Flight Crew Fatigue I: Objectives and Methods

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In 1980, NASA-Ames Research Center, Moffett Field, CA, initiated a program to assess flight crew fatigue, determine its potential operational consequences, and provide practical countermeasure suggestions. To assess the extent of the problem, crewmembers were monitored before, during, and after commercial short-haul (fixed-wing and helicopter aircraft), overnight cargo, and long-haul operations. A total of 197 volunteers were studied on 94 trip patterns with 1299 flight segments and 2046 h of flying time. The present paper outlines the program and describes the common methodology used in these studies, which are then presented in detail in the four subsequent papers. The sixth paper offers a synthesis of this work, reviewing the major causes of flight crew fatigue and making specific suggestions about ways to manage it in different operations.

IN 1980, IN RESPONSE to a request from Congress, NASA-Ames Research Center, Moffett Field, CA, developed a research program on flight crew fatigue. A workshop was held (30) at which representatives from the scientific community, airline pilots, and airline management concluded that fatigue in air transport operations constituted a potential safety problem of uncertain magnitude. A survey of confidential reports to NASA's Aviation Safety Reporting System indicated that about one-fifth of all incidents involved factors related directly or indirectly to fatigue (23). A review of the scientific literature emphasized the potential effects of sleep loss and circadian rhythm disruption on pilot performance (19). From these initial activities it became clear that, although there was already some potentially applicable information in the scientific literature, it was not readily accessible to the aviation community, regulatory authorities, and the flying public. Further, this information came primarily from laboratory studies. There was no comprehensive work on the effects of real flight operations on sleep, circadian rhythms, and subjective fatigue, or on the consequences for cockpit performance. To redress this situation, four observational field studies were undertaken in which flight crews were monitored before, during, and after a scheduled line of flying. The papers in the present series report the findings from these studies. The operations examined were as follows.

1) Short-haul commercial air transport operations on the east coast of the U.S. (DC-9 or Boeing-737 aircraft). The goal of this study was to examine the most challenging 3–4 d trips being flown by two-person crews, with specific features including early report times and long duty days.
2) Commercial helicopter air transport operations from Aberdeen, Scotland, to service rigs in the North Sea oil fields (Aerospatiale Super Puma; Aerospatiale Tiger; Bell 214 ST; or Boeing Vertol BV234 aircraft.) The two-person crews were operating 4–5 d trips. These studies were conducted in collaboration with the Medical Department of the United Kingdom Civil Aviation Authority. Both the short-haul fixed-wing and helicopter operations involved predominantly daytime flying, with multiple flight segments per day, and crossing no more than one time zone in 24 h.
3) Commercial overnight cargo operations in the central and eastern U.S. (Boeing-727 aircraft). In these operations, three-person crews flew multiple flight segments primarily at night, and crossed no more than one time zone in 24 h. The two trip patterns studied lasted 8 d and included one 45-h break from duty that interrupted successive nights of flying.
4) Four different commercial long-haul trip patterns with three-person crews flying Boeing 747–100/200 aircraft. A 4-d round trip from the west coast of the U.S. to Auckland, New Zealand, was selected as a primarily north-south trip, involving long overwater flights but with minimal time zone crossings. A 7-d round trip from the east coast of the U.S. to Bombay, India, was selected as an example of an eastward outbound trip. A 9-d round trip from the west coast of the U.S. to Singapore, which included multiple trans-Pacific flights, was selected as a westward outbound trip. An 8-d trip pattern was also studied which included 6 transatlantic flights (from the west coast of the U.S. to London and return).

In each of these different operating environments, the

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same measures were taken to assess the effects of the flight duties on sleep quantity and quality, circadian rhythms, and subjective fatigue and mood. It should be noted that no objective measures of performance were collected in the four field studies described in these papers. In addition, crewmembers completed demographic and lifestyle questionnaires and four personality inventories in an attempt to identify individual attributes that might influence how they adapt to operational demands. Detailed information on operational events was gathered by cockpit observers who accompanied participating crews throughout each trip.

