102.15	99.77	103.79

While BMI is not the best indicator of fitness, it still provides a useful assessment of an individual.[62] According to the standard measure of BMI, most of the firefighters in this study would be considered overweight. However it is widely recognized that highly-trained individuals may have an artificially high BMI because of increased muscle mass.[63] Due to this discrepancy, we also conducted the Sharkey Step-Test as a more reliable measure of individual fitness. As a result, most of the firefighters included in this study were considered generally fit, with the step test results showing only a typical negative relationship between the estimated VO_2 Max and age (Figure 1). In addition, no significant relationships were identified between the results of the Step-Test and other factors including heart rates or core temperatures.

62 For BMI calculations, we used the formula provided by the National Institute of Health: National Heart, Lung, and Blood Institute. Last Access 5/15/16. http://www.nhlbi.nih.gov/health/educational/lose_wt/BMI/bmicalc.htm

63 Centers of Disease Control and Prevention. Body Mass Index: Considerations for Practitioners. Last Accessed 5/15/16. http://www.cdc.gov/obesity/downloads/BMIforPactitioners.pdf

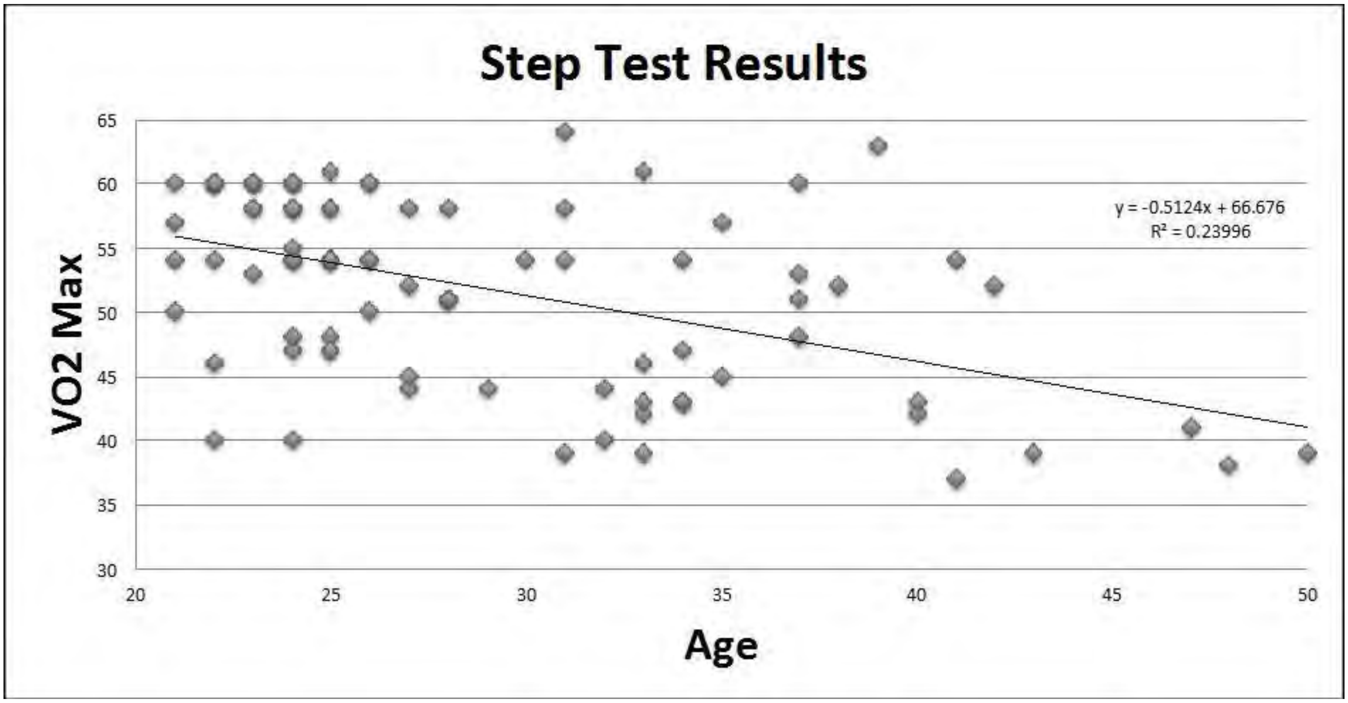


Figure 1. Step test results for 95 firefighters included in the study. Note that as age increases, the estimated VO_2 Max decreases.

To help us understand the potentially complex relationships between the variety of categorical, and continuous numerical data collected, and to summarize results across the firefighters included in the study, a Canonical Correspondence Analysis (CCA) was performed to determine which factors (if any) have the most significant influence on health and safety. The CCA summarizes the responses across all the factors, and expresses the results in terms of changes in heart rate, core temperature, and hydration, and fitness level relative to a variety of factors, including age, height, weight, nicotine use, ambient air temperature, incident type, and activity levels. More than one pattern can change in the response variables, and CCA can identify as many "axes" of change in composition as there are predictors. The strongest pattern (called CCA1) is found first, and subsequent axes characterize successively weaker patterns of change in composition. Randomization tests can be used to identify a significant CCA overall, and to test the significance of each CCA axis. While the CCA did not result in identifying strongly significant relationships (with no significant eigenvalues), maximum core temperature and maximum heart rate did seem to have the highest response levels (Figure 2). This provided additional (albeit limited) insight into the relationships among the data, and helped focus additional analyses that were specific to core temperature and heart rate.

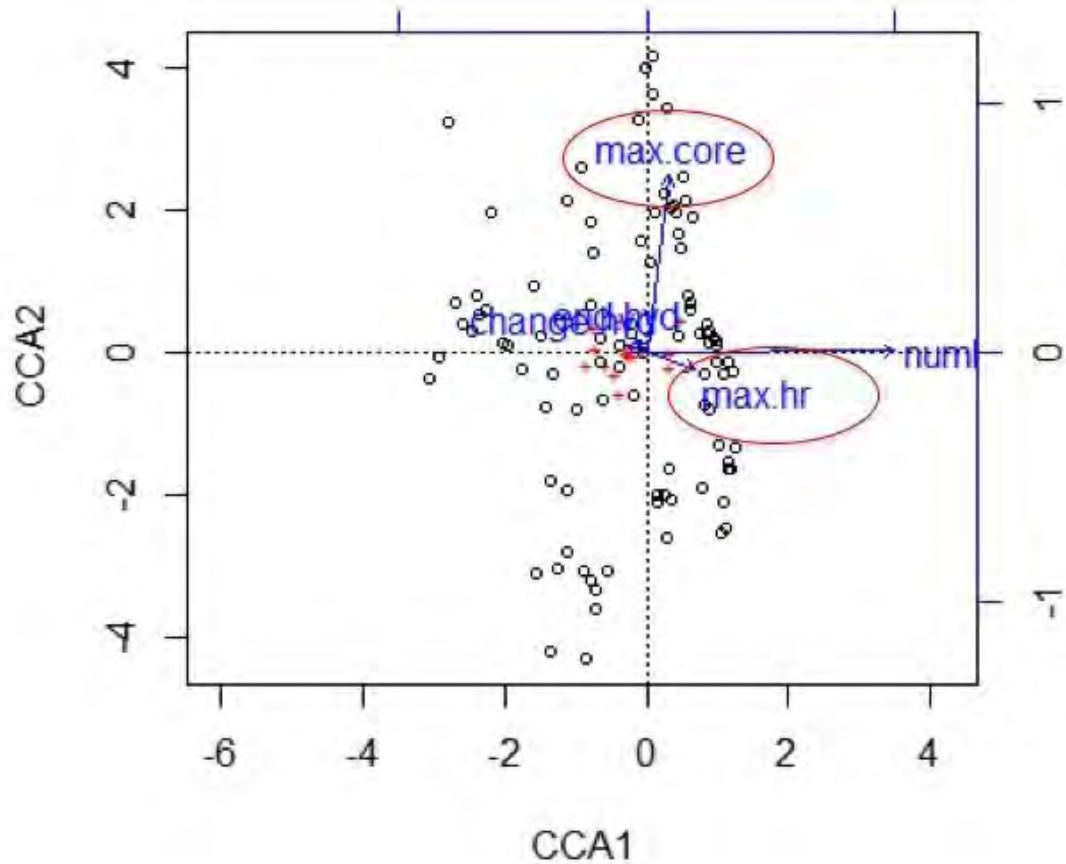


Figure 2. Results of the Canonical Correspondence Analysis showing slight influence related to a firefighter's maximum core temperature and heart rate.

3.1 Core Temperature

The mean core temperature of the firefighters during the study was 99.67°F (SD = 1.11), with a calculated maximum core temperature (per minute) of 99.73°F (SD = 1.13). If one assumes a normal core temperature of 98.7°F, this means that the firefighters generally maintained core temperatures throughout their shift above normal approximately 75% of the time (Figure 3).

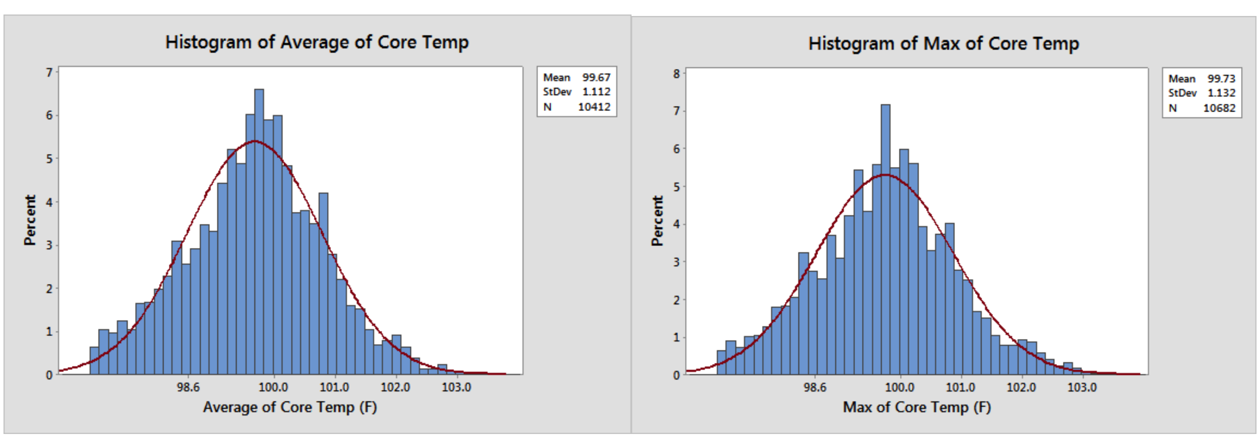


Figure 3. Histograms of the average and maximum core temperatures of firefighters.

