NAVIGATING EXTENDED DUTIES AND SLEEP: A DUAL-PHASE ANALYSIS OF OPERATIONAL DEMANDS AND SLEEP WAKE BEHAVIOUR IN SOUTH AFRICAN AERIAL FIREFIGHTING PILOTS

BY

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THESIS

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ABSTRACT

Aerial firefighting refers to the use of aircraft to combat wildfires, playing a critical role in wildfire suppression. These fixed-wing aeroplanes or helicopters allow for easier access to fires since they are less restricted by terrain and vegetation. As a result, they operate in high-risk, low-altitude environments and have a high fatality rate due to the complex manoeuvres needed in often turbulent, smoky, and congested fire environments, which often coincide with intense stress among pilots. Despite its importance, aerial firefighting has received little attention regarding its operational demands, as existing studies largely emphasise cost and effectiveness, with little to no research being done in the South African context. This underpins the first aim of this study, which was to characterise the working system of aerial firefighters to identify the risks and demands associated with aerial firefighting in South Africa. Like other emergency services, aerial firefighters are on-call and work away from home for extended periods since the key feature of these services is being ready to fly for low-probability events. These features of on-call work may impact the sleep-wake behaviour, which, when combined with the demands of the actual flying, may present risks for pilot fatigue, which in turn presents a risk to flight and public safety. Prior sleep-wake behaviour of individuals is measurable and potentially a verifiable factor influencing pilot fatigue. Thus, the second aim of this study was to understand the sleep-wake behaviour of pilots as part of the current fatigue risk management system. This study adopted a dual-phase mixed-methods approach to addressing these aims. This mixed-methods study used semi-structured interviews of four key stakeholders to characterise the work system and demands of aerial firefighting. Subsequently, sleep-wake behaviour was observed through actigraphy, Consensus Sleep Diary and the Pittsburgh Sleep Quality Index during 2021's duty period (4-6 weeks on, 2 weeks off). A key finding of this study is that aerial firefighting is a precision-driven, high-stakes field requiring pilots to manage uncertainty through deep knowledge of environmental, fire, and operational risks. Key roles (Spotter, Bomber, Huey pilot) necessitate specialised competencies for hazard navigation, team coordination, accurate execution, and real-time adaptation. Task variability emerged as a central insight, reflecting the profession's evolving demands. Furthermore, most pilots achieved

adequate sleep duration (>7 hours per night) and regular sleep, with 75% of pilots maintaining bedtime regularity (<60 min variation), and 83% had consistent wake times (<60 min variation) during the six-week duty period. Overall sleep quality, as rated by the PSQI (global score 4 ± 2.05) and sleep diary (3.80 ± 0.58), was positively assessed, with participants reporting good sleep quality. A notable finding was the elevated wake-after-sleep onset (WASO) in actigraphy data, and PSQI data reporting sleep disturbances as the major concern in pilots who were rated poor sleepers (n=3). Thus, this study found that most pilots sleep well on average during the six weeks of duty; however, there are a few pilots who are at risk with the current duty period. Thus, it is crucial to manage sleep and, by extension, fatigue risk on an individual basis alongside a one-size-fits-all fatigue management framework.

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CHAPTER I

1 INTRODUCTION: CHARACTERISING THE WORK DEMANDS OF AERIAL FIREFIGHTING

1.1 BACKGROUND

Aerial firefighting is integral to the management and suppression of wildfires, mainly through the use of fixed-wing aeroplanes and helicopters to enhance the effectiveness and efficiency of ground suppression firefighters during the initial attack. These aircraft allow for easier access to fires since they are less restricted by terrain and vegetation. As a result, they often operate in high-risk, low-altitude environments (Goldammer, 2004; Butler *et al*., 2015; Plucinski *et al*., 2019). Therefore, aerial firefighting presents unique operational challenges and risks for pilots (Dawson *et al*., 2021), as pilots are exposed to several stressors such as smoke which leads to a degraded visual environment, heat stress which is exacerbated by protective clothing and physical demands such as gravitational effects and the requirement to maintain a relatively stable physical seat (Sprajcer *et al*., 2022). This is known to cause a decrease in physical and mental performance as well as the propensity for crew error (Sprajcer *et al*., 2022). However, limited research has been done to provide insights into aerial firefighting and its associated demands, with the majority of this focused on the effectiveness and cost of aerial firefighting (Thompson *et al*., 2013; Calkin *et al*., 2014), with little to no research being done in the South African context. This served as the motivation for the first aim of this study - to characterise the systemic demands and challenges associated with aerial firefighting activities that are unique to the South African context.

Demand for round-the-clock emergency services, particularly fire safety, creates variable workloads requiring on-call working time arrangements (Dawson *et al*., 2021), which is practised in the South African context. While operating during the nighttime is not permitted in South Africa yet, to ensure that support is available wherever it is needed, pilots are often stationed at strategic remote bases, which requires them to be on call for extended periods of time. These services also tend to have very intense and very quiet seasons; the extreme example is wildland firefighting. These features of the work, along with pilots living at remote bases for several weeks, may impact the sleep-wake behaviour, which, when combined with the demands of the actual flying, may present risks for pilot fatigue, which in turn presents a risk to flight and public safety.

Possible factors contributing to fatigue in these unique environments include multiple flights in a duty period, extended-duration flights, and many consecutive duty periods. On-call operations may be unpredictably punctuated by high-tempo, safety-critical activity (Fletcher *et al*., 2022). Given that duty periods are extended (up to several weeks) and actual flight times are unpredictable, managing fatigue through prescriptive limits alone is argued to be insufficient and inappropriate in these contexts. In this case, the application of a Fatigue Risk Management System (FRMS) allowed for a more flexible, risk-based management of fatigue risks, which includes the tracking of sleep (through self-report) and the measurement of sleepiness symptoms before duty and the institution of appropriate measures to mitigate emergent fatigue risks. The second and larger phase of this study aimed to understand fatigue-related risks in the context of one of the largest aerial firefighting service providers in South Africa. The company in question had implemented a FRMS, which was being piloted before applying for approval by the South African Civil Aviation Authority (SACAA). In the aviation sector, a service provider must comply with hard duty limitations imposed by regulatory authorities, which aim to mitigate the safety risks associated with fatigue. In this context, the governing body is the SACAA. The FRMS system was necessary because it required their pilots to be on duty for extended periods, 4 - 6 weeks, which violated current flight duty period (FDP) rules. Subsequently, the company sought approval for a second trial. We partnered with them to provide additional data collection, specifically focused on the sleep-wake behaviour of the crew while on these extended calls of duty.

1.2 OVERALL AIMS OF THIS STUDY

Considering the above, there are two overarching aims of this study. Firstly, while some studies have discussed the role of aerial firefighting, there are few to no studies on characterising the actual work done by aerial firefighters internationally and in South Africa. Thus, the first aim of the study was to characterise the working system of aerial firefighters to identify the risks and demands associated with the work being done by aerial firefighting, particularly in South Africa. Due to their unique operating context and the proposed working time arrangements monitored under the company's FRMS, the second aim of this study was to understand the sleep-wake behaviour of pilots as part of the current fatigue risk management system in order to inform the development of future risk management strategies more suitable to this specific line of work. It is crucial to contextualise fatigue risk within the broader challenges of aerial firefighting to develop effective risk management strategies.

1.3 OUTLINE OF THE THESIS

To address each aim, the study was divided into two phases due each aim requiring a different methodological approach. Chapter 2 addresses the first aim by reviewing existing literature on aerial firefighting, followed by a methodology section detailing the approach used to characterise the nature of aerial firefighting work and its associated demands. This was achieved through semi-structured interviews with key stakeholders within the company. The results section then highlights the identified demands and risks associated with aerial firefighting, culminating in a summary of findings that provide the foundation for the second phase of the study. Chapter 3 focuses on the second phase, beginning with an introduction and literature review on sleep, fatigue, and fatigue management in aviation before homing in on aerial firefighting. This is followed by a methodology section outlining the approach for measuring sleep, and a results section presenting both proactive and retrospective sleep data. Finally, Chapter 4 integrates the findings from Chapters 2 and 3, emphasising their overall significance and implications for future research in aerial firefighting and fatigue management.

CHAPTER II

2 LITERATURE REVIEW: CONTEXTUALISING AERIAL FIREFIGHTING

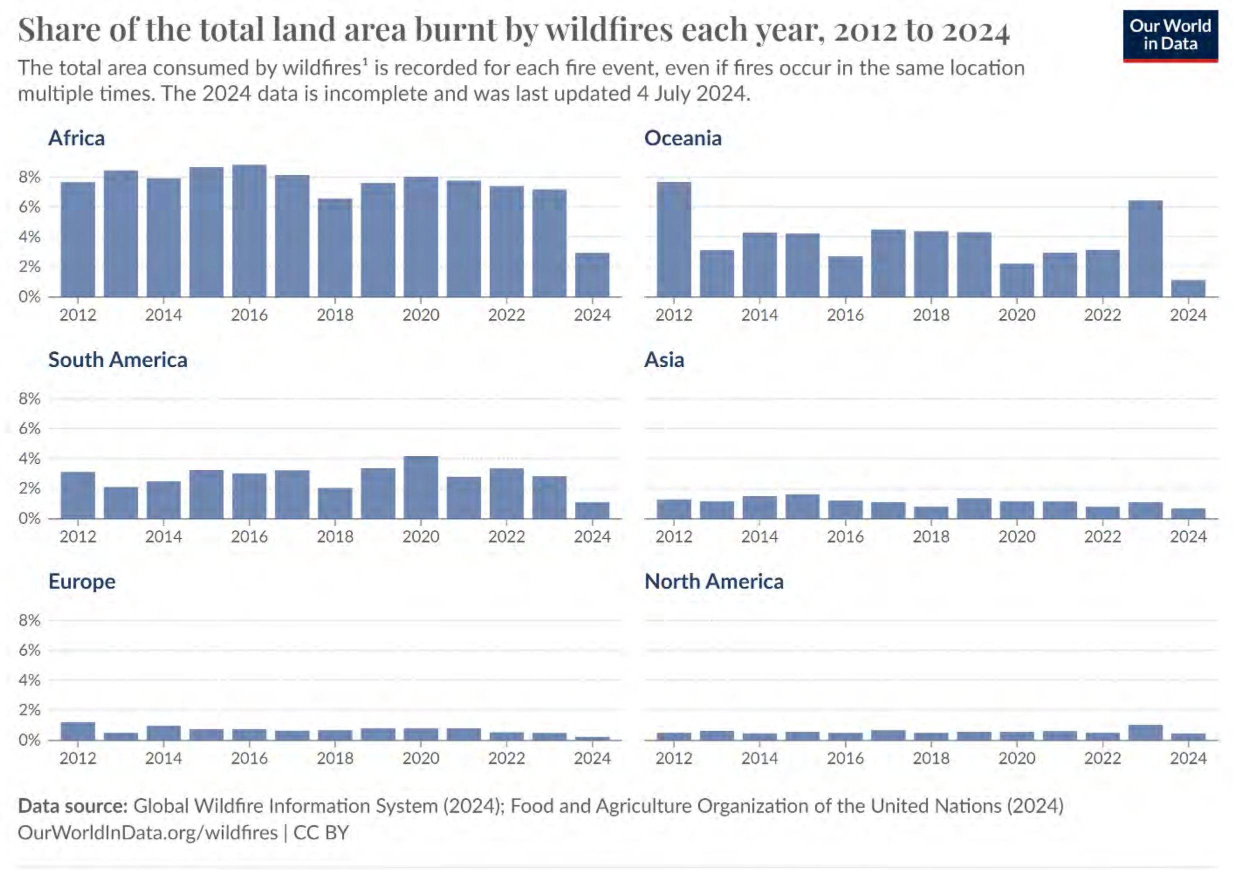
2.1 WILDFIRES

A wildfire is an uncontrolled burn of vegetation, which includes the burning of forests, shrublands, grasslands, savannas, and croplands (Samborska and Ritchie, 2024). Wildfires catastrophically impact communities through extensive land destruction, leading to property/livestock loss, degraded air quality, and human fatalities. Furthermore, wildfires have resulted in significant financial burdens for both individuals and governments across the globe (Williams-Bell *et al*., 2017; Abatzoglou *et al.*, 2018; Kganyago *et al.*, 2021). Consequently, significant attention has been drawn to the critical issues of intense wildfires, including their origins, causes, and repercussions (Pandey *et al.*, 2023). Wildfires are a threat to approximately 80% of the globe, including Central and Southern Africa, Australia, South Asia and South America (Flannigan *et al*., 2013). These fires are frequently caused by human activities or natural phenomena such as lightning. Dry conditions, extremely high temperatures, strong winds, as well as continued development and urban sprawl, increase the risk of wildfires (Williams-Bell *et al*., 2017; Kganyago *et al*., 2021).

Fire agencies, communities and a wide body of scientific literature suggest that climate change will increase wildfire frequency, duration and severity due to the more frequent and intense extreme weather events worldwide (Flannigan *et al*., 2013; Abatzoglou *et al*., 2018; Arriagada *et al*., 2020). Furthermore, climate change has resulted in shifting patterns caused by changing temperatures, heat waves, and fires (Arriagada *et al.*, 2020). Furthermore, wildfires play a crucial role in influencing both weather patterns and climate by emitting substantial amounts of carbon dioxide (CO_2), carbon monoxide (CO), and fine particulate matter (PM2.5) into the atmosphere. These pollutants contribute to atmospheric alterations that impact air quality, cloud dynamics, and the Earth’s radiation balance on both regional and global scales (Kganyago *et al*., 2021). Research on

Canadian wildfires occurring between 2013–2015 and 2017–2018 found a significant correlation between exposure to air pollution from fine particulate matter (PM2.5) from wildfire smoke and increased rates of mortality and respiratory illnesses (Matz *et al*., 2020). In addition to financial implications, wildfires substantially modify atmospheric composition by introducing large quantities of aerosols and trace gases, which can have lasting climatic effects. Numerous studies have examined the effects of wildfires on air pollution, human health, climate patterns, and land surface transformations (Marlon *et al*., 2012; Kganyago and Shikwambana, 2019). Notably, air pollution and hazardous particulate matter contributed to approximately 7 million deaths in 2012 alone (Chen *et al*., 2018), highlighting the serious public health risks associated with wildfire emissions and declining air quality.

However, despite concerns about worsening wildfire conditions, global wildfire trends from 2012 to 2024 indicate a decline in the annual extent of burned land, particularly in Africa and parts of Oceania, as seen in **Figure 1**. This decline is primarily attributed to the expansion and intensification of agriculture, which has reduced burn rates in grasslands and savannas (Samborska & Ritchie, 2024). These contrasting trends highlight the complexity of wildfire dynamics, where climate change exacerbates fire conditions, yet human-driven land-use changes significantly influence overall burn patterns. **Figure 1** is a reflection of the strong role that human activity and land use management play in wildfire extent, alongside weather- and climate-related factors. Both factors must be considered when trying to minimise the damage of increasing fire risk in a changing climate (Samborska & Ritchie, 2024). Although there is a decline in wildfires in Africa, the overall trend in South Africa from 2012 to 2023 does not show a clear and consistent reduction in wildfires, as seen in **Figure 2**. The trend is more variable, with periods of both increase and decrease. Pandey et al. (2023) provide insights that may elucidate the observed trends. In their article, Pandey examines the strengths and weaknesses of wildfire risk policies implemented by various countries to mitigate wildfire impacts. A notable strength identified for South Africa is the provision for establishing Fire Protection Associations, which enable landowners and other stakeholders to collaboratively manage wildfire risk across landscapes.



Share of the total land area burnt by wildfires each year, 2012 to 2024

The total area consumed by wildfires¹ is recorded for each fire event, even if fires occur in the same location multiple times. The 2024 data is incomplete and was last updated 4 July 2024.

Data source: Global Wildfire Information System (2024); Food and Agriculture Organization of the United Nations (2024)
OurWorldInData.org/wildfires | CC BY

Figure 1: Share of the total land burnt by wildfires each year, 2012 to 2024 (Samborska and Ritchie, 2024).

However, a significant weakness highlighted is that the legislation may lack adequate resources and enforcement, particularly in rural areas. The likelihood and severity of wildfires are projected to increase due to the anticipated rise in fire weather conditions associated with climate change. As seen in **Figure 2**, in 2021, South Africa experienced its second-highest number of wildfires on record, with approximately 4.12 million hectares burned (Pandey *et al*., 2023). Among significant wildfires, the Table Mountain fire highlighted major challenges in managing fire-dependent fynbos. While periodic burning is natural for fynbos regeneration, fire suppression, invasive alien trees, and climate change have significantly increased fire risks (Van Wilgen & Fill, 2021).

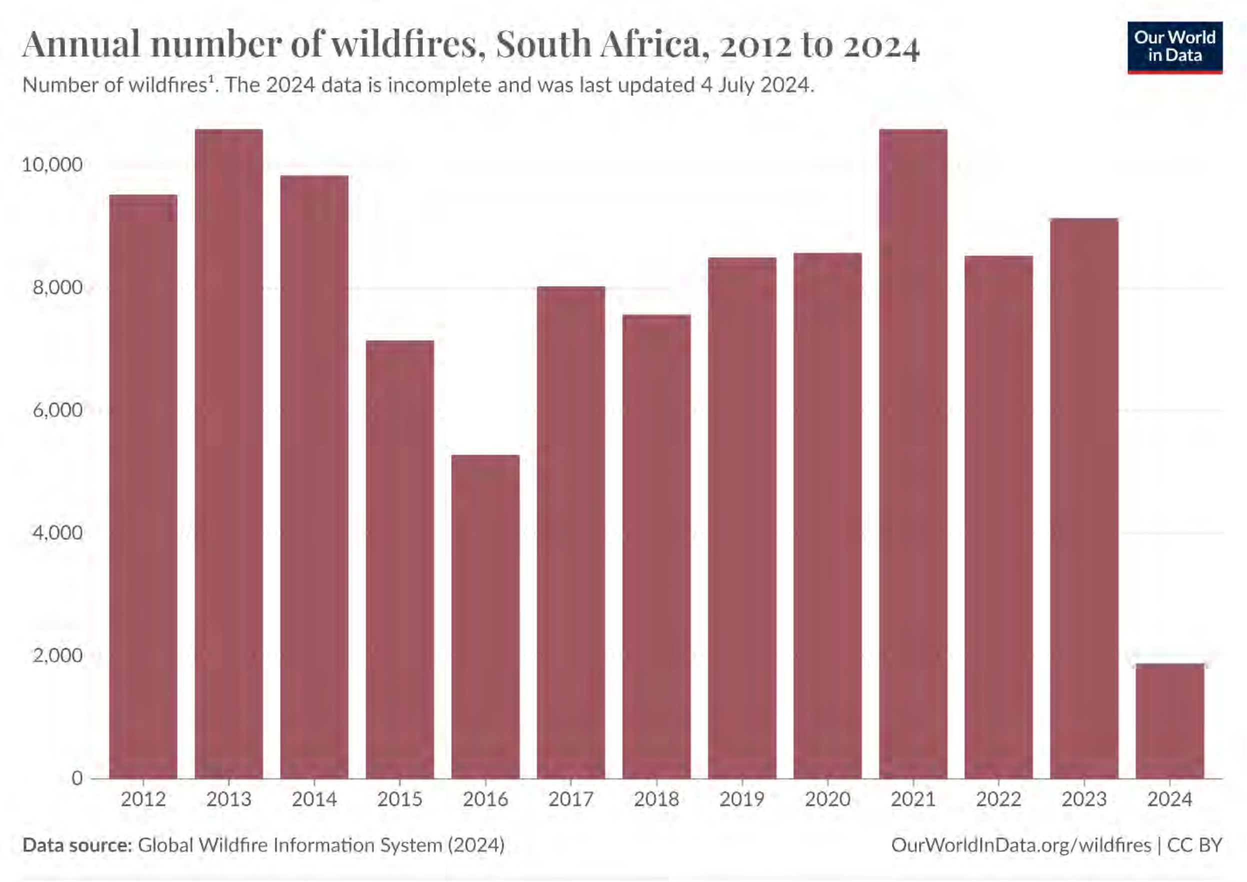


Figure 2: Annual number of wildfires in South Africa between 2012 to 2024 (Samborska and Ritchie, 2024).

In Cape Town, urbanisation has created "fire shadows" in areas like Newlands and Rondebosch, where development suppresses natural fires, serving as a fire break. Although this reduces fire activity, it also prevents vegetation clearance, leading to fuel buildup and, ultimately, more severe wildfires. Suppression has also allowed indigenous forests to expand on Table Mountain, disrupting the fire-adapted ecosystem (Van Wilgen & Fill, 2021). This wildfire underscores the complex interaction between climate change (rising temperatures, extreme weather), land-use changes, and fire policies. Human interventions, direct and indirect, continue to shape wildfire behaviour unexpectedly. Mitigating future risks requires urgent action: ecological restoration, strategic fire management, and policy reform (Van Wilgen & Fill, 2021; Pandey *et al*., 2023).

2.2 FIRE MANAGEMENT

Fire management encompasses all necessary activities to protect forests and vegetation from fire and uses fire to achieve land management goals. This involves strategically integrating various elements, such as understanding fire regimes, anticipating fire effects, determining the required level of forest protection, considering the costs associated with fire-related activities, and employing prescribed fire technology according to the Global Fire Monitoring Centre for FAO (1986, as cited in Rego *et al*., 2010). Fire agencies across the globe are moving towards integrated fire management systems to address wildfires. Integrated Fire Management combines different components of fire management - fire prevention, detection, suppression, and consideration of fire ecology (Rego *et al*., 2010). In addition, integrated fire management is seen as a method for addressing the challenges of harmful and beneficial fires (Rego *et al*., 2010). This approach involves evaluating and balancing the risks posed by fire with its beneficial or necessary ecological and economic roles. It also supports implementing cost-effective strategies to prevent harmful fires and maintain desirable fire regimes, acknowledging that managing beneficial aspects of fires may require various forms of fire use (Rego *et al*., 2010).

In South Africa, fire agencies implement an integrated fire management system that takes a comprehensive and systematic approach to wildfire management. This system aims to unify stakeholders and coordinate various management efforts into a cohesive yet adaptable strategy. Working on Fire, a local fire agency, cites four components of fire management: reduction, readiness, response, and recovery, as seen in **Figure 3** (Working on Fire, 2022). For the scope of this study, there will only be a focus on response as highlighted in **Figure 3**. The response focuses on the dispatch and coordination of firefighters and fire suppression. The main aim of fire suppression is to stop fires from spreading and ultimately contain the fire to make it safe (Plucinski *et al*., 2007). This usually entails reducing fire progression to new fuel sources and controlling damage to vegetation and trees, which involves extinguishing the outer edges of the fire (Plucinski *et al*., 2007).

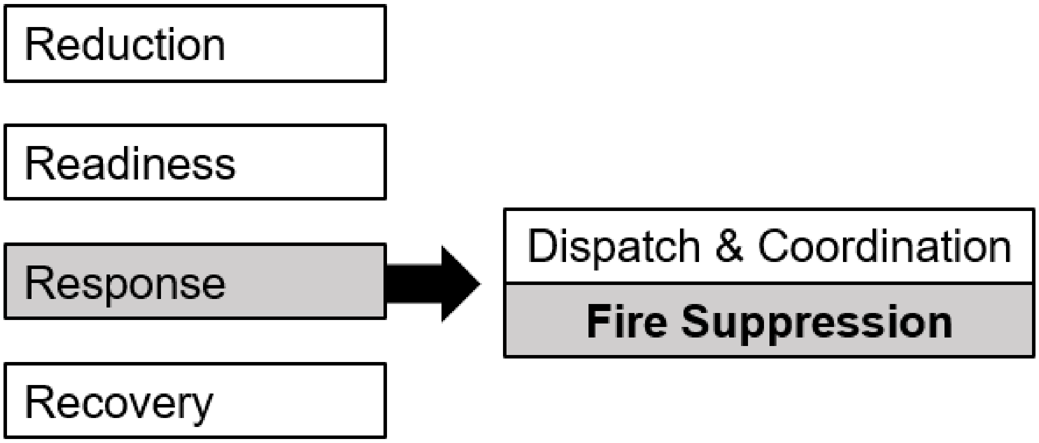


Figure 3. Working on fires' four components of fire management (Working on Fire, 2022).

During the response phase, agencies will deploy ground and aerial resources to effectively manage wildfires. Ground suppression, also known as handcrew, plays a critical role in wildfire suppression by constructing mineral earth firelines (fuel-free barriers) to contain low-intensity fires and patrolling contained firelines to prevent re-ignition (Plucinski, 2019). Their tactical applications include indirect attacks, where they create firebreaks ahead of an advancing fire; parallel attacks, in which they work close to the fire edge; and the controlled ignition of low-intensity backfires to limit fire spread. In addition to these core functions, handcrews undertake specialised tasks such as felling burning trees near the fire perimeter to enhance fire control efforts (Plucinski, 2019). Without ground firefighters, aerial firefighters are limited in what they can achieve. However, aerial resources offer three major advantages over ground suppression resources: speed, access, and observation. Thus, the combination of the aerial and ground crews creates a coordinated and effective effort to put out wildfires threatening property and life (Integrated Fire Management Working Group, 2016).

2.3 AERIAL FIREFIGHTING

Wildland firefighting demands an interagency approach, requiring multiple individuals to work together in a complex and often unpredictable and hazardous environment (Butler *et al.,* 2015). According to Butler et al. (2015), 298 wildland firefighter fatalities were documented in the United States between 2000 and 2013, averaging 21 per year. Of these, 78 (26.2%) were attributed to aviation-related activities. Contrary to what one might expect, the increased aviation safety of the 21st century did not decrease the trend of aerial firefighting casualties (Butler *et al*., 2015).

Aerial firefighting is integral to the management and suppression of wildfires (Butler *et al.,* 2015). The use of fixed-wing aeroplanes and helicopters can enhance the effectiveness and efficiency of ground suppression firefighters during the initial attack, as they allow for easier access to fires due to their less restricted movement by terrain and vegetation around the fire, which often results in operating in high-risk, low-altitude environments (Goldammer, 2004; Butler *et al*., 2015; Plucinski, 2019). However, aviation is one of the most expensive and dangerous suppression tools available in the fire management toolkit (Calkin *et al*., 2014). Aerial firefighting has a high fatality rate due to the complex manoeuvres needed in often turbulent, smoky, and congested fire environments, which are often accompanied by excessively high stress levels experienced by the pilots (Malaek & Mahrooz, 2016). This usually includes performing a variety of tasks such as reconnaissance missions, transporting and deploying firefighters (called “trooping”) and equipment to and from a fire, applying retardant and water and igniting prescribed fires (Integrated Fire Management Working Group, 2016). Prescribed fires are the strategic application of fire under strictly regulated environmental conditions to achieve specific resource management objectives. This practice is carefully planned to occur at a particular time, with a controlled intensity and rate of spread, ensuring that it meets the intended outcomes (Integrated Fire Management Working Group, 2016). Typically, prescribed burning is conducted only under authorised conditions and requires approval from the relevant fire management authority to ensure safety and effectiveness (Malaek & Mahrooz, 2016).

In addition to aerial firefighting being high-risk, these pilots have unpredictable operations due to this being an emergency service. In scheduled aviation, flight missions usually have a single, pre-planned flight profile. They are carried out in an operator-controlled environment to meet a single mission objective: transportation from point A to point B (McMillan & Xu, 2024). Conversely, aerial firefighter missions are carried out in a dynamic environment, where the pilot needs to respond in real-time to events to meet mission objectives (McMillan & Xu, 2024). These operations occur in real-time amidst unpredictable factors like hazardous weather and environments. Flight paths are seldom finalised at departure and often demand adaptations to mitigate critical risks to life and property. Consequently, such flights inherently possess less operational flexibility compared to scheduled aviation (McMillan & Xu, 2024).

In firefighting, the primary focus is on rapid arrival to control the fire until ground crews can take over. Risks are assessed based on initial dispatch information, and pilots must adapt to the evolving situation (McMillan & Xu, 2024). They may collaborate with incoming crews, follow drop instructions from other aircraft, or make independent decisions on how to tackle the fire. Although the goal of fire control is clear from the start, the specific conditions on the ground and the fire's behaviour are unpredictable (McMillan & Xu, 2024). Although there are some studies that highlight the role of aerial firefighting, there are few to no studies on the actual work done by aerial firefighters in a South African context. Thus, part one of the study aims to research and characterise the work of aerial firefighters, particularly in South Africa, to identify the associated demands. This was important to contextualise the second aim of the study.

2.4 METHOD

2.4.1 Study design

This phase adopted a qualitative, descriptive research design, which looked at characterising the work system of the collaborating company and the aerial firefighting arm and the associated demands of aerial firefighting through semi-structured interviews with key stakeholders within the company.

2.4.2 Participant selection

Phase one used a purposive sampling method to address the research aim of phase one. Participants were selected based on the fact that they have in-depth knowledge and experience of aerial firefighting within the company. With this in mind, the inclusion criteria developed for this study were that participants must be currently employed or previously employed by the company in question, with experience in working in the specialised areas of aerial firefighting. This included the Chief Pilot, the Person responsible for flight operations, the Chief Health and Safety Officer and the Former Chair of the Board.

2.4.3 Data collection methods

This part of the study used semi-structured interviews with subject matter experts to gain insights into the structure and purpose of the organisation in question and explore the roles and responsibilities of pilots and the challenges they encounter. Semi-structured interviews are a flexible interview style designed to ascertain subjective responses from persons regarding a particular situation or phenomenon. They typically consist of a dialogue between researcher and participant, guided by a protocol and followed by additional questions, probes, and comments (Flick *et al*., 2004; McIntosh & Morse, 2015).