These studies provide an unprecedented amount of information about fatigue in aviation operations. Field studies on this scale are rare because they require extensive cooperation and long-term financial and logistical support. They were made possible by the exceptional interest and dedication of individual flight crewmembers, their union representatives, airline management, the Federal Aviation Administration (FAA), by the ongoing commitment of NASA management to the program, and by the outstanding efforts of the many people who have been members of the NASA Fatigue and Jet-Lag program.

METHODS

Subject Recruitment and Confidentiality

A common approach and set of core measurements were developed and used in all of the fatigue field studies. For the short-haul fixed-wing, overnight cargo, and long-haul studies, which were all carried out with U.S. carriers, crewmember participation was solicited as follows. Once agreement had been obtained from the respective airline management and pilot representatives, letters and brochures were distributed at the selected domicile(s). These described the reasons for doing the research and outlined what would be involved if a crewmember decided to participate. The studies were reveiwed by the Ames Research Center Human Use Committee which classified them as exempt from further requirements since crewmembers were being observed in the course of their normal activities.

In the operations studied, crewmembers bid for monthly trip schedules which were then allocated on the basis of seniority. Members of the NASA research team received the monthly schedules in advance and selected particular trips for study. Crewmembers who were allocated these trips were subsequently contacted by telephone to solicit their participation in the study. This procedure was intended to minimize the potential bias inherent in an open call for volunteers. In the study of overnight cargo operations, crewmembers sometimes knew ahead of time which trips were being studied, which may have influenced their choice of schedules.

The helicopter study involved crews from four British commercial helicopter companies. Each company distributed a joint Civil Aviation Authority/NASA letter explaining the study and calling for volunteers. The response of pilots to this letter was universally positive, and the research team was therefore able to select the longest trips being flown at times when the cockpit observers were available to accompany crews.

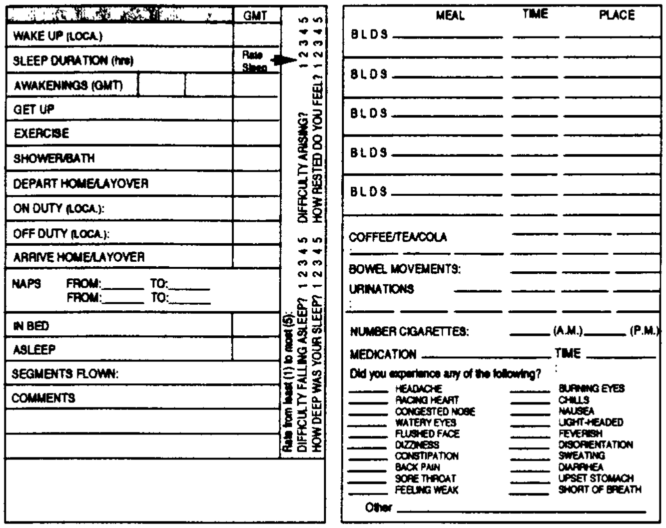
Confidentiality was a major consideration in the design of the studies and the corresponding databases, both to safeguard the volunteer participants and to encourage honesty in reporting. All data and information pertaining to a crewmember were identified only by a four-digit ID number. No records were kept which linked the names of crewmembers with their ID numbers. The only way to contact an individual subsequently, e.g., to clarify or complete data, was to broadcast a request for the person with the required ID number to contact the NASA researchers. Thus any subsequent contact was also voluntary. In addition, trips were coded in the databases by month, not by day or trip number. About 85% of crewmembers approached agreed to participate, and confidentiality was not a reason cited for refusal by those who declined.

As an incentive for participating, U.S. crewmembers had the opportunity to review and discuss their own data. In addition, they received a NASA certificate of appreciation and could request passes to a shuttle launch at Kennedy Space Center. No financial incentives were offered.

