Examining Fatigue Factors in Accident Investigations: Analysis of Guantanamo Bay Aviation Accident

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Introduction

In a recent consensus statement, an international group of scientists identified fatigue as "the largest identifiable and preventable cause of accidents in transport operations (between 15 and 20% of all accidents), surpassing that of alcohol or drug related incidents in all modes of transportation. Official statistics often underestimate this contribution." (JSR, 2000). Fatigue engendered by sleep loss and circadian disruption can degrade all aspects of human capability. Significant reductions in operator performance can affect judgement and decision-making, attention, reaction time, alertness, memory, and mood (REFs). These degraded performance factors can increase fatigue-related risks and reduce the operational safety margin.

In spite of these well-documented effects, the contributory or causal role that fatigue may play in an accident is often underestimated or potentially ignored. One reason for underestimating its contribution is that there is "no blood test for fatigue." Thorough accident investigations will include an analysis of alcohol and drug factors. If traces of these compounds are discovered, then they are generally identified as contributory or causal to the accident. However, no simple, practical or validated "blood test" for fatigue currently exists. Therefore, to include or exclude fatigue as contributory or causal in an accident requires the evaluation of two specific aspects of the accident. First, were identifiable fatigue factors present at the time of the accident? Second, if fatigue factors were present, did fatigue-related performance decrements contribute to or cause the accident?

This paper will outline a systematic approach to examine the role of fatigue factors in an accident investigation. First, four specific physiological factors that can create fatigue will be described, including scientific data regarding their relevance. Second, there will be discussion of how to examine whether fatigue–related performance changes played a contributory or causal role in an accident. Third, to demonstrate the application of this approach in an actual accident investigation, the crash of a DC-8 in Guantanamo Bay, Cuba will be used as a model analysis.

Four Fatigue Factors: Physiological and Operational Considerations

An extensive scientific literature indicates that there are four core physiological factors that are known to underlie fatigue and are relevant to an accident investigation. These four fatigue factors are: 1) sleep (acute loss and cumulative debt), 2) continuous hours of wakefulness, 3) circadian rhythms (time-of-

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day), and 4) sleep disorders. Each of these physiological factors will be described and their operational relevance discussed for their potential role in an accident.

Sleep (acute loss and cumulative debt). On average, human adults physiologically require about 8 hours of sleep. However, there is a range of sleep need from about 6 to 10 hours of sleep. Therefore, the average adult will need about 8 hours of sleep for optimal waking performance and alertness. Sleep loss can be considered in two ways: acute and cumulative. Acute sleep loss involves the total amount of sleep obtained in a 24-hour period. An average person that obtains only 5 hours of sleep one night has an acute sleep loss of 3 hours. Sleep loss that occurs over several days builds into a cumulative sleep debt. An average person that obtains only 5 hours of sleep for 3 consecutive nights has a cumulative sleep debt of 9 hours. Recovery from a cumulative sleep debt typically involves more deep sleep and not an hour-for-hour payback of lost sleep that requires extended sleep. Generally, two nights of usual sleep, at a person's regular bedtime, can reduce the cumulative sleep debt to 0. Calculating an individual's acute sleep loss or cumulative sleep debt should be based on the person's usual sleep requirement and pattern. A scientific review found that two hours of sleep loss can result in "impairment of performance and levels of alertness"` (MAC/Roth REF).

Continuous Hours of Wakefulness. How long an individual operator remains awake is another physiological factor that can affect performance and alertness. The physiological complement to sleep is the subsequent number of hours of continuous wakefulness. Shiftwork studies examining different duty lengths (e.g., 8 vs. 10 vs. 12 hours) have provided mixed findings. At 12 hours, some studies have shown significant decreases in performance and alertness and increases in errors and injuries (REFs). NTSB aviation accident data have shown an increased risk beyond 12 hours (REF). At 16 hours of work, a national occupational-injury database demonstrated a progressive increase three times the accident/injury rate at 9 hours (REF). Other studies have shown that performance decrements associated with 17 hours or longer of prolonged wakefulness can approximate the changes typical of alcohol consumption (2 REFs). Generally, performance and alertness can be maintained up to 12 hours of wakefulness. Data suggest that 16 or 17 hours of continuous wakefulness can be associated with significantly reduced performance and alertness. The changes associated with periods of 12 to 16 hours of continuous wakefulness are not well defined. It should be noted that the relevant physiological factor is the continuous hours of wakefulness and that a duty period may be a subset of this.