A variety of semi-structured interview types have emerged as their use has expanded. These types differ based on their purpose, underlying epistemology, role of participants, and intended research outcomes (McIntosh & Morse, 2015). Due to the nature of the research aim, this study used a descriptive/interpretive interview style. This type of interview views the participant as the primary source of knowledge. From the beginning, it recognises that the researcher's perspective is limited, and the participant's knowledge is essential to its expansion (McIntosh & Morse, 2015). McIntosh and Morse (2015) recommend three steps for creating semi-structured interview questions. First, the researcher must define the domain of the topic being investigated, including its boundaries. For this study, a literature review was conducted to understand what is known about aerial firefighting. Second, the categories of the topic should be identified. In this case, the topic was divided into two categories: understanding the structure and purpose of the organisation in question, and secondly, examining the roles and responsibilities of pilots along with the challenges they face. Finally, the question stems need to be identified and are outlined in **Table 2**.

Table 2. List of initial questions taken into the semi-structured interview.

Questions	**Reasons for inclusion**	**Analysis type**
What is the purpose of the organisation?	These questions were selected to understand the structure and purpose of the organisation in question. This allows the researcher to generate an understanding of the organisational factors and challenges involved in the working system, while allowing avenues for more specific questions.	Descriptive
How long have you been operating?		Descriptive
What is the structure of the organisation?		Descriptive
Where do you operate?		Descriptive
What are the different parts of the flight operations in the company? What aircraft do you use?	These questions aim to understand the roles and responsibilities of pilots and the challenges they face. This allows for the identification and exploration of the demands and risks associated with aerial firefighting in South Africa	Descriptive
What is the role and tasks of a spotter pilot? Of a bomber pilot? Of a helicopter pilot?		Descriptive
What are the challenging parts of these operations?		Thematic
What is the duty schedule of the different crews?		Descriptive
What does a typical duty day look like for a spotter pilot? Of a bomber pilot? Of a helicopter pilot?		Descriptive
How long are they on duty for?		Descriptive
Why did you design the duty periods like this?		Descriptive
What was the motivation to develop and implement your current FRMS?		Thematic

2.4.4 Ethical considerations

Ethical approval was obtained from the Rhodes University Human Research Ethics Committee before any data collection. The Ethics Committee granted provisional acceptance with pending Gatekeeper permission (ref: 2021-4924-6000) (Appendix A).

Once ethics was approved, the gatekeeper's permission was obtained by the company in question (Appendix B), followed by the signing of a non-disclosure agreement by the research team. Then, a letter of participation was sent out to participants explaining what would be expected of them if they decided to participate. It was made clear to participants that their participation in the study was voluntary and that they could choose to withdraw from the study at any point should they wish to do so. In this study, participants' rights to privacy and anonymity were preserved.

2.4.5 Study setting and context

The setting in which the study is situated is that of an aerial firefighting company that provides integrated fire management services to multiple sectors across South Africa. This company is regulated under Part 137, which focuses on agricultural aerial work, crop spraying and firebombing.

2.4.6 Participant recruitment and characteristics

The participants who took part in the semi-structured interview were the following: the Chief Pilot, the Person responsible for flight operations, the Chief Health and Safety officer and the Former Chair of the Board. These participants were chosen due to their extensive experience and knowledge of the company's working system and history. All four participants play a critical role in the design and organisation of the company's working system. The study occurred at the company headquarters providing the above service, where all the participants were based for work/duty at the time.

2.4.7 Procedures

This phase involved the use of semi-structured interviews that were recorded, transcribed, and analysed to characterise the company's activities and aerial firefighting in general. The interviews were conducted at the company's main base during the winter season within the parameters of the COVID-19 regulations. The interview process took place over two days. The first interview was conducted with the Chief Pilot, Person Responsible for Flight Operation and the Chief Health and Safety Officer present. A brief introduction and explanation of the intended aim of the research were given to the interviewee. The interviewer then highlighted the research procedure and explained how the results of the interview would be used before conducting the interview. The interviewee were reminded of their right to anonymity and their right to withdraw at any stage of the process. The interview commenced once each participant signed a consent form. Then the interviewer started recording on their cellular device. The order of interview questions was followed loosely, and further questions were asked about points of particular interest or areas where the author felt more information was needed. The following day, an interview was held with the Former Chair of the Board of the company. This interview process followed the same procedure as before.

2.4.8 Data analysis

Portions of the data were summarised to provide a descriptive overview of the system's structure, including organisational roles and the functions of various aircraft. This descriptive overview used a Multi-Level Analysis, which is fundamental to systems ergonomics (Karsh *et al*., 2014). These levels can be conceptualised as units of analysis (individual, group, organisation) or levels of organisational hierarchy (echelons). For instance, individual workers are nested within departments, departments within plants, and plants within larger companies (Karsh *et al*., 2014). In the context of this study, the function and context of the organisation were described in macro, meso, and micro levels.

Other parts of the data were analysed thematically to explore the specific demands and risks associated with different roles within the system. Thereafter, the thematic data were analysed using the method outlined by Braun and Clarke (2006):

2.4.8.1 Phase 1: Familiarising with the Data

In the first phase of the thematic analysis, the researchers immersed themselves in the data by repeatedly reading the transcript and listening to the audio recordings. Notes were taken during this process to deepen their understanding of the data set and to identify elements that might be relevant to the research question. Additionally, corrections were made whenever the transcribed text did not accurately reflect the recorded audio.

2.4.8.2 Phase 2: Generating Initial Codes

The second phase involved beginning the systematic analysis of the data through coding. As Braun and Clarke (2006) suggest, codes are the fundamental building blocks of analysis. Thematic analysis does not prescribe a specific method for segmenting and coding data. For this research, the researcher segmented the data based on what best described the work system and was most relevant to the research question. This process was facilitated through the use of mind maps.

2.4.8.3 Phase 3: Searching for Themes

During this phase, the analysis began to take shape as the researcher transitioned from codes to themes. A theme, as defined by Braun and Clarke (2006), "captures something important about the data in relation to the research question and represents some level of patterned response or meaning within the data set" (p. 82). In this study, the identified themes were categorised according to the organisational structure, the roles of various types of pilots, and the demands associated with these roles.

2.4.8.4 Phase 4: Reviewing Themes

In this phase, the researcher reviewed the candidate themes identified in phase 3. The goal was to ensure that the emerging themes had clear boundaries and were logically grouped together. The entire data set was re-read to verify that the themes aligned with the overall data set. This phase also provided an opportunity to code any additional data that might have been overlooked in earlier stages.

2.4.8.5 Phase 5: Defining and Naming Themes

When defining the themes, it was important for the researcher to clearly articulate what was unique and specific about each theme. In this study, all relevant information was paired with the respective headings. A final thematic analysis was conducted by refining and adjusting the work system map until there was consensus that the data were accurately represented. By the end of this phase, the researcher was able to define what the themes were and what they were not.

2.4.8.6 Phase 6: Producing the Report

The final phase began once the themes were fully defined, and it involved producing an analysis or report. This report needed to provide sufficient evidence of the prevalence of the themes extracted from the data. The researcher used vivid examples to illustrate the points being made. It is important to note that reports require more than just presenting the data; they must be embedded within the analytical narrative to persuade the reader that the data support the research question.

Semi-structured interview transcripts were used to describe the system. Once no more information could be extracted from the data set, the analysis was considered complete. Building on these methods, the next section presents the findings derived from semi-structured interviews and thematic analysis. The data were first summarised and then analysed to identify key patterns, with a particular focus on characterising the work system and uncovering the associated demands. These findings address the first aim of the thesis and are presented through a multi-level analysis structuring central themes regarding organisational context and function (Karsh *et al*., 2014)

2.5 RESULTS

This section presents the findings of the descriptive and thematic analysis, organised within the multi-level analysis to contextualise the company and its activities into the broader context of disaster and forest fire management in South Africa (Karsh *et al*., 2014). The results of this study were structured around key elements such as the organisational context, system functions, and operational challenges. The function and context of the organisation, as well as the roles of aerial firefighting, were identified through the results of the deductive descriptive analysis. In contrast, the nature of aerial firefighting work and the demands faced by pilots were based on the findings’ deductive thematic analysis. Additionally, due to the complexity of the organisation and context, the macro, meso and microsystem level approach will be used to assist in defining the boundaries within which the organisation exists. This characterisation of the broader system and where the company is located will be followed by an overview of the nature of the work and the demands, which then focuses on the working arrangements and how it has changed over time.

2.5.1 Function and context of organisation

2.5.1.1 Macro level

The company in question is an aerial firefighting company contracted to provide year-round aerial support to government entities. It operates in conjunction with other organisations to suppress fires across the country. On a macro level, as seen in **Figure 4**, various companies interact with the aerial firefighting company in question, namely, the National Government, Working on Fire and the greater holding company that owns the aerial firefighting company and their airbases. The company in question interacts with two national government departments, namely the Department of Fisheries, Forestry and the Environment and the Department of Transport. From an environmental perspective, the Department of Fisheries, Forestry and the Environment is a part of the South African government that aims to protect the country's natural resources and provide leadership in environmental management and conservation to create a more sustainable South Africa (Government of South Africa, 2023). To adhere to the aims mentioned above, the department launched various environmental Expanded Public Works Programmes (EPWP) to create work opportunities in various public environment and culture programmes. Working on Fire (Pty) Ltd is a part of the EPWP, which is a job-creation programme focusing on implementing Integrated Fire Management (Government of South Africa, 2023). As seen in **Figure 4**, Working on Fire is also a subsidiary company within the Holding company Group, which was awarded the tender by the National Government to implement the Working on Fire programme as a part of the Expanded Public Works Programme (EPWP). Working on Fire provides a range of operationally proven integrated firefighting operations and tactics to suppress wildfires. Resources include aerial and ground teams and equipment coordinated and controlled by an Incident Command System (Government of South Africa, 2023).

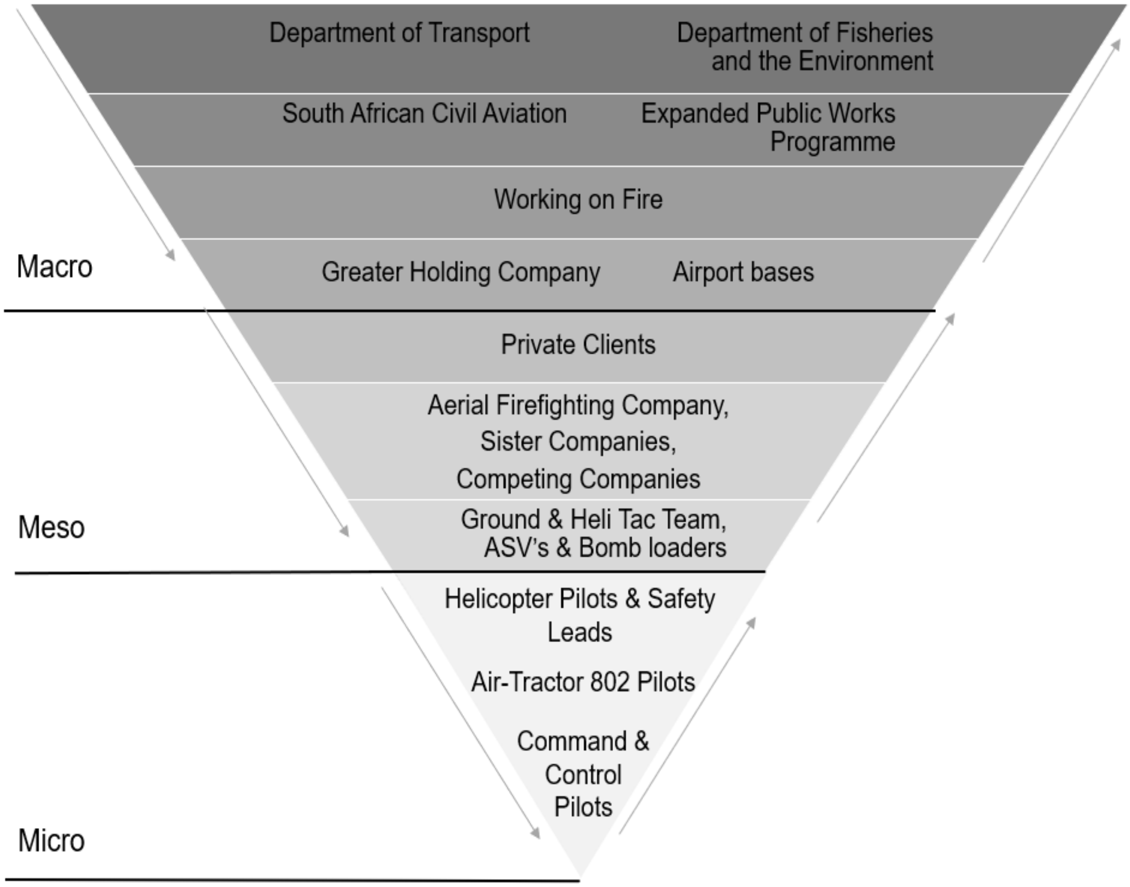


Figure 4. Summary of the elements within and directly around the aerial firefighting working system and categorising them into macro, meso and micro-level.

At a lower level, the aerial firefighting company is owned by a greater holdings company. The aerial firefighting subsidiary is contracted as a part of aerial support to Working on Fire. This contractual work makes up about 80% of the work performed by the aerial firefighting company (Chief of Flight Operations, 2021).

As highlighted in **Figure 4**, from a regulatory perspective, the South African Civil Aviation Authority (SACAA) is an agency of the Department of Transport in charge of "*controlling, promoting, regulating, supporting, developing, enforcing, and continuously improving levels of safety and security throughout the civil aviation industry"* (SACAA, 2022). This is executed through compliance with the Standards and Recommended Practices (SARPs) of the International Civil Aviation Organisation (ICAO) whilst considering the

South African context. The aerial firefighting company in question is subject to the Civil Aviation Technical Standard part 137, which focuses on Aerial Work Operations such as commercial agricultural and commercial firefighting operations (SACAA, 2022). Consequently, the chain of interactions between the Department of Fisheries, Forestry and Environment, the South African Civil Aviation Authority, Working on Fire, and the aerial firefighting company is critical to understanding the unique organisational conditions the aerial firefighting company is operating under.

Additional macro-organisational factors include the location of air bases around the country, as seen in **Figure 4**. The aerial firefighting company and its various subsidiaries are based in Mpumalanga, a province situated in the north-eastern part of South Africa. The company in question does service most parts of South Africa, resulting in the strategic distribution of airbases according to geographic locations with the highest propensity to fire (Responsible Person Flight Operations, 2021) to provide timely suppression support services. These bases are active (meaning that most of the resources and personnel are situated there) according to the respective fire seasons.

During the winter months (May until mid-November), pilots are based in Limpopo, Mpumalanga, the Eastern Cape, and small parts of Kwa-Zulu-Natal, as seen in **Figure 5**. In the summer season (mid-November until the end of April), the Western Cape is prone to fire, thus pilots are based there, as seen in **Figure 5** (Responsible Person Flight Operations, 2021). This requires the company to distribute its pilots among the bases as they are needed. Many pilots work from airbases that are situated relatively close to their homes. For instance, a pilot living in the Western Cape will not usually work from an airbase in Mpumalanga - the Mpumalanga pilots will usually consist of pilots living in the Mpumalanga province. However, sometimes ‘resources’ (crew and aircraft) from across the country are called upon to travel to a single location. This happened during the Table Mountain Fire in April of 2021 (Bega, 2023). This was “a disaster fire”, and pilots were dispatched from several air bases, flying their aircraft to Cape Town to assist with the fire (Chief pilot, 2021).

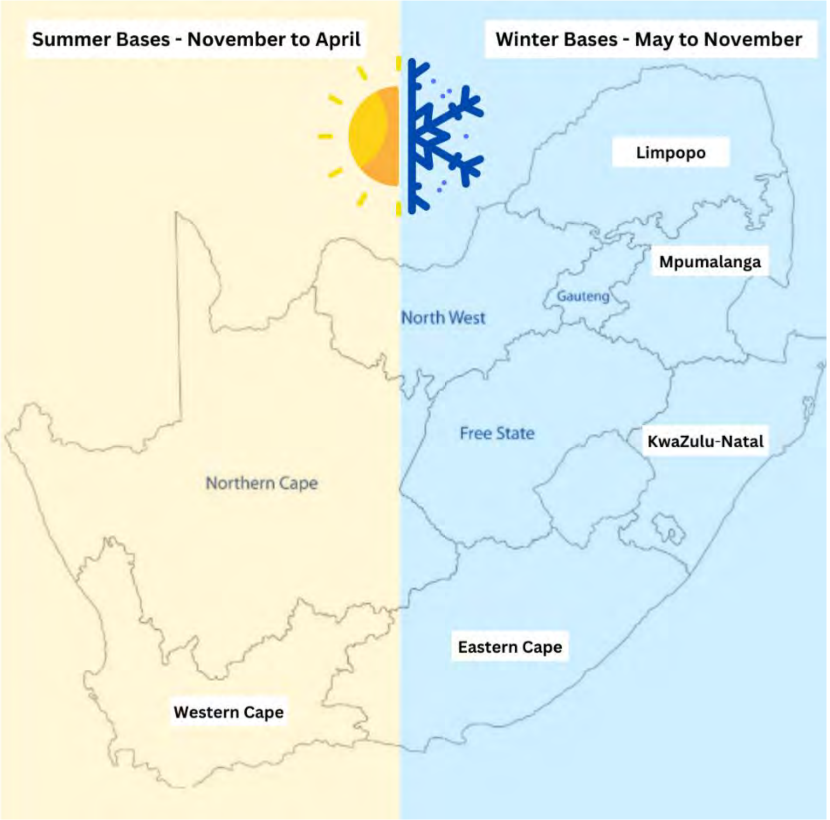


Figure 5. Geographic view of where aerial firefighter operates throughout the year (d-maps.com, 2007).

2.5.1.2 Meso level

An interaction overlapping the macro and meso-level boundary has already been established in the relationship between Working on Fire and the aerial firefighting company. The aerial firefighting company is owned by a greater holdings company, *"the mother company, with all the different subsidiaries"* (Health and Safety Officer, 2021). These subsidiaries include an 'aerial maintenance organisation' that ensures the upkeep and repair of aircraft used in aerial firefighting; a 'training organisation' used to train pilots and support crews, and an 'aerial firefighting company' which provides aerial support with specialised services such as aerial firefighting. The 'aerial firefighting company' deals specifically with the aircraft and the operation and is the holder of the aircraft operating certificate (Health and Safety Officer, 2021). All these subsidiaries interacting are essential to the success of the aerial firefighting companies' performance (Health and

Safety Officer, 2021). The aerial firefighting company aims to provide aerial support for fires to various clients throughout the various sectors of South Africa, as required (Responsible Person Flight Operations, 2021). The majority of the private clients' work is with owners of private plots undergoing the farming of trees for the manufacturing of paper. Working on Fire's relationship with these private clients involves "fire break preparations, prescribed burning, and supporting clients" (Person responsible for flight operations, 2021, personal communication).

2.5.1.3 Micro level

As seen in **Figure 4**, micro-level elements of the system consist of the individuals and equipment used at the sharp end of the work being done, and those involved in the physical fighting of the fire itself, which this research study focused on. The company in question has a medium-sized operation with approximately 53 personnel, including pilots and support staff. As seen in **Table 2,** there are three types of aircraft, varying between rotary wing and fixed wing aircraft, and each aircraft has a number of pilots able to crew it.

Table 2. Aircraft operation description

Type of aircraft	**Role**	**Number of aircraft**	**Number of pilots**	**Image**
Rotary wing				
UH-1H *"Huey"* Helicopter	Aerial fire attack and helicopter attack team deployment	10	16	
Fixed wing				
Cessna 100/200 series	Command and control, such as reconnaissance and surveillance	12	18 to 25	
Air-Tractor 802 series	Fire-bombing using retardant	4	6	

2.5.1.3.1 UH-1H "Huey" Helicopter

As seen in **Table 2,** the company in question uses the UH-1H or "Huey" helicopter for aerial fire attack and helicopter attack team deployment. The Huey is equipped with a Bambi bucket that hangs eight to ten feet below it and transfers approximately 1,000 litres of water, which is sometimes mixed with fire retardant, which is used as a fire line. If the water source is close, the aircraft has a very high turnaround time. This helicopter is ideal for navigating difficult terrain such as mountainous areas, "*because it can stop, hover, descend or ascend up to very steep hills and then drop the water over there*" (Chief Pilot, 2021). The company in question owns and operates 10 aircraft and has 16 pilots who crew the Huey (Appointee for flight operations, 2021).

2.5.1.3.2 Cessna 100/200 series

As seen in **Table 2**, the fixed-wing Cessna aircraft is used for its aerial Command and Control operations, such as reconnaissance and surveillance done by its "Spotter" pilot. It is equipped with VHF (Very High Frequency) Aircraft Radios and aircraft-approved Techni Sonic Mid Band radios for communication with other aerial resources such as the Incident Commanders (ICs) and the ground firefighting crews. These Cessna aircraft are also used in pilot training conducted by their sister company. The company in question currently owns twelve spotter aircraft and has eighteen to twenty-five pilots qualified to fly as a Spotter (Appointee for flight operations, 2021).

2.5.1.3.3 Air-Tractor 802 series

The Air Tractor 802 series is a fixed-wing Single-Engine Air Tanker (SEAT) that is a fast and manoeuvrable aircraft. This aircraft can carry and discharge approximately 3,500 litres of water in one drop. It uses a Fire-Retardant Dispersal System (FRDS), which allows pilots to optimise water and retardant dispersal and make precision drops on several critical points of fire. The retardant used is either gel-like or foam-like, mixed with water to increase the viscosity and improve the effectiveness upon impact with the flames. In the context of this study, retardent is only used during indirect attacks, whereas the company focuses 99% of the time on direct attacks (Chief Pilot, 2021). As seen in **Table**

2, the company in question owns and operates four aircraft and has six permanent personnel who crew Air-Tractor 802s (Appointee for flight operations, 2021).

2.5.2 Roles of Aerial Firefighters

When a fire occurs, there is a coordinated attack, which is called an Integrated Fire Management approach, in which aerial resources provided by the company in question and ground resources provided by WOF come together. This section will look at how aerial and ground resources interact and highlight the individual roles of each aircraft and pilot.

2.5.2.1 Command & Control (Spotter):

The spotter pilot does the command-and-control work of the entire aerial operation. The spotter pilot forms part of the initial attack and, therefore, will be airborne first and fly approximately 500 ft above the site and coordinate with the incident commander on the ground, as seen in **Figure 6**. These pilots are specifically trained in fire behaviour and can assess the fire and offer real-time information to the Incident Commanders (IC) on the ground, who need the information to make informed decisions regarding tactics and allocation of resources on the ground. As described by the Appointee for flight operations (2021), Spotters report weather updates, *“spotter pilot will also know what the weather is doing because, you know, the wind now at this time is blowing in this direction, but later today, he’s seen it's going to turn or go in that direction. That will then determine which flank [of the fire] is now the important one”*.

The spotter will communicate the placement of logistical support and coordinate the flow and outflow of resources (namely, the different aircraft) to ensure safe fire suppression. In addition, the spotter pilot also manages air-to-air communication, as their vantage point allows them to maintain situational awareness and direct the Hueys and AT 802 fixed-wing water bombers to where water is most needed, as seen in **Figure 6.** The main priority of a spotter pilot is ensuring the safety of the pilots to prevent collisions and ensuring the ground crew is clear before a drop. As described by the Person responsible for flight operations (2021), *“he will see where the trucks and the firefighters are moving* *on the ground, he ensures that whenever resources are coming in, that they maintain separation, don't fly into each other. So, he's like, coordinating everything in conjunction with the incident commander [on the ground]; and making sure everything is safe.”*

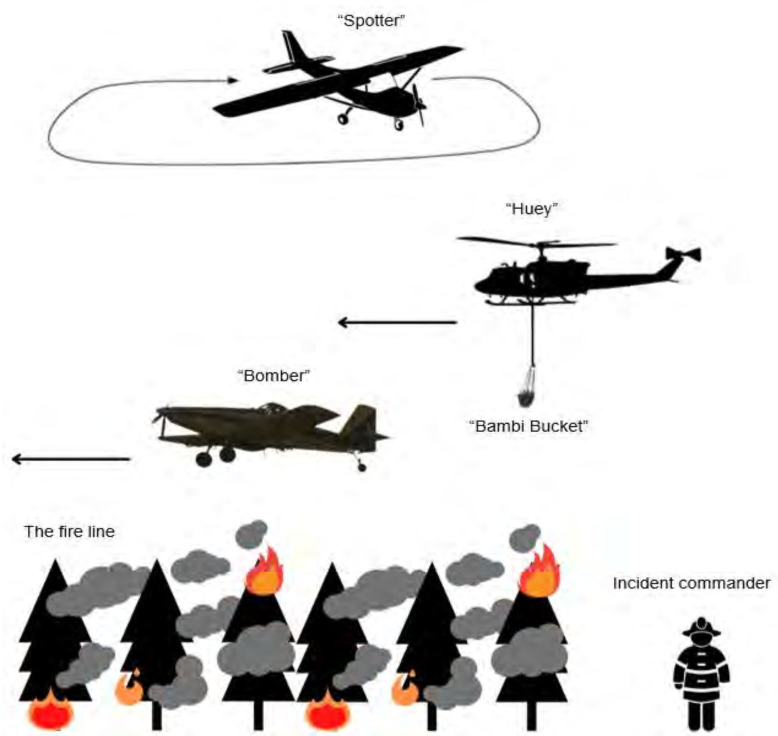


Figure 6. An overview of what the aerial firefighting operation may look like with all variants of aerial resources involved.

2.5.2.2 Air-Tractor 802 (Bomber)

The key role of the Bomber pilot is to deliver huge volumes of water during the initial attack on the fire. Pilots refer to this as throwing ‘*wet lines*’. Wet lines are long lines of water mixed with flame retardant spread along the fire line to prevent the fire from spreading further (Chief Pilot, 2021). The primary purpose of the drops is to cool down the fire. The bomber must fly quite low, approximately 20-50 feet above the fire, when they drop the water. As seen in **Figure 6,** the Bombers are reliant on Spotters as they help pilots navigate smoke and coordinate their drops. According to the Chief pilot (2021), *“We are not allowed to, when we get to the fire and the spotter is not there, to drop any water. There might be somebody on the ground that you don't see…” and if* *someone is hit by approximately three tons of water travelling at 250 km/h, "...the velocity of that, it will kill you."* Bombers are allowed to fly for eight hours but are allowed to extend up to ten hours. If a pilot flies ten hours, they are required to give written information to SACAA and are given time off the following day.

2.5.2.3 Helicopter: UH-1H (Huey)

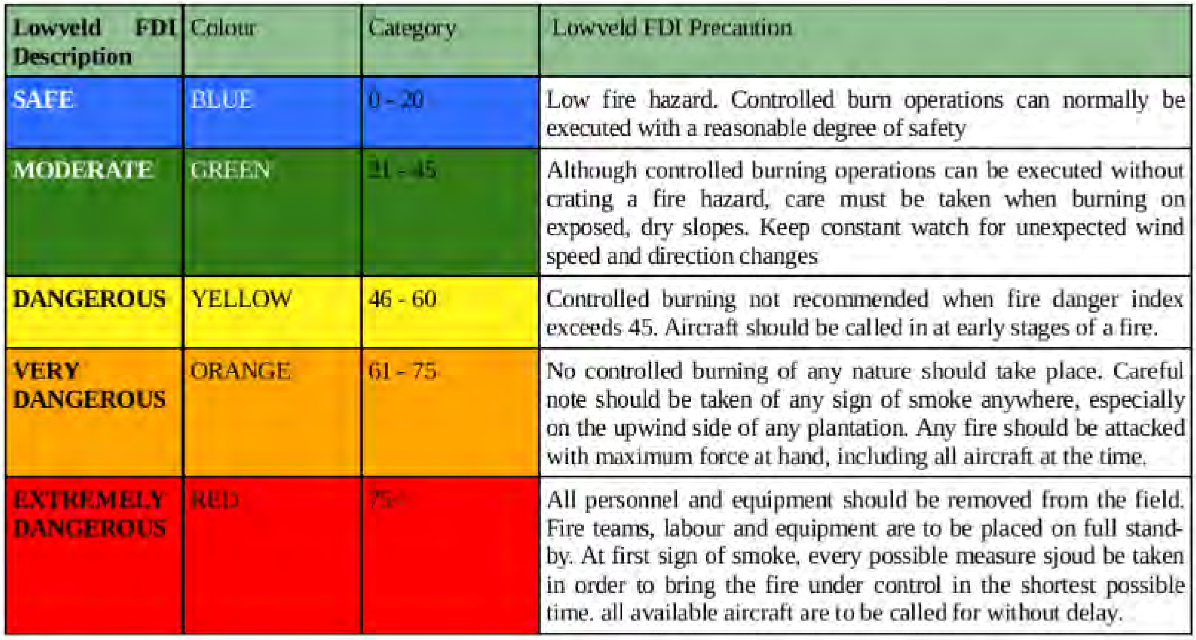
The primary roles of a Huey pilot are "*trooping*" and "*mopping*". "*Trooping"* is transporting firefighters to the fire scene where Aerial Support Vehicle (ASV) drivers are restricted or cannot get to the fire quickly enough. '*Mopping*' assists the initial attack by dropping the Bambi bucket of water, which the bombers might have missed. The water for the Bambi bucket is sourced at dip sites, which can be anything from a dam or swimming pool close by. This allows the Huey to have a rapid turnaround time to assist on the fire line, as seen in **Figure 6**. Huey pilots can only fly for two hours at a time due to the fuel quantity on board, which is limiting. Like the bomber, the Huey has a foam system. In harsh conditions, pilots would add gel to the water to make it very thick and gel-like. According to standard operating procedure, Huey's must land with a minimum of 45 min of fuel left in the aircraft's tank (Chief Pilot, 2021). Unlike their fellow pilots, Hueys have flying crewmen. This trained individual supports the helicopter pilot with tasks such as pre-flight procedures and doing what they need to do around the aircraft. They are trained to also work with a handheld radio. This flying crewman would accompany the helicopter to the fire site and help the pilot set up landing zones if needed.