Physiological Data

Crewmembers were monitored for up to 4 d prior to a scheduled trip, during the trip, and for up to 4 d after the trip. Throughout their participation in the study, they wore a Vitalog PMS-8 biomedical monitor (Vitalog Corp., Redwood City, CA). Every 2 min, this device recorded activity of the non-dominant wrist (from a watch-sized omnidirectional array of mercury switches), average heart rate (r-wave detector), and rectal temperature. The activity and heart rate data were used to cross-check self-reports of sleep timing, and were investigated as possible indicators of sleep quality. For each subject, mean activity, heart rate, and temperature during each sleep episode were calculated from 20 min after the reported sleep onset time until 10 min before the reported wakeup time. This trimming was adopted, after careful examination of many data sets, in order to minimize contamination of the estimates of mean levels during sleep by the comparatively high values which occur immediately before and after sleep. The variability in activity, heart rate, and temperature during sleep was estimated as the standard deviation of the raw scores for each sleep episode for each subject. In the short-haul fixed-wing study, heart rate during different phases of flight was also examined as a physiological indicator of the associated task demands.

In keeping with current convention, the rhythm of rectal temperature was taken as a marker for the daily cycle of the circadian clock. However, the measured rhythm reflects not only the circadian variation in temperature, but also shorter-term fluctuations (so-called masking) associated with changes in the level of physical activity, posture, and sleep. To help correct for the effects of masking on estimates of the phase and amplitude of the circadian cycle, a constant (0.28°C) was added to the raw temperature data for each subject whenever he or she was asleep. This was based on the 0.28°C difference between the temperature rhythm during sleep and wake that is observed when people live in time isolation and



	GMT
WAKE UP (LOCAL)	
SLEEP DURATION (hrs)	
AWAKENINGS (GMT)	
GET UP	
EXERCISE	
SHOWER/BATH	
DEPART HOME/LAYOVER	
ON DUTY (LOCAL):	
OFF DUTY (LOCAL):	
ARRIVE HOME/LAYOVER	
NAPS FROM: ____ TO: ____ FROM: ____ TO: ____	
IN BED	
ASLEEP	
SEGMENTS FLOWN:	
COMMENTS	

Rate Sleep: Rate from least (1) to most (5): DIFFICULTY FALLING ASLEEP? 1 2 3 4 5; HOW DEEP WAS YOUR SLEEP? 1 2 3 4 5; DIFFICULTY ARISING? 1 2 3 4 5; HOW RESTED DO YOU FEEL? 1 2 3 4 5

MEAL	TIME	PLACE
B L D S		
B L D S		
B L D S		
B L D S		
B L D S		
COFFEE/TEA/COLA		
BOWEL MOVEMENTS:		
URINATIONS		

NUMBER CIGARETTES: ____ (A.M.) ____ (P.M.)
MEDICATION ____ TIME ____
Did you experience any of the following?
HEADACHE, RACING HEART, CONGESTED NOSE, WATERY EYES, FLUSHED FACE, DIZZINESS, CONSTIPATION, BACK PAIN, SORE THROAT, FEELING WEAK
BURNING EYES, CHILLS, NAUSEA, LIGHT-HEADED, FEVERISH, DISORIENTATION, SWEATING, DIARRHEA, UPSET STOMACH, SHORT OF BREATH
Other ____

Fig. 1. Example of the pages that crewmembers completed each day to document the events of the day. The logbook was modified for the overnight cargo and long-haul studies to allow for recording of two sleep episodes per 24 h. All data were collected on Greenwich Mean Time.

adopt a sleep/wake pattern that has a periodicity different to that of the temperature rhythm (42). The effects of this mathematical "unmasking" procedure on circadian phase estimation are described in detail in reference 11.

Sleep, Subjective Fatigue, and Mood

Throughout their participation in the study, crewmembers documented their daily activities in a log book **(Fig. 1)**. These included: the timing of duty, exercise, and showers or baths; consumption of food, caffeine, and alcohol; the timing of bowel movements and urination; and the occurrence of medical symptoms and use of medications.

As soon as possible after waking up from a sleep episode, crewmembers noted in the log book the times of going to bed, falling asleep, waking up and getting up, together with the sleep duration (excluding the amount of time spent in bed awake), and the number and timing of any periods of wakefulness that they could recall during the time in bed. The quality of each sleep episode was rated from 1 (least) to 5 (most) on the questions: Difficulty falling asleep?; How deep was your sleep?; Difficulty rising?; How rested do you feel? These scores were converted so that higher values indicated better sleep, and added together to give an overall sleep rating. The timing of naps was also recorded.