Circadian Rhythms. Another major physiological determinant of waking performance and alertness is the internal circadian clock (REFs). Located in the suprachiasmatic nucleus (SCN) of the hypothalamus, the circadian clock controls the timing of physiological activity (e.g., thermoregulation, immune function, digestion), performance, alertness, and mood. Daily, the circadian clock is programmed for its lowest point at around 3 am to 5 am. This is the period of lowest activity across physiological systems and human functioning. Performance reductions can occur in a larger window from about 12 am to 6 am. A second programmed period of sleepiness occurs at about 3 pm to 5 pm. These windows of circadian low are associated with decreased performance, alertness, and mood and are especially relevant in an accident investigation when a critical phase of operation occurs during one of them. However, just operating during these periods is associated with physiological changes that reduce performance and alertness.

Sleep Disorders. Almost 90 different sleep disorders exist and are described in a diagnostic classification system (AASM REF). The primary presenting complaint for many of these disorders is excessive sleepiness. There are a broad range of physiological and psychological causes for these sleep disorders and the individual sufferer might be unaware of its existence. Most of these sleep disorders can be diagnosed and treated successfully by accredited sleep medicine specialists. This factor is a consideration because an operator may have a sleep disorder that predisposes the individual for excessive sleepiness. Altered circadian rhythms (e.g., shiftwork, timezone crossings) and other factors could further exacerbate the pre-existing sleepiness. One example sleep disorder is sleep apnea, a condition in which an individual has breathing pauses throughout sleep. This causes waking sleepiness and performance decrements, as well as other related health problems (e.g., cardiovascular risks). Studies of individuals with sleep apnea have shown up to a 7 times increased risk for car accidents. Sleep disorders, such as sleep apnea, put individuals at increased risk for sleepiness and potential performance reductions.

Examining these Four Fatigue Factors. In an accident investigation, each of these four fatigue factors should be evaluated to determine whether they were present at the time of the accident. The information regarding these factors should be obtained from a variety of sources whenever possible. For example, the sleep/wake history might be collected from the individual operator involved in the accident, from family members or coworkers. This involves obtaining information about usual sleep patterns and habitual bed times and then specifics for the period prior to the accident. Usually, a minimum of a 72-hour period before an accident should be examined. Depending on circumstances, it may be necessary to review a longer period of time (e.g., when was the last one or two nights of full sleep?). The continuous hours of wakefulness can be determined from an individual's report (e.g., when did they get up?) and operating information (e.g., reporting for duty). The circadian factor can be straightforward and would identify whether a critical phase of operation or significant performance requirement occurred during a window of circadian low. A sleep medicine specialist may be needed to determine whether an individual had a sleep disorder at the time of an accident.

It is important to consider the sources of information used to examine these fatigue factors. Typically, self-report data is obtained by interviewing an operator about circumstances prior to an accident. Self-reports of sleep and alertness can be discrepant from physiological measures and the reliability of the reports may be difficult to establish. Also, retrospective data can present limitations due to a variety of factors. Hence the importance of obtaining information about these fatigue factors from a variety of sources whenever possible.

Once the information related to these factors is obtained and analyzed, it should be determined whether each one was present at the time of the accident and to what extent. Basically, this translates to a listing of the individual fatigue factors that were relevant at the time of the accident and the data that indicates its severity. A variety of efforts are underway to develop an empirical risk factor based on this type of information. These are in development as mathematical models or weighting of different factors (REF—modeling supplement/Coast Guard).