Approximately 70% of the firefighters (at some point during their activity) had a maximum sustained core temperature above 102°F, with nearly 10% of them reaching a maximum sustained core temperature above 103°F. One individual reached a maximum core temperature of 103.79°F (notably, this was also the same individual that reached a maximum sustained peak heart rate of 238 bpm-discussed below).

When looking at the average or maximum core temperatures of the firefighters involved in the study, there were no significant relationships observed with regard to age, fitness (BMI and step test results), ambient temperatures, wet-bulb-globe temperatures, or hydration.

We did note a significant difference in core temperature based on the PPE worn, with wearers of single layer PPE having lower core temperatures than that of double layer (discussed in more detail in Section 3.4).

When combining all recorded data into one large dataset, we were able to observe general relationships (using simple linear regression) between average and maximum core temperatures, heart rate, and respiratory rate. The following analyses resulted in noticeable findings:

1) When looking at the average core temperature (°F) and average heart rate (per minute), a significant regression was observed ($F(1, 5891)=3084.33$, $p<0.0001$) with an R^2 of 22.88%. A firefighters average core temperature is predicted to increase by 0.2°F for every 10bpm increase in average heart rate. Similarly, when looking at the maximum core temperature (°F) and maximum heart rate (per minute), a significant regression was observed ($F(1, 164)=3430.53$, $p<0.0001$) with an R^2 of 24.34%. A firefighter's maximum core temperature is predicted to increase by 0.2°F for every 10bpm increase in average heart rate. (Figure 4).

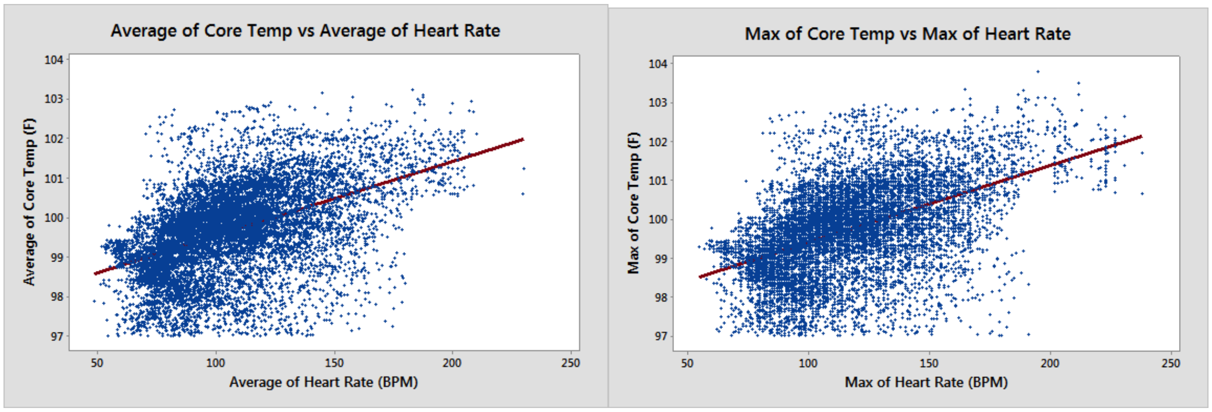


Figure 4. Linear regression of average core temperature v. average heart rate and maximum core temperature v. maximum heart rate.

2) While there were significant relationships observed when looking at the average core temperature (°F) and average respiratory rate (breaths per minute) ($F (1,2807)=299.82$, $P<0.0001$, and $R^2=2.8\%$), and the relationship between maximum core temperature and maximum activity level ($F (1,127)=213.2$, $P<0.0001$, and $R^2=1.96\%$), the R-squared values are remarkably low, suggesting that while there may be a significant relationship, too little of the data are explained by these relationships (Figure 5).

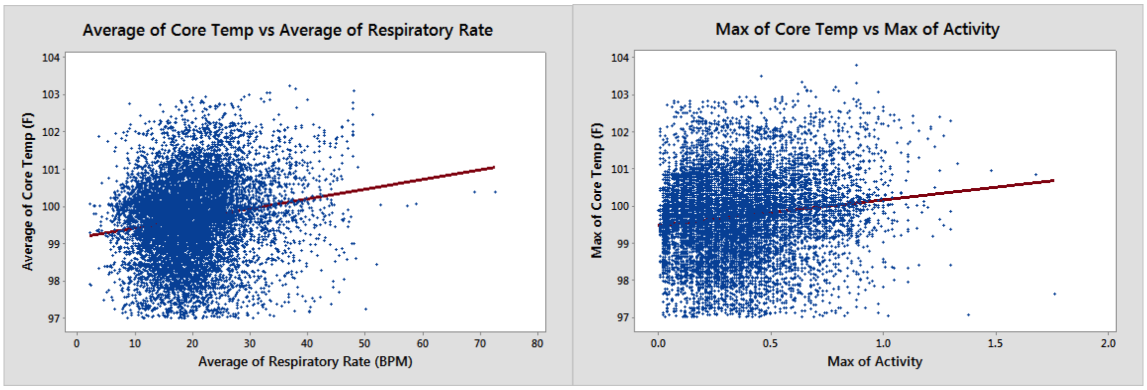


Figure 5. Linear regression of average core temperature v. average respiratory rate and maximum core temperature v. maximum activity level.

3.2 Heart Rate

The mean heart rate of the firefighters (recorded throughout the shift duration) was 108.9bpm (SD = 29.4), with a calculated maximum sustained heart rate (per minute) of 118.5bpm (SD = 29.22). If one assumes a normal resting heart rate of 60bpm, this means that the firefighters generally maintained average heart rates throughout their shift above the resting normal roughly 85% of the time (Figure 6).

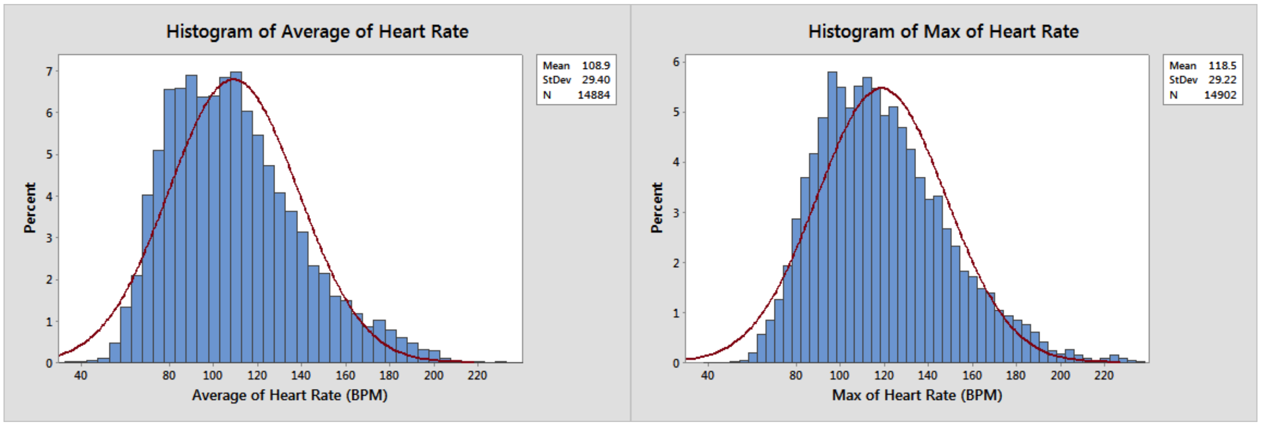


Figure 6. Histograms of the average and maximum sustained heart rates of firefighters.

Approximately 64% of the firefighters (at some point during their activity) had a maximum sustained peak heart rate above 200bpm, with 18% exceeding 220bpm. Similarly, 97% (N=92) of the firefighters regularly exceeded the recommended maximum heart rate for work (85% of the maximum heart rate of 220bpm – age). The firefighters exceeded this recommended threshold, reaching an average sustained peak heart rate that was 123% higher (±14%), with the highest level exceeding 165% for an individual, sustaining a peak heart rate of 238bpm.

When looking at the average or maximum heart rates of the firefighters involved in the study, there was no significant relationships observed with regard to age, fitness (BMI and step test results), ambient temperatures, wet-bulb-globe temperatures, or hydration. While nicotine use did not show any significant relationship to heart rate graphically, there appears to be a somewhat higher heart rate in those individuals that self-reported nicotine use (Figure 7). Furthermore, while there is no significant relationship between hydration levels, it does appear that there may be a nascent relationship with higher levels of dehydration resulting in elevated heart rates (Figure 8). We recognized a significant difference in heart rate levels based on the PPE worn, with wearers of single layer PPE having significantly lower heart rates than that of double layer (discussed in Section 3.4).

