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METABOLIC RATE AND HEAT STRESS ASSOCIATED WITH FLYING MILITARY ROTARY-WING AIRCRAFT

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This report focuses on the metabolic rates of front- and rear-seated crewmembers operating military rotary-wing aircraft. A review of the literature was performed and summarized to include U.S. Army and NATO aircraft. Based on the findings of this report, piloting such aircraft requires very light to light metabolic intensities (105-240 watts). Preflight activities and crewmember duties are considered moderate metabolic intensity (206-490 watts). The operational scenario for military aviators is described along with a brief explanation of U.S. Army helicopters including a summary of general crewmember tasks. Since heat stress is a limiting factor in the helicopter cockpit, a summary of temperature data is also included. Although temperature control devices have shown some success in alleviating heat stress in the cockpit, there is still evidence of decrements in aviator performance mainly due to wearing impermeable chemical protective clothing.

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TECHNICAL NOTE

METABOLIC RATE AND HEAT STRESS ASSOCIATED WITH

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by

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EXECUTIVE SUMMARY

This report focuses on the metabolic rates of front- and rear-seated crewmembers operating military rotary-wing aircraft. A review of the literature was performed and summarized to include U.S. Army and NATO aircraft. Based on the findings of this report, piloting such aircraft requires very light to light metabolic intensities (105-240 watts). Preflight activities and crewmember duties are considered moderate metabolic intensity (206-490 watts). The operational scenario for military aviators is described along with a brief explanation of U.S. Army helicopters including a summary of general crewmember tasks. Since heat stress is a limiting factor in the helicopter cockpit, a summary of temperature data is also included. Although temperature control devices have shown some success in alleviating heat stress in the cockpit, there is still evidence of decrements in aviator performance mainly due to wearing impermeable chemical protective clothing.

INTRODUCTION

The metabolic demand of flying has been studied since the early 1940s. Most of the early research involved U.S. Army fixed-wing fighter pilots and focused primarily on the effects of altitude and anoxia (9,29,33,43,54,58). These studies typically reported pulmonary and respiratory data which are insufficient in determining the metabolic requirement. Since these early studies, both the United States and United Kingdom have conducted numerous studies regarding the effects of heat stress on helicopter aviators. A review of the literature was compiled to determine the required removal of metabolic heat of front and rear crewmembers in rotary-wing aircraft. This information was requested by the U.S. Army Natick Research, Development and Engineering Center in support of the U.S. Army Air Warrior program. Computerized literature searches were performed by the Defense Technical Information Center (DTIC) and MEDLINE covering the period from 1976-1997 using the following key words: energy cost, heat strain, and helicopter pilots. Multiple searches were expanded beyond the United States to include all NATO countries. Documents were traced back as far as 1942 using references included in reports found in the expanded search.

US ARMY HELICOPTER DESCRIPTIONS

In order to assess the metabolic demands of Army aviators, it is necessary to include a brief description of cockpit and cabin configurations in a range of Army rotary-wing aircraft (30). The AH-64 (Apache) is a twin-engined attack helicopter with a crew of two in tandem: co-pilot gunner in front, pilot behind on an elevated seat. It accommodates a crew of two, but is also single-pilot operable. The OH-58 (Kiowa Warrior) is a turbine powered light observation helicopter. The forward crew compartment seats pilot and co-pilot side by side. The Kiowa Warrior provides the capability of performing scouting and observation missions using various weapon systems. The RAH-66 (Comanche) is an armed reconnaissance for attack helicopter and is one of the newest editions to the Army replacing the AH-1, OH-58, and OH-6. There is little technical data available on this helicopter. The UH-60 (Blackhawk) is a twin-turbine combat troop assault helicopter accommodating a crew of three, with the pilot and co-pilot on armor-protected seats. The main cabin is open to the cockpit to provide communication with flight crew and forward view for the squad commander. It can carry 11 to 22 combat equipped troops and is equipped to sling-load light vehicles and equipment. The Blackhawk is often used as an air ambulance carrying up to four litter patients. The CH-47 (Chinook) is a twin-engined medium transport helicopter. There are dual controls for two pilots on the flight deck, with a jump seat for the crew chief or combat commander. The main cabin accommodates 33 to 44 troops, or 24 litters plus two attendants. Seats can be removed to allow transport of vehicles and freight. Special Operations Aircraft (MH-60K and MH-47E) are similar in design to the Blackhawk and Chinook with additional avionics.