Clearly, these physiological factors can be highly related. Therefore, the relationship between the factors should also be a consideration. For example, one factor might be heavily loaded, such as no sleep, but minimal contribution of the other factors. In another situation, all factors might be present. For example, an operator had only 3 hours of sleep, was awake for 19 hours, the accident occurred at 4:30 am, and the individual had been diagnosed with sleep apnea.

Examining the Role of Fatigue-Related Performance Changes

The first step, as previously described, is to determine whether to include or exclude fatigue factors as present at the time of the accident. If fatigue factors were present, the second step is to determine whether fatigue-related performance decrements were contributory or causal in the accident. Fatigue created by sleep loss and circadian disruption can decrease waking performance, vigilance, and mood. These decrements are known to affect errors, accidents, and safety (REFs). The basic question is whether fatigue-related decrements can be linked to performance that contributed to or caused the accident. Obviously, this aspect of the determination relies heavily on the specifics of the accident.

Applying this Approach to an Actual Accident Investigation

In 1993, the National Transportation Safety Board (NTSB) investigated a DC-8 accident at Guantanamo Bay, Cuba. At the request of the NTSB investigators, members of the NASA Fatigue Countermeasures Program examined the fatigue factors related to the accident. A full NTSB report on the accident has been published and includes an appendix on the analysis of the fatigue factors by the NASA Group. The following section applies the analytical approach previously described in this paper to the specific circumstances of the DC-8 Guantanamo Bay accident. Details of the analysis are taken directly from the NTSB report and expanded further in this paper.

Analysis of Sleep/Wake Histories for AIA Flight 808 Crew

The four fatigue factors described above were analyzed for the AIA Flight Crew involved in an aviation accident that occurred at Guantanamo Bay, Cuba on August 18, 1993. The data analyzed were taken from the NTSB Human Performance Investigator's Factual Report, the Operations Group Chairman's Factual Report, and the Flight 808 Crew Statements. When there were discrepancies among the sources, conservative estimates and averages were used. The sleep/wake histories for the Flight Crew of AIA Flight 808 prior to the accident at Guantanamo Bay on August 18, 1993 at about 1656 EDT are presented in Figure 1. This figure provides an opportunity to examine the temporal organization and amount of sleep and wakefulness over the three days leading up to the accident. The days 8/16/93, 8/17/93, and 8/18/93 are identified at the top of the figure along with a 24-hour clock. The white bars indicate the duty periods and individual black lines show specific takeoff and landing activities during the duty periods. A single horizontal bar for each flight crewmember shows the sleep (black) and wakefulness (shaded) over the period leading up to the accident at about 1656 on 8/18/93.