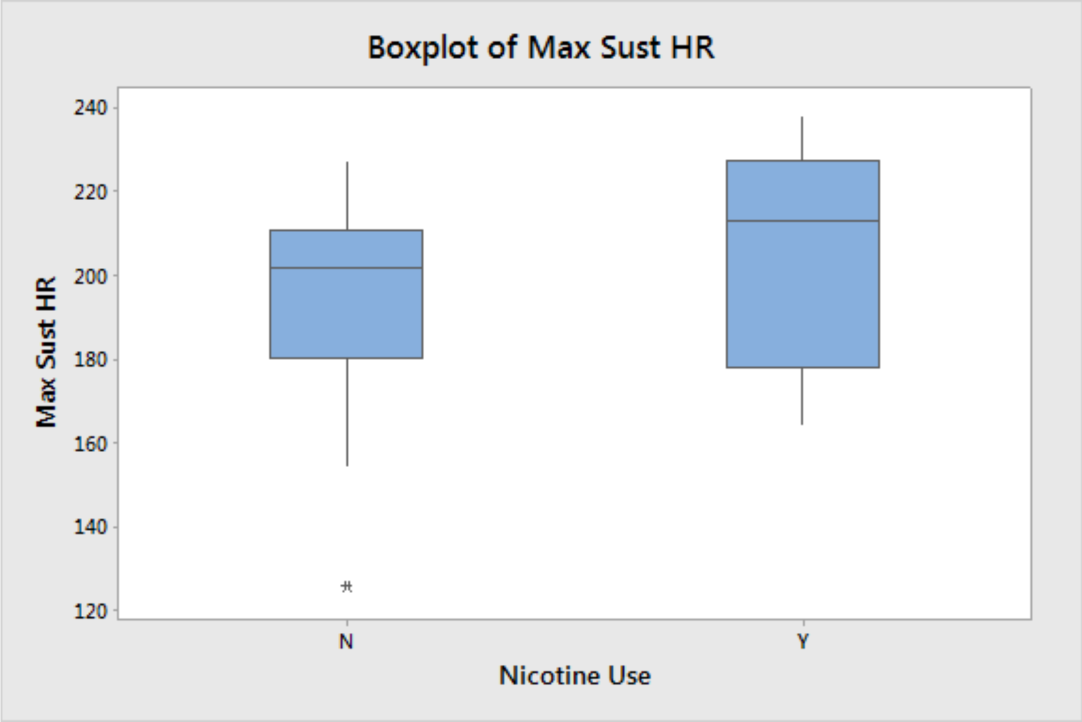


Figure 7. Comparison of maximum sustained heart rate and the reported use of nicotine by firefighters.

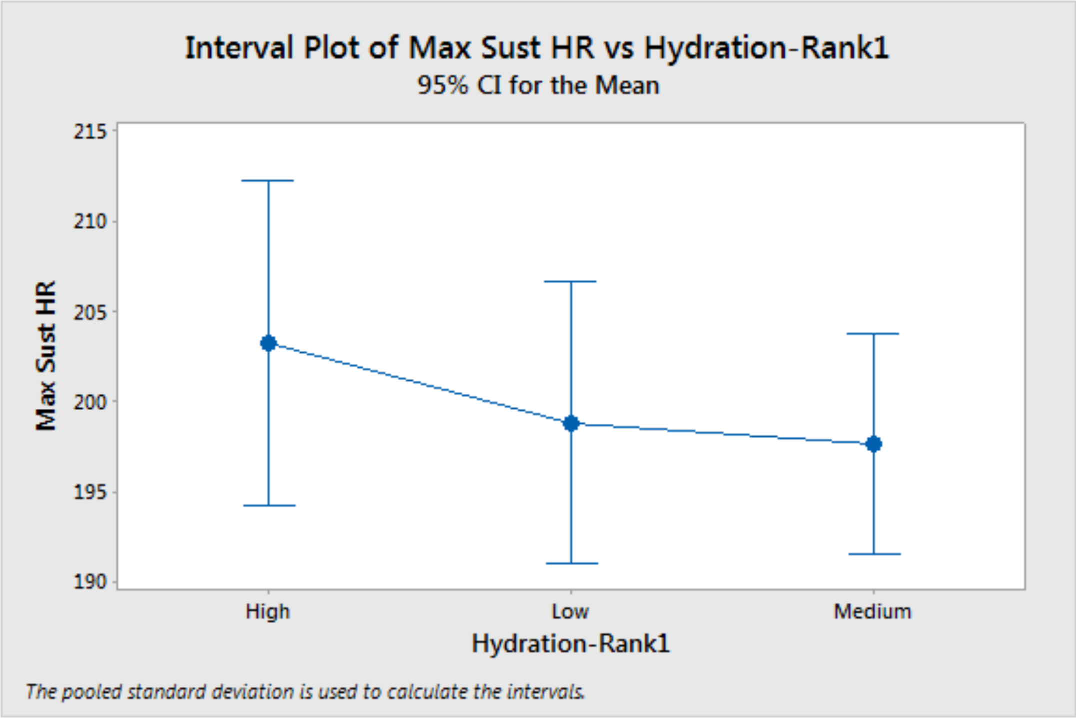


Figure 8. Comparison of maximum sustained heart rate and levels of hydration, where low is considered hydrated, medium is considered near dehydration, and high is dehydrated (U_{sg}>1.2).

When combining all recorded data into one dataset, we were able to observe general relationships (using simple linear regression) between average heart rates and maximum sustained peak heart rates and how they are influenced by factors such as: activity, respiration, and core temperature. Only the following analyses resulted in significant results:

1) When looking at the average heart rate and average activity level (per minute), a significant regression was observed ($F(1, 101)=4871.4$, $p<0.0001$) with an R^2 of 24.67%. A firefighter's average heart rate is predicted to increase by 13.3 beats per minute for each 0.1-unit increase of activity (as measured by BioHarness). Similarly, when looking at the maximum heart rate and maximum activity (per minute), a significant regression was observed ($F(1, 143)=3244.62$, $p<0.0001$) with an R^2 of 17.88%. A firefighter's maximum heart rate is predicted to increase by 5.2 beats per minute for each 0.1-unit increase of activity (Figure 9).

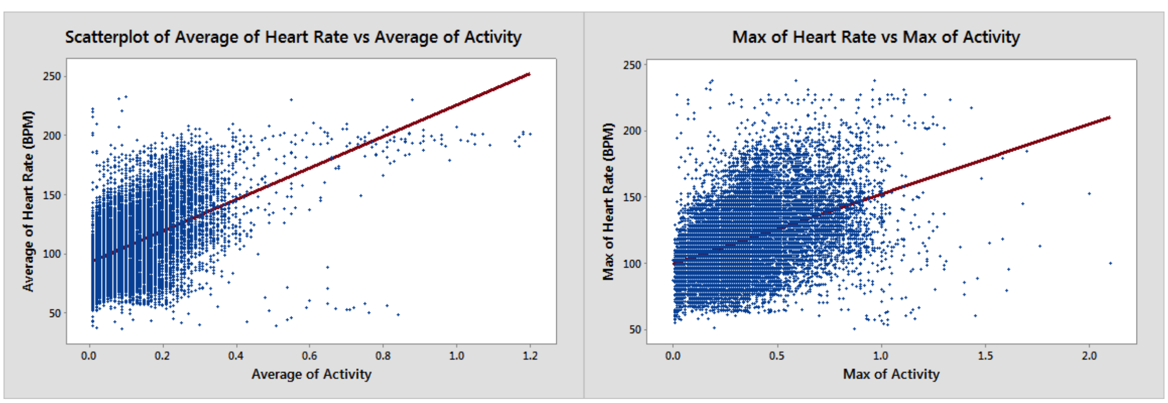


Figure 9. Linear regression of average heart rate v. average activity and maximum heart rate v. maximum activity.

2) When looking at the average heart rate and maximum core temperature (°F), a significant regression was observed (F (1, 377)=3405.35, $p<0.0001$) with an R^2 of 24.21%. A firefighter's average heart rate is predicted to increase by 12.2 beats per minute for each degree increase in maximum core temperature (Figure 10).

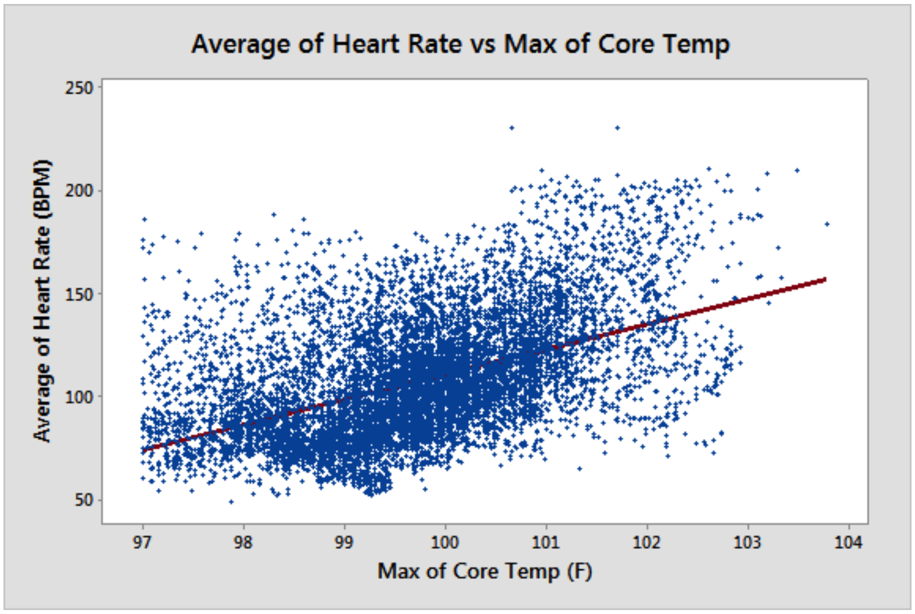


Figure 10. Linear regression of average heart rate and maximum core temperature.

3) When looking at the maximum heart rate (bpm) and maximum respiratory rate (breaths per minute), a significant regression was observed (F (1, 552)=2008.45, $p<0.0001$) with an R^2 of 11.9%. A firefighter's maximum heart rate is predicted to increase by 1.2 beats per minute for each additional breath taken per minute (Figure 11).