2.5.3 Work characteristics of aerial firefighters

2.5.3.1 Weather, Terrain & Fire Danger Index

Weather conditions play a significant role in the work done by aerial firefighters, largely due to weather conditions influencing the Fire Danger Index (FDI). In South Africa, the Lowveld Fire Danger Index is used, as seen in **Figure 7***.* Fire danger rating systems are used to assess the potential for bushfire occurrence, fire spread and difficulty of fire suppression. Typically, fire danger rating systems combine meteorological information with estimates of the moisture content of the fuel to produce a fire danger index.

Temperature, relative humidity, wind speed and previous rain, all factors are allocated values, and the total is allocated to a colour-coded group which has a rating from 0-100 and is graded in colours. Blue (0-20), Green (21-45), Yellow (46-60), Orange (61-75) and Red (75+) as seen in **Figure 7** (Enviro Wildfire Services, 2013). For example, dry, hot and windy conditions contribute to a high FDI, whilst wet, cold and calm conditions contribute to a low FDI. If the FDI is low, there is a very low chance of fire, and if there is one, "*it's a small fire… ...it's not likely to run away, they don't need to call all the resources"* (Chief Pilot, 2021).



Lowveld FDI Description	Colour	Category	Lowveld FDI Precaution
SAFE	BLUE	0 - 20	Low fire hazard. Controlled burn operations can normally be executed with a reasonable degree of safety
MODERATE	GREEN	21 - 45	Although controlled burning operations can be executed without crating a fire hazard, care must be taken when burning on exposed, dry slopes. Keep constant watch for unexpected wind speed and direction changes
DANGEROUS	YELLOW	46 - 60	Controlled burning not recommended when fire danger index exceeds 45. Aircraft should be called in at early stages of a fire.
VERY DANGEROUS	ORANGE	61 - 75	No controlled burning of any nature should take place. Careful note should be taken of any sign of smoke anywhere, especially on the upwind side of any plantation. Any fire should be attacked with maximum force at hand, including all aircraft at the time.
EXTREMELY DANGEROUS	RED	75+	All personnel and equipment should be removed from the field. Fire teams, labour and equipment are to be placed on full stand-by. At first sign of smoke, every possible measure sjoud be taken in order to bring the fire under control in the shortest possible time. all available aircraft are to be called for without delay.

Figure 7. The full list of warning states in the Lowveld Fire Danger Index (Meikle and Heine, 1987).

The Fire Danger Index (FDI) provides greater flexibility in managing work proximity; therefore, not all pilots may always be on duty and ready to deploy. However, the FDI significantly influences the crew's required level of readiness. With FDI forecasts typically available up to three days in advance, pilots can effectively coordinate and plan their schedules accordingly. If it has been raining, often pilots will not have to be on standby, *"you can go and have a beer if you like... ...Or you can go drive, go wherever, then you are off"* (Chief Pilot, 2021).

In contrast, if the FDI is forecasted as high for the next few days, pilots will be at the base by 9 am for prefight checks (Person responsible for flight operations, 2021). They will have more resources, and therefore more pilots, who will have to be on standby, ready to be dispatched. For example, on days where the FDI is high, there may be two of the same variation of pilot situated at the airbase, with a third pilot on standby from home, namely, *"first call, second call, third call, on a rotation."* (Person responsible for flight operations, 2021). "*As soon as there's a call out, then obviously the guy who's on home reserve will know there's a call out now, meaning when the pilot on first call gets dispatched, the pilot on the second call will then become the first call, ready for rotation into an ongoing fire, or to be dispatched to a new one, whilst the pilot on third call makes his way to the airbase to take over the second call position"* (Person responsible for flight operations, 2021).

In addition to the FDI, the weather conditions, particularly the wind, also influence the flying conditions; in flat areas, *"the wind howls"*, creating a lot of turbulence, whilst, in mountainous areas, prefrontal conditions, downdrafts, and updrafts make the area a challenge to navigate (Chief Pilot, 2021, personal communication). When conditions are too turbulent, pilots may have to *"bail out"* and drop their load of water prematurely due to winds making it difficult for the aircraft to peel away from the face of a mountainside - as the ability to do so may otherwise be *"limited because it's got that (heavy) load of water" (Chief Pilot, 2021, personal communication).* If pilots experience such difficult conditions, and one pilot feels it is becoming too dangerous, *"we stand down. All of us. Not one guy who says, "Yah, listen, I'm going to continue." That's the last word you'll ever hear from him because we've made the decision, it's dangerous now".* (Chief Pilot, 2021, personal communication). Thus, weather conditions play a significant role in the work done by aerial firefighters, largely due to weather conditions influencing the Fire Danger Index (FDI).

2.5.3.2 Vegetation/Fuel Types

The organisation in question have bases in areas with a higher propensity to fire. The type of vegetation within an area may also affect the propensity for fire within an area.

The vegetation within the area that allows the fire to burn is referred to as '*fuel*', and different fuel types can influence the behaviour of the fire and the level of difficulty in extinguishing the fire. According to the Person responsible for flight operations (2021), *"There are various different types of fuel; grass, trees, fynbos, which is not a pleasant fuel to maintain because of its oil content, as well as Eucalyptus, which has got a lot of oil, also very, very flammable"*. Trees with larger tree trunks are known to carry on burning for days as they are more susceptible to smouldering and being reignited due to the wind (Person responsible for flight operations, 2021).

Another challenge to consider is the management of lands such as plantations. When plantations are not well managed and overgrown, pilots find it difficult to use some of their resources, such as retardant with water, due to the thick vegetation that the water and foam cannot reach the ground. If plantations are well managed, pilots often deal with "*stack fires*". "*Stack fires*" are trees that have been harvested, packed, and are ready to be taken to the mill, which can present significant challenges to the operation. *"If a fire starts in a stack, then it's almost disastrous, because it burns so hot, and the ground crew can't get close",* so the pilots are instructed to hit the stack hard enough with enough water that the stack dismantles and breaks apart (Chief Pilot, 2021).

2.5.3.3 Obstacles and Debris

Obstacles and debris present during firefighting missions greatly threaten aerial firefighters. Because bombers and helicopter pilots fly relatively low, they are often faced with strong winds, resulting in burning debris being thrown up from the fire, power lines, and what pilots would call '*widow-makers'*. According to the Chief Pilot (2021), *"The widow makers, it's a plantation, and then there will be one tree that's dead. It's got no branches, just standing like a tower, we call them widow makers. Sometimes you can't see it, the spotter will tell you, "Be careful of widow makers".* It is then the Spotter pilots' job to warn pilots of potential hazards.

2.5.4 Demands Specific to Each Pilot

2.5.4.1 Command & Control (Spotter)

The command and control role is considered a high workload position due to the spotter pilot managing all air-to-air communication, coordinating water drops and maintaining safety within the airspace. The chief pilot (2021) uses an example to describe this high workload, "*two helicopters or two three helicopters and four bombers. And the thing is, which makes their job so difficult, is he's got to coordinate everything out of the area. He's got to speak to us, like I said, to speak to the bomber pilots, to the helicopter pilots... And I think what also makes it difficult for them is the speed. A helicopter is much slower than when we [bombers] are coming for the drop. So, he's got to see that everybody's, you wait there, wait for the bomber, you number two, or three or whatever, and I think it's a very, very high workload".* Therefore, spotter pilots can only fly a maximum of four hours before landing, refuelling their aircraft and having a comfort break. If the spotter pilot is the only command and control present at the airbase, they may have to take a relatively short break, approximately 30 to 45 minutes, before taking off again. If there is more than one pilot available at the airbase, the outgoing pilot will perform a "handover" briefing with the incoming pilot. Once the pilot requests a handover, the incoming pilot will meet at the fire site, where both pilots will circle the fire together. Before heading back to the airbase, the outgoing pilot will explain to the incoming pilot *"This is what I've done, this is what the IC [Incident Commander] must look out for, this is where the IC is, that us what you must do''* before the outgoing pilot heads back to base and the incoming pilot takes over for the next 4 hours (Person responsible for flight operations, 2021).

2.5.4.2 Air-Tractor 802 (Bomber)

In overextended aerial attacks, where suppression efforts are stretched too thin, bomber pilots endure a high workload from numerous take-offs, water collections, and landings. Following an attack, the pilots will land at the airbase to fill up for the next fire, *"...it could be that we dispatch again within the next 15 minutes, or on return from that fire, you might get dispatched to another fire"* (Chief Pilot, 2021). The 802 aircraft is also categorised as heavier than the other aircraft, making them harder to land because they are a “tail dragger” – this means that when they land, they are required to land on two front tyres and as they slow down, the tail can drop onto a smaller wheel located at the rear of the plane. Thus, bombers are allowed to fly for eight hours, according to law, but can be extended up to 10 hours. If the pilot feels capable of flying longer than eight hours, he will notify the Person responsible for flight operations. Once the ninth hour has been reached, a written statement is submitted to the SACAA. Once the tenth hour is reached, the pilot will be granted time off the following day.

Another challenge that bombers face is the need to fly as low as 500 ft above the designated drop site. This can be dangerous due to obstacles such as power lines, trees and “widow makers*”. “That’s another part of their stressful job, they've got to look out for hazards for you because you’re too low, you can’t see it.”* (Chief Pilot, 2021). So, it is essential that bombers maintain a balance between being low enough for water drops and high enough to avoid hazards. If bombers drop water too low, the speed of the water can result in a new fire starting. If the bombers are too high, then the water loses its effectiveness.

2.5.4.3 Helicopter: UH-1H (Huey)

The challenge of flying this aircraft is having an additional attachment to the aircraft, namely a Bambi bucket. Flying a Huey requires different skills than flying the Spotter or Bomber. Fixed-wing aeroplanes depend on a forward motion to move air over the wings and create lift; a helicopter creates lift using rotating blades. Helicopters require both hands and both feet to fly to operate different controls at the same time. Pilots described flying the Huey with a Bambi bucket as having to *“swap your brain around on your movements. So, you're looking at the mirror; if you want to go forward, you must move backwards on the controls. So, that’s something I think that they need to adjust to.* Since the pilot cannot see the bucket hanging below the Huey, he must use a mirror to view and control the bucket's direction. “*Also, sometimes they get to, when they take water, it's a confined area. They’ve got to be wary of the diameter of the rotor and also where his tail rotor’s sitting.”* The pilot must be cautious of the area around the water to ensure there is enough space to descend and collect water without damaging the Huey. *So I think they've got challenges, the same as the bombers, a little bit different. Flying wise, condition wise and so on.”* Correspondingly, to the bomber pilot, Hueys have a high workload due to multiple take-offs, water collection, and landings - thus they only fly for two hours at a time. Hueys do not fly with their Bambi buckets out to the fire, as it restricts their speed. The Huey pilot and their assistant will identify water sources close to the fire and deploy the Bambi bucket there. The helicopter assistant will stay at the water site and help the pilot collect water for the next attack. Once a Huey completes the attacks, their assistant will pack up the Bambi bucket and return to base.

In summary, the company in question provides nationwide aerial support for wildfire suppression. It operates as a subsidiary of a larger holding company, primarily contracted by Working on Fire, which accounts for 80% of its operational workload. The remaining 20% involves services to private clients, including fire break preparations and prescribed burning. The company utilises three aircraft types, rotary-wing and fixed-wing aircraft. Operational roles are divided among spotter pilots, who coordinate a safe air space and direct water drops; The Huey pilots responsible for transporting firefighters and dropping the Bambi bucket water; and a bomber pilot, who deploys water and fire retardant. While all pilots face common challenges such as difficult terrain, obstacles, debris and adverse weather conditions, the specific demands they face differ according to their aircraft type and assigned roles. The following section will explore pilots' changing working arrangements over time and the circumstances leading to their current working arrangements, and the focus of the second part of the study.

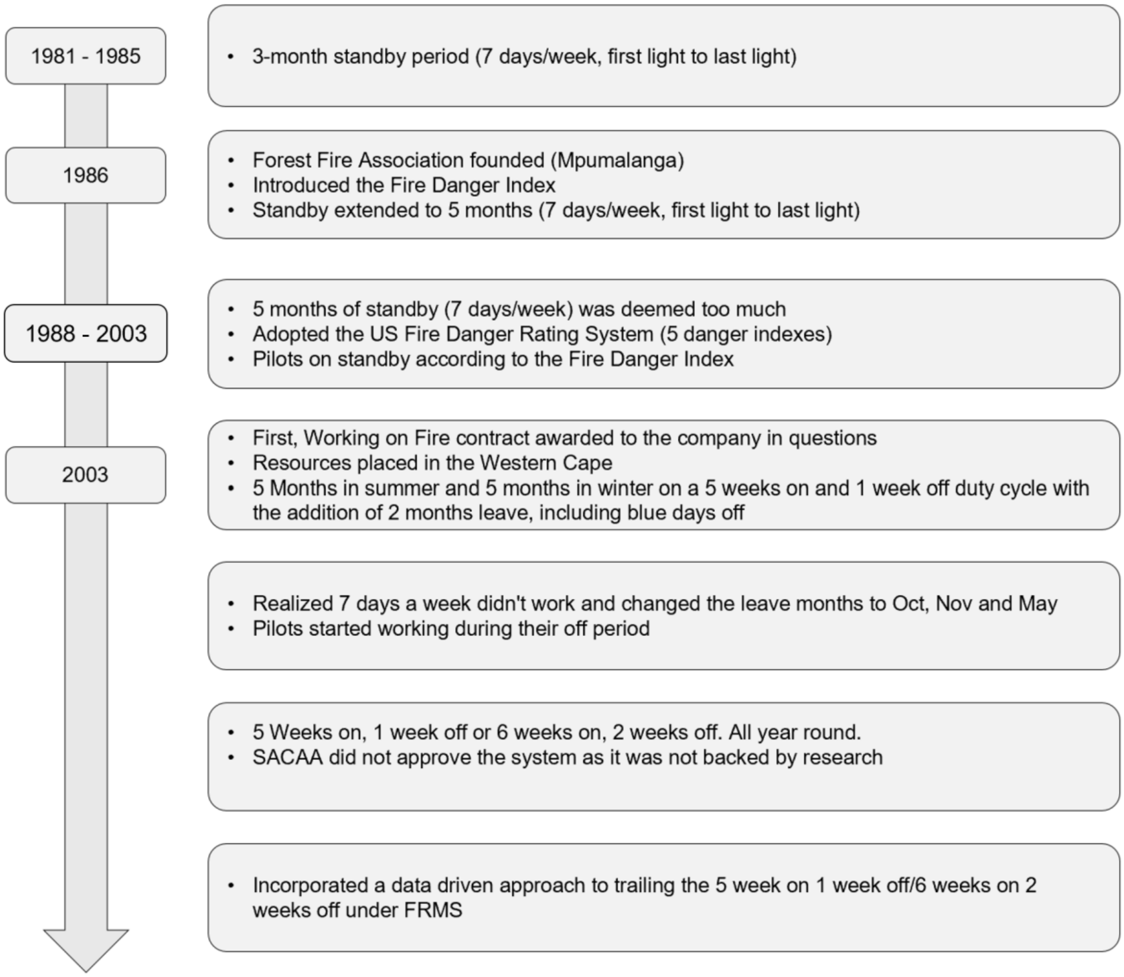
2.5.5 Change in work arrangements of Aerial Firefighting in South Africa over time

In 1980, multiple fires in the area of Pietermaritzburg, as well as wildfires on Sappi Forest plantations, prompted new measures to control fires. Consequently, aerial firefighting was introduced by the general manager of Sappi Forests (Pty) as an additional tool to counter the wildfire surge in the KwaZulu-Natal province, resulting in Sappi contracting the first firefighting bomber and spotter to drop on that plantation in 1981 (Former Chair of the

Board, 2021). This was followed by employing additional aircraft in Mpumalanga. This consisted of pilots working seven days a week from first light to last light for three months out of the year, as seen in **Figure 8**. During the three months, pilots would be on standby while staying at their homes “*very close to you, within three to five minutes of your aircraft. You were not sitting in the crew [rooms].*” (Former Chair of the Board, 2021).

In 1986, the Forest Fire Association was introduced in Mpumalanga, thus leading to the introduction of the fire danger index, and during this time, pilots' stand-by periods were extended from three months to five months due to work being arranged according to the fire danger index. Between 1987-1988, the five-month duty period continued with bomber pilots spending the rest of the seven months training. According to the Former Chair of the Board (2021), “*we realised after a year or two, that seven days a week for five months, is a bit of much bit much. So, we brought in a rating, fire danger rating system*”. Thus, they moved to a US Fire Rating System with 5 danger indexes, and this rating system allowed for more flexibility regarding the proximity to work.

In 2003, the company in question was awarded the first tender for Working on Fire (WOF), resulting in resources being placed in the Western Cape for five months. Thus, the standby period changed to five months of winter and five months in summer, as seen in **Figure 8**. After one or two seasons, pilots started complaining about the length of the current season and as a means to address this, the pilots and the company in question settled on a work schedule that worked for both parties. This schedule consists of five weeks on duty and one week off duty, including a two-month holiday and blue days off. It is important to note that after 2003, the dates of changes in duty were not provided. The two-month holiday got extended to three months during October, November, and May. However, pilots started working during holiday months in hopes of earning overtime pay and essentially “blurred the lines” between the holiday period and working periods. This led to five weeks on duty and one week off duty all year round. Following the work system change, the SACAA conducted a fatigue risk management phase inspection, which ultimately led to the rejection of the system due to the system being unilaterally introduced, as seen in **Figure 8.**



1981 - 1985

- 3-month standby period (7 days/week, first light to last light)

1986

- Forest Fire Association founded (Mpumalanga)
- Introduced the Fire Danger Index
- Standby extended to 5 months (7 days/week, first light to last light)

1988 - 2003

- 5 months of standby (7 days/week) was deemed too much
- Adopted the US Fire Danger Rating System (5 danger indexes)
- Pilots on standby according to the Fire Danger Index

2003

- First, Working on Fire contract awarded to the company in questions
- Resources placed in the Western Cape
- 5 Months in summer and 5 months in winter on a 5 weeks on and 1 week off duty cycle with the addition of 2 months leave, including blue days off

- Realized 7 days a week didn't work and changed the leave months to Oct, Nov and May
- Pilots started working during their off period

- 5 Weeks on, 1 week off or 6 weeks on, 2 weeks off. All year round.
- SACAA did not approve the system as it was not backed by research

- Incorporated a data driven approach to trailing the 5 week on 1 week off/6 weeks on 2 weeks off under FRMS

Figure 8. Change in work arrangements of Aerial Firefighting in South Africa over time.

The SACAA proposed the five weeks on and two weeks off system to be trialled for an extended period; however, this trial eventually failed due to a single complaint, according to the Former Chair of the Board (2021). This led to the present, where a second attempt at the trial was implemented, which includes a data-driven approach to trialling five weeks on and one week off and six weeks on duty and two weeks off duty. Pilots are on duty for four to six weeks and off duty for 2 weeks as part of the trial. During this duty period, pilots are expected to fly anytime from 10:00 am to 16:00 pm; however, this period may differ depending on where they are based, and the season they are in due to the change in sunrise and sunset times throughout the year. For example, the sun goes down far later during the summer in the Western Cape, so pilots may be expected to be on duty until 5 pm. It’s important to note that within this standard duty period, there is a lot of flexibility, dependent on the working requirements at a particular airbase. Other bases may have particularly quiet seasons, where the pilots *“could be on standby for five months and not fly anything”* but are still expected to be on duty, as a fire may break out at any point (Person responsible for flight operations, 2021). Some bases are *“very, very busy…”* and would require more working hours.

2.5.6 Current working arrangements

In general, the company in question requires that the crew work on a work-to-rest ratio of six weeks on duty and two weeks off duty. This is the current agreement established with the SACAA to trial a six-week on and two weeks off period monitored under the company’s FRMS. As a part of their fatigue risk management system, pilots must report their self-reported sleep using an Air Maestro application. According to the Chief pilot (2021), “*We’ve got to log in to Air Maestro every day to report that you’re ready for duty. So, when you open that timesheet, your roster. Obviously, when you're on duty, it’s a whole timesheet. I can show you when we have some time. And then you’ve got to put in how much sleep you’ve had in the last 48 hours and the last 24. And then also you wake up. So, this morning, I got up at 6:30. And I slept 7.7 hours last night, and I slept 8 hours the previous night. So, you’ve just got to put that in, and you can't go out of that time sheet without putting that in”*. During days off, pilots are not expected to report on their sleep.

In addition to reporting their sleep, pilots have a cognitive test that gauges their levels of alertness, which they must complete twice a day. The test shows pilots a set of pictures, and the crew must select the different/ the same image. It is important to note that sometimes pilots fail tests due to disruptions while taking the test, such as losing a wi-fi connection or being distracted by a colleague. According to the Chief Pilot (2021), there is a perception that the test may be susceptible to subjective interpretation. For example, individuals might perform well on the assessment despite experiencing fatigue following inadequate rest or alcohol consumption. This raises concerns about the test’s sensitivity to actual alertness levels. Throughout their six-week duty period, pilots are required to systematically report their sleep patterns and perceived alertness as part of standard operational procedures.

It is important to note that, according to the Former Chair of the Board (2021), the six weeks on duty and the two weeks off duty do not present a threat of fatigue due to their workload over the six-week period, but due to *"the after-hour activities"* when pilots are off-duty. This is because pilots only fly between 50 to 100 hours in five months on average. However, fatigue has been cited due to monotony when there are no fires for extended periods, social engagements multiple times a week and commuting home. According to a Former Chair of the Board (2021), when blue days are forecasted, some pilots would opt to travel home after their duty period ends to spend the night or two at home, which can be a commute of up to 300km and will commute back early in the morning to start their duty at 10 am.

2.5.6.1 Flight procedures

Pilots have pre-flight and post-flight procedures when on duty. Before their duty officially starts, all pilots must complete a pre-flight inspection, ensuring their aircraft is fit for flight and filled with fuel and water. It takes approximately 20 minutes to complete the pre-flight. Once the duty period starts, pilots are expected to be ready to fly at any time from 10 am to 4 pm. However, this period may differ due to light availability in a specific part of the country at a particular time of year. For example, the sun goes down far later during the summer in the Western Cape, so pilots may be expected to be on duty until 5 p.m. Within this standard duty period, there is a lot of flexibility, dependent on the working requirements at a particular airbase. Some bases are "*very, very busy*…" and would require more working hours; however, there would "*be more resources and more crew there*" allowing rotations if a pilot is feeling as though they are "*on my third week now but I'm not feeling well, I need a few days off*" (Chief Pilot, 2021). Upon return to base, pilots are expected to complete a post-flight inspection and, after that, complete a set of paperwork detailing the *"actual dispatch time, when you started up, what time was your first drop, and when was your shutdown"* that goes to the financial department of the company to invoice clients (Chief Pilot, 2021).

2.6 SUMMARY OF KEY FINDINGS OF THE RESULTS

Aerial firefighting demands and operational stressors are considerable. As highlighted in the introduction, aerial firefighting, like other emergency services, often has unique operating challenges that could present fatigue vulnerability. However, after developing an understanding of the working system of aerial firefighters, the risks and demands associated with them can be compared to those of other emergency services in some instances. They can prove to be unique in others. Like other emergency services, aerial firefighters are on-call and work away from home for extended periods since the key feature of these services is being ready to fly for low-probability events. Conversely, other emergency services are vulnerable to fatigue stemming from working during the night and crossing time zones. These aerial firefighter pilots, however, operate during daylight hours and are not allowed to fly at night. Additionally, aerial firefighters use multiple aircraft types, including rotary-wing and fixed-wing aircraft, requiring pilots to perform different roles and responsibilities. This study found that pilots share some task demands; however, most of the time, there is a great deal of task variability within aerial firefighting. Each role, whether Spotter, Bomber, or Huey pilot, requires a distinct skill set to navigate hazards, coordinate efforts, perform precise firefighting operations, and adapt to changing demands.

One of the shared demands that emerged is that pilots are all operating on a work-to-rest ratio of six weeks on duty and two weeks off duty during winter and summer seasons. In addition to the two weeks off, aerial firefighters are given flexibility during their duty period, due to the introduction of the fire danger index, and pilots are positioned at bases closer to home. Due to their participation in a trial with the SACAA, all pilots must report their sleep timing and duration for the last 48 hours and alertness twice a day, daily during their six weeks on duty. Pilots are expected to perform pre- and post-procedures before and after their duty or flight. Overall, their duty time generally in winter is from 10 am to 4 pm; this duty length will not necessarily leave adequate time for recovery between duty periods, nor will duty timing interfere with natural sleeping patterns.

Unique to aerial firefighting is the task variability between pilots. Unlike the Spotter pilot, helicopter and bomber pilots are often required to fly low to deliver vast volumes of water. They are frequently faced with strong winds, resulting in burning debris being thrown up from the fire, power lines, and what pilots would call ‘widow-makers’. The spotter pilot is considered a high-workload position because the spotter pilot manages all air-to-air communication, coordinates water drops, and maintains safety within the airspace. This requires considerable situational awareness and focus; thus, spotter pilots can only fly a maximum of four hours before landing, which is a shorter flying period than other pilots. Helicopters, on the other hand, require both hands and feet to fly compared to fixed-wing aircraft. Additionally, Huey pilots are unique because they operate an external load, namely the Bambi buckets. The Huey pilot and their assistant will identify water sources close to the fire and deploy the Bambi bucket there. Bomber pilots have a high workload due to multiple take-offs, water collection, and landings. Because bomber aircraft are heavier than other aircraft, they require a different skill set and are harder to land.

Furthermore, this study found that aerial firefighting pilots are potentially exposed to fatigue in different ways. Due to pilots being on-call for up to six weeks and ready to fly for low-probability events, pilots can experience monotony and boredom of being on duty. Pilots may spend time away from the airbase when the fire danger index rating is low. However, when fire danger index ratings are high, pilots are expected to be on standby with no guarantee of active fire or flight, resulting in crew spending duty hours waiting for something to happen. Monotony can be a causal factor of fatigue due to boredom, lack of alertness and low arousal. Conversely, in the case of a disaster fire such as the Table Mountain Fire in Cape Town (as highlighted by the Person responsible for flight operations), pilots are required to work consecutive flying duty periods. These duty lengths span multiple days from sunrise until sunset, resulting in a high workload for pilots. This potential increase in workload, resulting from extended flight times and highly stressful situations, could put pilots at risk of fatigue, which in turn endangers flight safety and public well-being. Due to their unique operating context and the proposed working time arrangements monitored under the company’s FRMS, the second and much larger phase of this thesis aims to understand the sleep-wake behaviour of pilots as part of the current fatigue risk management system, to explore how extended duty periods impact their sleep. The following chapter aims to review sleep, fatigue, and fatigue management in aviation before homing in on sleep in aerial firefighting.

CHAPTER III

3 INTRODUCTION: INVESTIGATING SLEEP WAKE BEHAVIOUR IN AERIAL FIREFIGHTERS

The aviation industry’s primary concern is safety, as it has become one of the world's safest forms of transportation (ICAO, 2017). However, a safety-critical industry must actively manage hazards with the potential to impact safety. Fatigue has been cited as a contributing factor to serious accidents and incidents, with the implication that a fatigued pilot is less likely to produce safe task performance, resulting in higher operational risks (Karanikas & Nederend, 2018; Wingelaar-Jagt *et al*.,2021). Fatigue can be understood as a naturally occurring state, an almost universal feature of contemporary life; therefore, as fatigue cannot be eliminated, it must be managed (Dawson & McCulloch, 2005; Siniscalchi *et al*., 2013). Authors such as Dawson & McCulloch (2005) highlighted that prior sleep/wake behaviour is a crucial part of managing fatigue. However, fatigue is considered multidimensional, which may imply that complex patterns of relationships exist between fatigue and sleep characteristics.

In the context of aerial firefighting, which plays a critical role in wildfire suppression, pilots work in high-risk, low-altitude environments and face multiple stressors, such as smoke, heat stress, and physical demands, which degrade performance and increase error rates and as highlighted in the previous chapter (Dawson *et al*., 2021). The work is characterised by intense and quiet seasons, unpredictable on-call demands, and extended duty periods, often in remote locations. Fatigue management in this field is particularly challenging compared to more structured sectors like mining due to the unpredictable and safety-critical nature of operations. Despite existing research offering some insights, most literature on aerial firefighting focuses on the cost and effectiveness of the service, with limited attention given to fatigue-related risks (Thompson *et al*., 2013; Calkin *et al*., 2014). Thus, the second aim of this study is to understand the sleep-wake behaviour of pilots and evaluate the current fatigue risk management system. This will help inform the development of future risk management strategies more suitable to this specific line of work.

3.1 DEFINING FATIGUE

Defining fatigue has been notoriously difficult due to its heterogeneous (occurring across different conditions) and multidimensional nature (Dawson & McCulloch, 2005; Landmark-Høyvik *et al*., 2010; ICAO, 2016). This suggests that more than one mechanism can contribute to its expression in an individual (Landmark-Høyvik *et al*., 2010). Fatigue, resulting from various demands, manifests in multiple theorised dimensions. These include acute and chronic fatigue, mental and physical fatigue, sleepiness, and emotional symptoms such as irritability, miscommunication, and lack of motivation (Wilson et al., 2007; Göker, 2018; Landmark-Høyvik et al., 2010; Seitz, 2014). In aviation, mental fatigue and sleepiness are considered the most significant forms of fatigue (Williamson *et al*., 2011). According to the International Civil Aviation Organisation, fatigue is a result of an imbalance of physical and mental demands during waking activities and the recovery of those demands, which requires sleep (ICAO, 2017). In the context of fatigue in aviation, fatigue is best defined, “as physiological state of reduced mental or physical performance capability resulting from sleep loss, extended wakefulness, circadian phase, and/or workload (mental and/or physical activity) that can impair a person’s alertness and ability to perform safety related operational duties” (ICAO, 2017, p. xv).