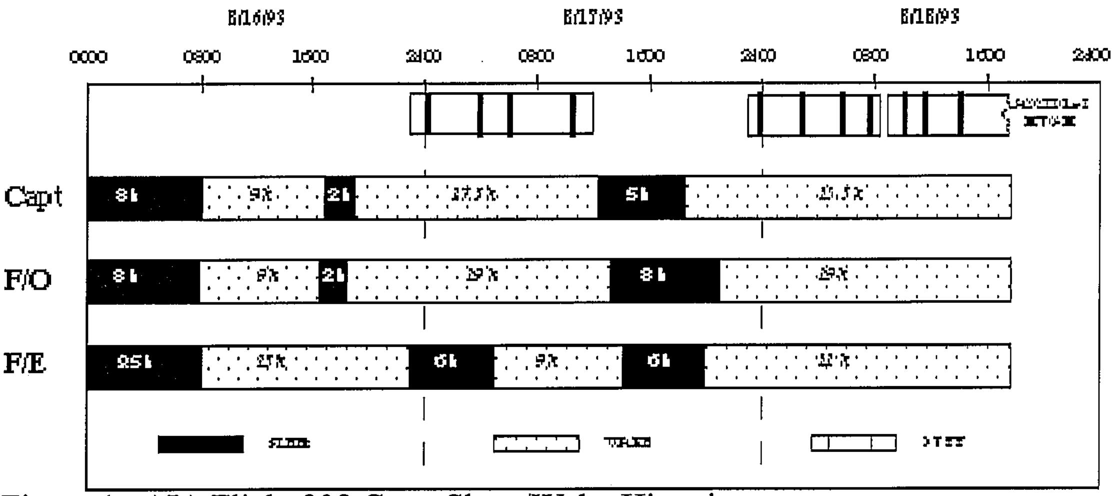

Figure 1. AIA Flight 808 Crew Sleep/Wake Histories

The first horizontal bar in Figure 1 displays the sleep/wake history of the Captain. He reported a typical sleep requirement of 8 hours. The Captain awakened on 8/16/93 after 8 hours of sleep and was awake for 9 hours before taking a 2-hour nap prior to his all-night duty period. Following his nap, the Captain was awake for 17.5 hours. He reported a 5-hour sleep period during a daytime sleep opportunity in a Dallas-Ft. Worth Airport hotel during layover. The Captain was then awake for 23.5 hours until the accident occurred at Guantanamo Bay. This 23.5-hour period included an all-night duty period after which the Captain was released from duty. However, he was called back to operate Flight 808 prior to his return home, and therefore was continuously awake until the accident.

The second bar in Figure 1 displays the sleep/wake history of the First Officer. He also reported a usual sleep requirement of 8 hours. The First Officer awakened on 8/16/93 after 8 hours of sleep and was awake for 9 hours before taking a 2-hour nap prior to his all-night duty period. Following his nap, the First Officer was awake for 19 hours. He reported an 8-hour sleep period during a daytime sleep opportunity in a Dallas-Ft. Worth Airport hotel during layover. The First Officer was then awake for 19 hours until the accident occurred at Guantanamo Bay. This 19-hour period included an all-night duty period after which the First Officer was released from duty. However, he was called back to operate

Flight 808 prior to his leaving the airport, and therefore was continuously awake until the accident.

The third bar in Figure 1 displays the sleep/wake history of the Second Officer. He reported a usual sleep requirement of 9.5 hours. The Second Officer awakened on 8/16/93 after 9.5 hours of sleep and was awake for a 15-hour day before going to sleep at 2300 for a usual night of sleep. The Second Officer was then called at home after 6 hours of sleep and reported for duty at the airport, joining the Captain and First Officer. The Second Officer was then awake for 9 hours. He reported a 6-hour sleep period during a daytime sleep opportunity in a Dallas-Ft. Worth Airport hotel during layover. The Second Officer was then awake for 21 hours until the accident occurred at Guantanamo Bay.

An examination of the cumulative totals for sleep and continuous wakefulness is informative. For the entire 65-hour period portrayed in Figure 1, which includes the last full 8-hour sleep period at home, the Captain was awake for 50 hours with 15 hours of sleep. Including the 2-hour nap, in the last 48 hours, the Captain was awake for 41 hours with 7 hours of sleep. For the 46 hours after the nap, the Captain was awake for 41 hours with 5 hours of sleep. In the last 28.5 hours prior to the accident, the Captain was awake for 23.5 hours with 5 hours of sleep.

For the entire 65-hour period portrayed in Figure 1, which includes the last full 8-hour sleep period at home, the First Officer was awake for 47 hours with 18 hours of sleep. Including the 2-hour nap, in the last 48 hours, the First Officer was awake for 38 hours with 10 hours of sleep. For the 46 hours after the nap, the First Officer was awake for 38 hours with 8 hours of sleep. In the last 27 hours prior to the accident, the First Officer was awake for 19 hours with 8 hours of sleep.