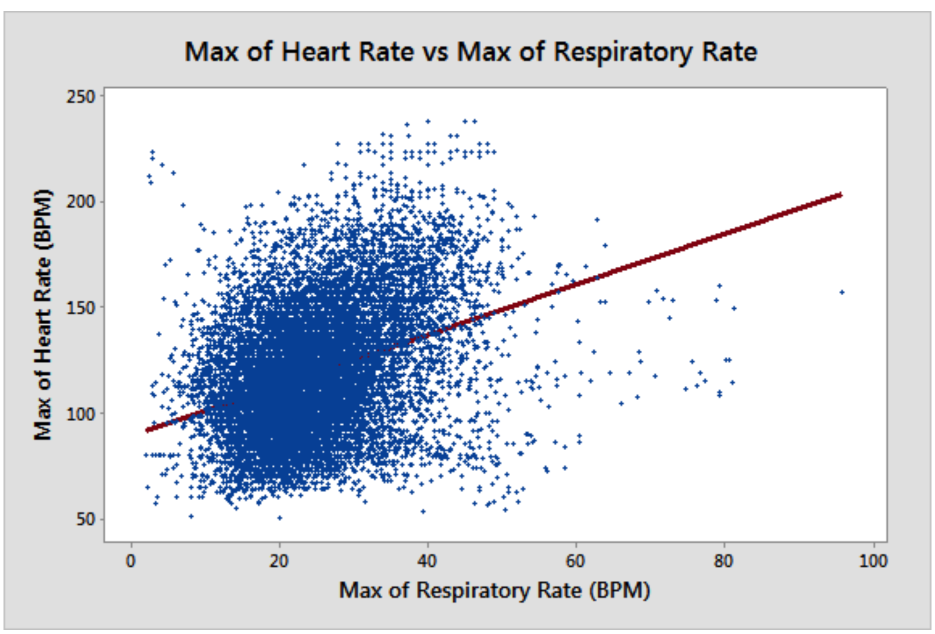


Figure 11. Linear regression of maximum heart rate and maximum respiratory rate.

3.3 Hydration

We recorded hydration on 95 firefighters, with urine samples collected before and after duty. The hand-held refractometer had a scale from 1.01 to 1.04; firefighters with a Usg of 1.02-1.022 were considered "near dehydration," while any values above that level were classified as dehydrated. Nearly two-thirds of the firefighters started their shifts at or near a level of dehydration. Dehydration rates significantly increased across all firefighters at the end of duty. Of those individuals that started off the shift at or near dehydration (N=62), 63% (N=39) were more dehydrated by the end of the shift, 8% (N=5) had no change in hydration, and only 26% (N=16) self-corrected and were better hydrated by the end of the shift. In a paired t-test comparing the mean differences between start and end hydration, there was a significant difference among all firefighters; they all generally ended their shift less hydrated than they started ($t = -3.89$, $df = 94$, $p<0.0001$) (Figure 12).

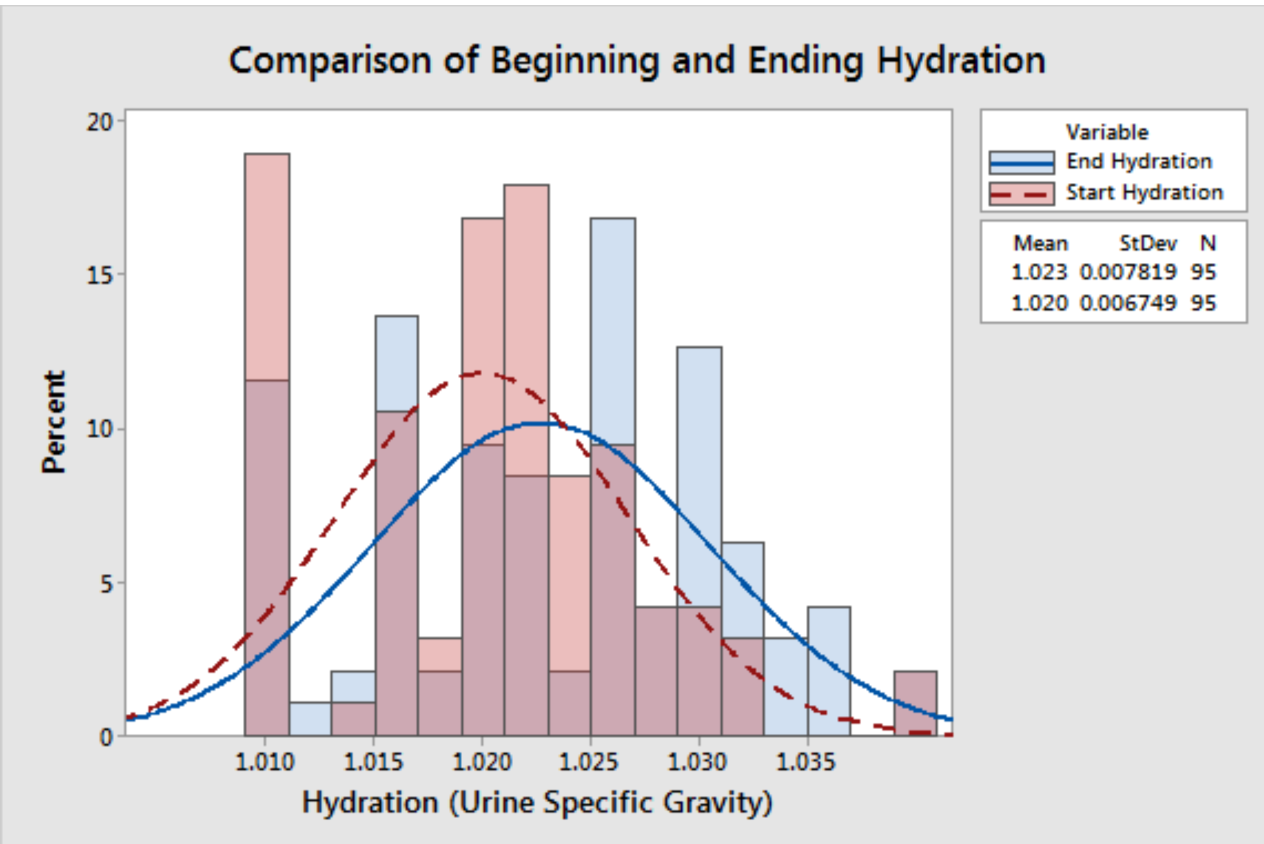
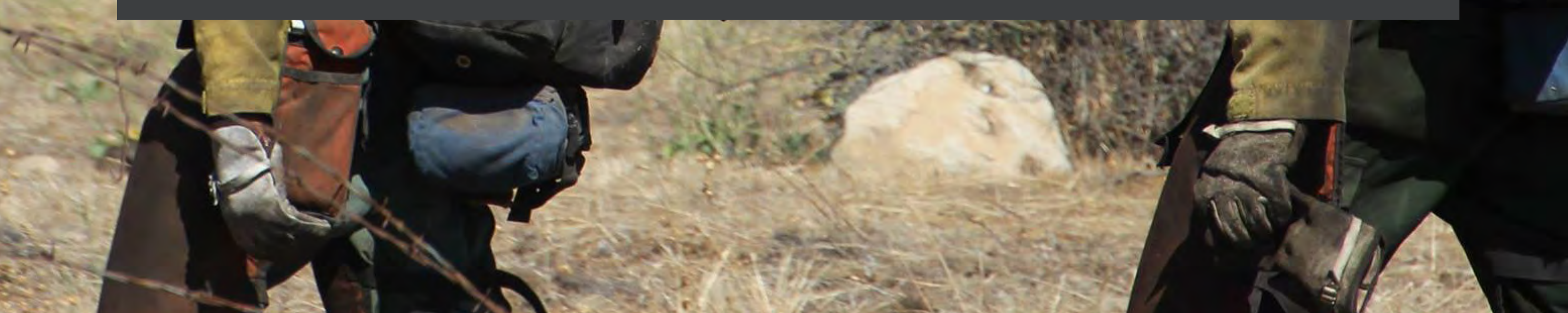


Figure 12. Histogram and summary statistics on the starting and ending hydration for 95 firefighters included in the study.



There were no significant relationships between hydration and other factors including BMI, fitness level, nicotine use, ambient temperature, wet-bulb-globe temperature, and activity. The type of event (actual wildfire, controlled burn, and training exercise) showed no significant influence on hydration levels (Figure 13). There was however a significant difference in hydration levels based on the PPE worn, with wearers of single layer PPE having higher levels of hydration than that of double layer (discussed in Section 3.4).

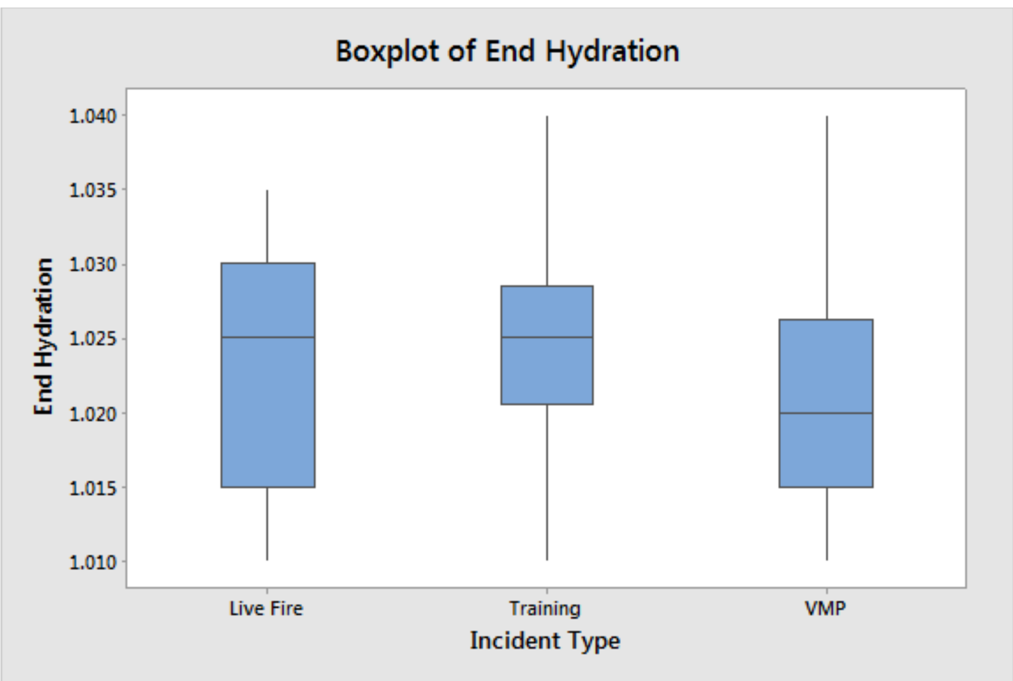


Figure 13. No significant differences were observed between incident types [actual wildfire, training, and controlled burn (VMP)] and the hydration level of the firefighters at the end of the day.