Subjective sleep data can be discrepant from physiological sleep measures obtained from polygraphic recordings. Long-haul flight crews may be better able to estimate their sleep duration than the general population (5). A NASA-coordinated study (14), which measured the subjective and objective sleep and sleepiness of 56 long-haul crewmembers before and after the first segment of an international trip, found that they had a 95% probability of correctly estimating their objective sleep duration to within 30 min. However, they were less reliable at estimating sleep latency. The longer they took to fall asleep, the more they tended to overestimate how long it took. It is not known whether flight crews in other operations are able to assess their sleep more accurately than the general population. The level of internal consistency among the subjective sleep measures used in the fatigue field studies was examined in the data from the short-haul fixed-wing study (10). Longer sleep latencies were correlated with reports of greater difficulty falling asleep ($r = 0.46$, $p < 0.01$) and shorter sleep durations ($r = 0.20$, $p < 0.01$). Longer sleep durations were correlated with less difficulty falling asleep ($r = 0.22$, $p < 0.01$), deeper sleep ($r = 0.14$, $p < 0.05$), feeling more rested on awakening ($r = 0.22$, $p < 0.01$), and better overall sleep quality ratings ($r = 0.26$, $p < 0.01$). Overall, the changes in the subjective sleep measures on trips were large and consistent with the different duty demands in each type of operation.

Every 2 h while they were awake, crewmembers rated their subjective fatigue on a 10 cm line ranging from most alert to most drowsy **(Fig. 2)**. This measure has previously been shown to exhibit circadian rhythmicity in the presence or absence of environmental synchroniz-

Day ______

GMT ____ Leg/LO ____	not at all	a little	moderately	quite a bit	extremely
active	0	1	2	3	4
vigilant	0	1	2	3	4
annoyed	0	1	2	3	4
carefree	0	1	2	3	4
cheerful	0	1	2	3	4
considerate	0	1	2	3	4
alert	0	1	2	3	4
dependable	0	1	2	3	4
sleepy	0	1	2	3	4
dull	0	1	2	3	4
efficient	0	1	2	3	4
friendly	0	1	2	3	4
full of pep	0	1	2	3	4
grouchy	0	1	2	3	4
happy	0	1	2	3	4
jittery	0	1	2	3	4
kind	0	1	2	3	4
lively	0	1	2	3	4
pleasant	0	1	2	3	4
relaxed	0	1	2	3	4
forgetful	0	1	2	3	4
sluggish	0	1	2	3	4
tense	0	1	2	3	4
clear thinking	0	1	2	3	4
tired	0	1	2	3	4
hard working	0	1	2	3	4

MOST DROWSY — MOST ALERT

Fig. 2. Example of the mood adjective checklist and the visual analog scale for subjective fatigue rating. These were completed every 2 h while crewmembers were awake.

ers (27,42). Each time that they rated their fatigue, they also completed the 26-adjective checklist mood scale developed by the Naval Health Research Center (28). This scale has previously been shown to exhibit circadian rhythmicity and to be sensitive to sleep loss (29,34).

Individual Attributes

All crewmembers completed a background questionnaire compiled to obtain information on demographic and lifestyle variables, sleep and nutritional habits. They also completed three personality inventories and the circadian-type questionnaire of Horne and Ostberg (20).

The Personal Attributes Questionnaire (40) includes two scales, "instrumentality" and "expressiveness", which have both been found to correlate with check airman ratings of flight crew performance (15). Individuals scoring high in both scales are also reported to be more effective in group problem solving situations (35).

The Work and Family Orientation Questionnaire was designed to measure achievement motivation and attitudes toward family and career (16). High scores on the "work" and "mastery" scales, combined with a low score on the "competitiveness" scale, have been reported to be associated with highest attainment in groups of scientists, students, and businessmen (41).

The Eysenck Personality Inventory (7) includes two scales, "extroversion" and "neuroticism" which have been related to individual differences in circadian rhythms. There is some evidence that people scoring high on these two scales may adjust more rapidly to time-zone and schedule changes (4,12).