For the entire 65-hour period portrayed in Figure 1, which includes the last full 9.5-hour sleep period at home, the Second Officer was awake for 45 hours with 21.5 hours of sleep. In the last 42 hours, the Second Officer was awake for 30 hours with 12 hours of sleep. In the last 27 hours prior to the accident, the First Officer was awake for 21 hours with 6 hours of sleep.

Overall, this information demonstrates that the entire crew displayed cumulative sleep loss and extended periods of continuous wakefulness. It should be noted that the cumulative sleep loss can be partially attributed to the reversal of the circadian pattern, with nighttime sleep periods at home followed by daytime sleep periods due to all-night duty periods. Sleep obtained in opposition to the body's circadian rhythms is more disturbed than sleep that coincides with times when the body is programmed for sleep. Also, the accident occurred at about 4:56 PM in the 3-5 PM window of sleepiness.

In a typical 24-hour period, most individuals would be awake about 16 hours and sleep about 8 hours. This represents a 2:1 wake/sleep ratio. Based on this general pattern, a calculation of the cumulative sleep/wake debt is portrayed in Figure 2. The wake/sleep ratio is displayed along the left axis. A ratio of 2:1 or 2 represents a usual baseline pattern (shown by the solid line) with a wake/sleep ratio less than 2 representing a sleep gain. A wake/sleep ratio greater than 2:1 or 2 would represent a sleep loss. The three days prior to the trip are portrayed on the horizontal axis.

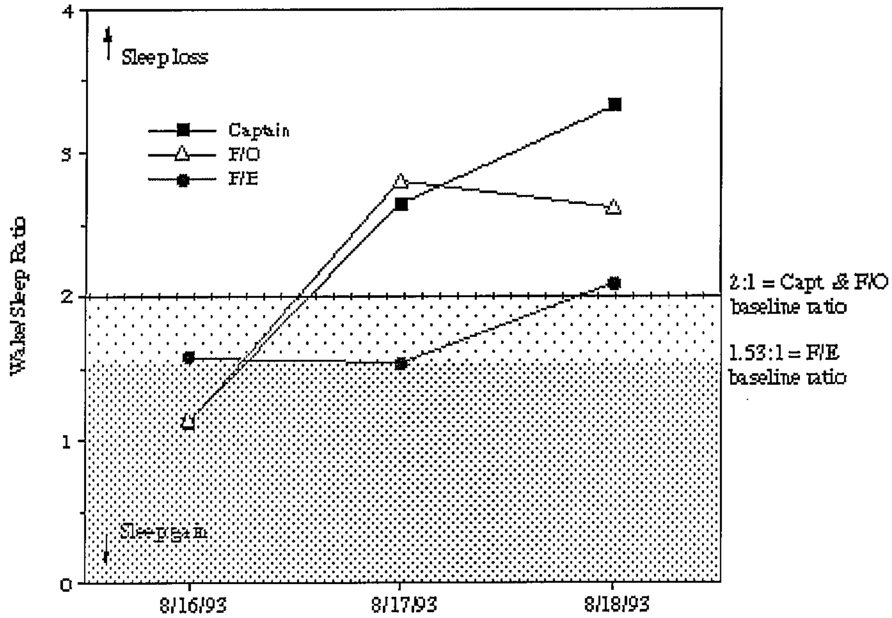

Figure 2. Cumulative Sleep/Wake Debt

The Captain and First Officer reported a usual sleep requirement of 8 hours and therefore, a wake/sleep ratio of 2 would be their appropriate self-defined norm. As evidenced in Figure 2, the wake/sleep ratio for both the Captain and First Officer is greater than 2 (indicated by the solid line) over the two days prior to the accident, reaching greater than 3 for the Captain. The Second Officer reported a usual sleep requirement of 9.5 hours. This represents a wake/sleep ratio of 1.53 as his self-defined norm (indicated by the dashed line). He approximates this on 8/16 and 8/17 and exceeds a ratio of 2 prior to the accident.