3.4 Personal Protective Equipment (PPE)

During the study, we recorded 26 individuals wearing the CAL FIRE Legacy PPE that consisted of a double-layer PPE jacket with cotton lined sleeves, and 69 individuals wearing the interim garment that consisted of a a single layer top (no sleeve linings) made from Nomex® IIIA material. In addition, each firefighter included in the study was wearing a base-layer that consisted of a cotton under shirt and two layers of pants that included standard issue uniform work pants and wildland firefighter Nomex® IIIA pants (we did not control for socks or underwear). Although the sample sizes were not equivalent, we were able to perform simple statistics to identify potential relationships. The following analyses provided significant results:

1) In a two-sample t-test, firefighters wearing double-layer PPE had significantly higher maximum core body temperatures (102.3°F) than those wearing single-layer PPE (101.9°F), (t=2.11, df=41, p=0.041), (Figure 14).

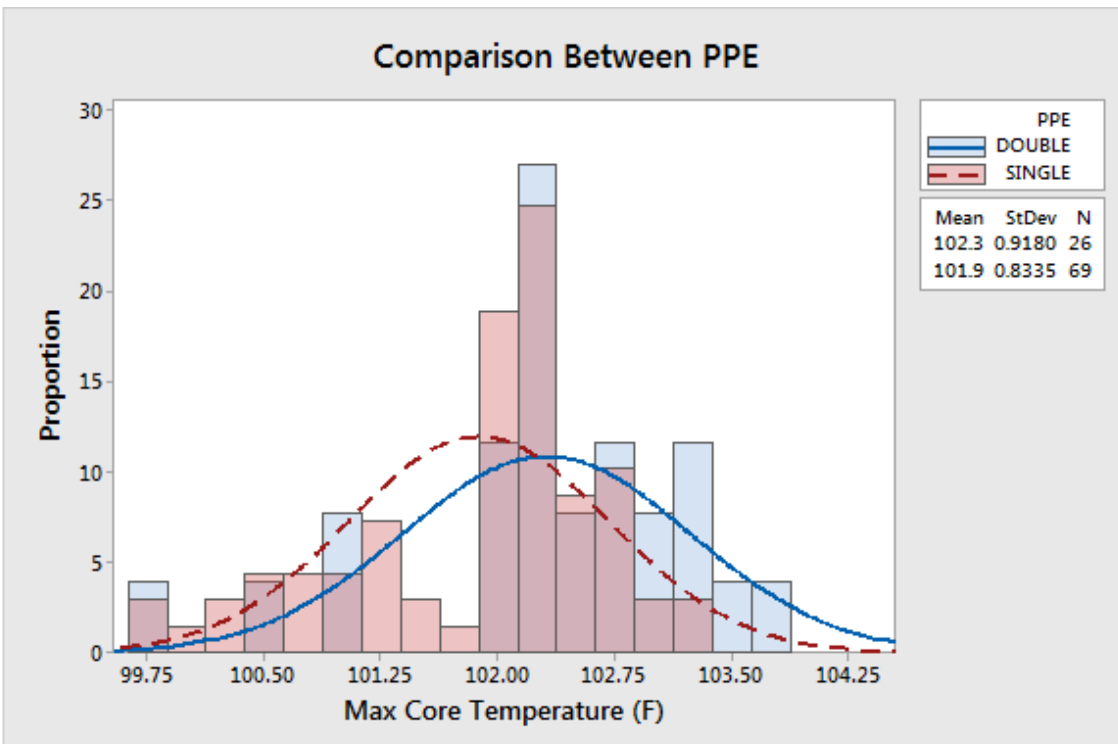


Figure 14. Histograms comparing the distribution of maximum core body temperatures of firefighters wearing double- and single-layer PPE

2) In a two-sample t-test, firefighters wearing double-layer PPE had significantly higher levels of dehydration ($1.025U_{sg}$) than those wearing single-layer PPE ($1.022U_{sg}$), ($t=2.04$, $df=41$, $p=0.048$), (Figure 15).

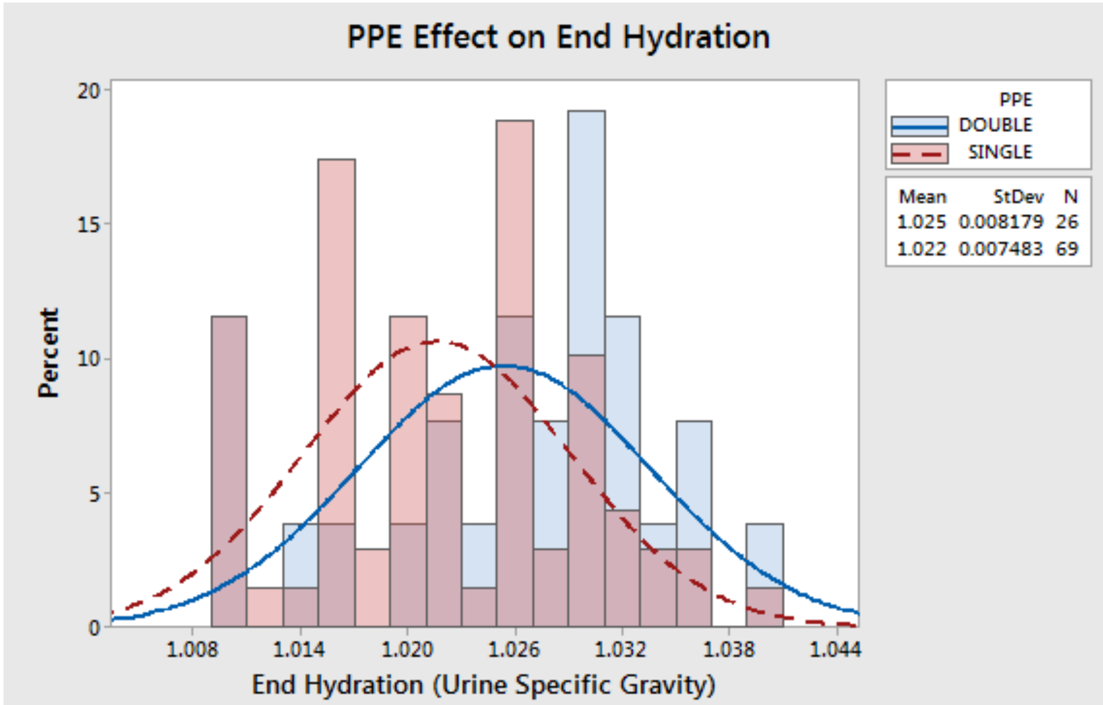


Figure 15. Histograms comparing the distribution of end of shift hydration levels of firefighters wearing double- and single-layer PPE.

3) In a two-sample t-test, firefighters wearing double-layer PPE had significantly higher average sustained heart rates, and maximum sustained peak heart rates than those wearing single-layer PPE, ($t=32.2$, $df=41$, $p<0.0001$; and $t=38.4$, $df=41$, $p<0.0001$ respectively), (Figure 16)

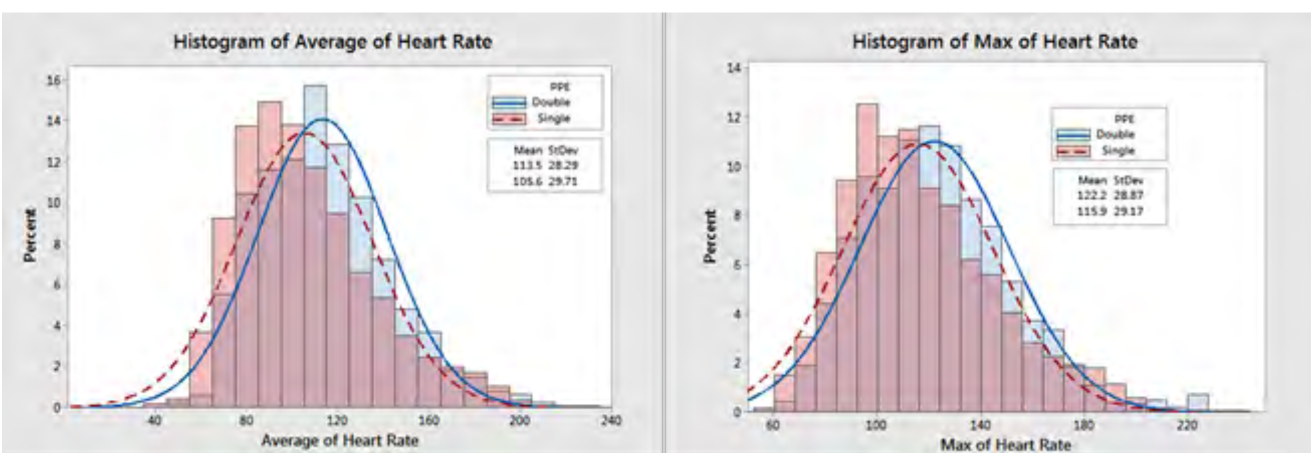


Figure 16. Histograms comparing the distribution of average and maximum heart rates of firefighters wearing double- and single-layer PPE.

4.0 Discussion

An ongoing debate is ensuing throughout the United States that questions the adequacy of modern firefighter staffing, resources, response protocols, and land management. Critical decisions are driven by such malleable and extrinsic factors as public perception, environmental concerns and budgetary constraints. As a result, decisions can be made without adequate empirical support or even any in-depth understanding of the issues. This has led to serious consequences for wildfire/WUI response, community safety, attack effectiveness, and firefighter health and safety. Although firefighting response and effectiveness has vastly improved, many of the basic issues have not been researched and considerable uncertainty remains. Consequently, wildland and WUI fires have not kept pace with the advancements seen in structure and high-rise fires.[64]

The health and safety of our firefighters is secondary only to the protection of the citizens they have sworn to serve, yet our ability to clearly understand how to avoid, minimize, and mitigate risk is confounded. For example, the notion of a discrete fire season and "traditional wildland fire" is antiquated. A paradigm shift is occurring as our country continues to build, and in many instances, recklessly into the WUI. A clear result is an increase to our community risks, and that of our firefighters; every season is wildfire season. The results of this study provide useful insights into how changing environmental conditions, duties, and PPE relate to the health and safety of firefighters. This study also provides recommended steps that can be taken to improve the health and safety of our wildland and WUI firefighters.