In aviation, fatigue occurs in response to certain conditions, these conditions include unpredictable work hours, insufficient sleep, shift work, and long duty cycles that can result in pilots becoming inattentive, careless, and inefficient (Caldwell *et al.,*2009; Missoni *et al*., 2009; Reis *et al.,*2013; Bendak & Rashid, 2020). Operational demands often require pilots to work early and late hours, which leads to irregular sleeping patterns (Mallis & DeRoshia, 2005; Lee & Kim, 2018). Evidence-based research has demonstrated that such misalignments can result in performance decrements, increased subjective and objective sleepiness, and decreased alertness, thus leading to sleep loss (Lee & Kim, 2018). As a result, crew members can experience fatigue when trying to perform critical operational tasks, thus compromising flight safety and increasing the risk of accidents and possible injuries (Mallis & DeRoshia, 2005). Multiple authors suggest that sleep loss, sustained periods of wakefulness, and circadian misalignment all contribute to fatigue and fatigue-related mishaps (Caldwell, 2005; Lee & Kim, 2018; Bendak & Rashid, 2020). Managing crew sleep is critical. As a point of departure, it is important to first understand what sleep is and how it is regulated.

3.2 AN OVERVIEW OF SLEEP

From a behavioural perspective, sleep is a rapidly reversible state characterised by the absence of consciousness, temporary inactivity of voluntary muscles and sensory activity or reduced responsiveness to external stimuli (Carskadon & Dement, 2011; Arzi *et al*., 2012). Sleep health involves characteristics such as sleep depth, quality and timing (Hirshkowitz *et al.*, 2015).

3.2.1 Sleep architecture

Human sleep has been divided into two types of sleep: non-rapid eye movement (NREM) sleep and rapid eye movement (REM) sleep. Accounting for 20% to 25% of total sleep time, REM sleep generally happens in four to six separate periods (Carskadon & Dement, 2011). NREM sleep is categorised into three progressively deeper stages (N1, N2, N3) and accounts for 75-80% of sleep time. Alongside REM sleep (20-25%), these stages cycle in an approximately 90-minute ultradian rhythm (Walker *et al*., 2009). A standard night involves roughly five such cycles, each beginning with NREM stages 1-3 and culminating in REM sleep. Early night sleep is dominated by deep N3 (slow-wave sleep, characterised by 0.5-4 Hz EEG oscillations), while N2 and REM sleep (marked by rapid eye movements, theta oscillations 4-10 Hz, and dreaming) prevail later. Transitions between these phases involve profound, yet distinct, neurochemical changes in the brain. Collectively, these distinct sleep stages represent discrete neurobiological processes essential for modulating, regulating, and priming various brain functions (Walker *et al*., 2009).

3.2.2 Sleep regulation

Sleep and wakefulness occur in synchronised cycles regulated by the internal circadian clock, an approximately 24-hour biological pacemaker (Kyriacou & Hastings, 2010). Found across diverse organisms (Roenneberg & Merrow, 2016), this clock evolved as an adaptation to Earth's rotation. Environmental cues like light, temperature, and resource availability (zeitgebers) synchronise these endogenous timing systems with the day-night cycle (Roenneberg *et al*., 2007; Roenneberg & Merrow, 2016). Central to this system is the suprachiasmatic nucleus (SCN) within the hypothalamus. Positioned above the optic nerve crossing, the SCN acts as the master pacemaker, generating and orchestrating circadian rhythms over approximately 24 hours (Kyriacou & Hastings, 2010; Roenneberg *et al*., 2007). In essence, the SCN is the master clock that dictates the body's internal timing, and its synchronisation with the external 24-hour day is critically dependent on environmental zeitgebers, with light being the most powerful (Roenneberg et al., 2007). Interference with the entrainment of the SCN by light can desynchronize endogenous circadian rhythms, potentially increasing the risk for a range of health issues.

3.2.2.1 Circadian Regulation of Sleep-Wake Cycles

Circadian regulation describes the biological clock's control over roughly 24-hour rhythmic changes in behaviour and physiology (Vitaterna *et al*., 2001). This timing process functions as an endogenous near-24-hour oscillation governing sleep propensity—a clock-like mechanism responsive to environmental cues (zeitgebers) (Schmidt *et a*l., 2007). Typically, these periodic signals synchronise the circadian system and its driven rhythms with the external environment, enabling anticipation of daily challenges and opportunities. However, humans can cognitively override their internal clock, potentially causing sleep disturbances when sleep-wake cycles become misaligned with circadian timing, as occurs in shift work or jet lag (Vitaterna *et al*., 2001).

Sleep and wake timing normally align with the circadian regulation of the sleep cycle and other circadian rhythms (Vitaterna *et al*., 2001). The propensity for sleep dictated by circadian rhythms is minimal in the early evening 17:00+, and peaks in the early morning

(02:00-04:00), known as the window of circadian low. Disruptions to the circadian clock or its synchronisation (e.g., shift work, jet lag) impair sleep and cause physiological and cognitive dysfunction (Kyriacou & Hastings, 2010). This desynchronization is particularly evident in workplaces that disrupt the SCN-environment interaction, leading to serious accidents from impaired alertness and problem-solving (Kyriacou & Hastings, 2010).

3.2.2.1.1 Homeostatic Regulation of Sleep

The homeostatic process is a sleep-promoting mechanism that progressively builds during wakefulness (Schmidt *et a*l., 2007). Its accumulation correlates with declining cognitive performance and alertness, alongside increasing sleepiness and fatigue (Schmidt *et al*., 2007). This accumulated sleep pressure dissipates during sleep, primarily in non-REM (NREM) slow-wave sleep (Schmidt *et al*., 2007). The duration, quality, and efficiency of sleep significantly influence this homeostatic component.

3.2.2.1.2 The two-process model of sleep

The two-process model of sleep-wake regulation, initially developed by Borbély and colleagues (Borbély, 1982), conceptualises sleep control through the interaction of a homeostatic process (Process S) and a circadian process (Process C). Process S refers to the need for sleep that builds up during wakefulness, similar to a pressure system. That pressure is dissipated during restorative sleep (Borbély, 1982; Durmer & Dinges, 2005). Sleep onset occurs when Process S reaches its upper threshold (T1), while wakefulness resumes when it falls below its lower threshold (T2), as illustrated in **Figure 9** (Borbély, 1982).

Process C, on the other hand, represents an approximate 24-hour endogenous rhythm in sleep propensity (Van Dongen & Dinges, 2003). Its influence is weak (low sleep propensity) early in the evening when homeostatic pressure (Process S) is great. Process C peaks (high sleep propensity) in the early morning when Process S pressure is low (Van Dongen & Dinges, 2003). The circadian process determines fundamental aspects of sleep timing and is marked by physiological rhythms, including cortisol and melatonin secretion and core body temperature fluctuation (Borbély, 1982; Borbély, 2016).

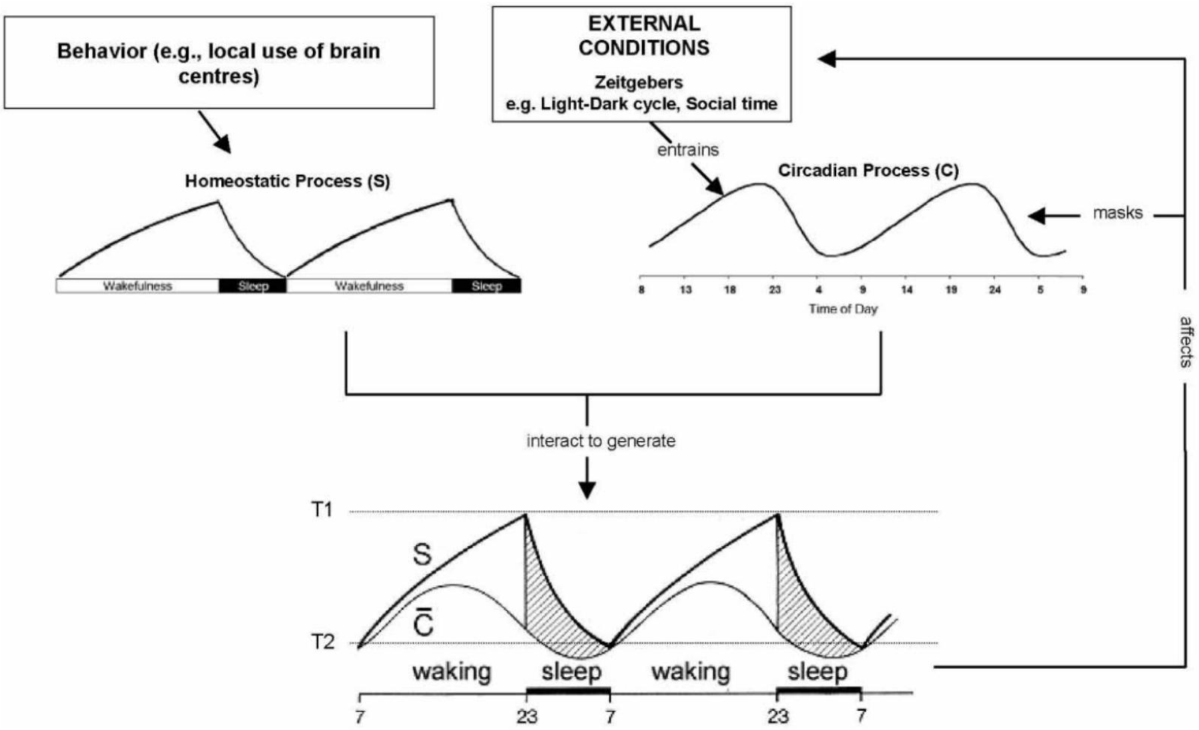


Figure 9. The Two-Process Model of Sleep Regulation was established by Borbély (1982). Sleep propensity, reflectedby the homeostatic process S, builds up during wakefulness and declines during sleep (Borbély, 2016).

As shown in **Figure 9**, Process S and Process C are inversely correlated: the greater the difference between their trajectories, the higher the overall sleep propensity (Borbély, 1982). This two-process model provides a foundational framework for understanding how homeostatic sleep pressure and circadian rhythmicity jointly regulate sleep and wake states. Grasping these regulatory mechanisms is essential for identifying how their disruption contributes to fatigue, especially within high-demand sectors like aviation.

3.3 DIMENSIONS OF SLEEP

Sleep is complex, but it is an essential part of health. Whereas sleep medicine has historically focused on disorders and deficiency (Buysse, 2014), a comprehensive assessment requires viewing sleep health as a positive, multidimensional construct, not merely the absence of problems (Buysse, 2014; Knutson *et al*., 2017). Evaluating sleep habits across diverse contexts, such as weekdays, weekends, and holidays, is essential, as sleep duration fluctuates with social and work schedules.

Sleep health is a sleep-wake behaviour pattern that adapts to individual, social, and environmental needs, fostering mental and physical health (Buysse, 2014). It exists on a spectrum for every individual. Buysse (2014) originally defined five measurable dimensions: Sleep Duration, Sleep Continuity/Efficiency (also latency and wake after sleep onset), Sleep Timing, Alertness/Sleepiness, and Sleep Quality, with Regularity added later to encompass six dimensions (Buysse, 2014; Meng *et al*., 2023). Thus, good sleep health encompasses more than just duration measurements.

3.3.1.1 Sleep duration

This dimension refers to total sleep obtained per 24 hours (Buysse, 2014). Individual needs vary, but public health guidelines recommend seven to nine hours nightly for adults (18-64) and seven to eight hours for older adults (Hirshkowitz *et al*., 2015). Population-level recommendations provide broad guidance, while individual clinical advice requires personalisation.

3.3.1.2 Sleep quality

Sleep quality is often used, measured, and employed as an outcome criterion of restorative success; however, there has been no consistent guidance for normal, optimal, or healthy sleep (Ohayon *et al*., 2017). Ohayon et al. (2017) outline two primary definition approaches:

3.2.3.2.1 Self-Rating/Subjective Approach

Self-rated sleep quality relies on an individual's personal satisfaction with their sleep ("how good or bad it is") and perceived impact on daily functioning (Ohayon *et al*., 2017). Adults typically report satisfaction with their sleep patterns, though validated definitions for children are lacking (Buysse, 2014).

3.2.3.2.2 Objective Components Approach

Determine sleep quality by specific, quantifiable characteristics. The National Sleep Foundation's Sleep Quality Consensus Panel (SQCP) listed consensus indicators (Ohayon *et al*., 2017): sleep continuity, as it contributes significantly to good quality in the majority of ages. The interpretation of sleep architecture is restricted by the absence of data from a healthy population. Two critical considerations emerge from the available data: first, a REM sleep percentage greater than 41% cannot be assumed to represent good sleep quality in adults of any age. Second, an N3 sleep percentage of 5% or less is indicative of impaired sleep quality, though this threshold may not apply to older adults. Lastly, napping, as the fewer naps taken throughout the day are linked with higher quality sleep, and more than one nap reflects poorer quality.

3.2.3.2.3 Sleep continuity/efficiency

This dimension describes the ease of initiating sleep (sleep onset) and returning to sleep after awakenings (Buysse, 2014). It is measured as sleep efficiency: the percentage of total time in bed actually spent asleep (Shrivastava *et al*., 2014; Vincent *et al*., 2016), widely used as an objective sleep quality indicator. Ohayon et al. (2017) established consensus thresholds: an efficiency of ≥85% indicates good sleep quality across all ages. An efficiency <74% signifies poor quality for all age groups except young adults; specifically, for young adults (18-25 years), an efficiency <64% indicates poor quality.

3.2.3.2.4 Sleep Latency

Sleep latency measures the time (minutes) taken to transition from full wakefulness to sleep onset. A latency of ≤30 minutes is associated with good sleep quality. Latencies of 45-60 minutes indicate poor quality (except in older adults), and latencies ≥60 minutes indicate poor quality universally (Ohayon *et al*., 2017)

3.3.1.3 Awakenings

Defined as the number of episodes per night where wakefulness lasts >5 minutes (Ohayon *et al*., 2017). The National Sleep Foundation consensus is that one or fewer awakenings per night indicates good quality for ages 18-64; up to two awakenings/night indicates good quality for adults ≥65 years. More than four awakenings/night is associated with poor sleep quality across age groups (Ohayon *et al*., 2017).

3.3.1.4 Wake After Sleep Onset (WASO)

WASO measures total wake time (minutes) occurring after initial sleep onset, excluding pre-sleep wakefulness. Consensus indicates that WASO ≤20 minutes signifies good sleep quality for all ages. Conversely, WASO ≥41 minutes (e.g., 41-50 min, 51-60 min, >60 min) indicates poor quality from childhood through adulthood (Ohayon *et al*., 2017).

3.3.1.5 Sleep timing and regularity

Sleep timing denotes the placement of sleep within the 24-hour cycle (e.g., bedtime, wake time, sleep midpoint), while sleep regularity refers to the daily consistency of such timings (Buysse, 2014). Both are essential dimensions of sleep health (Buysse, 2014; Chaput *et al*., 2019). Research associates later sleep timing and greater irregularity with adverse health outcomes in adults (Chaput *et al*., 2020). Emerging evidence suggests regularity may be a more reliable predictor than duration for certain health risks (Windred *et al*., 2024). Shift work or jet lag, which decouples sleep-wake patterns from endogenous circadian rhythms, was shown to disrupt energy metabolism (Czeisler, 2015), which compromises cognition, neurobehavioral performance, mood and both cardiovascular function and glucose metabolism (Sletten *et al*., 2023). While clear optimal targets remain undefined by current evidence, earlier sleep timing and greater regularity achieved through consistent bed and wake times are recommended for health benefits (Chaput *et al*., 2020).

Modern societal factors, such as environmental factors and behavioural factors, influence sleep timing via patterns of light exposure, physical activity and meal consumption (Sletten *et al*., 2023). Individual chronotype (the innate preference for morning or evening activities) (Simpkin *et al*., 2014) further shapes sleep-wake patterns, potentially affecting both sleep need and the capacity to adjust sleep times between weekdays and weekends

(Sletten *et al*., 2023). Evening chronotypes typically obtain less weekday sleep than morning types but extend sleep duration on weekends (Sletten *et al*., 2023).

3.4 THE EFFECTS OF ALCOHOL AND CAFFEINE ON SLEEP

Alcohol and sleep interaction is complex; however, alcohol misuse is bidirectionally associated with sleep disorders (He *et al*., 2019). Ebrahim et al. (2013) reviewed alcohol's dose-dependent effects on nocturnal sleep in healthy individuals. In the current study, levels of alcohol drinking are referred to as low-dose alcohol (0.15–0.49 mg/kg; 1-2 standard drinks), moderate-dose alcohol (0.5-0.74 mg/kg; 2-4 standard drinks) and high-dose alcohol (>4 standard drinks) (Ebrahim *et al*., 2013). All doses reduce sleep onset latency and WASO, consolidating early sleep. However, later sleep shows increased WASO. Heavy drinkers (≥5 drinks/day for ≥5 days/month) experience prolonged sleep onset, reduced sleep efficiency, and elevated WASO versus placebo. Declining blood alcohol levels later in sleep increase N1/N2, REM sleep, and awakenings, reducing efficiency (He *et al*., 2019).

Caffeine, which is the most widely used psychoactive drug on the planet, plays a significant role in adult sleep. To combat fatigue and enhance alertness, professionals like truck drivers, shift workers, and airline pilots rely on caffeine (Clark & Landolt, 2017). Population data indicate that 90% of adults aged 18 to 58 consume caffeine in the afternoon (12:00–18:00) and 68.5% in the evening. Caffeinated energy drinks generally contain around 300–320 mg/L of caffeine. Caffeine antagonises brain adenosine A1/A2A receptors, thereby inhibiting sleep promotion, and is metabolised in the liver by the cytochrome P450 enzyme CYP1A2 (Ursing *et al*., 2003; Clark & Landolt, 2017). Its overall effects are complex, varying according to dosage, timing of consumption, susceptibility of the individual, and habitual intake (The European Food Safety Authority, 2015).

Caffeine has been found to prolong sleep latency. This effect has been consistently observed across various studies (Drake *et al*., 2013; Clark & Landolt, 2017). It reduces total sleep time and sleep efficiency, also worsening perceived sleep quality (Drake *et al*., 2013; Clark & Landolt, 2017). Additionally, a significant observation was that individuals who self-reported poor sleep quality as per the PSQI consumed significantly more total caffeine (mean 192.1 ± 122.5 mg) compared to those reporting good sleep quality (mean 125.2 ± 62.6 mg). This difference amounted to approximately 62.2 mg, which is roughly equivalent to one cup of instant coffee.

For healthy adults in the general population, excluding pregnant women, habitual caffeine consumption of up to 400 mg daily from all dietary sources does not pose safety risks when consumed throughout the day (European Food Safety Authority, 2015). Daily caffeine intake of 400 mg amounts to drinking three to five cups of coffee per day (Wierzejska, 2024). However, 400 mg of caffeine can differ depending on the type of coffee; for example, 630 mL of Americano is approximately 2.8 servings, however, 2800 mL of coffee grounds is approximately 17.5 cups (Wierzejska, 2024). Energy drinks also typically contain varying concentrations of caffeine. Still, EFSA found that Energy drinks most often include a caffeine concentration of about 300–320 mg/L and some "energy shots" can contain 50–200 mg of caffeine per portion, which is a higher concentration than typical energy drinks (EFSA, 2015).

The adverse effects of caffeine on sleep parameters, including sleep latency, wake after sleep onset (WASO), total sleep duration, and sleep efficiency, demonstrate explicit dose dependency. Timing is essential; even taking 400 mg of caffeine a full 6 hours before bed can cut your night's sleep short by over an hour (Drake *et al*., 2013). Consequently, caffeine restriction before 17:00 is recommended, particularly given the elevated caffeine concentrations in speciality coffee beverages and energy drinks. Older adults exhibit heightened pharmacodynamic sensitivity: 200 mg evening caffeine administration disproportionately impairs their sleep latency, sleep efficiency, total sleep duration, and stage N2 sleep relative to younger cohorts.

3.5 SLEEP IN AERIAL FIREFIGHTING

There is limited research on sleep in aerial firefighting. Of the work that has been done, the Sprajcer et al. (2022) article is one of the few studies that examined sleep in aerial firefighting. This study aimed to investigate the impact of aerial firefighting work on workload, sleep, fatigue, and performance during the Australian fire season with a potential for night operations. The study collected data from nine aerial firefighting crew members over a 21-day period. Daily pilots would populate the sleep diary and duty diary, as well as provide saliva cortisol samples and actigraphy data. They also had measures related to flights. Pre-flight, they would rate their fatigue and get additional saliva samples. During flight, they would track their heart rate and heart rate variability. Post-flight, they would measure the workload using the NASA Task Load Index. Key findings from this study relevant to this study are that, on average, aerial firefighters obtained 7.4 hours of sleep per night, in line with recommendations for sufficient sleep. Participants reported an average bedtime of 22:45, a sleep onset latency of 10 minutes, and a wake time of 07:00, with a mean global Pittsburgh Sleep Quality Index (PSQI) score of 3.7 ± 1.7 points, indicating that only one subject scored above the cutoff for poor sleep quality. Despite generally sufficient sleep, there were several instances where participants remained awake for more than 16 hours after a work period. Overall, this specific study of Australian aerial firefighters found that these crews generally achieved "sufficient sleep" (>7 hours/night) as per actigraphy through proactive strategies, but it still pointed to increased post-flight fatigue and risks associated with extended wakefulness during sporadic night operations.

Expanding the scope beyond aerial firefighting, Fletcher et al. (2022) conducted a multinational study of 210 emergency aviation personnel (94% male; 14% aerial firefighters) across medical, firefighting, search/rescue, offshore transport, and air taxi operations. Their 21-day study (2014-2018, 7 countries) utilised actigraphy, sleep/duty diaries, and Psychomotor Vigilance Task assessments to analyse sleep patterns, alertness, and performance across duty/non-duty days and seasonal variations (peak vs. off-peak periods). Key findings revealed significantly reduced 24-hour sleep duration during duty days (5.9 hours) versus non-duty days (6.9 hours), with sleep quality and duration varying by operational status, location, and season. Although participants generally reported sustainable sleep quality, suggesting adequate fatigue management under current conditions, duty periods and peak seasonal demands consistently prevented achievement of the recommended 7-hour sleep minimum. Crucially, even with compensatory strategies like napping, converging factors, including chronotype-shift misalignment, extended wakefulness requirements, and seasonal workload surges, maintained significant fatigue risks. This evidence establishes that sleep sufficiency is context-dependent, requiring consideration of operational variables, seasonal rhythms, individual chronobiology, and mitigation strategy efficacy beyond mere duration metrics.

3.6 FACTORS THAT CONTRIBUTE TO FATIGUE IN AVIATION

In aviation, where precision and alertness are critical, disruptions to sleep regulation can lead to significant fatigue, impacting both performance and safety. The following section explores the factors that contribute to fatigue in aviation, such as duty length, timing of duty, workload, on-call duties and sleeping at home, with a focus on their relevance to aerial firefighting operations.

3.6.1 Length of duty

According to ICAO (2016), a duty period can be defined as the period that starts when a crew member is required by an operator to report for or commence a duty and ends when that person is free from all responsibilities. A study by Powell et al. (2007) investigates how length of duty, number of sectors, time of day, and departure airport affect fatigue levels in short-haul operations. Tentative parallels can be drawn between aerial firefighters on flying days and short-haul pilots, as both operations involve multiple takeoffs and landings during their duty period (Powell *et al*., 2007; Honn *et al.*, 2016; Fletcher *et al*., 2022). This study reported that duty length has a significant influence on pilot fatigue and identified duty length as one of the most critical factors, alongside the number of sectors flown. Furthermore, this study reported that fatigue increases linearly with the length of duty, with an average duty time of 7.2 hours.

Additionally, scientific literature strongly supports the notion that pilots should have the opportunity for 8 hours of sleep during a rest period, and any flight duty assignment must consider the likelihood of being fully rested before reporting for duty (Roach *et al*., 2012a). This can be seen in a study by Samel et al. (2004) that investigated helicopter-based emergency medical services pilots in Germany who were on a 7-day duty period, operating from sunrise to sunset. This study reported that long duty periods resulted in reduced rest periods. Helicopter pilots on 7-day duty for emergency medical services often face up to 15.5 hours of continuous duty during the summer months, operating from sunrise to sunset. This leads to rest times shorter than the standard 10 hours for single-pilot operations, frequently being only 8.5 hours per night, especially in summer (85% to 99% of the time, depending on the month). Thus, the mean sleep duration for these pilots decreased from an average of 7.8 hours (at home) to 6 hours or less during the 7-day duty period. In some cases, pilots slept less than 4 hours. This reduction is primarily due to early awakenings (around 05:45-06:00 for a 06:30 duty start), as pilots tended to maintain their habitual bedtime (around midnight), needing 2-3 hours to "unwind" from duty before sleeping.

3.6.2 Timing of duty periods

Another aspect to consider regarding duty periods is when they start and end, as this affects sleep and, by extension, contributes to fatigue (Powell *et al.*, 2007; Roach *et al.*, 2012a). Powell et al. (2007) demonstrated that duty periods with early starts are a significant contributor to fatigue among short-haul pilots in the commercial aviation industry. According to Marqueze et al. (2017), pilots who have day shifts typically start at dawn. In addition, considering commuting time (home × workplace, hotel × workplace), the duration of sleep is reduced, and one often has to wake up at a time of circadian low (around 3 a.m. or 4 a.m.).

Moreover, pilots obtained less sleep and experienced higher levels of fatigue when duty periods began earlier in the morning compared to when they began later in the morning (Powell *et al.*, 2007). In particular, at the start of duty periods that began relatively late (i.e. 09:00–10:00 h), pilots reported longer sleep of approximately 7h the night before as opposed to pilots who started at (04:00 – 05:00 h) and thus lower levels of fatigue. The wake-up time can significantly reduce the amount and quality of sleep before starting work (Powell *et al.*, 2007). In a study by Roach *et al*. (2012a), the findings of the study indicated that the earlier a pilot, or indeed any shift worker, has to start work, the less sleep he/she will obtain and the more fatigued he/she will be, and that approximately 30–

40 min of sleep is lost for every hour that duty periods are advanced before 09:00 (Roach *et al*., 2012a). McGillis et al (2017) found that early shift start times (0500–0600 hours) reduced total sleep time by 45–75 minutes compared with later shift start times. In a more recent study, Arsintescu et al. (2022) revealed that pilots experience higher fatigue and poorer performance during early morning and late-night duties compared to mid-morning shifts.

It is important to note that while early starts are a reality for scheduled aviation, the concern of early start periods is only relevant in aerial firefighting in two specific scenarios, as highlighted in the previous section's interviews. Suppose pilots are required to fly from first light to sunset to attend to a fire. The latter is that on forecasted blue days, some pilots would opt to travel home after their duty period ends, which can involve a commute of up to 300km, and then commute back early in the morning to start their duty at 10 am.

3.6.3 On-call duties

On-call work entails a scheduling arrangement where employees must remain available for unscheduled duty during emergencies or unpredictable situations (Vincent *et al*., 2018). In aviation contexts, "standby duty" specifically requires personnel to wait at designated locations, ready to commence flight operations at the operator’s discretion. This arrangement typically allows for 24/7 work coverage of demanding industries such as health care, transportation, emergency services, maintenance, and information technology (Robert *et al*., 2019). Although being on-call is not a new form of work arrangement, the impact of this working arrangement on employees in scientific literature is not as vast compared to other non-standard working time arrangements, such as overtime, night, or rotating-shift rosters (Robert *et al*., 2019).

The defining feature of on-call work that distinguishes it from irregular shifts or extended hours is its inherent unpredictability: workers cannot anticipate if they will be summoned or when they must report (Vincent et al., 2018b). Typically occurring outside standard hours (often overnight), on-call periods frequently reduce sleep duration. The uncertainty of call scheduling also induces significant stress, as workers must abruptly transition from personal to professional roles, disrupting home life (Nicol and Botterill, 2004). These challenges differ fundamentally from those of fixed or rotating schedules.

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Critically, merely being on-call, regardless of actual summons, can impair sleep. Anticipation of duty can fragment sleep continuity and reduce sleep quality (Vincent *et al*., 2018b), partly due to anxiety-induced hyperarousal (Shanahan *et al*., 2014). Field experiments confirm that on-call groups exhibit increased wakefulness after sleep onset (WASO) and diminished sleep efficiency, even without active calls, due to psychological alertness for potential missions (Wuyts *et al*., 2012; Ziebertz *et al*., 2017). This sleep disruption heightens injury risks, particularly given on-call workers' critical societal roles (Vincent *et al*., 2018b).

3.6.4 Sleeping at work while on-call

Aerial firefighters are required to live away from home for extended periods of time on remote bases during their duty period. Due to the limited literature available on the impact of this on aerial firefighters, this section will draw from other relevant industries. Numerous industries, such as mining, oil, gas, nursing, and other emergency services, require an on-site workforce where employees work and sleep at or near their workplace. Many workers who sleep in work facilities are away from home for significant periods of time. Typically, employees are provided with a specific type of sleep environment depending on the nature of their work (e.g., hotel/motel room, tent, aircraft bunk, crew rest facilities). An example of this type of work is fly-in fly-out/drive-in drive-out (FIFO/DIDO) operations, and although these industries are not directly related to aerial firefighting, some parallels can be drawn from FIFO/DIDO operations regarding extended working hours, family balance, fatigue management, and shift work (Lagdon *et al*., 2016).

Work schedules vary across industries, with employees following either even-time schedules (e.g., 14 days on, 14 days off) or asymmetrical designs (e.g., 21 days on, 7 days off) (Lagdon *et al*., 2016). These schedules can involve day shifts, night shifts, or rotations between the two. Moderate roster schedules, such as 14 days on, 7 days off, have been shown to increase employee satisfaction and reduce turnover in the mining industry. Many FIFO (fly-in, fly-out) and DIDO (drive-in, drive-out) workers face extended work hours (10–12-hour shifts) and travel in their own time, which adds to fatigue-related safety risks. Longer asymmetrical rosters, like 28 days on and 7 days off, may exacerbate fatigue and limit recovery time, affecting both workers and their families (Voysey, 2012). Research also highlights the importance of ensuring adequate family engagement time for workers in FIFO/DIDO arrangements to maintain work-life balance (Lagdon *et al*., 2016). In addition, the sleeping environment may play a role in sleep. A widely held assumption is that sleep at home is better than sleep away, particularly when away for work (Jay *et al.*, 2014). This is based on the idea that simply remaining at work to sleep, especially if workers are not physically removed from the environment, might be akin to being on-call in that there is no separation from work. Such feelings may reasonably be exacerbated for those whose ‘away’ environment is actually located in the workplace.