There was no history, report, or information that suggested any of the flight crew had a sleep disorder, though none of them were clinically evaluated in a sleep disorders center.

Taken together these data demonstrate that the entire flight crew displayed cumulative sleep loss, operated during an extended period of continuous wakefulness, obtained sleep at times in opposition to the circadian clock time for sleep, and that the accident occurred in the afternoon window of physiological sleepiness. Specifically, the Captain and second officer had an acute sleep loss of 3 and 3.5 hours respectively, all three crewmembers had a cumulative sleep debt, all crewmembers had been awake for an extended period of time ranging from 19 to 23.5 hours, and the critical landing phase of the operation occurred during the afternoon window of circadian low. Three of the four fatigue factors were present at the time of the accident. In consideration of the previous scientific information and the specific factors examined in this accident, the data clearly support the finding that fatigue was a physiological factor for the entire crew.

Evidence that Fatigue-Related Performance was Contributory or Causal in the Accident

The data presented in the previous section demonstrated that the entire crew had experienced sleep loss, extended periods of continuous wakefulness, and circadian disruption (both the timing of sleep periods and time of accident). Given the sleep/wake and circadian history of the entire flight crew, it is clear fatigue was present. However, to determine how fatigue may have contributed to or caused the accident, one would have to determine whether performance and behavioral changes associated with fatigue played a role in the accident.

Several sources of data were available for examination to provide specific information regarding flight crew performance and actions before the accident. The transcript of the cockpit voice recorder (CVR) was made available at the NTSB hearing on this accident, and the Captain provided testimony at the hearing.

Based on an analysis of this data, four fatigue-related performance changes were identified that contributed to or were causal in this accident. Each will be described.

1. Degraded Judgement and Decision-Making

The CVR transcript provides information about flight crew performance, decisions, and responses leading up to the accident at Guantanamo Bay. One piece of information is related to the decision to use runway 10 (Figure 3). Two of the crewmembers, including the Captain (the pilot flying), had never flown into Guantanamo Bay; the First Officer had only flown into Guantanamo Bay years before in small military jets. The crew acknowledged that it was a difficult airport with special considerations. The plan had been to use the straightforward approach available on runway 28. With essentially no discussion, the Captain decided to change plans and use runway 10, which requires a more severe maneuver to complete the landing. By all reports, the Captain was lauded for his airmanship and good judgment, especially in emergency and landing procedures. Therefore, for an experienced Captain to make a sudden decision to change runways, with no prior experience at a special airport, with minimal crew discussion, indicates a degraded decision-making process. In this situation, fatigue may have affected the crew's decision-making in the following ways: a) they did not consider important information (i.e., their unfamiliarity with the airport, their level of fatigue), b) their lack of discussion about the decision to change runways, and c) misreading of potential outcomes. In this case, the entire flight crew, all of whom were affected by the fatigue factors previously outlined, shared the decision-making process.

2. Cognitive Fixation

Another piece of information from the CVR was the Captain's fixation on finding a strobe light that was a landing cue. In the transcript, the Captain makes seven references to finding the strobe light (Figure 4). During the critical period leading up to the accident, the Captain displayed an overwhelming focus and concern to locate the strobe light. This cognitive fixation on the strobe light, to the exclusion of other critical information, is another potential fatigue affect on performance. It would fit laboratory research that demonstrates that this effect can result from sleep loss (ref. 15-21).

3. Poor Communication/Coordination

Also evident from the CVR was the Captain's disregard of critical information just prior to the accident. While the Captain was fixated on locating the strobe light and was making multiple references to its location, the other crewmembers questioned whether they were going to successfully make the landing. The Captain did not acknowledge the question, certainly did not process the potential implications of the question, and finally disregarded the critical information to continue his search for the strobe light. While the transcript reveals that words were expressed, the crew actions indicate poor communication and coordination of efforts.