No one questions that firefighters experience extreme physical strain. While this is expected on a wildfire (given the dramatic and chaotic working environment), it was surprising that trainings and controlled burns created nearly identical physiological impacts to firefighters. Despite these results (across all incident types), it is important to note that this study has limits. It was not possible to collect data on initial attack firefighters that work under the most extreme conditions, nor was it possible to track

64 Rahn and McHale, 2015.

wildland firefighters over multiple, consecutive days as they worked without reprieve. It can probably be argued successfully that this may be where the largest idiosyncrasies in health and safety impacts occur. Given the extreme physiological responses observed in this study, and the consistency with which they were detected, regardless of incident type, it can safely be assumed that firefighters working under the most extreme of conditions are likely to experience even higher heart rates, core temperatures, and levels of dehydration. The results of this study may explain why there is a high propensity of cardiovascular events in firefighters. As a result, it is increasingly important to identify protocols, tactics, strategies, equipment, and rehabilitation measures that can help mitigate stressors and improve firefighter resilience.

The complex working environment and diversity of intrinsic and extrinsic variables makes this a challenging field of study. A pervasive issue throughout the analyses was that, while there appeared to be significant relationships between various factors, low probability values were confounded by low R-squared values. Basically, while there may be a statistically significant relationship between some variables, there is also considerable variability within that relationship that is not well described by traditional linear models. Although this is not ideal for a regression analysis, this is not an uncommon outcome, particularly when working with large datasets and human physiology. Many studies on humans have R-squared values far less than 50% because people tend to be fairly unpredictable and physiological responses can be complex.[65] The data may contain inherently high amounts of unexplained variability as the low p-values indicate that there is a real (and significant) relationship between predictors and the response variable; pooling the data on all firefighters may explain this discrepancy.

When we look closer at how individuals responded to certain conditions, the distribution of the data still tends to be heteroskedastic. The relationships become clearer, with continued low p-values ($P<0.0001$), but higher R-squared values (of approximately 40%) (Figure 17).

65 REFERENCE NEEDED

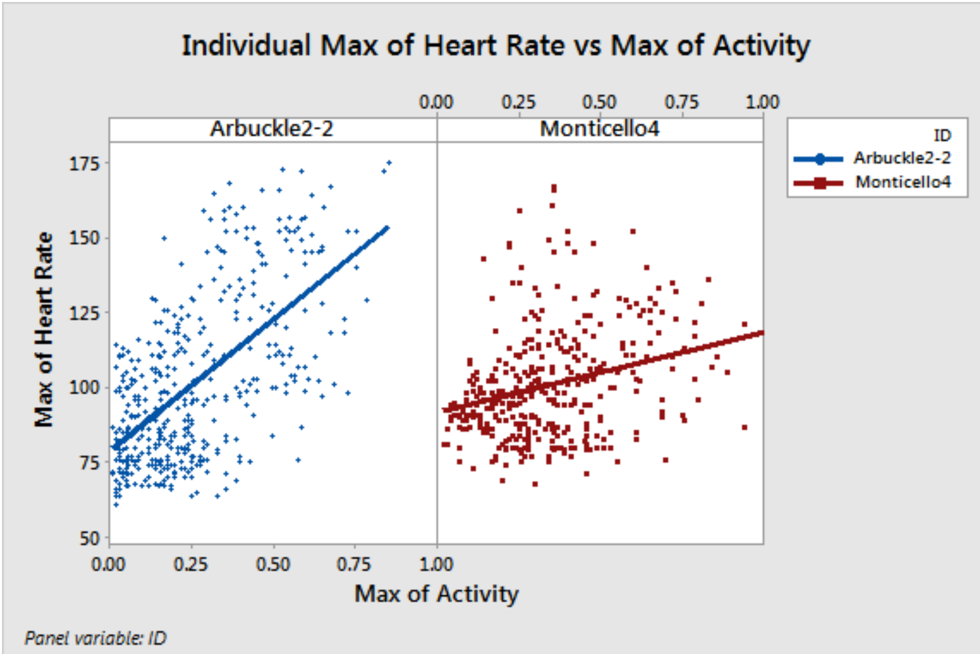


Figure 17. Individual regression results for firefighters showing similarly low p-values, considerably less variability than the overall population, and over twice the resulting R-squared values.

Likewise, data collected on individual firefighters show that there are strong observable relationships within an individual that become convoluted when looking across a cross section of wildland firefighters (Figure 18).

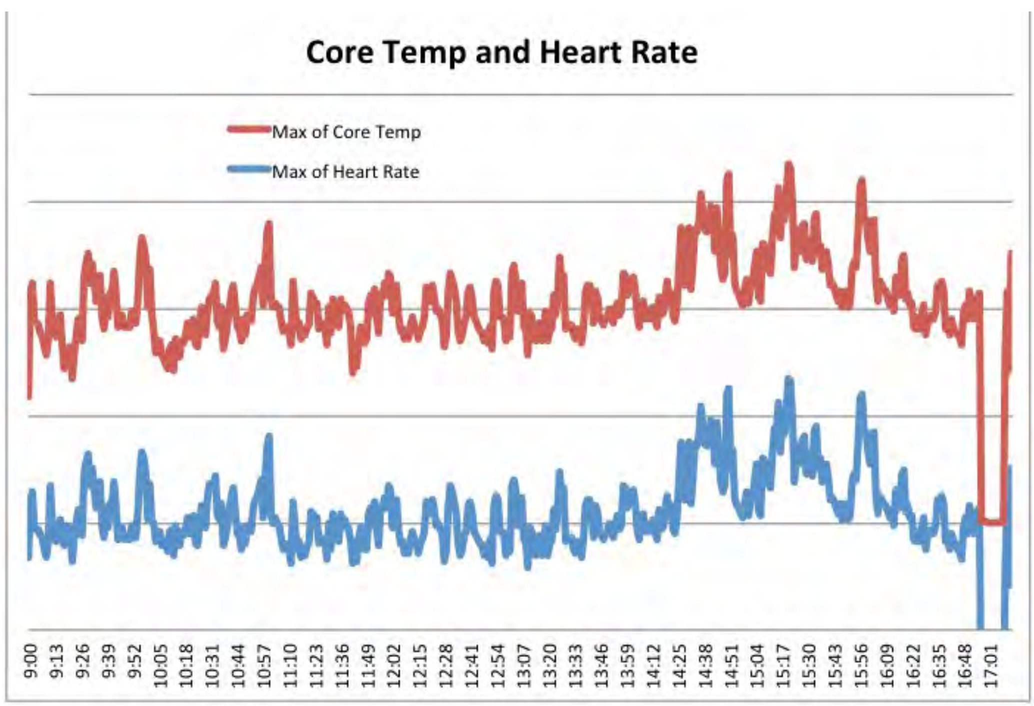


Figure 18. Individual time-series results for an individual firefighter showing the correlation between maximum core temperature and maximum heart rate recorded while on an eight-hour shift.

These results suggest that while we can make reasonable predictions and generalizations across a population of wildland firefighters, ultimately the individual matters. An overall pattern of response to exertion and stress exists, but each firefighter may have a discrete response to activities, environmental conditions, and stressors, confounded by an individual's fitness, physiology, psychology, and acclimation. The following sections specifically address the research results related to core body temperature, heart rate, hydration, and PPE.

4.1 Core Body Temperature

The National Institute for Occupational Safety and Health (NIOSH) recommended a heat exposure standard to the Occupational Safety and Health Administration (OSHA) in 1972, 1986, and 2016.[66,67,68] Despite the history and the large body of evidence that suggests heat stress on a wildland/WUI fire is an occupational hazard, OSHA has not promulgated standards for environmental heat exposure under the U.S. Code of Federal Regulations; uniform heat stress prevention policies do not exist. This is not entirely surprising, particularly given the results of this study. We are only beginning to understand the relationships between environmental and occupational stressors and the resultant health and safety of firefighters. Absent sufficient data and understanding it is not credible to implement exhaustive regulations.

Published empirical and epidemiological data on occupational heat stress are sparse and fragmented, particularly with regard to wildland firefighters. In general, the human body should maintain a core temperature within about 1.8°F of the normal core body temperature, or a maximum of 100.4°F.[69] Again, firefighters included in this study carried core temperatures above this recommended level over half of the time. Heat-related issues can arise from stressors including high air temperatures, humidity, radiant heat, and individual metabolic heat that is generated though physical activity.[70] Results from this study demonstrated that

66 National Institutes for Occupational Safety and Health (NIOSH). 1972. Criteria for a Recommended Standard...Occupational Exposure to Hot Environments.
67 NIOSH 1986.
68 National Institutes for Occupational Safety and Health (NIOSH). 2016. Criteria for a Recommended Standards: Occupational Exposure to Heat and Hot Environments.
69 American Conference of Governmental Industrial Hygienists (ACGIH). Heat Stress and Stain. TLVs. 2009.
70 Weeks, J., B. Levy, and G. Wagner, editors. Preventing Occupational Disease and Injury. Washington, D.C: American Public Health Association Press; 1991.

wildland/WUI firefighters regularly experience high core body temperatures, regardless of whether they are participating in a wildfire, controlled burn, or training incident. In analogous studies conducted by the U.S. Forest Service, it was also found that firefighters regularly exceeded recommended core temperatures during sustained submaximal exercise in the heat.[71] These results have serious implications for the health and safety of our wildland/WUI firefighters.

Although heat related illness (HRI) can occur in an otherwise healthy individual, major risk factors include dehydration, obesity, poor physical fitness, alcohol use, and prior or recent diagnosis of an HRI.[72] These factors also interfere with the ability to acclimate to extreme temperatures. Although this did not seem to be an issue for our test subjects, this study essentially collected data on comparatively fit firefighters – this is certainly an issue worth addressing within the fire services as these factors can potentially contribute to dangerous health circumstances (particularly given that those firefighters willing to volunteer for this study may be predisposed to have higher fitness levels than those that did not volunteer).