The sleep environment of individuals may influence sleep. While conventional belief holds that sleep at home is better than sleep away, particularly when workers remain onsite without physical separation from occupational demands, creating an "on-call" psychological state (Jay *et al*., 2014), empirical evidence reveals nuance. Paradoxically, studies of offshore oilrig workers found control-room operators slept longer and reported better sleep quality during night shifts away than at home, attributed to darker, distraction-free work-site environments (Parkes *et al*., 1994; Jay *et al*., 2014). Similarly, Bjorvatn et al. (2006) observed comparable total sleep duration at work and home for rig personnel, suggesting context-specific factors mediate outcomes.

Research across safety-critical professions, including long-haul flight crews (Holmes *et al*., 2012), marine pilots (Ferguson *et al*., 2008), and train drivers (Darwent *et al*., 2008), further challenges assumptions. These studies consistently concluded that sleep obtained during work assignments sustains operational safety, evidenced by maintained reaction times, low sleepiness scores, and acceptable fatigue metrics. Thus, rather than presupposing home-sleep superiority, evaluations should prioritise whether sleep, regardless of location, enables safe performance. Key moderating factors include break timing/duration, commute length, environmental conditions, circadian alignment, and individual demographics (Jay *et al*., 2015). Sleep adequacy should be assessed through objective performance measures and fatigue scales, not merely sleep location (Jay *et al*., 2015).

3.6.5 Workload

The profession of being a pilot requires a high level of attention to detail, mental and physical coordination and accurate decision making in preparation for, during and after each flight. These characteristics are often associated with the term 'workload' to evaluate the usability of the aircraft cockpit human-machine-environment system (Zhang *et al.*, 2015). According to the definition of fatigue relevant to this study, "workload is a mental or physical activity", and acknowledges that it is a potential cause of fatigue (ICAO, 2016). According to Hart and Staveland (1988), workload is defined as the cost incurred by an individual, given their capacities, while achieving a particular level of performance on a task with specific demands. Although numerous definitions have been offered, it is evident that there is no universal agreement between the disparate statements. The concept of mental workload has become a subject matter of increased importance in aviation research as the nature of the industry imposes ever greater cognitive demands on pilots. When flying a plane, there are four fundamental duties: aviate, navigate, communicate, and manage (Schutte, 2015; Liu *et al*., 2016). In commercial aviation, these duties are often shared between the Pilot Flying (the aircraft) and the pilot monitoring; however, in general aviation, particularly aerial firefighter pilots such as the Spotter and Bomber, these roles are often done by single-pilot operations.

Commercial aviation operations demonstrate significantly higher safety levels than single-pilot configurations, where pilot incapacitation presents catastrophic risks. Single-pilot environments also impose substantially greater cognitive workloads compared to traditional two-crew operations (Schutte, 2015). When these demands exceed human performance capacity, fatigue compromises task execution capabilities, a critical vulnerability in safety-critical roles. This risk amplification is particularly acute in aerial firefighting, where specialised tasks (e.g., precision delivery of fire suppressants) occur in degraded visual environments (e.g., smoke-obscured terrain). Simultaneously, ground personnel operate under emergency-induced stress levels far exceeding standard aviation contexts.

Additionally, aerial firefighters often have to do multiple takeoffs and landings during the fire suppression process. According to Honn et al. (2016), the workload associated with multiple take-offs and landings during multi-segment operations contributes to escalating fatigue throughout the duty day. While this was conducted in a laboratory setting and in a scheduled aviation context, it may have relevance to the AFF context, given that these pilots also perform multiple takeoffs and landings, combined with other complex tasks. This aligns with results from laboratory-based fatigue research where task load was deliberately varied (Van Dongen & Dinges, 2007; Goel *et al*., 2014). Thus, fatigue-related risks and safety impairment in aerial firefighting operations are significantly amplified by the concurrent effects of environmental hazards (extreme heat, poor visibility from smoke) and high-intensity physical/mental workloads(Sprajcer *et al*., 2022).

3.7 MANAGING FATIGUE

Fatigue is inevitable due to it being a natural state of being (Fletcher *et al*., 2015). In much of the literature, there is a consensus that fatigue has been placed in the context of impairment, and the suggestion often made is that it is a problem to be fixed (Fletcher *et al*., 2015). Historically, this approach has had limited success, largely because it addresses only one part of the problem, that is, fatigue is related to work duration (Fletcher *et al*., 2015). Furthermore, it has become more evident that accidents and injury and their severity can be increased by a fatigued pilot (Dawson *et al.,* 2021). Thus, the emergence of fatigue risk management systems and their evolution is a logical approach towards mitigating the risks associated with fatigue, as fatigue cannot be eliminated but can only be managed. Fatigue management is defined as the methods used to address the safety implications of fatigue for service providers and operational personnel (ICAO, 2016). In aviation, there are two approaches to fatigue management as seen in **Figure 10.**

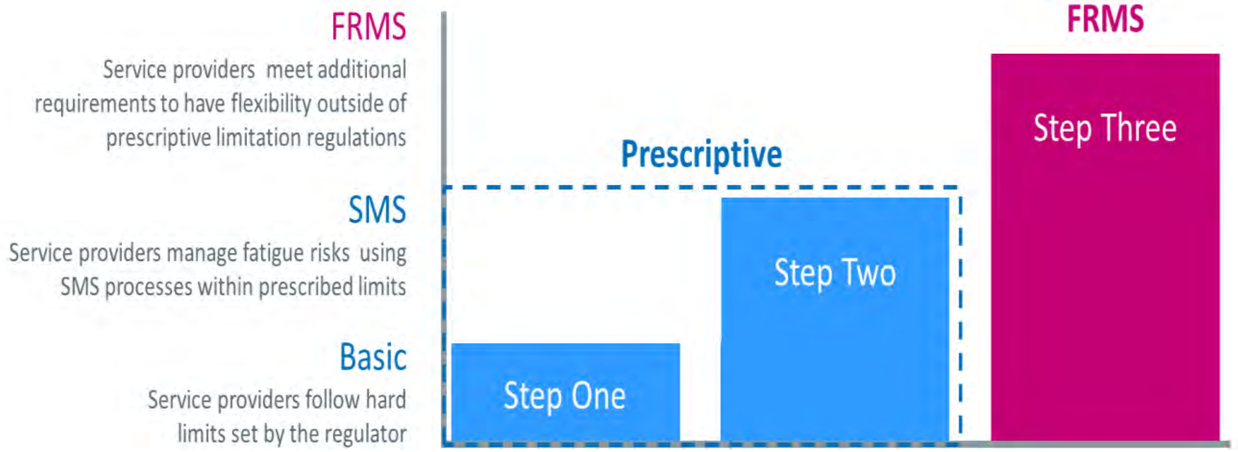

Figure 10. Two approaches to fatigue management.

3.7.1 Prescriptive approach

In aviation, the default regulatory mechanism for addressing fatigue is the prescriptive approach. The prescriptive approach requires the service provider to comply with hard duty time limits defined by the State (ICAO, 2016). These Prescriptive limitations are based on two underlying assumptions: (1) to identify maximum work periods and (2) to define the minimum non-work time periods for specific groups of aviation professionals (Honn *et al.*, 2016). These limits are usually identified over specific periods set according to a 7, 28, and 365-day period to provide crew members with an adequate opportunity to recover from fatigue and reduce the cumulative effect of fatigue that accrues over multiple duty periods (Dawson & McCulloch, 2005; Gärtner *et al.*, 2019). The core of the prescriptive approach is to ensure that crew members remain sufficiently alert in order to operate at a satisfactory level of performance and safety under all circumstances (IATA and IFALPA, 2011).

In addition to the prescriptive limits, ICAO requires the use of a safety management system (SMS) (Figure 10). Aviation organisations design SMS with the view that there will always be threats to safety: an essential component of ensuring safety is about identifying and managing threats before accidents occur (Gill *et al.,*2004). For operations that comply with the prescriptive flight and duty time limits, an operator's SMS should include fatigue as one of the hazards it manages (IATA and IFALPA, 2011). However, based on the advancements within sleep and safety science, utilising solely the prescriptive approach may not be enough to address the complexities of fatigue. This may be the case for multiple reasons.

Prescriptive limits pertain only to fatigue related to work duration. Thus, even if a roster complies with hours of work regulations, an individual may still experience fatigue (Sprajcer *et al*., 2022). As discussed in the previous section, to manage fatigue effectively in this work environment, other factors contributing to fatigue such as non-work-related time must also be accounted for since this includes but is not limited to commuting, in the calculation of rest opportunities as they cannot regulate behaviours and routines outside of work (Honn *et al*., 2016; Gardner *et al*., 2011). Prescriptive rule sets do not address the underlying biological factors, such as the relationship between circadian and homeostatic processes that drive mental fatigue, which are essential modulators of the relationship between work time arrangements and fatigue-related risk (Honn *et al*., 2016; Gardner *et al*., 2011). They are also better suited to schedule aviation environments where the demands are established and the schedule is set, thus not as appropriate for operations that are unpredictable and where the working demands are variable. To address these gaps, the aviation industry has developed FRMS. Unlike the prescriptive approach, FRMS adopts a proactive, data-driven method that integrates scientific principles and operational experience to monitor and control fatigue risk. The following section discusses FRMS, exploring how it offers a more flexible and comprehensive approach to mitigating fatigue, especially in non-standard or unpredictable aviation environments. While the prescriptive limitations are suitable for predictable aviation operations with fixed schedules, these rigid frameworks could prove inadequate for dynamic environments. In emergency services, where operational demands frequently exceed prescribed limits, such frameworks are often impractical or untenable and typically fall on resource-deprived areas (Dawson *et al*., 2021). In such cases, the operational necessities and unpredictable demands necessitate a more adaptive approach to FRMS.

3.7.2 Fatigue risk management systems

Fatigue Risk Management Systems (FRMS) represent a complementary regulatory framework that systematically addresses fatigue mitigation protocols. These evidence-based approaches are adaptable to diverse operational contexts, including night operations, on-call duties, and non-standard schedules with customizable implementation for specific industries (Honn et al., 2016)

ICAO defines a Fatigue Risk Management System (FRMS), pg. 47 as:

“A data-driven means of continuously monitoring and managing fatigue-related safety risks, based on scientific principles and knowledge as well as operational experience, which aims to ensure relevant personnel are performing at adequate levels of alertness.

3.7.2.1 Developing a conceptual framework for fatigue management

An essential aspect of FRMS is the identification of risk, rather than compliance set by prescriptive limitations. This is fundamentally different, as compliance does not automatically indicate fatigue, risk, or safety (Sprajcer *et al*., 2022). It is suggested that a SMS framework provides a sounder conceptual basis for managing fatigue-related risk. Authors such as Dawson & McCulloch (2005) suggest fatigue risk management can be represented using Reason’s (1997) hazard control framework. A fatigue-related accident or incident (FRI) is viewed as only the final point in a longer causal chain of events or ‘error trajectory’. An examination of the error trajectory associated with an FRI will indicate that there are four levels of antecedent events.

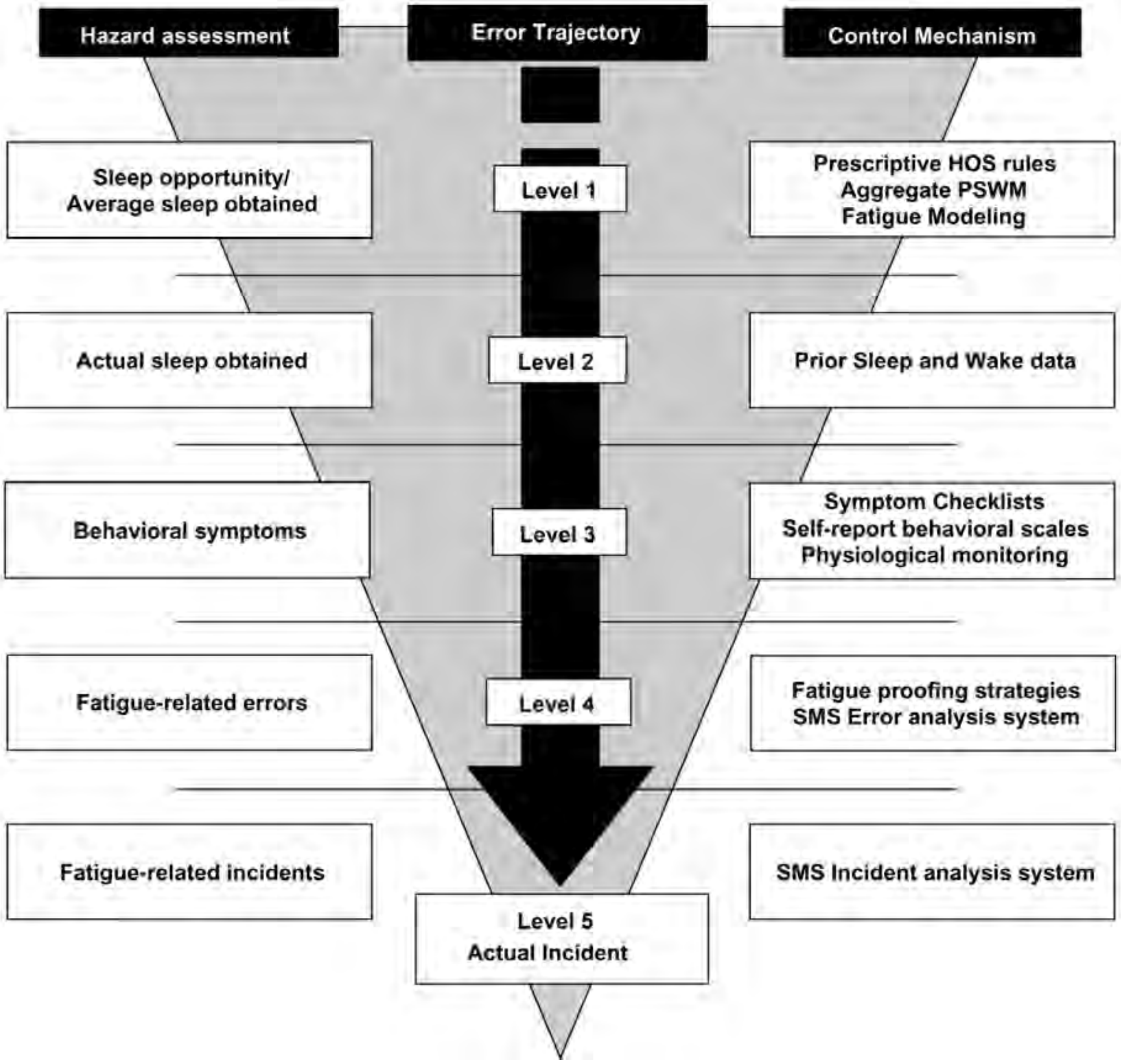

Figure 10. Fatigue-risk trajectory, displaying the multiple layers that precede a fatigue-related incident, for which there are identifiable hazards and controls (Dawson & McCulloch, 2005).

Effective Fatigue Risk Management Systems (FRMS) require managing risk at every level, encompassing hours of Service and SMS. As depicted in **Figure 10**, Fatigue-Related Incidents (FRIs) stem from fatigued individuals exhibiting fatigue-impaired behaviours, preceded by either insufficient recovery sleep or excessive wakefulness. These sleep deficits arise from either: (a) failing to sleep adequately within an available break or (b) inadequate break time for recovery sleep due to scheduling constraints

(Dawson & McCulloch, 2005). The four-stage error trajectory leading to a FRI provides multiple points for identifying potential incidents and evaluating existing control measures, as seen in **Figure 10.** It is crucial to note that near misses significantly outnumber actual incidents. Monitoring these near misses provides critical data on fatigue risks, enabling organisations to adjust processes and prevent FRIs proactively. Thus, an effective FRMS should implement control procedures at level 1 of the error trajectory to ensure that employees have enough opportunities for sleep. Additionally, it must also establish control procedures at level 2 to ensure that employees not only have the opportunity for sleep but also actually achieve adequate rest (Dawson & McCulloch, 2005). In the context of this thesis, the development of appropriate control procedures at levels 3 and below is beyond its scope. The thesis will instead focus on levels 1 and 2, which look at actual sleep obtained by pilots through measuring sleep-wake behaviour.

3.8 SLEEP MEASUREMENT METHODS

Techniques to estimate sleep are based on subjective (self-reported questionnaires) sleep measures and objective sleep (including polysomnography with EEG, electro-oculography, and actigraphy) measurements (Goker, 2018). Sleep measurement methods may influence the results and interpretation of clinical sleep studies, thus emphasising the importance of understanding how various sleep assessment methods compare to one another. In addition, factors such as cost and participant burden are often considered when deciding a method that best aligns with the interest of the study (Lehrer *et al*., 2022). The next section of the review unpacks various sleep measurement methods relevant to aviation fatigue.

3.8.1 Objective measures

3.8.1.1 Polysomnography

When it comes to measuring sleep objectively, there are multiple methods that can be used. Polysomnography is considered the “gold standard” for measuring sleep as it provides the most detailed information on sleep architecture and clinical diagnoses (Ancoli-Israel *et al*., 2003). Polysomnography can identify sleep-wake behaviour by integrating the measurement of brain activity, eye movement, muscle activity, oxygen saturation sensors and cardiac activity (Ancoli-Israel *et al.*, 2003). Jointly, these measurements provide indicators of: (1) sleep quality and the timing of sleep; (2) the quantity of pathological events indicating sleep disordered breathing patterns, oxygen saturation, eye movements and periodic limb movement disorder; and (3) the sleep architecture of an individual (Buysse *et al*.,1989). However, using polysomnography can be cumbersome, expensive, and usually, only one or two nights can be afforded. Due to the length of this study and the nature of aerial firefighters' working environments, polysomnography can be an impractical method to assess sleep.

3.8.1.2 Actigraphy

A more practical and cost-effective alternative to polysomnography is actigraphy. Actigraphy is a wristwatch-like device containing an accelerometer to detect movement. Devices are generally placed on the wrist (although they can also be placed on the ankle or trunk) to record movement (Van Someren, 2011). Actigraphy functions on the premise that lack of movement is a characteristic of sleep, and movement is a characteristic of wakefulness. This refers to the clear alternation between sleep and wakefulness, with no intermediate state, implying that sleep can be measured through wrist movement (Marino *et al.*, 2013). The Standards of Practice Committee for the American Academy of Sleep Medicine released a report with key recommendations for the use of actigraphy in research and clinical settings (Smith *et al*., 2015). According to Smith et al. (2018), actigraphy is a reliable and valid method for detecting sleep in normal, healthy adult populations. It is particularly suitable for continuous monitoring of sleep over extended periods, with a minimum recommended duration of actigraphy recording of 72 hours.

Actigraphs typically contain an analogue system to detect movements, where these movements are translated into digital counts that are frequently sampled (e.g. every 10th of a second) and averaged at a constant interval, which is referred to as an epoch (Sadeh *et al.*, 1995). Actigraphy aggregates digital movement counts within predefined temporal segments (e.g., 1-minute epochs). Accelerometer readings are sampled at high frequencies per epoch and archived for subsequent analysis (Ancoli-Israel *et al*., 2003).

Following data download, activity/inactivity patterns are quantified to infer sleep-wake states. Unlike polysomnography, actigraphy enables continuous 24/7 monitoring over extended durations (days to weeks). Its validation against polysomnography in laboratory and ecological settings supports its utility for objective, non-invasive sleep assessment (Ancoli-Israel *et al*., 2003). In the context of aviation, objective measures such as actigraphy have been employed in a wide range of studies across the aviation field, including commercial aviation (Rosekind et al., 2006; Kandera *et al.,* 2019).

In addition, objective sleep measures such as actigraphy are often accompanied by subjective measures, namely sleep diaries in aviation (Petrilli *et al.,*2006). These pairings can be seen in the Sprajcer et al. (2022) that looks at sleep in aerial firefighting, as well as the Fletcher et al (2022) study, which examines sleep, work, alertness, mental performance, firefighting, and other mission-critical contexts.

3.8.2 Self-report measures

3.8.2.1 Sleep diaries

While subjective measures carry inherent bias risks, their integration with objective data yields more robust analyses than purely objective datasets can provide (Seitz, 2014). The sleep diary is the gold standard for subjective ratings (Carney *et al.*, 2012), and enables the collection of large amounts of data at low cost and provides information on an individual's perceptions regarding their sleep (Signal *et al*., 2005). Universally, there are but a few diaries that are recognised, namely, Morin Sleep Diary (Sloan *et al*.,1993); Karolinska Sleep Diary (Akerstedt *et al*.,1994); Pittsburgh Sleep Diary (Monk *et al*., 2002) and Consensus Sleep Diary (Carney *et al*.,2012). The content of these diaries is based on the objective of the research, with differences in the number of questions asked, the definition of common sleep parameters, the time of day the respondents should complete the diary, and whether the diaries should elicit quantitative or qualitative responses (Carney *et al*., 2012).

3.8.2.2 The Pittsburgh Sleep Quality Index

The Pittsburgh Sleep Quality Index (PSQI) is a retrospective self-report instrument designed to evaluate sleep quality and disturbances over one month. Developed to deliver reliable, standardised measurement of sleep patterns, its primary objectives include distinguishing individuals with healthy versus impaired sleep, providing clinicians and researchers with an interpretable global metric, and identifying common sleep disruptions affecting restorative quality (Buysse *et al*., 1989, p. 194). This 19-item questionnaire assesses seven core dimensions: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep-promoting medications, and daytime functional impairments. Responses are anchored to the respondent's typical experience during the preceding month, with dimensional scores aggregated into a composite global index (Grandner *et al*., 2006). Though valuable for detecting chronic problematic sleep patterns retrospectively, the PSQI serves as a discriminative screening tool rather than a definitive diagnostic instrument for specific sleep disorders. Within aviation research contexts, it has been validated for measuring sleep quality across diverse pilot populations, including collegiate aviation trainees (Mendonca *et al*., 2023) and commercial airline pilots (Kandera *et al*., 2006; Zhen *et al*., 2023).

3.9 METHOD

3.9.1 Phase 2

The second phase aimed to assess the effects of the current work scheduling on the sleep-wake behaviour of pilots involved in aerial firefighting during one full duty period.

3.9.1.1 Study design

Phase 2 adopted an observational study design for an extended period of time that focused on characterising the effects of the current duty arrangements (under the FRMS) on the sleep-wake behaviour of pilots involved in aerial firefighting during one full duty period. At the time of data collection, one duty arrangement was eight weeks in length and included six weeks on duty at a base or on home reserve and two weeks off duty at home. This study focused on the six-week on-duty period as well as two two-week rest periods. As seen in **Figure 14,** prospective and retrospective sleep measures were used to measure the effects of the current duty arrangements. Prospective measures included Actigraphy and the Core Consensus Sleep Diary. Retrospective measures employed the Pittsburgh Sleep Quality Index.

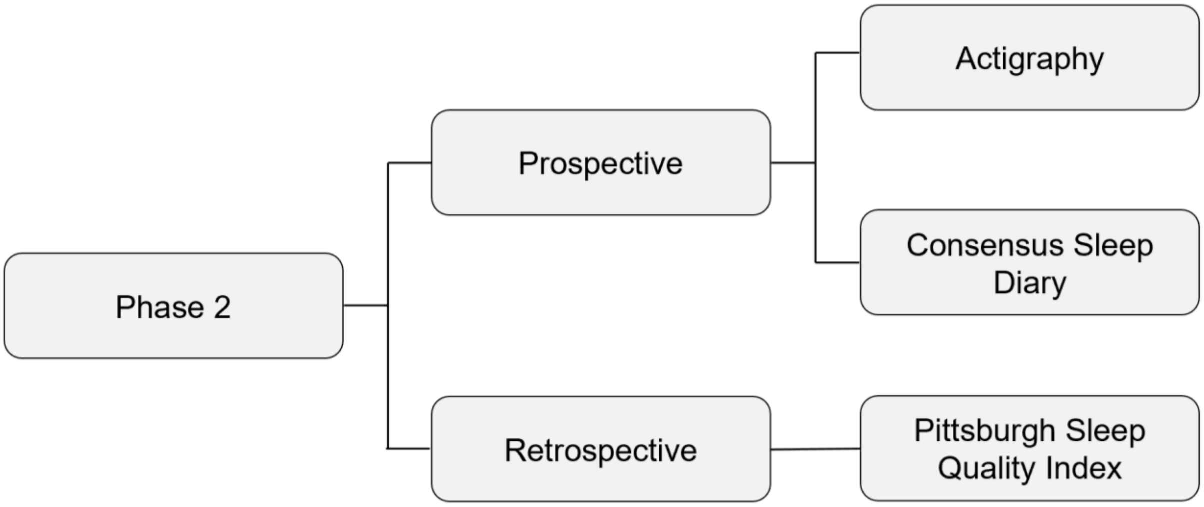

Figure 14. Schematic diagram of the methodology of phase two.

3.9.1.2 Study setting and duration of data collection

As mentioned earlier, the company in question has multiple bases around the country; however, for this study, the participants were stationed across five bases, namely, Nelspruit, Ermelo, Vryheid, Wartburg and Stutterheim, as seen in the map in **Figure 15**. Data collection occurred at the respective participants' bases for a six-week duration. Participants whose duty period started at the same time were grouped together. As seen in **Figure 15,** participants are stationed along the east side of South Africa during the winter months.

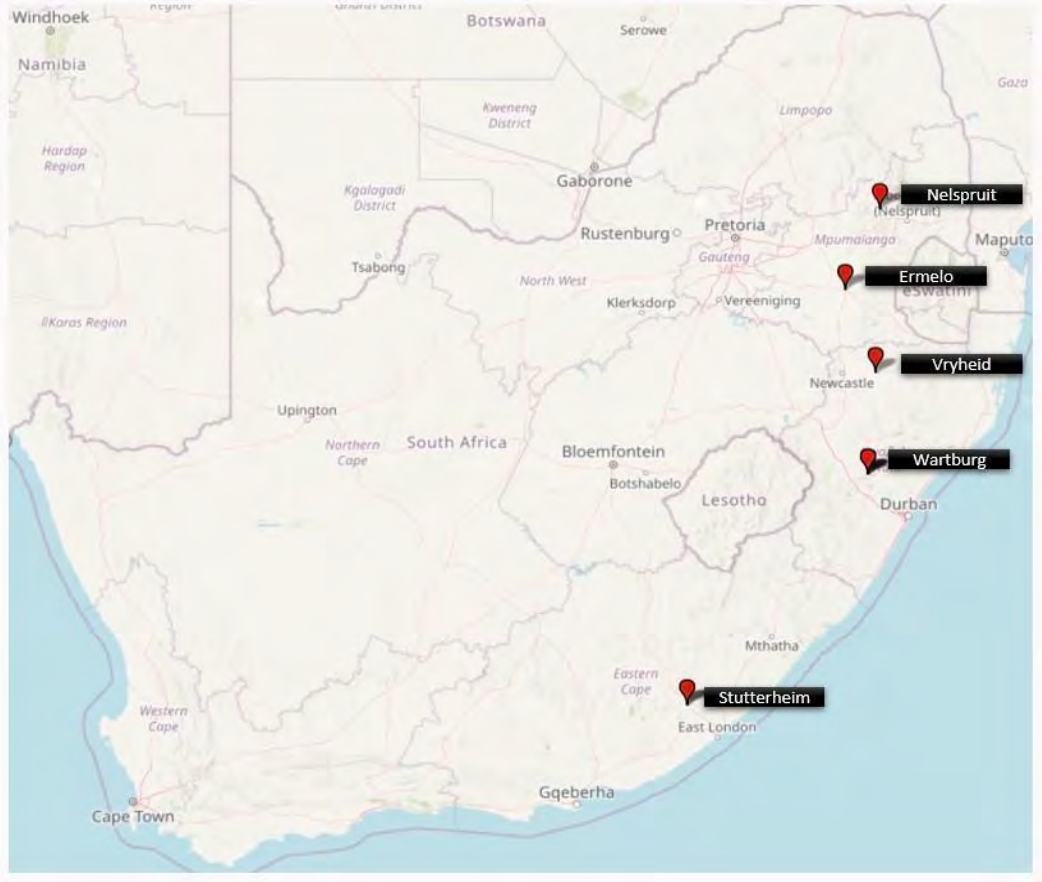

Figure 15. A map of where participants were stationed during data collection (Google Maps, 2022).

3.9.1.3 Measures

3.9.1.3.1 Sleep tracking using Actigraphy

The second phase of this study included six weeks of Actigraphy recording using the ActTrust Wrist Actimeter (Condor Instruments, 2013). The device measures activity, wrist temperature and light exposure and can be worn on one of the limbs, in this case, the wrist, and it is used to assess sleep parameters for up to 3 months (using a 60s epoch). These ActTrust watches were set to use the Condor Instruments algorithm to do a complete sleep analysis. When using the device, there were various aspects that needed to be set up before giving it to the participant. The time zone was set to South African Standard Time, which is Greenwich Mean Time (GMT +2). On the Actiwatch, the activity-sampling mode was configured at PIM/TAT/ZCM (Proportional Integral Mode/Time Above

Threshold/Zero Crossing Mode). To calculate the start time light/dark phase, the longitude and latitude were set to the coordinates of the respective bases. The main sleep period was set to be recorded during nighttime with a minimum sleep period of 30 minutes and only one main sleep period as per standard settings (Condor Instruments, 2023. Sleep start and sleep end thresholds were 10 minutes of immobility. The actiwatch is considered to provide valid and accurate estimates of sleep patterns in normal, healthy adults (Sadeh *et al,* 2011; Stone & Ancoli-Israel, 2011). Further, the reliability of the Actigraphy is found to increase with extended study length (> 5 d; Sadeh *et al,* 2011). The devices recorded averages of the following sleep parameters: bedtime (BT), wake time (WT), time in bed (TIB), total sleep duration (hours), sleep onset latency (minutes), percentage of sleep efficiency, wake after sleep onset (minutes) and number of awakenings.