4. Reduced Reaction Time

Another piece of information from the CVR was the response to the stall warning when the operation was clearly in trouble. Several pilots reviewed the CVR transcript and spontaneously commented on how slowly the Captain and crew responded to the stall warning prior to the accident. The warning is intended to provide a window for immediate response and an opportunity to recover the aircraft. An experienced pilot will have been trained to immediately respond to the stall warning with an automatic response. However, fatigue can degrade reaction time and psychomotor responses. Therefore, the Captain and crew appear to have been slow to respond to the stall warning as a consequence of the prior sleep loss, circadian disruption, and extended period of continuous wakefulness.

Other Considerations

There are several other instances from the CVR that suggest the presence of fatigue but are subtler. For example, there appears to have been excessive checking of information (e.g., were waypoints entered, radio frequencies). These more subtle occurrences may also reflect decreased memory and mental functioning but are less clearly defined than the previous four examples from the CVR.

The level of performance demonstrated by the Captain is below that normally expected of a Captain with his level of experience. However, the Captain's aviation record does not suggest that he was a substandard pilot. The Captain's airmanship was lauded from several sources. Therefore, some factor must have interfered with his performance on this flight. Also note that some of the CVR performance decrements identified above were also Crew Resource Management (CRM) failures. This further supports the data that the entire crew, not just the Captain, were affected by fatigue at the time of the accident.

Another piece of information that became available at the NTSB hearing was the Captain's testimony. Perhaps the most telling statement was in response to the question about how he felt just prior to the accident and he said, "lethargic and indifferent." Individuals use a variety of words to express their state associated with sleep loss and circadian disruption, for example, 'fatigued,' 'tired,' 'sleepy,' and 'lethargic.' Also, controlled laboratory studies of sleep deprivation have shown that individuals will increase their effort to perform, though their performance is degraded, and they become indifferent to the outcome. The Captain's report of being "lethargic and indifferent" in the period leading up to the accident is quite consistent with the typical effects of sleep and circadian disruption.

Conclusions

This paper outlines a systematic approach to examine fatigue factors in an accident investigation. Four core fatigue factors are identified and a summary of their physiological and operational relevance is provided. Determining whether these fatigue factors can be included or excluded is the first step of analysis. Next, it is critical to examine whether fatigue-related changes can be linked to actions that caused or contributed to an accident. This analytical approach was applied to the investigation of a DC-8 accident at Guantanamo Bay, Cuba. Based on its analysis, the NTSB determined "that the probable causes of this accident were the impaired judgment, decision-making, and flying abilities of the captain and flightcrew due to the effects of fatigue" (REF). Based on their findings, the NTSB made the following recommendations related to fatigue: require that flight time accumulated in noncommercial "tail end" ferry flights be included in total flight and duty time accrued; expedite the review and upgrade of Flight/Duty Time Limitations of the Federal Aviation Regulations to ensure that they incorporate the results of the latest research on fatigue and sleep issues; and require U.S. air carriers to include, as part of pilot training, a program to educate pilots about the detrimental effects of fatigue, and strategies for avoiding fatigue and countering its effects.

It is important to acknowledge the limitations of human physiology regarding sleep, circadian rhythms, and fatigue. The flight crewmembers involved in this accident were clearly professional, well trained, experienced, and highly motivated to perform their best. As humans, there are limitations to performance that are purely a reflection of physiological capabilities and can be independent of training, motivation, and experience.

It is hoped that the structured analytical approach outlined here can provide a model for the examination of fatigue factors in accident investigations. Applying this approach provides a method for refining analysis of individual accidents and can create better estimates of fatigue-related risks than current statistics provide. This approach also can be used to examine errors or incident occurrences or to consider schedules prior to their implementation. These types of analyses offer the opportunity to identify fatigue-related vulnerabilities before an accident occurs and can be used as a preventive measure. Addressing the fatigue-related risks identified in such an analysis provides a mechanism to improve performance and alertness and enhance operational safety.

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