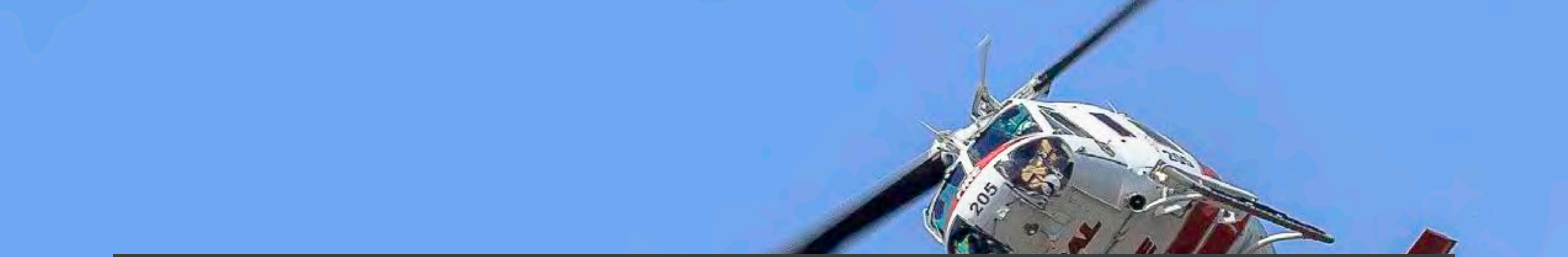
The individual's fitness level put aside, adaptation to environmental conditions is universal. However, even though humans are capable of adapting to discrete periods of high heat (e.g. acclimatization), this generally occurs over a 4–6 day period where the individual experiences continuous daily exposure (with peak acclimatization generally occurring in two weeks).[73] Despite this potential evolutionary advantage, it is unlikely that sufficient acclimatization occurs during episodic and intermittent extreme heat events.[74] In contrast to these findings however, sports medicine research suggests that short-term, repeated heat exposures can improve performance and decrease thermal stress and exertion (although subjects in these studies do not experience the extreme environmental, psychological, or physiological

71 Domitrovich, J. 2014. Wildland firefighter health & safety report: No. 14. Tech. Rep. 1351–2811–MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center. 10 p.

72 Adelakun, A., E. Schwartz, and L. Blais. 1999. Occupational heat exposure. Appl Occup Environ Hyg. 14(3): 153-4.

73 World Health Organization (WHO). 1969. Technical Report series No 412. Geneva: 1969. Health factors involved in working under conditions of heat stress. Report of a WHO Scientific group.

74 Patz, J., M. McGeehin, S. Bernard, K. Ebi, P. Epstein, A. Grambsch, D. Gubler, P. Reiter, I. Romieu, J, Rose, J. Samet, and J Trtanf. 2000. The Potential Health Impacts of Climate Variability and Change for the United States: Executive Summary of the Report of the Health Sector of the U.S. National Assessment. Environ Health Perspect. 108(4):367–76.



stresses of a wildland firefighter).[75,76] It is worth studying this issue further, particularly for those wildland firefighters that are on an incident for an extended period of time.

Finally, occupational exposure related to climate change effects has received very limited attention, and is an area critical to the everyday experiences of wildland firefighters.[77] From 1979 through 2000, the U.S. death rate attributed to heat exposure was generally around 0.5 deaths per million, however, since 2000, that number seems to have tripled.[78] It is important that agencies are cognizant of changing climatic conditions and the increased risks to wildland firefighters, ensuring that policies, protocols, and technology respond to this change.

4.2 Heart Rate

A high occupational rate of injuries and cardiac-related fatalities among wildland firefighters (compared with other professions) suggests that we need to improve our understanding of the relationship between the working environment and the physiological response by wildland firefighters. While NIOSH reports that structural firefighters often work "*at near maximal heart rates for long periods,*" [79] our study confirms that this is also the case for wildland firefighters. More importantly however, is the fact that wildland firefighters often exceed maximal heart rates across a variety of activities, including training, controlled burns, and actual wildfire incidents. A concomitant concern is the extraordinary length of intensive effort displayed by a wildland firefighter in comparison to a structural firefighter.

While the maximum heart rate was estimated using the formula HR_{max} = 220bpm – age,[80] the American Heart Association provides additional guidance in suggesting that the peak sustained heart rates do not exceed roughly 70-90% of the maximum

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75 Garrett, A., R. Creasy, N. Rehrer, M. Patterson, and J. Cotter. 2012. Effectiveness of Short-Term Heat Acclimation for Highly Trained Athletes. European Journal of Applied Physiology 112: 1827–1837.
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77 See generally: Kjellstrom, T., I. Holmer, and B. Lemke. 2009. Workplace heat stress, health and productivity – an increasing challenge for low and middle-income countries during climate change. Glob Health Action.
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78 U.S. Environmental Protection Agency (EPA). 2015. Climate Change Indicators in the United States: Heat Related Deaths. Last accessed 5/15/2016. https://www3.epa.gov/climatechange/science/indicators/health-society/heat-deaths.html
79 NIOSH, 2004.
80 Miller et al. 1993.

heart rate during intense physical activity.[81] We therefore estimated the maximum peak sustained heart rate at 85% of the HR_{max} given that the fitness levels of firefighters is generally higher than the general population. Despite this more generous calculation, we saw a significant number of wildland firefighters exceeding the HR_{max}. On average, firefighters in this study reached an HR_{max} that was 38% higher than recommended (123% ±14%), with one individual sustaining a HR_{max} of nearly 240bpm. Similarly, the U.S. Forest Service has observed comparable results.[82]

The high incidence of cardiac-related injuries and death in wildland firefighters may be related to regularly exceeding recommended cardiac thresholds, however the myriad of other often co-occurring and interrelated risk factors confounds a clear understanding of this relationship (which likely influences the high levels of variability seen in the data). Despite this, it is important to identify strategies for managing and reducing stressors and variables that contribute to potentially dangerously high heart rates and their resultant health and safety implications.

Beyond avoidance, minimization, and mitigation strategies for managing cardiac issues, it is important that agencies are not only aware of how environmental conditions and workload influence heart rate, but also how incident response protocols and industry practices can significantly influence outcomes. In a study of structure firefighters, researchers found that the average peak heart rate for those on the first responding engine were greater than 80% of the age-predicted maximum values when only two firefighters were deployed. In fact, the driver had an average peak heart rate of nearly 90% of age-predicted maximum when there were only two firefighters on the engine. When three and four firefighters were deployed per apparatus the peak heart rate was just above 70% (on average) across the three positions.[83] Similar studies concluded that staffing levels can also have a significant impact on the heart rate of wildland firefighters. Not only did attack effectiveness increase by over 60% as staffing progressed from a two-person to a four-person engine, but this also resulted in significantly lower heart rates, with no firefighters exceeding 195bpm on a four-person engine (while three- and two-person engines experienced peak heart rates above 200 and 220bpm, respectively).[84] This research has been disregarded to the point that we are only now starting to understand the implications of being a wildland firefighter and cardiac health.

4.3 Hydration

Notwithstanding personal statements and self-reporting to the contrary, empirical data reveals that most firefighters included in this study began duty at or near dehydration. While some of them self-corrected during the day, the vast majority were less hydrated at the end of their shift. The enduring conviction that the simple feeling of thirst is a reliable indicator of dehydration remains controversial, although our understanding of this sensation and its role in managing hydration continues to improve. Recent studies in sports medicine have found thirst as one of the most reliable indices for achieving optimal hydration.[85] However, the reliability of thirst diminishes with age[86] and in situations

81 See generally: http://www.heart.org/HEARTORG/HealthyLiving/PhysicalActivity/FitnessBasics/Target-Heart-Rates_UCM_434341_Article.jsp#.V1X7nlfg_Dk
82 George Broyles, U.S. Forest Service. Personal Communication. 2016.
83 Smith, D.L. and R. B. Benedict. 2010. Effect of Deployment of Resources on Cardiovascular Strain of Firefighters. Fire Fighter Safety and Deployment Study. International Association of Fire Fighters, Washington, DC.
84 Rahn, M. 2010. Initial Attack Effectiveness: Wildfire Staffing Study. Wildfire Research Report No. 2, Summer 2010. Montezuma Press, San Diego, CA.
85 Heneghan C, Howick J, O'Neill, et al. The evidence underpinning sports performance products: a systematic assessment. BMJ Open 2012
86 Grandjean AC, Reimers KJ, Buyckx ME. Hydration: Issues for the 21st Century. Nutrition Reviews. 2003;61:261271.

where there is excessive sweating (a phenomenon called "voluntary dehydration").[87] It is also unclear how other extrinsic factors (e.g. smoke exposure, hazardous air pollutants, high core temperatures, thermal insulation, and high ambient temperatures) affect the usefulness of thirst as a motivator in managing personal hydration. Although thirst is certainly not an exclusive, satisfactory indicator of hydration, there is sufficient evidence that it should not be ignored.[88] The challenge is identifying other measures that can be used to monitor and mitigate dehydration in wildland firefighters.

Studies related to firefighter hydration suggest that ad libitum drinking (e.g. at one's pleasure) was an adequate method for maintaining hydration status, even in hot conditions.[89] Yet extra (compulsory) fluid consumption or a pre-shift fluid bolus did not improve firefighter activity or physiological function (although core temperature was lower earlier in their shift), and self-regulation of fluids seemed to influence euhydration.[90,91] We need to develop better standards and protocols to ensure proper hydration.

This is particularly important, since it appears that firefighters may have a propensity toward baseline dehydration.[92] There is a strong imperative to encourage proper hydration before being on an incident. Firefighters also need to be able to better assess and maintain safe hydration levels while on duty, particularly during an extended attack or extreme heat days. This is particularly important given the relationship between hydration levels, core temperature, and heart rate. As a person becomes dehydrated, their blood becomes thicker, and causes the heart to work harder.[93] This can lead to elevated HR_{max}, core temperatures, and a myriad of other issues that can significantly diminish a firefighters health and safety.