The circadian type questionnaire of Horne and Ostberg (20), quantifies the anecdotal distinction between "morning-types" and "evening-types." The extreme types identified by the questionnaire apparently differ in sleep timing and the time of day of the circadian temperature minimum. Some studies also indicate that evening types may adapt better to shift work and time zone changes (2,3,8,11,13,17,18,21,24,39).

Cockpit Observations

In the short-haul fixed-wing, overnight cargo, and long-haul field studies, all crews were accompanied throughout the trip by a NASA cockpit observer who held at least a private pilot's license and was familiar with air transport operations. In the helicopter field study, most crews were accompanied by a cockpit observer who was an applied psychologist familiar with helicopter operations, but not a pilot. The observers completed a log of significant operational events **(Fig. 3)** for each segment flown. They also aided crewmembers in the use and care of study equipment, and showed interested crewmembers their own physiological data during downloading of this data from the Vitalog monitor to a microcomputer.

Data Management and Analysis

For each field study, all data were entered into a relational database (Relational Information Management: NASA Contract NASA-14700). Different data types were separated into different relations, with all data for each crewmember indexed by a unique four-digit code. This organization facilitated comparative analysis among the databases, (i.e., among different types of flight operations).

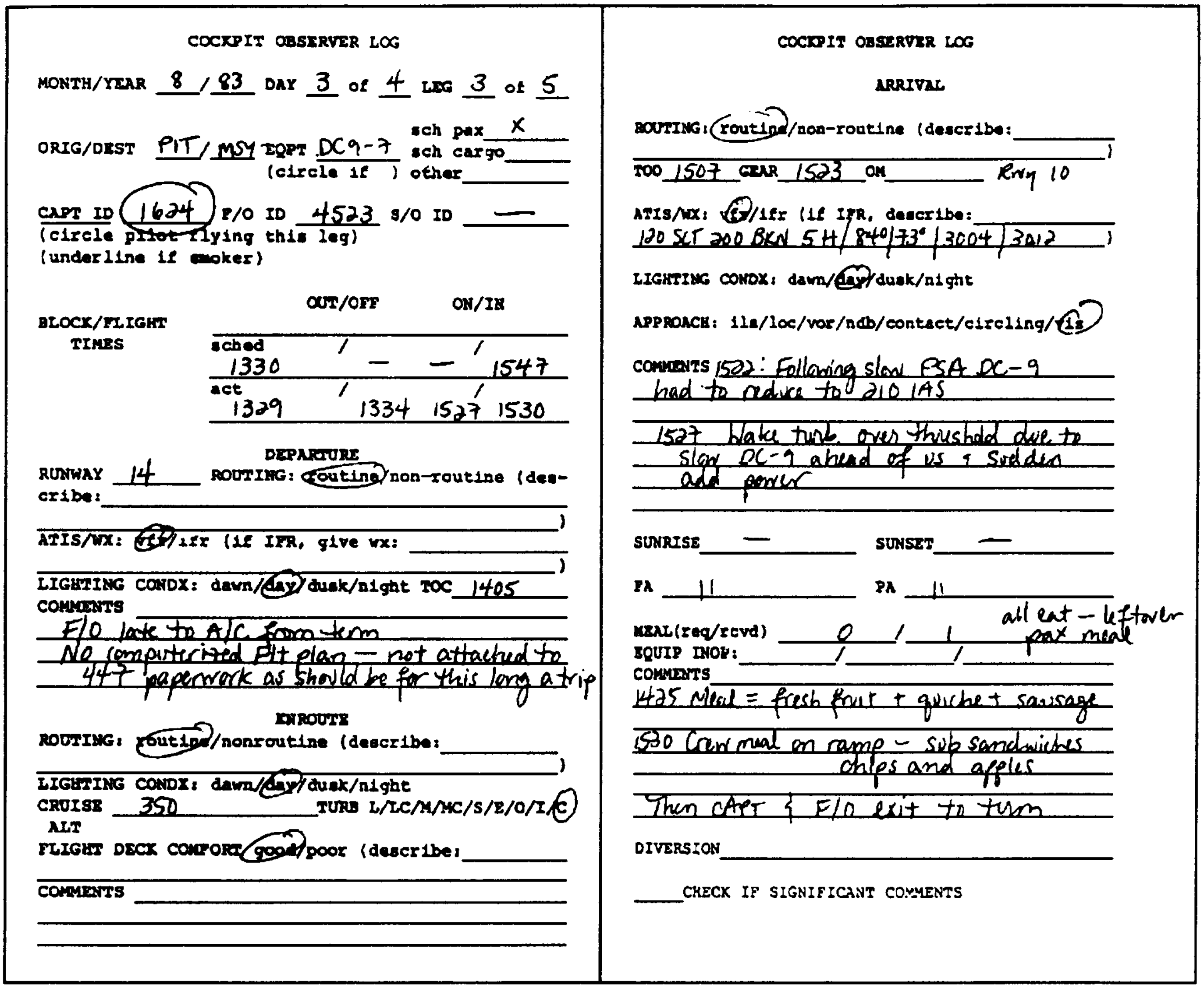
Data were accessed using the S-Plus (Statistical Sciences Inc., Seattle, WA) package which provides an interactive programming environment for data processing, analysis, and graphics. S-Plus was used for primarily for preliminary data analyses and to produce data files in appropriate formats for the BMDP (University of California, Los Angeles) and ANOVA (analysis of variance; University of California, San Diego) statistical packages.