3.9.1.3.2 Consensus Sleep Diary

The Consensus Sleep Diary (Carney *et al*.,2012) is offered in two formats: a core version with nine questions about nighttime sleep, and an expanded version with 20 questions that also address daytime sleep factors. Both versions include general and specific instructions for each question. Responses are provided in various formats, such as free-text (e.g., bedtime, use of sleep aids), yes/no, number of occurrences (e.g., awakenings), and subjective ratings on a Likert scale (e.g., sleep quality). Additionally, there’s a section for personal comments (e.g., noting if you're unwell). Participants were asked to complete their sleep diary daily after each sleep period for the duration of the 6-week data collection period. These questions allowed for the calculation of the following quantitative variables related to sleep: Total time in bed (TIB), sleep onset latency (SOL), number of awakenings (NWAK), wake after sleep onset (WASO), total sleep time (TST) and sleep efficiency (SE) (i.e., TST divided by TIB ×100). Participants also rated the “Quality” (QUAL) of their sleep on a 5-point Likert-type scale (1 = poor to 5 = very good). Lastly, participants had the opportunity to provide additional information that may be relevant to their sleep in a free-response comment box. For this study, the Core Consensus Sleep Diary (Carney et al.,2012) was chosen due to its high construct validity and the ability of the Actigraphy to provide the same output sleep values so that the two can be compared.

3.9.1.3.3 Pittsburgh Sleep Quality Index

The Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989) was administered once, at the end of the 6-week period, as a retrospective questionnaire to assess subjective sleep quality. The PSQI is a self-administered questionnaire that assesses sleep quality and disturbances over the past month. The PSQI consists of 19 self-rated questions, divided into seven components: subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbances, use of sleep medication and daytime dysfunction. The PSQI includes items that produce a global score and seven component scores, some of which overlap with sleep diary-generated parameters: QUAL, SOL, TST, and SE. Scores, each with a scale of 0–3; higher scores indicate poorer sleep outcomes. Component scores were then totalled for a global PSQI score ranging from 0 to 21, with higher scores indicating worse overall sleep quality. Most studies have consistently stated that a total PSQI score of ≤ 5 suggests good sleep quality, whereas a total PSQI score of > 5 suggests poor sleep quality.

3.9.1.4 Participant recruitment and characteristics

For phase 2, the research team presented to the company in question's weekly Zoom meeting to discuss the intended methods for data collection to promote buy-in and to dispel any concerns participants had regarding their privacy. For this phase inclusion criteria were that participants must fly as a spotter pilot, bomber pilot, or helicopter pilot for the aerial firefighting company in question. In phase two, the sample size was limited to the number of Actigraphy devices available in the Human Kinetics and Ergonomics Department, and currently, there are only fourteen devices. In terms of the completion of the Pittsburgh Sleep Quality Index, all crew members who finished their duty cycle after the six-week period were invited to complete this survey.

3.9.1.5 Ethics and Recruitment

The Ethics Committee granted provisional acceptance with pending Gatekeeper permission (ref: 2021-4924-6000) (Appendix A). Once ethics was approved, the gatekeeper's permission was obtained by the company in question (Appendix B), followed by the signing of a non-disclosure agreement by the research team. Then a letter of participation was sent out to participants explaining what would be expected of them if they decided to participate. It was made clear to participants that their participation in the study was completely voluntary and that they could choose to withdraw from the study at any point should they wish to do so. In this study, participants' rights to privacy and anonymity were preserved.

3.9.1.6 Procedure

The research team visited the main base situated in the Mpumalanga provincewhere most pilots were based. If they were not based there, the devices were sent via courier or distributed by the Chief of Operations. Upon arrival, the researchers and participants were introduced to one another, and the researchers were taken on a tour of the facilities to become familiar with the working environment before the interview. Participants were requested to wear the Act Trust watch for the duration of their duty period and were advised to remove it only when washing. Participants were asked to press the event button when attempting to sleep and at the point of final awakening. This was to be used to define the Actigraphy bed and wake times. After the presentation on Actigraphy, each participant was added to a WhatsApp group and received a link to the Google Form version of the Core Consensus Sleep Diary daily. They were instructed to fill them in upon waking and just before bed. Following the six weeks, a link to the Google Forms version of the Pittsburgh Sleep Quality Index was sent via the WhatsApp group to each participant. Participants were then shown how to complete the questionnaire and were requested to do so. After six weeks, the data on the ActTrust watch was loaded onto the PI's laptop, and the devices were wiped clean, fully charged, and given to the next group. This was done over time with multiple crews who are on different duty cycles, as explained in **Figure 16**. However, for this particular research paper, only one cycle of data was used. Participants were handed a watch and then shown how to use the Act Trust watches.

3.9.1.7 Data Reduction and Statistical Analysis

Data from the ActTrust was extracted with the ActDock accessory and analysed using the ActStudio software version 1.0.9 (Condor Instruments, 2023). After extraction, if there were any inconsistencies with the data collected, the software allowed for the data to be treated. Participants were instructed to press an event marker when getting into bed at night and on waking up in the morning. In the case that participants forgot to press the events button indicating that they were going to bed or waking up, a manual scoring protocol approach was used. The manual scoring process involves human visual inspection and adherence to a decision tree that provides a structured approach for determining these intervals, especially in ambiguous cases (Chow *et al*., 2016). This protocol defines bedtime and rise time by systematically considering three types of information: activity level, light level, and the event marker. The manual protocol prioritises a significant drop in activity level; when activity levels fall, it more reliably signals that someone is going to bed. If the event marker was not pressed, but there is a significant drop in activity accompanied by a drop in light level to zero, the epoch following this drop in activity will be considered the start of the rest interval. When ambient light and event markers differ by more than 10 minutes, bedtime is determined using both indicators (Chow *et al*., 2016). For wake time, the manual protocol would identify the wake time using the increase in activity level, the presence of a solid wake (red) bar on the actogram, and an increase in light level (above 1.0 µW/cm2) (Chow *et al*., 2016).

In addition to this, sleep diary data were scored and manually added by the researcher to formulate a complete report. Sleep scoring was plotted for each participant. The Actigraphy data was exported to Microsoft Excel. The Google Forms with the sleep diary and PSQI information were exported into Excel as well. Data was converted from time into decimals in the Excel file. Any answers in words were converted to numbers using a pre-determined code. Regarding the PSQI, it was calculated using the guide in Excel. Based on the Actigraphy and sleep diary data, weekly analyses of sleep performance were calculated for variables such as bedtime, wake time, total sleep time, sleep latency, sleep efficiency, nocturnal awakenings, and wake after sleep onset (WASO). After the data reduction process, information was then uploaded onto Microsoft Excel, along with data obtained from the Core Consensus sleep diary and the Pittsburgh sleep quality index. Descriptive statistics were then calculated, such as the means, standard deviations. Thereafter, data were uploaded onto Statistica (Statistica, Statsoft, Inc.). This data set was then evaluated for normality using the Shapiro-Wilk test for normality. This study employed descriptive analysis to characterise the sleep-wake behaviour of aerial firefighters, an understudied population. As the level of participant compliance varied, resulting in differing numbers of days, inferential comparisons were challenging; hence, descriptive statistics were deemed the most appropriate method. Data are reported as mean ± standard deviation (SD) unless otherwise stated.

3.9.1.8 Overview of the data collection period for each participant

As seen in **Table 3**, the actigraphy data had recorded twelve participants' data for over 44 days of data collection, and the sleep diary data had recorded fourteen participants' data for a combined total of 374 days. For actigraphy and the sleep diary, the participants' compliance varied significantly; however, due to device failures, only a total of twelve participants collected Actigraphy data. In total, 292 days of actigraphy data were collected for all participants, with some participants consistently recording data for the entire data collection period of 44 days and others not recording data at all, as seen during off-duty days. As seen with the sleep diary, some participants consistently recorded data for the duration of 45 days, and others recorded as little as eight days. In this study, an analysis was done on flying days vs non-flying days and working days and non-working days. Working days are defined as days during which pilots were on-call, regardless of whether flight operations were conducted; this category includes both flying and non-flying days. Specifically, a flying day is a type of working day characterised by the operational cycle of starting and shutting down an aircraft, which encompasses active firefighting missions and training. Conversely, a non-flying day is a working day where no flight operations are conducted. In contrast, off-duty days refer to periods when pilots are not required to be on-call or present at the base, constituting a complete release from professional duties.

For participant one, the data collected for non-flying days was not included due to the participant not having any flying days during the data collection period.

Table 3. Summary of the number of days participants collected for actigraphy and sleep diary data during their testing period.

Participants	**P1**	**P2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Total days for all participants**
Actigraphy overall days	-	40	24	18	25	44	-	34	18	8	30	5	14	32	292
Sleep diary overall days	33	42	27	22	39	45	19	35	44	8	34	5	22	32	407
Actigraphy working days	-	40	24	18	12	31	-	27	18	8	30	-	14	21	243
Sleep diary working days	32	37	27	21	26	32	16	27	18	8	34	5	22	24	329
Actigraphy off duty days	-	0	0	0	13	13	-	7	0	0	0	0	0	9	42
Sleep diary off duty days	1	5	0	1	13	13	3	8	2	0	0	0	0	8	54
Actigraphy flying days	-	8	5	6	2	4	-	5	0	2	5	3	2	4	46
Sleep diary flying days	-	9	5	6	2	3	3	6	8	2	1	3	3	5	56
Actigraphy non-flying days	-	32	19	12	23	41	-	28	18	6	25	2	12	28	246
Sleep diary non-flying days	-	33	22	16	42	42	16	29	36	6	33	2	19	26	322

3.10 RESULTS

Fourteen male aerial firefighters participated in this study. Data collection spanned 41 days, but the compliance between participants varied. As seen in **Table 3**, the mean age of all participants was 45.8±9.3 years. Out of the fourteen participants, six (42.86%) pilots disclosed their years of experience. They had a mean of 16.8± 5.8 years of experience in aviation while reporting having worked in the current company for 7.68 (±5.8 years). The sample included a diverse range of roles: 50% (n = 7) were Spotter pilots, 28.57% (n = 4) were Bomber/802 pilots, and 21.43% (n = 3) were Helicopter pilots.

Table 3. Summary of descriptive statistics detailing sociodemographic information of aerial firefighting pilots using mean (*M*) and standard deviation (±*SD*) where appropriate.

	N (%)	**M ± SD**
Age		45.8 ± 9.3
Years of experience	6 (42.86)	16.8 ± 5.8
Number of years working for the company	6 (42.86)	7.6 ± 5.1
Pilot type		
Spotter	7 (50)	
Bomber/802	4 (28.57)	
Helicopter "Huey"	**4** (21.43)	

3.10.1 Summative overview of sleep-wake behaviour

This section will present the summative overview of actigraphy and a select part of the sleep diary data showing pilots' objective and subjective sleep parameters for the full data collection period. Actigraphy metrics include bedtime, get up time, time in bed, total sleep time, onset latency, sleep efficiency, wake after sleep onset (WASO) and number of awakenings (#Awak). The sleep diary data reflect self-reported sleep quality, perceptions of restedness, waking up earlier than planned, and how much earlier.

The data in **Table 4** represents a combined summative overview of actigraphy and sleep diary data showing sleep parameters of all pilots for the full data collection period.

Table 4. A combined summative overview of actigraphy and sleep diary data shows the sleep parameters of pilots for the full data collection period. Data presented as means (M) ± standard deviations (SD) or percentages (N%).

	Actigraphy (M ± SD)	**Sleep Diary (M ± SD or N%)**
Bedtime (h:m)	22:16 ± 00:56	
Get up time (h:m)	06:34 ± 00:48	
Time in Bed (h:m)	08:18 ± 00:36	
Total Sleep Time (h:m)	07:14 ± 00:37	
Onset Latency (min)	4.89 ± 3.19	
Sleep Efficiency (%)	87.11 ± 4.30	
WASO (min)	53.02 ± 19.73	
#Awak. (No.)	13.27 ± 8.34	
Sleep Quality		3.80 ± 0.58
Perceptions of rest		3.79 ± 0.62
Wake up earlier than planned		17%
How much earlier (min)		14.44 29.44

On average pilots' sleep timing was at the appropriate sleep time with bedtime at 22:16 (± 00:56) and get up time at 06:34 (± 00:48). Additionally, they achieved a total sleep time of 7:14 minutes. On average, participants fell asleep quickly (4.89 ± 3.19); however, some variation in onset latency was observed. Sleep efficiency was relatively high (87%), indicating that participants slept most of their time in bed. The participants experienced an average of 53 minutes of wakefulness after falling asleep, with high variance between participants. Additionally, on average, participants experienced 13.27 (8.34) awakenings during the night, with some participants waking up more frequently than others. In **Table 4, (N%)** represents the average frequency of pilots who selected yes (17%) to waking up earlier than expected. Sleep quality (3.80 ± 0.58) and perceptions of rest (3.79 ± 0.62) were generally rated positively, with their ratings being above average, indicating participants felt their sleep quality was good and that their degree of restedness was good.

3.10.2 Summative overview of alcohol and caffeine consumption

The data seen in **Table 5** represents a summative overview of alcohol and caffeine consumption over the full data collection period. The data reflect the responses of 13 participants who indicated consuming alcohol and caffeine. During the 331-day data collection period, pilots reported consuming caffeine and alcohol on 20% of monitored days.

Table 5. Descriptive statistics of alcohol and caffeine consumption and pilots' use of these substances are presented using means (M), standard deviations (±SD), and Ranges.

	Caffeine	**Alcohol**
Daily Average (M ± SD)	2.74 ± 1.59	1.90 ± 1.00
Range (#)	0 - 7	0 - 5
Time of Last Serving (hh:mm)	17:50 ± 02:58	19:44 ± 01:10
Time Range (hh:mm)	08:48 - 19:57	18:00 - 22:00

According to **Table 5**, pilots had an average caffeine intake of 2.74 (±1.59) servings per day. Their consumption ranged from 0 to 7 servings, indicating significant variability. Typically, the last caffeine intake occurred around 17:50 (±02:58. This suggests that most pilots consume caffeine in the late afternoon. The consumption time for alcohol is predominantly consumed in the evening, later than caffeine, with an average time of last serving at 19:44 (±01:10).

3.10.3 Sleep Regularity

To evaluate sleep regularity among participants, the intraindividual variability of four key sleep parameters, namely bedtime, wake-up time, time in bed, and total sleep time, was assessed using standard deviation (SD) for each participant. For each participant, the SD was calculated using actigraphy data. This approach is consistent with established methodologies in sleep research, wherein variability in sleep patterns is quantitatively assessed through the standard deviation of repeated measures over time. The resulting SD values, originally expressed in hours, were converted to minutes by multiplying each value by 60. This conversion facilitated clearer interpretation and enabled direct comparison across participants. To enable categorical analysis of sleep regularity, the converted SD values were classified into four predefined groups: ≤60 minutes (more regular), 61–90 minutes, 91–120 minutes, and >120 minutes (less regular). These thresholds were selected to reflect differing levels of regularity.

As seen in **Table 6**, bedtimes (75%), wake times (83%), and total sleep time (75%) were the most regular across participants, with the majority of participants maintaining a regular schedule within a 60-minute window during the data collection period.

Table 6. Sleep regularity of participants according to actigraphy.

	<= 60 min	**61-90 min**	**91-120 min**	**>120 min**
Bedtime	75%(n=9)	25%(n=3)	0%(n=0)	0%(n=0)
Get up time	83% (n=10)	8%(n=1)	8%(n=1)	0%(n=0)
Time in bed (h)	67% (n=8)	17%(n=2)	8%(n=1)	8%(n=1)
Total Sleep Time (*h*)	75%(n=9)	0%(n=0)	25%(n=3)	0%(n=0)

However, time in bed and total sleep time exhibited greater variability: 18% of pilots deviated by more than 90 minutes in time spent in bed (8% in 91–120 minutes, 8% in

>120 minutes), while 25% experienced total sleep time fluctuations exceeding 90 minutes (all in the 91–120-minute range).

3.10.4 Sleep-wake behaviour: Working and off-duty periods

This section provides a summative overview of pilots' sleep-wake behaviour during working days and off-duty periods, integrating objective actigraphy data and subjective sleep diary metrics collected throughout the study.

As shown in **Table 7**, data for actigraphy were recorded by only five participants during both work and off-duty periods. Consequently, the analysis focused solely on these five individuals who agreed to have their sleep tracked during both periods. For the sleep diary, we reviewed data from nine participants, as some participants kept their sleep diary during the rest days but did not wear watches. This resulted in 257 days of data for working days and only 54 days for off-duty periods.

Participants, on average, went to bed later (17 minutes later) and woke up later (10 minutes later) during the off period compared to working days. During the off-duty periods, participants experienced shorter sleep onset (4.78 ± 3.79), higher and more consistent sleep efficiency (85.58 ± 1.73), and better sleep continuity with lower wakefulness after sleep onset (56.67 ± 19.42). However, participants had more awakenings during off-duty. On average, pilots rated their sleep quality as "fair" during working days and reported feeling "somewhat rested." A similar pattern was observed on off-duty days, with pilots rating their sleep quality as "fair" and feeling "somewhat rested." In addition, pilots reported that they felt like they woke up much earlier on working days (44.21 ± 29.20) than on off days (17.23 ± 8.45).

Table 7. A combined summative overview of actigraphy and sleep diary data of working days and off periods of pilots for the full data collection period. Data presented as means (M) ± standard deviations (SD) or percentages (N%). TD = Total days measured.

	Actigraphy Working Days (M ± SD)	**Actigraphy Off period (M ± SD)**	**Sleep Diary Working Days (M ± SD or N%)**	**Sleep Diary Off period (M ± SD or N%)**
	(n = 5, TD = 101)	**(n = 5, TD = 33)**	**(n = 9, TD = 257)**	**(n = 9, TD = 54)**
Bedtime (h:m)	22:19 ± 1:04	22:36 ± 0:59		
Get up time (h:m)	7:00 ± 0:49	7:10 ± 0:32		
Time in Bed (h:min)	8:42 ± 0:27	8:34 ± 0:37		
Total Sleep Time (h)	7:42 ± 0:58	7:19 ± 0:26		
Onset Latency (min)	6.06 ± 4.46	4.78 ± 3.79		
Sleep Efficiency (%)	83.14 ± 9.01	85.58 ± 1.73		
WASO (min)	71.50 ± 37.91	56.67 ± 19.42		
#Awak. (No.)	12.46 ± 4.13	16.32 ± 6.29		
Sleep Quality			3.85 ± 0.45	3.66 ± 0.47
Perceptions of rested			3.79 ± 0.5	3.79 ± 0.41
Wake up earlier than planned			20%	10%
How much earlier (min)			44.21 ± 29.20	17.23 ± 8.45

As shown in **Table 8**, on working days, caffeine consumption (3.05 ± 1.35) and alcohol consumption (1.67 ± 0.75) were higher per day, with a greater difference seen in caffeine.

On off days, caffeine consumption (1.46 ± 0.7) dropped, and alcohol consumption (1 ± 0.45) remains moderate but later in the evening (20:28 ± 00:08).

Table 8. Descriptive statistics of alcohol and caffeine consumption on working days and off days of pilots as per the sleep diary using means (M), standard deviations (±SD) and Range.

	Caffeine (Working Days)	**Caffeine (Off Days)**	**Alcohol (Working Days)**	**Alcohol (Off Days)**
Daily Average (M ± SD)	3.05 ± 1.35	1.46 ± 0.70	1.67 ± 0.75	1.00 ± 0.45
Range (#)	0 - 7	0 - 4	0 - 5	0 - 5
Time of Last Serving (hh:mm)	17:13 ± 03:07	17:44 ± 01:38	19:53 ± 01:15	20:28 ± 00:08
Time Range (hh:mm)	10:00 - 20:38	15:24 - 19:00	18:30 - 21:45	18:00 - 22:00

3.10.5 Sleep-wake behaviour: Flying days and non-flying period

This section will review the summative overview of actigraphy and sleep diary data of flying days and non-flying days, synthesising pilots' objective and subjective sleep parameters for the full data collection period.

As shown in **Table 9,** 223 days of data were collected for non-flying days and 44 days for flying days from the 10 participants who wore devices during both periods. Total sleep time (TST) was longer on flying days (7:10 ± 1:13) than on non-flying days (7:03 ± 0:56). There was a higher sleep onset latency on flying days (8.76 ± 12.59) vs non-flying days (5.75 ± 4.34). Wake after sleep onset showed little difference between flying days and non-flying days (56.23 ± 28.78 vs. 57.78 ± 20.67). Overall sleep efficiency stabilised (~85.6%), but there was more variability in sleep efficiency on flying days. There were fewer awakenings on flying days, with an average of 8.62 compared to 10.26 on non-flying days.

Table 9. A combined summative overview of actigraphy and sleep diary data of flying days and non-flying periods. Data presented as means (M) ± standard deviations (SD) or percentages (N%).

	Actigraphy Flying Days (M ± SD)	**Actigraphy Non-flying Days (M ± SD)**	**Sleep Diary Flying Days (M ± SD or N%)**	**Sleep Diary Non-Flying Days (M ± SD or N%)**
	(n = 10, TD = 44)	**(n= 10, TD = 223)**	**(n = 13, TD = 56)**	**(n = 13, TD = 323)**
Bedtime (h:m)	22:11 ± 1:15	22:20 ± 0:58		
Get up time (h:m)	6:23 ± 0:53	6:33 ± 0:49		
Time in Bed (h:min)	8:07 ± 0:37	8:13 ± 0:37		
Total Sleep Time (h)	7:10 ± 1:13	7:03 ± 0:56		
Onset Latency (min)	8.76 ± 12.59	5.75 ± 4.34		
Sleep Efficiency (%)	85.66 ± 11.19	85.56 ± 5.36		
WASO (min)	56.23 ± 28.78	57.78 ± 20.67		
#Awak. (No.)	8.62 ± 2.07	10.26 ± 2.07		
Sleep Quality			4.04 ± 0.47	3.84 ± 0.50
Perceptions of rested			4.01 ± 0.36	3.83 ± 0.54
Wake up earlier than planned			13%	13%
How much earlier (min)			32.02 ± 19.22	37.81 ± 21.75

As detailed in **Table 9**, data were collected from 13 participants over 56 flying days and 323 non-flying days. On average, pilots rated their sleep quality as 4.04 (±0.47) on flying days, which can be considered "good," and 3.34 (±0.50) on non-flying days, indicating "fair" quality. As shown in **Table 10**, caffeine consumption is consistent across both flying (2.21±0.9) and non-flying days (2.27±1.29). However, alcohol consumption was slightly higher on non-flying days (1.97 ± 0.9), with a later time mean consumption range of 19:30. On non-flying days, the range of units consumed of both alcohol (0 – 5) and caffeine (0 – 8) is greater compared to flying days.

Table 10. Descriptive statistics of alcohol and caffeine consumption on flying days and non-flying days of pilots as per the sleep diary using means (M), standard deviations (±SD) and Range.

	Caffeine (Flying Days)	**Caffeine (Non-flying Days)**	**Alcohol (flying Days)**	**Alcohol (Non-flying Days)**
Daily Average (M ± SD)	2.21 ± 0.90	2.27 ± 1.29	1.22 ± 0.16	1.97 ± 0.90
Range (#)	0 - 5	0 - 8	0 - 3	0 - 5
Time of Last Serving (hh:mm)	14:01 ± 02:31	16:58 ± 02:37	19:16 ± 00:28	19:48 ± 00:43
Time Range (hh:mm)	11:00 – 18:20	12:58 – 19:45	18:38 – 20:04	18:00 – 21:00

3.10.6 Changes in pilots' sleep over four weeks

As seen in **Table 11**, changes in actigraphy-measured sleep parameters such as sleep timing, continuity, and efficiency are illustrated over four weeks. This data is that of 12 participants, with a total of 243 days of actigraphy data collected over four weeks. As summarised in Table 11, bedtime showed minor fluctuations, peaking latest in Week 2 (22:28 ± 1:18) before shifting slightly earlier in subsequent weeks. Similarly, get-up times varied marginally, with the earliest mean in Week 2 (6:29 ± 1:17) and the latest in Week 4 (6:52 ± 1.63), reflecting moderate week-to-week shifts despite high individual variability. Time in bed followed a similar trend, decreasing to its lowest duration in Week 2 (8:01 ± 1:26) before rising in Weeks 3 (8:24 ± 0:47) and 4 (8:40 ± 1:37), while Week 1 recorded intermediate values (08:19 ± 1:14). Total sleep time mirrored this pattern, dipping in Week 2 (6:56 ± 1:38), peaking in Week 3 (07:26 ± 0:50), and declining slightly in Week 4 (07:16 ± 1:23), though large standard deviations underscored substantial individual differences.

	Week 1	Week 2	Week 3	Week 4
Bedtime (h:mm)	22:16 ± 1:17	22:28 ± 1:18	22:14 ± 1:16	22:13 ± 1:32
Get Up Time (h:mm)	06:33 ± 1:04	06:29 ± 1:17	06:38 ± 1:17	06:52 ± 1:38
Time in Bed (h:mm)	08:19 ± 1:14	08:01 ± 1:26	08:24 ± 0:47	08:40 ± 1:37
Total Sleep Time (h:mm)	07:13 ± 1:06	06:56 ± 1:21	07:26 ± 0:50	07:16 ± 1:23
Onset Latency (min)	7.72 ± 16.34	4.07 ± 8.23	1.58 ± 3.69	8.70 ± 28.18
Sleep Efficiency (%)	87.10 ± 6.45	85.81 ± 10.00	88.28 ± 6.01	83.31 ± 9.46
WASO (min)	54.48 ± 31.83	55.53 ± 39.31	51.20 ± 29.58	53.83 ± 27.20
#Awak. (No.)	11.40 ± 5.77	10.32 ± 5.42	10.45 ± 5.10	11.88 ± 5.33

Sleep onset latency displayed fluctuations, dropping from Week 1 (7.72 ± 16.34) to Week 3 (1.58 ± 3.69) before increasing in Week 4 (8.70 ± 28.18), with Week 2 intermediate (4.07 ± 8.23). Sleep efficiency peaked in Week 3 (88.28 ± 6.01) and declined to its lowest in Week 4 (83.31 ± 9.46), while Weeks 1 and 2 showed moderate values (87.10% ± 6.45 and 85.81 ± 10.00, respectively). Wake after sleep onset (WASO) remained stable across weeks (51.20 ± 29.58 to 55.53 ± 39.31), though there was high individual variability. Similarly, awakenings remained stable across the four weeks.

3.10.7 Self-reported sleep-wake behaviour and quality: PSQI

3.10.7.1 Sleep behaviours and characteristics of aerial firefighter pilots

As shown in **Table 12**, the mean bedtime was (21:29 ± 01:00). The mean time it took to fall asleep was 8 min and 34 sec (+6 min 22 sec). Mean wake time was 06:20 (±1 h 30 min). On average, pilots reported sleeping for 7 h 33 min (± 6 min). The average reported time in bed was 8 h 35 min (±1 h 30 min).

Table 12. Descriptive statistics of sleep characteristics of pilots using means (M) and standard deviations (±*SD*). The number of total responses is represented as *N* with the percentage (%) provided.

Variable	**N (%)**	**M ± SD**
Estimated bedtime (hh: mm)		21:29 ± 01:00
Time taken to fall asleep (min.sec)		8:34 ± 6:22
Wake time (hh: mm)		06:20 ± 01:30
Estimated sleep duration (h. min)		7.33 ± 0.6
Time in bed (h.min)		8.35 ± 1.3
Subjective sleep quality		
Very good	2 (18.18)	
Fairly good	9 (81,82)	
Fairly bad	-	
Very bad	-	
Sleep efficiency (%)	11(89,35%)	

In terms of subjective sleep quality of the prior month, 18.18% of pilots rated their sleep as very good, and 81.82% rated their sleep as fairly good, with none reporting any bad sleep. In **Table 12**, 63.64% of pilots reported no difficulty falling asleep within 30 minutes, while 36.36% experienced it less than once a week. All pilots woke up during the night, with 45.45% waking three or more times weekly. Some pilots (45.45%) also reported getting up to use the bathroom three or more times a week, while 36.36% did so less than once a week. Nearly half (45.45%) did not snore or cough loudly, but 18.18% reported doing so three or more times weekly. Some pilots (81.82%) did not feel too hot, and

63.64% did not feel too cold during the prior month. Additionally, 63.64% of pilots did not experience bad dreams, and 90.9% reported no pain disrupting their sleep.

Table 12. Frequencies of different sleep disturbances and restlessness experienced by pilots over the prior month. *N* of total responses is provided if less than the total *N* of respondents (i.e., *N* = 4).

Frequency n (%)	**Not during the past month**	**Less than once a week**	**Once or twice a week**	**Three or more times a week**
Cannot get to sleep within 30 minutes	7 (63.64)	4 (36.36)	-	-
Wake up in the middle of the night or early in the morning.	-	2 (18.18)	4 (36.36)	5 (45.45)
Must get up to use the bathroom	1 (9.09)	4 (36.36)	1 (9.09)	5 (45.45)
Cannot breathe comfortably	10 (90.9)	1 (9.09)	-	-
Cough or snore loudly	5 (45.45)	3 (27.27)	1 (9.09)	2 (18.18)
Feel too cold	7 (63.64)	4 (36.36)	-	-
Feel too hot	9 (81.82)	1 (9.09)	1 (9.09)	-
Have bad dreams	7 (63.64)	2 (18.18)	2 (18.18)	-
Have pain	10 (90.9)	1 (9.09)	-	-
Other reasons, N = 6	1 (9.09)	2 (18.18)	5 (45.45)	3 (27.27)

3.10.7.2 Experiences and frequencies of sleep disturbances and restlessness of the prior month

Regarding **Table 13**, only 36.36% (n=4) of respondents had a bed partner/roommate they shared a bed with and less than once a week and once or twice a week received 25% (n=1) respectively for loud snoring and 50% for three or more times a week. 75% (n=3) of pilots reported not experiencing breathing problems while asleep in the past, followed by 25% (n=1) once or twice a month. Half (n=2) of respondents experienced leg twitching/jerking while asleep, and the other half (n=2) less than once a week.