87 Ganio MS, Casa DJ, Armstrong LE, et al. Evidenceapproach to lingering hydration questions. Clin Sports Med. 2007;26:116.
88 HewButler T, Verbalis JG, Noakes TD. Updated fluid recommendation: Position statement from the International Marathon Medical Directors Association (IMMDA). Clin J Sport Med. 2006;16:283292.
89 Raines, J., R, Snow, D. Nichols, and B. Aisbett. 2015. Fluid Intake, Hydration, Work Physiology of Wildfire Fighters Working in the Heat Over Consecutive Days. Ann Occup Hyg. 59(5):554-65.
90 Raines, J., R. Snow, A. Petersen, J. Harvey, D. Nichols, and B, Aisbett. 2013. The Effect of Prescribed Fluid Consumption on Physiology and Work Behavior of Wildfire Fighters. Appl Ergon. 44(3): 404-13.
91 Raines, J., R. Snow, A. Petersen, J. Harvey, D. Nichols, and B. Aisbett. 2012. Pre-Shift Fluid Intake: Effect on Physiology, Work and Drinking During Emergency Wildfire Fighting. Appl Ergon. 43(3):532-40
92 Horn G., J. DeBlois, I. Shalmyeva, et al. 2012. Quantifying Dehydration in the Fire Service Using Field Methods and Novel Devices. Prehosp Emerg Care. 16:347–355.
93 INSERT REFERENCE HERE.

It is therefore important to develop self-awareness and evaluative procedures so that firefighters can effectively assess their personal status, and that of their coworkers.

4.4 Personal Protective Equipment (PPE)

The focus of the study was not specifically on PPE. Yet the data collected on firefighters wearing two different types of wildland PPE show that heavier, thicker PPE can significantly and negatively impact the core temperature, heart rate, and hydration of a wildland firefighter. When ambient temperatures are high, the body relies on evaporative cooling; anything that restricts evaporation can interfere with this physiological response and its resulting benefits.[94] Fortunately, ongoing research is working to improve wildland PPE, balancing the need to shield the firefighter from extreme environmental conditions, while also allowing for evaporative cooling and the dissipation of heat. A simple one-size-fits all approach does not avail itself, especially as wildland firefighting continues to tackle the risks associated with the wildland urban interface. The results of this study highlight the significant role that PPE plays with regard to core temperature, hydration, and heart rate.

Firefighters deserve an assessment that properly identifies and prioritizes operational requirements for PPE worn in wildland and WUI environments. This includes an evaluation of the differences involved in a "traditional" wildland fire versus a WUI incident where firefighters are responding to an environment that includes both the wildland and structural firefighting hazards. This combination requires a rethinking of how the NFPA 1977 and NFPA 1971 requirements can be integrated in response to the WUI. The data will identify requirements for wear, comfort and protection in daily use clothing (including base layers and station uniforms) and the combination of wildland/WUI PPE needed for prolonged wear in different geographic, climatic, and environmental conditions.

94 Budd, G. 2008. Wet-bulb globe temperature (WBGT) – its history and its limitations. J Sci Med Sport. 11(1):20–32.

5.0 Conclusions and Recommendations

Based on the results of this study, the following recommendations are provided to improve wildland firefighter health and safety:

- Consider the importance of understanding wildland/WUI firefighting as equal importance to that of structure
- Provide educational programs to firefighters on how individual factors and lifestyle may predispose firefighters to increased risk for heat related injury, dehydration, and cardiac issues
    - Provide education on the effects of obesity, poor physical fitness, alcohol and nicotine use, and prior or recent diagnosis of a heat related injury as they relate to core body temperature and cardiac risk
- Develop education programs on self-assessment and/or monitoring devices used to track personal heart rate, core temperature, and hydration levels
    - Provide training on the early identification of elevated core temperature, heart rate, and dehydration
    - Train firefighters on how to utilize this information to limit and/or avoid heart rates that exceed their age-calculated HR_{max}, core temperatures in excess of 100.4°F, and dehydration
    - Provide recommended best practices to avoid, minimize, and mitigate health and safety concerns, with an emphasis on strategies employed before, during, and after duty (including actual incidents, controlled burns, and training events)[95]
    - Provide education on the signs and symptoms of extreme core temperature, heart rate, and dehydration (heat related injury signs and symptoms)
    - Provide protocols and the measures that should be taken if dangerous levels are reached[94]

The following recommendations are provided to identify future research needs and better characterize and understand health and safety issues:

- Collect additional data on firefighters working under extreme exertion and environmental conditions, in both the wildland and WUI environment, during initial attack and extended deployment

95 See generally: http://www.nifc.gov/PUBLICATIONS/redbook/2016/Chapter07.pdf

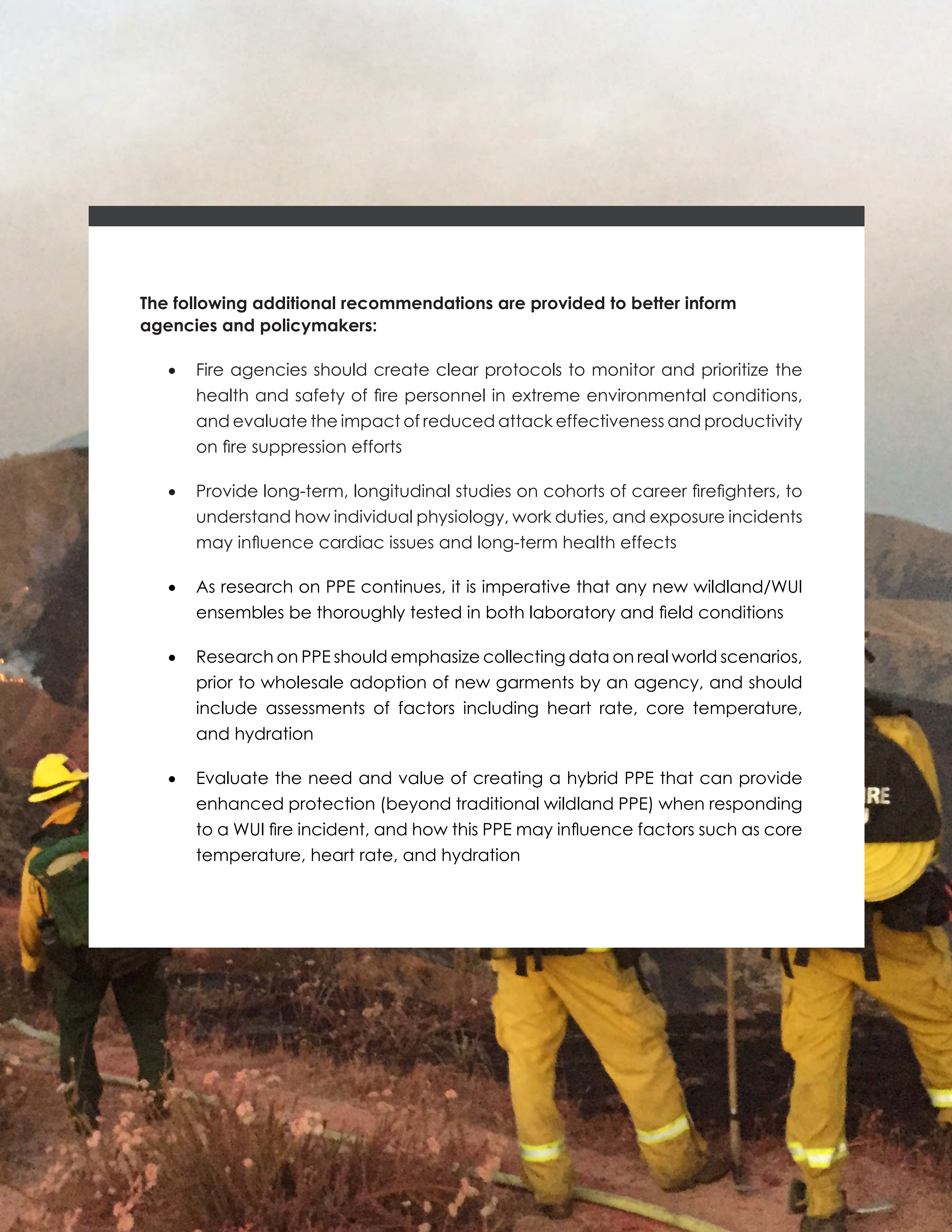
- Conduct additional research into nascent factors including nicotine use, caffeine, alcohol consumption, and their potential impact on physiological effects experienced during incidents, and health and safety of wildland firefighters

- Evaluate how specific activities (e.g. hose lays, cutting line, hiking, etc.) are related to the resultant level of activity or exertion (as measured by the BioHarness or similar device) and the resulting effect on core temperature, heart rate, and hydration

- Continue to test and develop rapid, field-based protocols for measuring and monitoring hydration levels, heart rate, and core temperature of wildland firefighters, and novel strategies to identify, avoid, minimize and mitigate these issues

- Conduct studies related to core body temperature and the effects of acclimatization during initial attack, different shift durations, and during extended attack

- Study the relationship between hydration, core body temperature, and heart rate – specifically addressing the role that fluid intake (volume and temperature) plays in reducing core temperature (and heart rate), and identifying strategies and protocols to ensure adequate levels of hydration (and peripheral benefits) for wildland firefighters
    - Study the effects that extended attack has on the hydration levels of firefighters, and identify mitigation measures that can improve healthy hydration levels and rehabilitation on the line and when returning from the field



The following additional recommendations are provided to better inform agencies and policymakers:

- Fire agencies should create clear protocols to monitor and prioritize the health and safety of fire personnel in extreme environmental conditions, and evaluate the impact of reduced attack effectiveness and productivity on fire suppression efforts

- Provide long-term, longitudinal studies on cohorts of career firefighters, to understand how individual physiology, work duties, and exposure incidents may influence cardiac issues and long-term health effects

- As research on PPE continues, it is imperative that any new wildland/WUI ensembles be thoroughly tested in both laboratory and field conditions

- Research on PPE should emphasize collecting data on real world scenarios, prior to wholesale adoption of new garments by an agency, and should include assessments of factors including heart rate, core temperature, and hydration

- Evaluate the need and value of creating a hybrid PPE that can provide enhanced protection (beyond traditional wildland PPE) when responding to a WUI fire incident, and how this PPE may influence factors such as core temperature, heart rate, and hydration

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**WILDLAND FIREFIGHTER EXPOSURE STUDY:
EVALUATING CORE TEMPERATURE, HEART RATE & HYDRATION**