Additional Field Studies

In addition to these field studies, the NASA-Ames Fatigue and Jet-Lag Program has undertaken a variety of other studies addressing the issue of fatigue in flight operations (38). The same measures were collected in a study of the adjustment of sleep and the circadian temperature rhythm in nine Royal Norwegian Air Force volunteers operating P-3 Orion aircraft during westward and eastward flights across nine time zones. Crewmembers flew from Andoya, Norway, via an overnight layover in Brunswick, ME, to Moffett Field, CA. After at least 5 d in simulator training they undertook the return journey to Andoya. Adjustment was slower after the return eastward flight than after the outbound westward flight. The temperature rhythm of one crewmember apparently adjusted to the 9 h eastward time zone change by undergoing a reciprocal 15 h delay. More extraverted crewmembers showed larger delays of the temperature rhythm after 5 d at Moffett Field. The findings from this study are described in detail in reference 12.

An international cooperative study was conducted to better understand the effects of commercial long-haul operations on flight crew sleep. The crews that took part came from four different airlines and were based either in San Francisco, Tokyo, London, or Frankfurt. Crewmembers had their sleep and daytime sleepiness recorded polygraphically in a sleep laboratory before departing for a scheduled trip. The first flight segment of the trip crossed either 8–9 time zones westward (Frankfurt-based or London-based crews to San Francisco, San Francisco-based crews to Tokyo) or 8 time zones eastward (Tokyo-based crews to San Francisco, San Francisco-based crews to London). During the first layover, the sleep and daytime sleepiness of crews was again recorded polygraphically in a local sleep laboratory. Sleep disruption was greater after eastward than after westward flights. There was also some evidence that, after an eastward flight crossing eight time zones, morning types were more sleepy during the day than evening types. The findings from this study are described in detail in reference 14.

To address the issue of age-related changes in circadian rhythms and sleep, a meta-analysis was carried out on combined data from all the fixed-wing commercial field studies together with identical measurements from military flight crews in a number of different types of fixed-wing operations (a total of 205 crewmembers aged 20–60, of whom 91 gave complete baseline physiological data). Older crewmembers were more morning-type,



COCKPIT OBSERVER LOG

MONTH/YEAR 8 / 83 DAY 3 of 4 LEG 3 of 5

ORIG/DEST PIT / MSY EQPT DC9-7 sch pax X sch cargo ___ (circle if) other ___

CAPT ID (1624) F/O ID 4523 S/O ID —
(circle pilot flying this leg)
(underline if smoker)

BLOCK/FLIGHT TIMES	OUT/OFF		ON/IN	
sched	1330	—	—	1547
act	1329	1334	1527	1530

DEPARTURE

RUNWAY 14 ROUTING: (routine)/non-routine (describe:)

ATIS/WX: (vfr)/ifr (if IFR, give wx:)