Table 13. Frequencies of different sleep disturbances and restlessness experienced by pilots with a bed partner over the prior month.

Frequency n (%)	**Not during the past month**	**Less than once a week**	**Once or twice a week**	**Three or more times a week**
Presence of bed partner n=4 (36.36)				
Loud snoring	-	1 (25)	1 (25)	2 (50)
Long pause between breaths while asleep	3 (75)	-	1 (25)	-
Legs twitching/jerking while you sleep	2 (50)	2 (50)	-	-
Episodes of disorientation/ confusion during sleep	4 (100)	-	-	-
Other reasons	3 (75)	-	1 (25)	-

All (n=4) participants reported not having episodes of disorientation/confusion during sleep for other reasons in the past month.

As seen in **Table 14**, none of the respondents used medication as they all (100%) reported not during the past month. Additionally, 90.9% (n=10) of the respondents have not had trouble staying awake while engaging in activities. Regarding *how much of a problem it has been to keep enthusiasm to get things,* 63.64% (n=7) of respondents claimed it is not a problem at all, followed by 36.67% (n=4) reporting only a very slight problem.

Table 14. Medication intake and daytime dysfunction experienced by pilots over the prior month.

Frequency n (%)	**Not during the past month**	**Less than once a week**	**Once or twice a week**	**Three or more times a week**
Use of sleep medication				
How often was medication (prescribed or 'over the counter')	11 (100)			
Daytime dysfunction				
How often have you had trouble staying awake while driving, eating meals, or engaging in social activity?	10 (90.90)	1 (9.90)		
	No problem at all	**Only a very slight problem**	**Somewhat of a problem**	**A very big problem**
How much of a problem has it been to keep enthusiasm to get things done	7 (63.64)	4 (36.67)		

3.10.7.3 Sleep Quality of the Aerial Firefighter Pilot's Sample

3.10.7.3.1 PSQI Component score

As seen in **Figure 16**, sleep disturbance (1.45) and sleep latency (1.08) are the highest-scoring domains, indicating that pilots experienced fragmented sleep and took longer to fall asleep. In addition, their assessment of sleep quality (0.82) scored relatively high, suggesting their sleep was 'fair'.

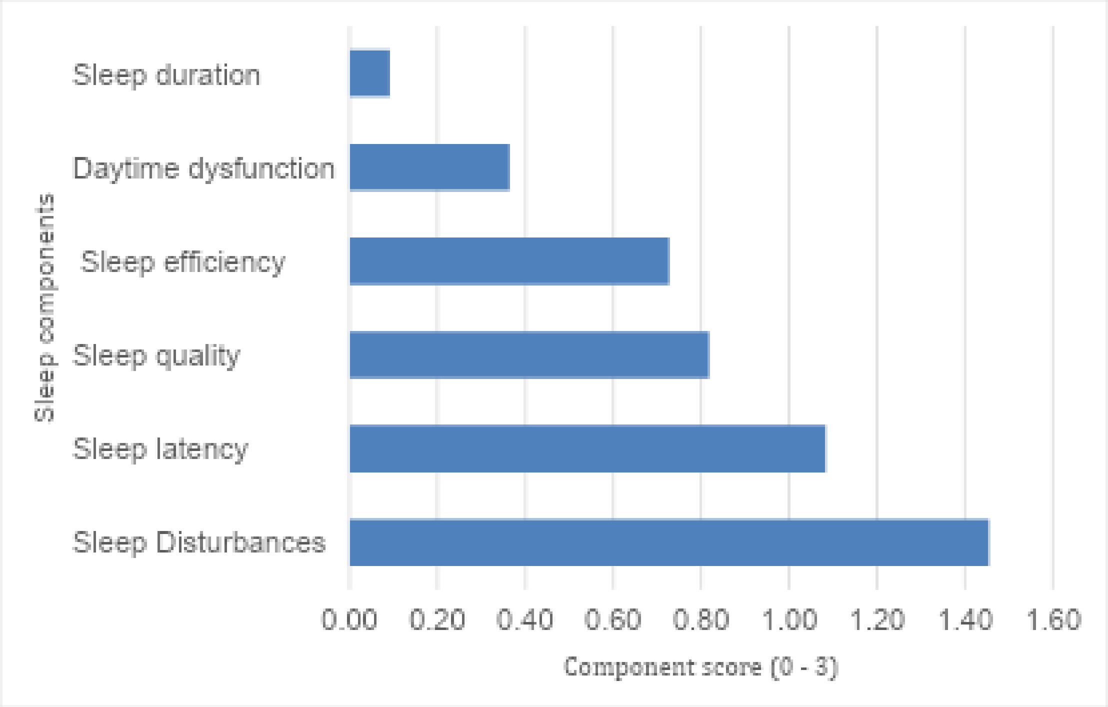

Figure 16. Component scores of pilots ranged from 0 – 3 (component scores exclude sleep medication).

3.10.6.3.2 Proportion of good and poor sleepers among pilots

Table 20. Pittsburgh Sleep Quality Index global score mean (M) and standard deviation (±SD).

Sleep quality	**N (%)**	**M ± SD**
Global PSQI score	11 (78,57)	4 ± 2.05

Regarding **Table 20**, the global PSQI was computed from 11 full responses, with a mean of 4 ± 2.05. The majority (73%, n = 8) of the sample was categorised as good sleepers, on average, and only 27% (n = 3) of the sample was classified as poor sleepers due to their scores being five or more (≥5).

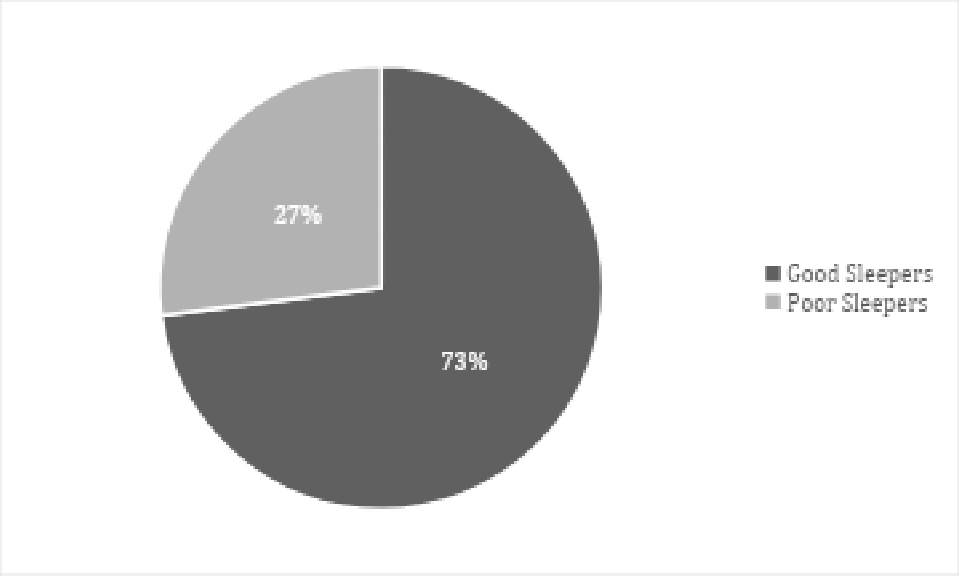

Figure 17. Percentage (%) of good and poor sleepers among the sample (N = 11) of pilots. Obtaining global scores of five or more (≥5) classifies participants as poor sleepers and indicates the clinical cut-off point for potential sleep disorders.

CHAPTER IV

4 DISCUSSION

4.1 SUMMARY OF FINDINGS

4.1.1 Phase 1

To the authors' knowledge, this study is one of the few to characterise the working system of aerial firefighters, with a focus on identifying the demands associated with aerial firefighting and potential fatigue risks, specifically related to extended periods of duty and their impacts on sleep. This study found that aerial firefighting is a highly specialised, high-stakes field requiring pilots to operate in unpredictable circumstances and possess a deep understanding of environmental factors, fire behaviour, and potential operational hazards. Each role, whether Spotter, Bomber, or Huey pilot, requires a distinct skill set to navigate hazards, coordinate efforts, perform precise firefighting operations, and adapt to changing demands, highlighting task variability and unpredictability as a key finding.

Another key finding of this study is that the standby duty periods of aerial firefighters have intensified over the years. In 1981, the first spotter and bomber pilot in South Africa was stationed in KwaZulu-Natal for a three-month standby period, seven days a week. This has evolved substantially since then through the introduction of formalised fire associations, operational expansion to cater to government tender requirements, and increasing availability to meet the needs of clients. This ultimately led to the implementation of a six-week duty cycle followed by two weeks off, all year round.

Furthermore, this study found that aerial firefighting pilots are potentially exposed to fatigue in different ways. Due to pilots being on call for up to six weeks and ready to fly for low-probability events, they can experience monotony and boredom while on duty. Pilots may spend time away from the airbase when the Fire Danger Index (FDI) rating is low. However, when FDI ratings are high, pilots are expected to be on standby with no guarantee of an active fire and the need to fly, resulting in crew spending duty hours waiting for something to happen. Conversely, in the case of a disaster fire such as the

Table Mountain Fire in Cape Town (as highlighted by the Person responsible for flight operations), pilots are required to work consecutive flying duty periods. These duty lengths span multiple days from sunrise until sunset, resulting in a high workload, extended workdays and stress for pilots.

4.1.2 Phase 2

The second objective of this study was to examine pilots' sleep-wake behaviour and assess the impact of extended duty periods on sleep as part of the FRMS that the partnering company had in place. Phase 2 employed an observational study to characterise the effects of the current duty arrangements on the sleep-wake behaviour of pilots during six weeks of duty at a base or on home reserve and two weeks off duty at home. Actigraphy, Consensus sleep diary and the Pittsburgh Sleep Quality Index were used to measure sleep. For actigraphy and the sleep diary, the participants' compliance varied significantly. Due to device failures, only a total of twelve participants collected Actigraphy data, and fourteen participants collected data for the sleep diary. In this study, an analysis was conducted comparing flying days and non-flying days, as well as working days and non-working days. For participant one, the data collected on non-flying days was excluded because the participant had no flying days during the data collection period.

This study found that pilots generally achieved adequate sleep duration (>7 hours per night) on average, as recommended by current guidelines (Chaput *et al*., 2018), with regular sleep patterns. Furthermore, findings of this study show that pilots had regular sleep timing, with 75% of pilots maintaining day-to-day bedtime regularity (<60 minutes of variation), and 83% of pilots had <60 minutes of daily variation in their wake time. Additionally, these findings suggest that throughout the four- to six-week work periods, the pilots settle into some form of routine and the majority of the pilots exhibit good sleep habits. However, a notable finding was the elevated wake-after-sleep onset (WASO) in some pilots, as indicated by pilot reports of sleep disturbances when reviewing their sleep diary data. One pilot in particular highlighted that caring for his baby was a cause of his sleep disturbances. Additionally, this study found that self-reported sleep quality was high, as reflected in the sleep diaries and Pittsburgh Sleep Quality Index (PSQI) scores, with the majority of pilots indicating good sleep quality. While in general, this sample of pilots demonstrated relatively consistent and adequate amounts of sleep, these findings highlight the importance of managing sleep on a case-by-case basis and understanding the factors that may influence sleep and fatigue risk in specific pilots. The following sections will unpack the demands of aerial firefighting and the sleep characteristics of the general sample.

4.2 DEMANDS OF AERIAL FIRE FIGHTING

The profession of being a pilot requires a high level of attention to detail, mental and physical coordination and accurate decision-making in preparation for, during and after each flight. This research identifies aerial firefighting as a highly specialised, high-risk domain where pilots must navigate unpredictable conditions and master environmental/operational hazards. Distinct skill sets are required per role to mitigate dangers, coordinate teams, and execute precision operations, underscoring task variability as a central insight. The spotter plays a central command-and-control role in aerial operations, overseeing the allocation and deployment of resources, managing logistical support, and maintaining situational awareness to facilitate safe and effective fire suppression. This includes monitoring weather conditions, coordinating with ground crews, and tracking the movements of other aircraft. The bomber focuses on delivering large quantities of water or retardant during the critical initial attack phase. Flying at low altitudes through hazardous terrain, bomber pilots face substantial risks from obstacles and depend heavily on the spotter for navigation in these challenging conditions.

Additionally, the roles of the spotter and bomber are done by single-pilot operations. Single operations, such as aerial firefighting, are deemed less safe compared to commercial operations, as they far exceed the safety levels seen in single-piloted operations (Schutte, 2015). This is because the individual pilot on board may suffer incapacitation, potentially resulting in fatal accidents (Schutte, 2015). Compared to conventional two-pilot operations, individual pilots are exposed to a high workload, which poses greater cognitive demands. These demands, should they exceed the pilot’s cognitive capacity, can result in fatigue, which will ultimately adversely affect the pilot’s ability to accomplish the task at hand, which in this case is aerial firefighting (Schutte, 2015). The Huey helicopter is pivotal for trooping and mopping-up tasks. Trooping involves transporting firefighters to the fire site, while mopping up requires the use of a Bambi Bucket to help extinguish remaining flames and prevent reignition. The Huey operation is unique due to the pilot having flying crewmen fly with them on board, as well as having to fly with an external load. Although there is additional support for the Huey pilot, flying with the Bambi bucket may result in demands that are often greater within suboptimal environmental conditions (e.g., smoke and debris).

In South Africa, aerial firefighting was introduced as a tool to counter the surge in wildfires in the KwaZulu-Natal province and later in Mpumalanga. This consisted of pilots working seven days a week from first light to last light for three months out of the year. In 1986, the fire danger index was introduced, allowing for more flexibility regarding proximity to work. In 1986, the Forest Fire Association was founded in Mpumalanga, introducing a fire danger index that resulted in an expansion to 5 months, while retaining the 7 days from first light to last light. By 2003, the company in question was awarded the first tender, resulting in resources being deployed in the Western Cape for five months. The standby period was adjusted to five months in winter and five months in summer, with five weeks on duty followed by one week off duty. This also includes two months of leave, including blue days off. After a few seasons, a teething process was required to find a working system that worked for both parties. Ultimately, this resulted in five weeks of duty and one week off duty. Following this change, the SACAA conducted a system phase inspection, which ultimately led to the rejection of the system due to its unilateral introduction**.** The company in question proposed a new working system that eventually failed due to a single complaint, according to the Former Chair of the Board (2021). This has led to a second attempt at implementing a trial, which now includes a data-driven approach consisting of five weeks on duty followed by one week off, and six weeks on duty followed by two weeks off, which is the current working arrangement for pilots. During their six-week duty, pilots are required to systematically report their sleep patterns and perceived alertness as part of standard operational procedures.

Additionally, aerial firefighters are often on-call and work away from home for extended periods, without active fire deployment, as well as lifestyle factors such as social engagements and commuting. As noted by the Former Chair of the Board (2021), during forecasted blue days, some pilots elect to travel home at the end of their duty to spend time with family. This may involve commutes up to 300km each way. Return early the following morning to commence duty by 10:00 am. This is synonymous with some FIFO/DIDO workers who travel to/from sites in their own time, which poses additional safety hazards concerning fatigue management (Langdon *et al.,*2016). On the one hand, disaster fires such as the Table Mountain Fire in Cape Town required pilots to work consecutive flying duty periods, duty lengths that start at sunrise until sunset, spanning over multiple days, resulting in a high workload for pilots. However, most days, they face minimal fatigue risks, as they do not fly if there are no fires and they do not operate at night, as regulations prohibit nighttime flying. Their typical duty hours, generally from 10 a.m. to 4 p.m., depending on the season, should, in principle, allow sufficient recovery time between shifts and align with natural sleep patterns. The current work-to-rest ratio, six weeks on duty followed by two weeks off duty, suggests an evolving duty system that reflects the management of pilot fatigue by reducing pilots' commute to work while maintaining operational readiness to respond to emergencies by being close to their designated area. To understand the effects of the six weeks on duty and two weeks off duty on pilots, the effects on their sleep-wake behaviour must be considered.

4.3 SLEEP CHARACTERISTICS OF THE GENERAL SAMPLE

This study collected objective and self-reported data on the sleep-wake behaviour of aerial firefighters. Data collection spanned 41 days, but the compliance between participants varied; this included 292 days of actigraphy data for 12 participants and 407 days of sleep diary data for 14 participants. On average, participants generally obtained the minimal recommended sleep duration of 07:14 (± 37 minutes) throughout the data collection period, in line with current recommendations that adults between 18 and 64 years of age should sleep between 7 - 9 hours (Hirshkowitz *et al*.,2015). This finding is consistent with a study on sleep in Australian aerial firefighting crews, which also reported an average of 7.4 hours of sleep per night (Sprajcer *et al*., 2022). Additionally, these findings align with Powell et al. (2007) suggestion if start of duty periods that began relatively late (i.e. 09:00–10:00 h), which in this case, pilots report for duty at 10:00, pilots reported longer sleep of approximately 7h the night before as opposed to pilots who start at (04:00 – 05:00 h). This suggests that their allocated rest period allows for sleep to align with their circadian and homeostatic processes, as well as the environmental cues.

Furthermore, Sprajcer et al. (2022) study reported an average bedtime of 22:45, a sleep and a wake time of 07:00. The findings of this study show that bed time was earlier, 22:16 (± 56 minutes), and wake time 06:34 (± 48 minutes), was earlier than that of the Sprajcer et al. (2022) study. When reviewing the regularity of sleep timing, this study found that for bedtimes, 75% of pilots maintained day-to-day bedtime regularity (<60 minutes of variation), while 25% showed slightly higher variability (61–90 minutes). Wake times were even more consistent: 83% of pilots had <60 minutes of daily variation, with only 16% exceeding this threshold. This regularity in bed and wake times suggests that pilots are able to develop a routine during their extended duty periods, particularly given that most of them were operating at remote bases and away from home. Additionally, these findings suggest that the majority of the pilots exhibit good sleep habits, as they align with the study by Chaput et al. (2022), which reports that earlier sleep timing and regularity, along with consistent bedtimes and wake-up times, are recommended to promote health benefits.

While adequate sleep duration and timing are crucial, the quality of sleep also plays a significant role in determining good sleep health (Ohayon et al., 2017). Sleep quality can be viewed from both subjective and objective perspectives. According to subjective assessments of sleep by pilots in the Consensus Sleep Diary data indicated that sleep quality (3.80 ± 0.58) and perceptions of rest (3.79 ± 0.62) were generally rated positively, with ratings above average, suggesting that pilots felt satisfied with their usual sleep pattern. Additionally, findings from the PSQI reported that the global PSQI scores were computed for 11 participants, yielding a mean score of 4 ± 2.05. Eight pilots were classified as good sleepers, while three pilots fell into the poor sleeper's category due to scores of five or higher (≥5). Conversely, Sprajcer *et al* (2022) pilots reported a mean global PSQI score of 3.7 ± 1.7 points, indicating that only one subject scored above the cutoff for poor sleep.

Among the components of the PSQI, sleep disturbances emerged as the most significant concern, with an average score of 1.45 (±0.68). This was followed by sleep latency, which had a mean score of 1.08 (±1.19), indicating some difficulty in falling and maintaining sleep for specific participants. Sleep diary data further supported these findings. Nine participants reported waking up in the middle of the night or during the early morning hours. Specifically, 5 participants experienced these three or more times a week, while 4 participants encountered it once or twice weekly. One of the participants attributed caring for young children to be a potential contributor to disrupted sleep. Another factor to consider is the environments of the remote location, excessive winds or extreme heat and cold. Participants were away from home for extended periods during the COVID-19 pandemic, which has been known to be a stressful time for separated families. Travel was also limited during this period, meaning that the flexibility of being able to commute home on blue days was restricted. Furthermore, five participants also reported needing to use the bathroom three or more times a week.

These subjective reports of fragmented sleep align with objective actigraphy data revealing longer wake-after-sleep-onset (WASO) durations. A high average WASO of 53.02 ± 19.73 minutes was observed, exceeding the ≥41-minute threshold for poor sleep quality (Ohayon et al., 2017). There could be several reasons for this observation: the high WASO could be attributed to their consumption of caffeine and alcohol. When pilots did report on this data, they on average consumed 2.74 (±1.59) servings of caffeine daily with an average serving time of 17:50 (± 02:58). Although the exact caffeine consumption in mg was not recorded, studies show that recommended caffeine doses, taken even 6 hours before habitual bedtime, can significantly disrupt sleep. In this study, caffeine is consumed on average 50 minutes later than the recommended limit of 17:00 (Drake *et al.*, 2013). Moreover, a study by Clark and Landolt (2017) found that increasing doses of caffeine generally lead to a longer WASO. Another factor to highlight is that the participants in this study are older (45.8 ± 9.3), and older adults may be more sensitive to caffeine compared to younger adults. When observing pilots' alcohol consumption, this study found that on average, pilots consumed 1.90 (± 1.00) servings of alcohol daily. According to Ebrahim et al. (2013), pilots would be consuming a low dose of alcohol based on their average serving; however, even a low dose of alcohol has been shown to increase WASO in the second half of sleep.

This study found that participants had approximately 13.27 (± 8.34) awakenings on average. This is considerably higher than Ohayon et al. (2017) suggest that four or more awakenings per night, which was associated with poor quality of sleep quality. Although pilots' self-rate their sleep as "fair," indicating some adaptation to disruptions, extended WASO, and multiple awakenings imply that even seemingly adequate sleep duration may not fully mitigate fatigue of at-risk pilots in high-stress roles. In combination, data from the Pittsburgh Sleep Quality Index (PSQI) and actigraphy underscore the importance of pairing subjective reports with objective data for a complete picture of sleep. Pilots had well-perceived sleep satisfaction and compromised physiological sleep continuity. This could be attributed to adaptation to fragmented sleep and potentially normalising interruptions, lowering their subjective impact on pilots.

4.4 COMPARING SLEEP ON WORKING DAYS VS NON-WORKING DAYS

This study focuses solely on the five individuals who agreed to have their sleep tracked with actigraphy during both periods. On average, participants generally obtained 7:42 (± 0:58) hours of sleep on working days and 7:19 (± 0:26) hours of sleep on non-duty days. These differences are notably better when compared to the Fletcher et al. (2022) study, where pilots experienced challenges in obtaining 7 hours of sleep irrespective of whether it was work or rest days. Their sleep time was significantly shorter on duty days (average 5.9 hours) compared to non-duty days (average 6.9 hours), even with compensatory behaviours like napping or sleep banking. In this study, pilots did not report any napping; this could be due to pilots feeling like they had had enough sleep during their sleep period, limiting the need for compensatory behaviours.

Sleep Efficiency on working days (83.14 ± 9.01) is marginally lower than that of off-duty days (85.58 ± 1.73). The sleep efficiency on working days did not meet the recommended percentage suggested by Ohayon et al. (2017), which states that for all age groups, a sleep efficiency of 85% or more is considered a good indicator of sleep quality. However, the rating does not fall below 74% Ohayon et al. (2017) consider to be poor sleep quality. Additionally, these findings are similar to that of Flaa et al.(2020) study, where working days in summer (85.4%) and in winter (84.4%) were lower than those of non-duty days a week before duty (summer: 87.4%; winter: 86.6%) and a week after duty (summer: 86.2%; winter: 85.5%). Although the difference in sleep efficiency is marginal, the lower sleep efficiency on working days could be attributed to the anticipation of a fire the following day, which increases wakefulness and reduces sleep efficiency.

This study reported that WASO overall exceeded the ≥41-minute threshold for poor sleep quality with working days (71.50 ± 37.91) being higher than that of off-duty days (56.67 ± 19.42) (Ohayon *et al*., 2017). However, participants had more awakenings during off-duty periods (16.32 ± 6.29) compared to working days (12.46 ± 4.13), implying that pilots were awake for longer during their awakenings on working days. Furthermore, the increased WASO aligns with the Flaa et al.(2020) study, which found that actigraphy exceeded the ≥41-minute threshold for a higher (longer) wake after sleep onset during the workweek compared to both off-duty weeks in both seasons.

On working days, pilots consumed more caffeine (3.05 ± 1.35 servings per day) compared to off days (1.46 ± 0.7 servings per day). On working days, they consumed caffeine earlier and for an extended period (10:00 - 20:38) compared to off-duty periods where consumption was mainly in the late afternoon and early evening (15:24 - 19:00). This higher intake likely serves to maintain alertness during demanding shifts or as a means to keep themselves occupied during a quiet period as caffeine promotes wakefulness by antagonising adenosine A1 and A2A receptors in the brain (Clark & Landolt, 2017).

The decrease in sleep efficiency and increased wake after sleep onset (WASO) observed in pilots sleeping on base during workdays may stem from psychological factors inherent to being on call. Results from an on-call experimen-tal field study have indicated that wake after sleep onset increases and sleep efficiency decreases in on-call groups, even when calls did not occur, probably because of the mere anticipation of a mission (Wuyts et al., 2012). This may also explain why some participants wake up earlier on working days (20%) compared to non-working days (10%), with an average time of 44.21 minutes (± 29.20). Interestingly, on working days, pilots experienced fewer awakenings throughout the night, despite poorer sleep continuity. This may be attributed to the effects of a preceding high workload during the day, which may have contributed to increased physical and mental activity, as well as overall tiredness and fatigue (Chui et al., 2018; Sprajcer et al., 2022). Pilots reported their sleep quality as "fair" on both working and non-working days, and a perception of feeling "somewhat rested" across both schedules, suggesting a moderate level of restfulness that may meet operational demands but could benefit from enhancements.

4.5 COMPARING SLEEP ON FLYING VS NON-FLYING DAYS

To the author's knowledge, limited studies are comparing flying days vs non-flying days in aerial firefighting and fields related to fixed-wing and helicopter pilots. This study found that the Total sleep time (TST) was marginally higher on flying days (7:10 ± 1:13) compared to non-flying days (7:03 ± 0:56). The present study found that on both flying and non-flying days, pilot sleep duration aligns with the sleep recommendation of 7-9 hours (Hirshkowitz et al., 2015).

On flying days, pilots rated their sleep quality as "good," while on non-flying days, this dropped to "fair" (4.04 ± 0.47 vs 3.84 ± 0.50). These findings align with shifts in sleep timing on flying days, when pilots went to bed and woke earlier, while on non-flying days, they tended to go to sleep and wake later. The perceived good sleep quality on flying days may be attributed to the excitement pilots feel about flying. As one pilot stated, "*You get so addicted to it (the adrenaline); when that siren goes off, you’re like a bulldog—you just want to go!*" This sense of satisfaction in being able to fly may be linked to their perception of improved sleep quality.

Sleep showed similar sleep efficiency, with shorter sleep onset latency, reduced WASO duration, and fewer awakenings on flying days compared to non-flying days. This could be attributed to the fact that on flying days, task demands are often greater (e.g., delivery of fire retardant, multiple take-offs and landings) within suboptimal environmental conditions (e.g., smoke, widow makers), resulting in pilots being physically and mentally tired, potentially enhancing restfulness. However, WASO and the number of awakenings were still higher than the recommended threshold for both flying days and non-flying days. These results suggest that flying days promote a more structured and efficient sleep routine. In contrast, non-flying days are more variable, with lower sleep efficiency and rest perceptions.

4.6 LIMITATIONS OF STUDY

This study employed a unique two-phase methodological approach, combining initial qualitative findings from semi-structured interviews (Phase one, n = 4) with objective sleep-wake data collection (Phase two, n = 14). A limitation of this study is that the semi-structured interviews (Phase one, n = 4) only made up a small sample size. Furthermore, this study had a small sample of 14 male aerial firefighters, which restricts the generalizability of findings.

Technical issues during data collection resulted in one participant's actigraphy data not being recorded. Additionally, inconsistent actigraphy compliance varied, particularly during off-duty days, which limited the comparability of sleep-wake behaviours between duty periods. Additionally, the limited number of flights taken during the data collection period may make our comparison of flying days versus non-flying days preliminary. It may change as more data is collected on flying days. Thus, due to the small sample size and varied compliance, inferential statistical analyses were limited.

Moreover, this study only examined sleep patterns during winter in the northern part of the country. As noted by Chief Pilot (2021) in Phase One, duty periods may vary seasonally due to daylight availability in specific regions. Typically, the duty period is from 10 am until 4 pm or from first light to last light in the event of continuous emergency fire; however, in the Western Cape, summer daylight extends significantly later, requiring pilots to remain on duty for up to 10 hours. These seasonal adjustments, coupled with airbase-specific operational flexibility, could influence sleep-wake patterns in ways not captured here. Furthermore, this study found that pilots can experience monotony and boredom while on duty; however, the current study did not look at alertness or performance on duty and on flying days. However, despite their preliminary nature, the findings of the present study can help inform our understanding of the challenges faced by South African aerial firefighting.

4.7 RECOMMENDATIONS

4.7.1 Recommendations to the company

The company in question should educate pilots on the importance of good sleep health and highlight the relationships between caffeine and alcohol and how they affect sleep. Given the elevated wake after sleep onset (WASO) and sleep disturbances experienced by some participants during working days, the company in question may benefit from reviewing the duty cycle of these participants. If they are operating on 6 weeks on duty with two weeks rest, this participant should move to a lower duty cycle, such as four to five weeks on duty and have their sleep reviewed. Furthermore, data collection should be done for at least a year to review whether there are any seasonal changes in their sleep-wake behaviour. Incorporate more objective measures, such as actigraphy, on a day-to-day basis to aid the subjective data they are currently collecting.

4.7.2 Recommendations for future studies

Future studies could address these limitations of sample size by recruiting more participants to partake in the study. Furthermore, although there was some overlap in the participants, a more cohesive design would have included the entire cohort of Phase two participants (n = 14) in the Phase one semi-structured interviews to learn more about the pilots' experiences on being on duty. This would have allowed for a direct triangulation of subjective experiences of their extended duty with their objective sleep patterns, thereby strengthening the interpretability of findings. Additionally, future research should implement strategies to enhance compliance with actigraphy methods and explore how seasonal changes, such as variations in daylight hours and extended summer duty periods, affect sleep-wake behaviour in aerial firefighting.

Future studies should integrate additional objective measures that will be implemented pre- and post-flight and during the duty period, such as the Psychomotor Vigilance Task (PVT). The PVT is a reliable and valid test measuring sustained attention and has been widely used in aviation settings (Dawson and McCulloch, 2005; Goker, 2018; Fletcher *et al*., 2022). Moreover, future studies should incorporate more subjective metrics such as the Karolinska Sleepiness Scale (KSS) to assess pilots' sleepiness while on duty (ICAO, 2017; Goker, 2018; Flaa *et al.,* 2019). Incorporating these measures would clarify how perceived sleep satisfaction interacts with compromised physiological sleep continuity.

CHAPTER V

5 CONCLUSION

The dual-phase analysis characterises the work systems of aerial firefighting by identifying the demands of aerial firefighting and the specific risks associated with fatigue. The second objective of this study was to examine pilots' sleep-wake behaviour and the existing fatigue risk management system, to inform the development of improved, context-specific fatigue management strategies. The findings indicate that aerial firefighting is a highly specialised, safety-critical operation that demands pilots to operate in unpredictable circumstances and possess tacit knowledge of the environment, fire behaviour patterns, and potential operational hazards. Each role requires specific competencies enabling a distinct skill set to navigate hazards, coordinate efforts, perform precise firefighting operations, and adapt to rapidly evolving demands, ultimately underpinning task variability. Aerial firefighters are typically on-call and often work away from home for extended periods. However, the introduction of the Flight Duty Index has provided greater flexibility for pilots.

This study found that the majority of the pilots got adequate sleep as per recommendations. Most pilots' sleep was regular, suggesting that pilots can develop a routine during their extended duty periods, particularly given that most of them were operating at remote bases in the absence of domestic distractions. Additionally, overall sleep quality, as assessed by the PSQI and sleep diary, was generally rated positively, indicating that participants felt their sleep quality was good and their degree of restedness was satisfactory. These findings suggest that on the spectrum of sleep health, most pilots are doing better; however, this is not true for all participants. A notable finding was the elevated wake-after-sleep onset (WASO) in actigraphy data, with several pilots reporting sleep disturbances when reviewing their sleep diary data. In some pilots, sleep disturbances were a concern. There could be many factors contributing to the elevated levels of WASO, such as caffeine and alcohol consumption, social obligations when off duty and or separation from family during COVID-19. These effects should be beneficial to examine in future studies.

Thus, the current duty period of six weeks on duty and two weeks off duty could pose a fatigue risk to individuals with reduced sleep quality. It could be helpful to review what duty cycle these participants are on. If they are operating on a 6-week on duty with two weeks rest, this participant should move to a lower duty cycle, such as four to five weeks on duty and have their sleep reviewed.

Overall, the majority of the pilots slept enough on average during the six weeks on duty; however, a minority of individuals who showed poor sleep quality could be at a fatigue risk. Hence, it would be helpful to incorporate into future studies to implement control procedures at level 3 of the error trajectory and incorporate assessments of the PVT to measure alertness and the KSS to measure sleepiness into future studies to understand how reduced sleep quality impacts pilots on duty. Thus, these findings highlight that individual differences in fatigue susceptibility of extended duty periods cannot be reliably predicted; therefore, it is essential to manage sleep and, by extension, fatigue risk on an individual basis alongside a one-size-fits-all fatigue management framework.

CHAPTER VI

6 REFERENCES

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1. APPENDICES

2. APPENDIX A: ETHICAL APPROVAL

RHODES UNIVERSITY
Where leaders learn

Rhodes University Human Ethics Committee
PO Box 94, Makhanda, 6140, South Africa
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f: +27 (0) 46 603 8822
e: s.manqele@ru.ac.za
NHREC Registration number: RC-241114-045

https://www.ru.ac.za/researchgateway/ethics/

19/04/2021

Dr. Jonathan Davy

Email: jonathan.davy@ru.ac.za

Review Reference: 2021-4924-6000

Dear Dr. Jonathan Davy

Re: Characterising the sleep-wake behaviour of aerial firefighters to inform strategies to manage fatigue

Principal Investigator: Dr. Jonathan Davy

Collaborators: Ms Shaurissa Borchard, Mr Markus Zahn, Mr Motheo Moroane, Dr Swantje Zschernack,

This letter confirms that the above research proposal has been reviewed by the Rhodes University Human Ethics Committee (RU-HEC) and **PROVISIONALLY APPROVED PENDING PERMISSION/GATEKEEPER LETTER(S)**.

Gatekeeper permission is required from:

[redacted]

Once the Gatekeeper permission letter/s has been received please forward it to the Ethics Coordinator, (s.manqele@ru.ac.za) in order to finalize your ethics approval.

Sincerely,

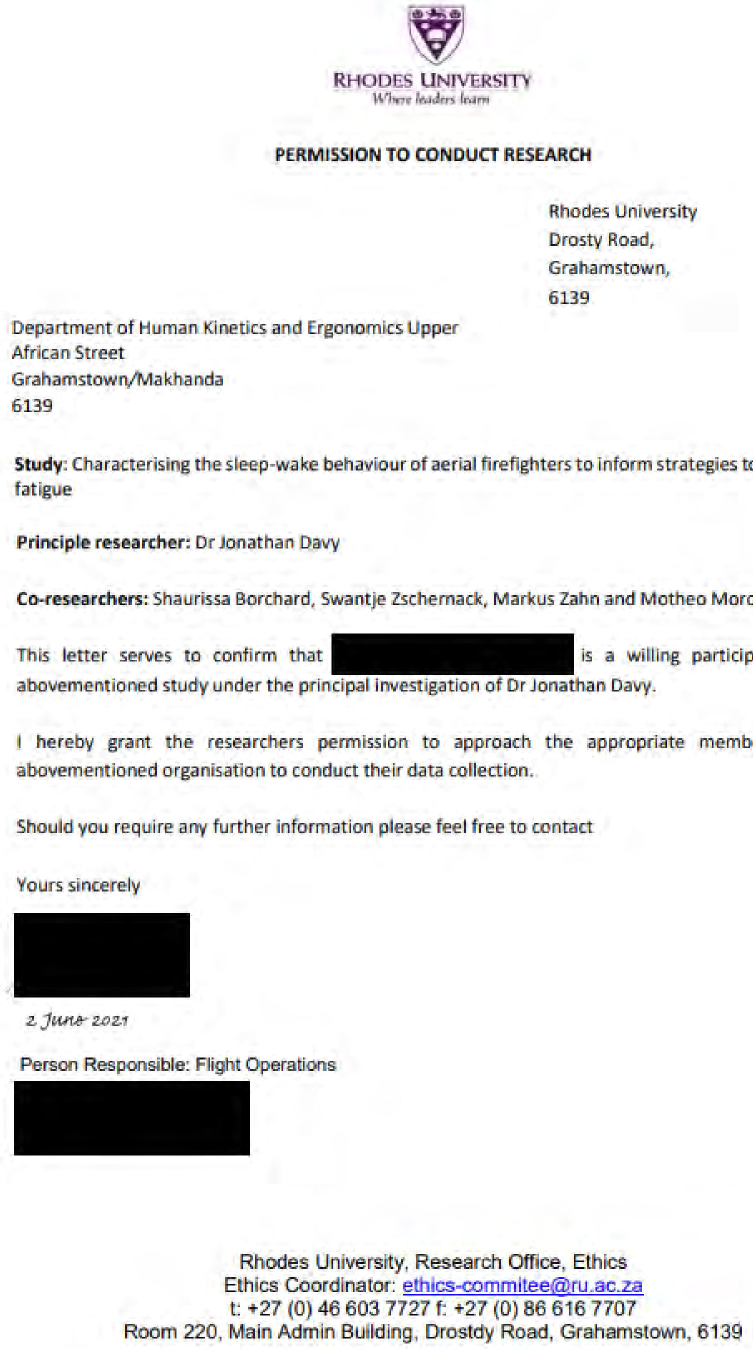
Arthur Webb

Prof. Arthur Webb

Chair: Rhodes University Human Ethics Committee, RU-HEC

cc: Mr. Siyanda Manqele, Ethics Coordinator

APPENDIX B: GATEKEEPER PERMISSION LETTER



RHODES UNIVERSITY
Where leaders learn

PERMISSION TO CONDUCT RESEARCH

Rhodes University
Drosty Road,
Grahamstown,
6139

Department of Human Kinetics and Ergonomics Upper
African Street
Grahamstown/Makhanda
6139

Study: Characterising the sleep-wake behaviour of aerial firefighters to inform strategies to manage fatigue

Principle researcher: Dr Jonathan Davy

Co-researchers: Shaurissa Borchard, Swantje Zschernack, Markus Zahn and Motheo Moroane

This letter serves to confirm that [redacted] is a willing participant of the abovementioned study under the principal investigation of Dr Jonathan Davy.

I hereby grant the researchers permission to approach the appropriate members of the abovementioned organisation to conduct their data collection.

Should you require any further information please feel free to contact

Yours sincerely

[redacted]

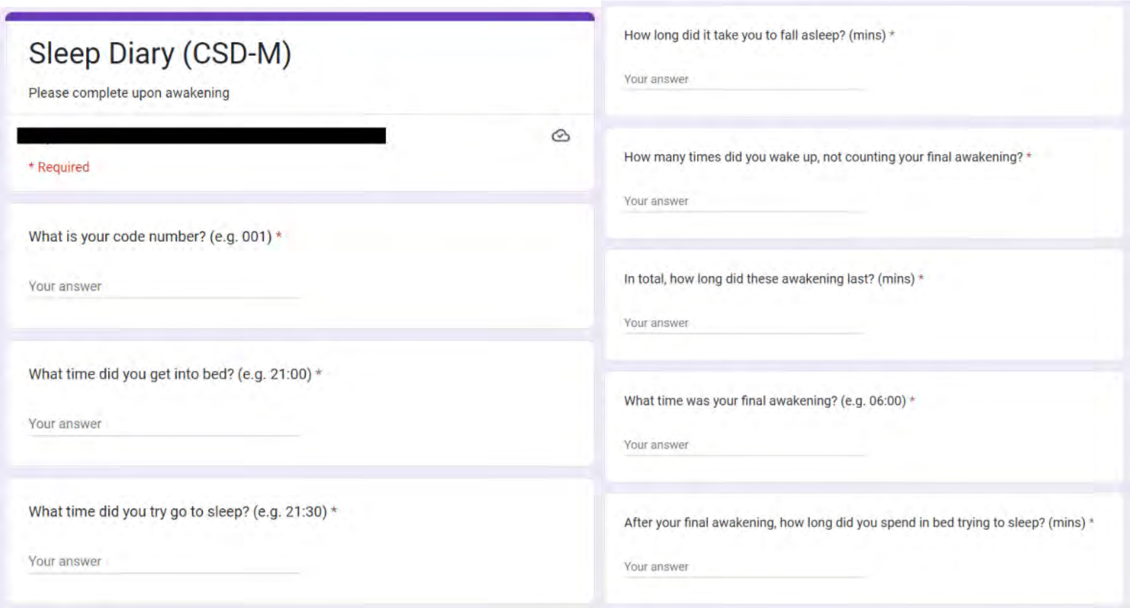
2 June 2021

Person Responsible: Flight Operations

[redacted]

Rhodes University, Research Office, Ethics
Ethics Coordinator: ethics-commitee@ru.ac.za
t: +27 (0) 46 603 7727 f: +27 (0) 86 616 7707
Room 220, Main Admin Building, Drostdy Road, Grahamstown, 6139

0. APPENDIX A: CORE CONSENSUS SLEEP DIARY



Sleep Diary (CSD-M)

Please complete upon awakening

[redacted]

* Required

What is your code number? (e.g. 001) *

Your answer

What time did you get into bed? (e.g. 21:00) *

Your answer

What time did you try go to sleep? (e.g. 21:30) *

Your answer

How long did it take you to fall asleep? (mins) *

Your answer

How many times did you wake up, not counting your final awakening? *

Your answer

In total, how long did these awakening last? (mins) *

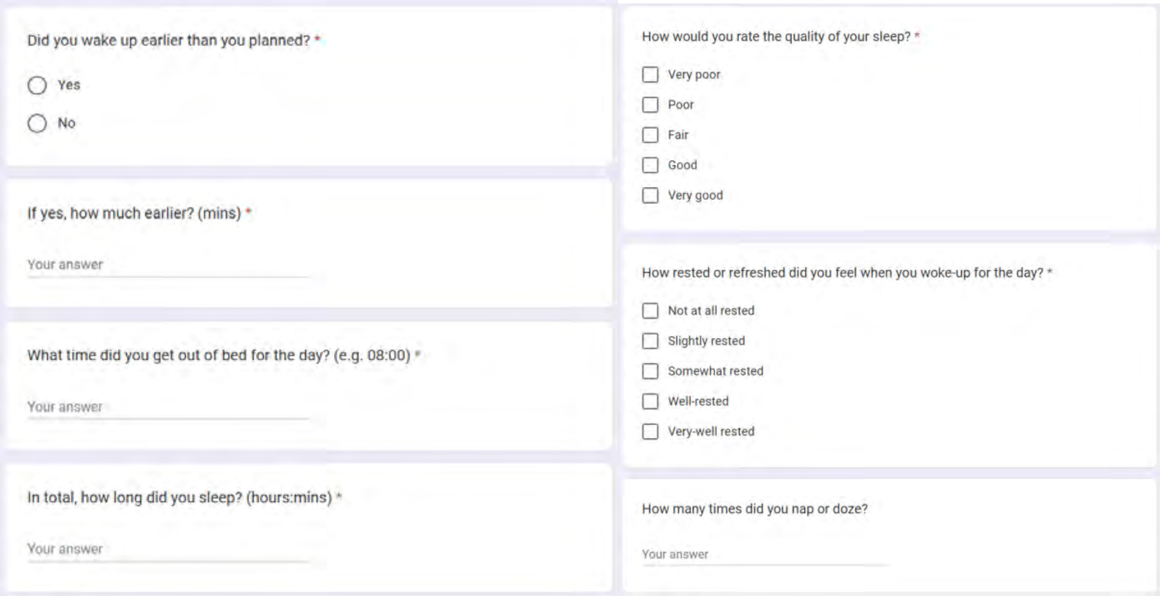
Your answer

What time was your final awakening? (e.g. 06:00) *

Your answer

After your final awakening, how long did you spend in bed trying to sleep? (mins) *

Your answer



Did you wake up earlier than you planned? *

○ Yes

○ No

If yes, how much earlier? (mins) *

Your answer

What time did you get out of bed for the day? (e.g. 08:00) *

Your answer

In total, how long did you sleep? (hours:mins) *

Your answer

How would you rate the quality of your sleep? *

☐ Very poor

☐ Poor

☐ Fair

☐ Good

☐ Very good

How rested or refreshed did you feel when you woke-up for the day? *

☐ Not at all rested

☐ Slightly rested

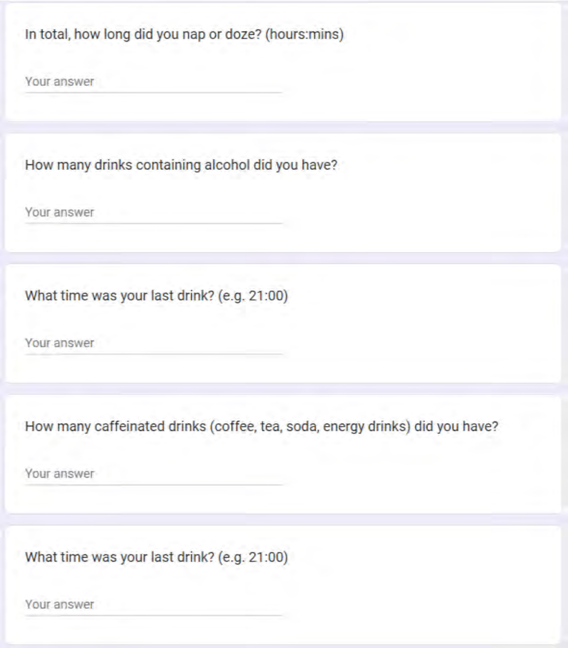
☐ Somewhat rested

☐ Well-rested

☐ Very-well rested

How many times did you nap or doze?

Your answer



In total, how long did you nap or doze? (hours:mins)

Your answer

How many drinks containing alcohol did you have?

Your answer

What time was your last drink? (e.g. 21:00)

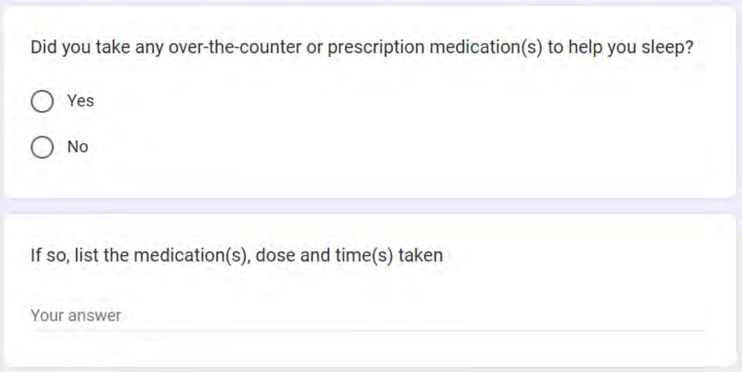
Your answer

How many caffeinated drinks (coffee, tea, soda, energy drinks) did you have?

Your answer

What time was your last drink? (e.g. 21:00)

Your answer



Did you take any over-the-counter or prescription medication(s) to help you sleep?

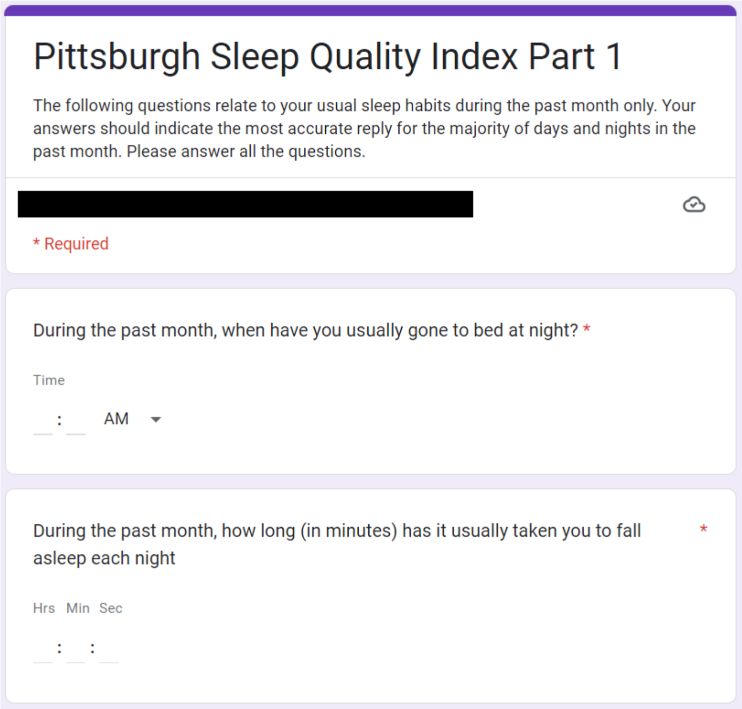
○ Yes

○ No

If so, list the medication(s), dose and time(s) taken

Your answer

0. APPENDIX A: CORE CONSENSUS SLEEP DIARY



Pittsburgh Sleep Quality Index Part 1

The following questions relate to your usual sleep habits during the past month only. Your answers should indicate the most accurate reply for the majority of days and nights in the past month. Please answer all the questions.

[redacted]

* Required

During the past month, when have you usually gone to bed at night? *

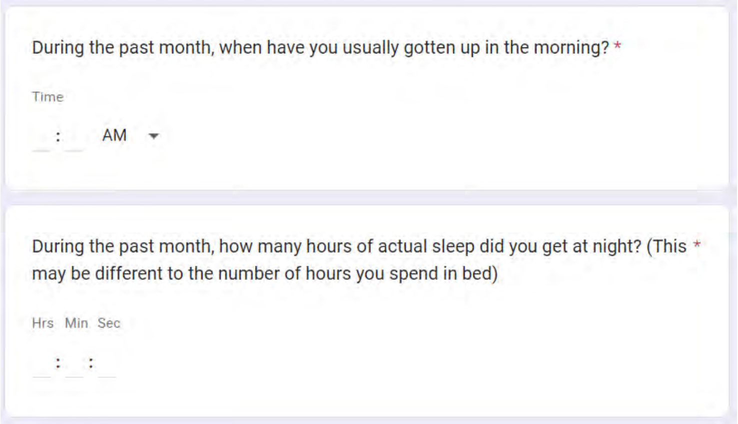
Time

__ : __ AM

During the past month, how long (in minutes) has it usually taken you to fall asleep each night *

Hrs Min Sec

__ : __ : __



During the past month, when have you usually gotten up in the morning? *

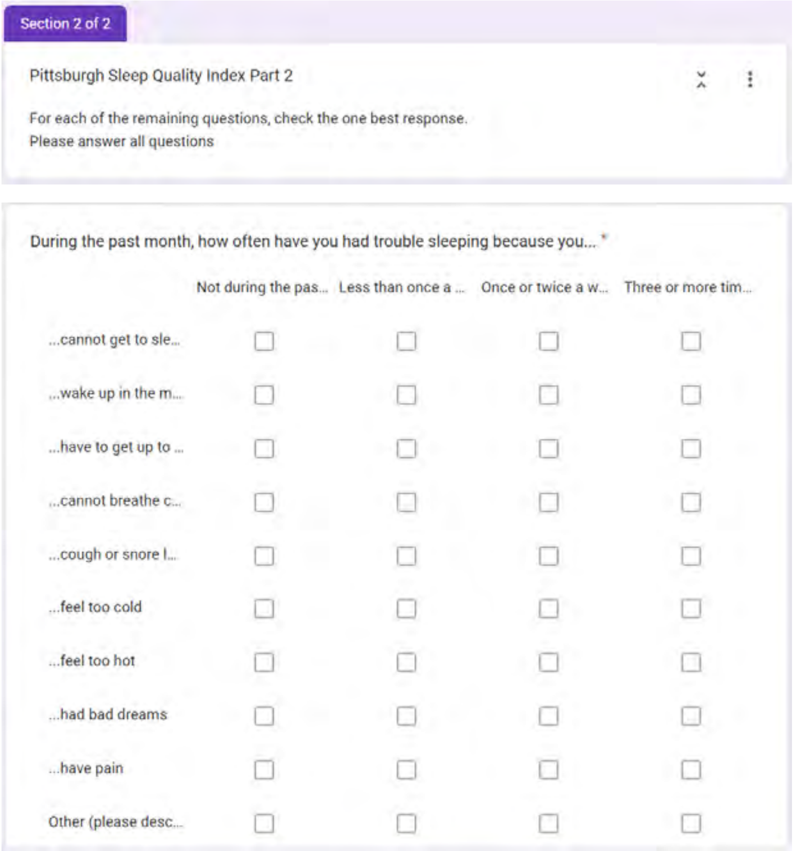
Time

__ : __ AM

During the past month, how many hours of actual sleep did you get at night? (This may be different to the number of hours you spend in bed) *

Hrs Min Sec

__ : __ : __



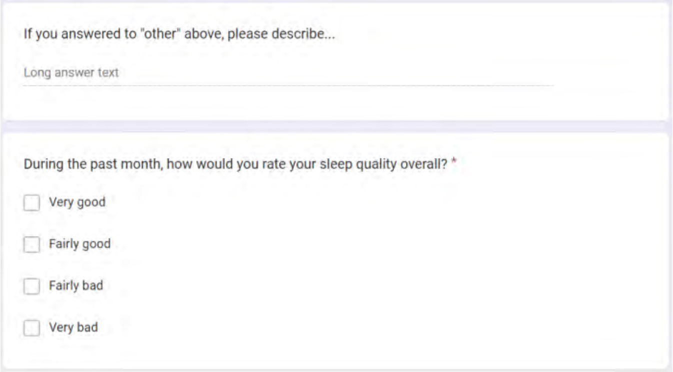
Section 2 of 2

Pittsburgh Sleep Quality Index Part 2

For each of the remaining questions, check the one best response.
Please answer all questions

During the past month, how often have you had trouble sleeping because you... *

	Not during the pas...	Less than once a ...	Once or twice a w...	Three or more tim...
...cannot get to sle...	☐	☐	☐	☐
...wake up in the m...	☐	☐	☐	☐
...have to get up to ...	☐	☐	☐	☐
...cannot breathe c...	☐	☐	☐	☐
...cough or snore l...	☐	☐	☐	☐
...feel too cold	☐	☐	☐	☐
...feel too hot	☐	☐	☐	☐
...had bad dreams	☐	☐	☐	☐
...have pain	☐	☐	☐	☐
Other (please desc...	☐	☐	☐	☐



If you answered to "other" above, please describe...

Long answer text

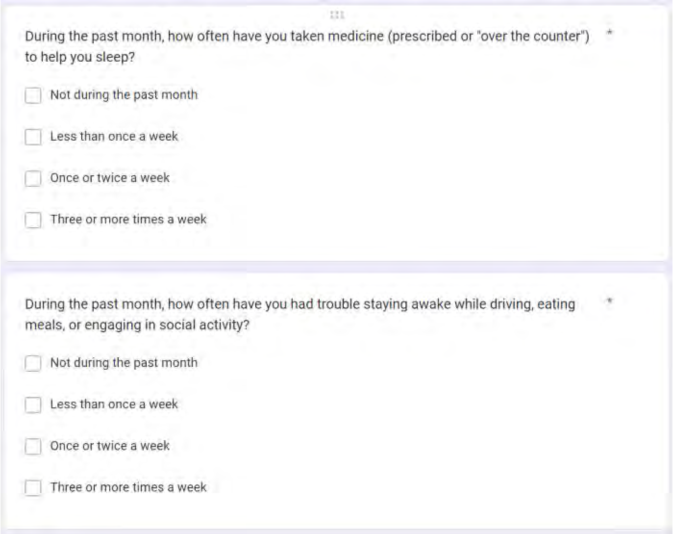
During the past month, how would you rate your sleep quality overall? *

☐ Very good

☐ Fairly good

☐ Fairly bad

☐ Very bad



During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep? *

☐ Not during the past month

☐ Less than once a week

☐ Once or twice a week

☐ Three or more times a week

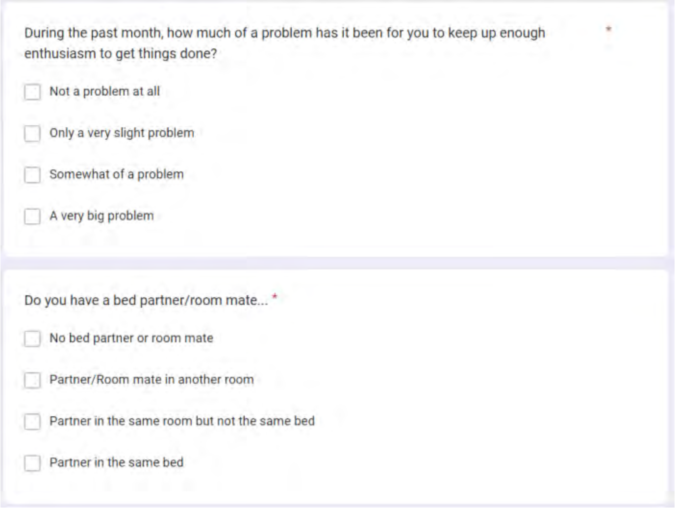
During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity? *

☐ Not during the past month

☐ Less than once a week

☐ Once or twice a week

☐ Three or more times a week



During the past month, how much of a problem has it been for you to keep up enough enthusiasm to get things done? *

☐ Not a problem at all

☐ Only a very slight problem

☐ Somewhat of a problem

☐ A very big problem

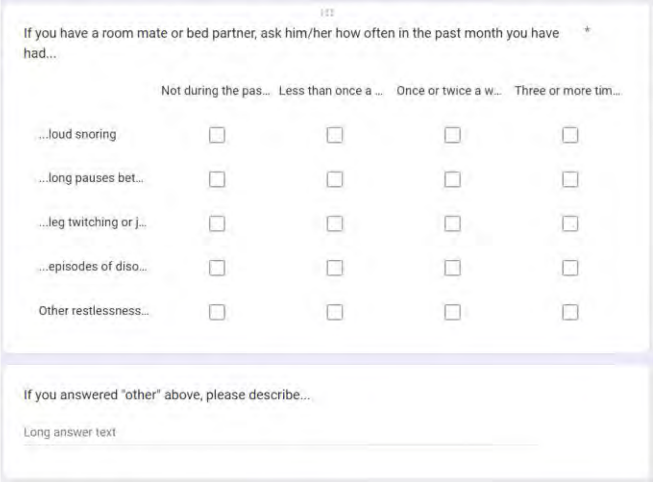
Do you have a bed partner/room mate... *

☐ No bed partner or room mate

☐ Partner/Room mate in another room

☐ Partner in the same room but not the same bed

☐ Partner in the same bed



If you have a room mate or bed partner, ask him/her how often in the past month you have had... *

	Not during the pas...	Less than once a ...	Once or twice a w...	Three or more tim...
...loud snoring	☐	☐	☐	☐
...long pauses bet...	☐	☐	☐	☐
...leg twitching or j...	☐	☐	☐	☐
...episodes of diso...	☐	☐	☐	☐
Other restlessness...	☐	☐	☐	☐

If you answered "other" above, please describe...

Long answer text