LIGHTING CONDX: dawn/(day)/dusk/night TOC 1405

COMMENTS
F/O late to A/C from term
No computerized Flt plan — not attached to 447 paperwork as should be for this long a trip

ENROUTE

ROUTING: (routine)/nonroutine (describe:)

LIGHTING CONDX: dawn/(day)/dusk/night

CRUISE ALT 350 TURB L/LC/M/MC/S/E/O/I/(C)

FLIGHT DECK COMFORT (good)/poor (describe:)

COMMENTS

COCKPIT OBSERVER LOG

ARRIVAL

ROUTING: (routine)/non-routine (describe:)

TOD 1507 GEAR 1523 OM ___ Rwy 10

ATIS/WX: (vfr)/ifr (if IFR, describe:
120 SCT 200 BKN 5H / 84°/73° / 3004 / 3012)

LIGHTING CONDX: dawn/(day)/dusk/night

APPROACH: ils/loc/vor/ndb/contact/circling/(vis)

COMMENTS 1522: Following slow PSA DC-9 had to reduce to 210 IAS
1527 Wake turb. over threshold due to slow DC-9 ahead of us & sudden add power

SUNRISE — SUNSET —

FA 11 FA 11

MEAL(req/rcvd) 0 / 1 all eat — leftover pax meal

EQUIP INOP: / /

COMMENTS
1435 Meal = fresh fruit + quiche + sausage
1530 Crew meal on ramp - sub sandwiches chips and apples
Then CAPT & F/O exit to term

DIVERSION

___ CHECK IF SIGNIFICANT COMMENTS

Fig. 3. Example of the cockpit observer log. One such report was completed for every segment flown.

and their pretrip baseline temperature rhythms were of lower amplitude than those of younger crewmembers. Among crewmembers flying long-haul operations, those aged 50–60 averaged 3.5 times more sleep loss per duty day than those aged 20–30. The findings from this study are described in detail in reference 13.

DISCUSSION

The primary objective of the four fatigue field studies was to measure the extent of fatigue in different types of flight operations, and to better understand the factors producing it. To ensure that data were as representative as possible, data gathering procedures were designed to cause minimum disturbance to the normal flow of flight operations, and crewmembers were instructed to continue their usual behavior. The strength of observational field studies is that they document real-world behavior as faithfully as possible. This gives them face-validity with the operational community. Their major weakness is that, although they may indicate correlations between different factors, they cannot investigate cause and effect. This requires controlling some factors while systematically varying others. Thus, observational field studies and controlled laboratory studies are complementary. For this reason, we have drawn heavily on the scientific literature to interpret the findings from these field studies. Particular emphasis was placed on sleep changes and circadian disruption because of the extensive scientific literature linking these physiological factors to degradation of alertness and performance (e.g., 1,6,25,26). In these four studies, no attempt was made to measure cockpit performance. More recent studies have included measures designed to probe the functional capability of crewmembers (37).

Simulator studies offer a useful compromise between operational realism and experimental control. An early study by Klein and colleagues showed circadian variation in simulator performance, and greater performance disruption after eastward vs. westward transmeridian flights (22). As part of the NASA-Ames Fatigue and Jet-Lag Program, a simulator study was conducted in which two-person short-haul crews flew a simulator scenario either as the first leg prior to a scheduled short-haul trip or as the final leg after a 3-d scheduled short-haul trip (9). The crews who had flown together out-performed the crews who had not flown together in every performance category. This was attributed to their improved crew coordination. The fatigue measures used did not permit a definitive statement about possible differences in fatigue between the two groups.

The four fatigue field studies are distinctive because of the broad diversity of measures that were collected. Large individual variability was observed in most measures. Therefore, to identify duty-induced changes, within-subjects comparisons of pretrip, trip, and posttrip values were the analytical technique of choice. A unique aspect of these studies is that the same measures were collected in different operational settings, which permits comparisons of the fatigue induced by different kinds of operational demands. This work thus provides a more comprehensive picture of fatigue in flight operations. The following four papers describe in detail the results and implications of the individual studies. The final paper provides comparative analyses and an integrated overview of the findings.

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