TASKING DESCRIPTIONS

The following information was compiled regarding the physical tasks of front and rear crewmembers in U.S. Army rotary-wing aircraft. Several electronic and telephone contacts were made to the U.S. Army Aeromedical Research Laboratory at Fort Rucker, Alabama. Some information was obtained by telephone conversations and training/field manuals (10-22). The reconnaissance, attack, and observation helicopters require one or two pilots. These pilots are sitting in a confined space where arm and leg movement is limited to reaching and bending. In the utility and transport models, greater metabolic demands are placed on crewmembers. These helicopters involve loading and hoisting procedures which may involve standing, reaching, kneeling and bending. Preflight activities for most helicopter models are numerous, including outside inspection of the aircraft, arming, and refueling. Forward arming and refueling point (FARP) organizations provide fuel and ammunition for aviation units in combat (6). Taskings may involve kneeling, squatting and climbing.

FINDINGS

There are sparse data on the metabolic rates of front and rear helicopter crewmembers operating U.S. Army helicopters. By expanding the literature review beyond the United States, reports containing data involving other similar types of helicopters and helicopter simulators were found. **Table 1** is a summary of metabolic data compiled from reports on various helicopter operations dating back to 1967. **Table 2** is a chart of metabolic rates associated with helicopter flight by Thornton *et al.* (49). Metabolic rates have been converted to watts for standardization purposes.

Table 1. Summary - Metabolic Data For Helicopter Operation

AUTHOR	PREFLIGHT		FLIGHT		TYPE OF HELICOPTER
	WORK	TIME	WORK	TIME	
Joy 1967 (US-Army)	n/a	n/a	140 W (est.)	n/a	OV-1 (Mohawk)
Littell and Joy 1969 (US-Army)	n/a	n/a	120 W	n/a	OH-6A, UH-1D, CH-47A
Kaufman *et al.* 1970 (US-Army)	n/a	n/a	90 W (routine) 130 W (emerg)	n/a	J-CH3
Billings *et al.* 1970 (US-Army)	220 W (206-234 W)	approx. 12 min	183 W (150-216 W)	approx. 20 min	Hiller 12-E Hiller 12-EL
Gibson *et al.* 1978 (UK-RAF)	343 W (305-380 W)	n/a	120-150 W	n/a	sortie simulation
Belyavin *et al.* 1979 (UK-RAF)	408 W (325-490 W)	w/r	120-150 W	w/r	sortie simulation
Thornton *et al.* 1983 (UK-RAF)	n/a	n/a	200 W (pilot) 330 W (crew)	2 hrs w/r	sortie simulation
Thornton *et al.* 1984 (UK-RAF)	275 W (G) 418 W (P)	n/a	128 W (G) 197 W (P)	n/a	Gazelle (G) Puma (P)
Thornton *et al.* 1985 (UK-RAF)	walking	10 min	200 W (pilot) 330 W (crew)	2 hr w/r	simulation (Puma)
Kaufman *et al.* 1988 (US-Navy)	n/a	n/a	120-150 W	7 min. periodic	8 hr chamber simulation
Vallerand *et al.* 1991 (DCIEM)	walking	10 min	240 W	150 min w/r	chamber simulation
Thornton *et al.* 1992 (US Army)	370 W	10 min	n/a	2 hrs 3x/day	UH-60 helicopter simulator
Reardon *et al.* 1996 (US Army)	357- 426 W	10 min	n/a	4 hrs	UH-60 helicopter simulator
Reardon *et al.* 1997 (US Army)	370 W	20 min	n/a	2 hrs	UH-60 helicopter simulator

w/r - work/rest
n/a - not available

Table 2 - Metabolic Data Associated With Helicopter Flight

SOURCE	AIRCRAFT TYPE	MEAN AND RANGE OF ENERGY EXPENDED (watts)		
		REST	LEVEL FLIGHT	HOVER
Littell and Joy (1969)	OH-6A (Light)	115 (104-124)	106 (102-109)	144 (135-154)
	UH-1D (Medium)	107 (98-117)	106 (102-109)	118 (107-130)
	CH 47A (Heavy)	104 (91-117)	111 (107-117)	133 (130-137)
Billings *et al.* (1970)	UH-12E (Light)	104 (94-109)	157 (137-172)	209 (183-237)
Kaufman *et al.* (1970)	J-CH3 (Heavy)	115 (107-120)	111 (106-118)	—
French *et al.* (1973)	Scout (Light)	91 (83-94)	107 (85-131)	120 (117-128)
Thornton *et al.* (1984)	Gazelle (Light)	89 (67-100)	122 (100-133)	139 (133-167)
	Puma (Medium)	113 (96-161)	181 (128-289)	215 (161-320)

Adapted from: Thornton R., G.A. Brown and C. Higenbottam. The Energy Expenditure of Helicopter Pilots. Aviat Space Environ Med, 55:746-50, 1984.

As indicated in **Table 1**, the work of Joy (32) appears to be one of the first studies of U.S. Army helicopter pilots. A standard utility uniform with an armored vest was worn. Metabolic heat production was not measured, but estimated from the literature at 120 kcal per hour (140 watts). Littell and Joy (37) collected metabolic data on helicopter pilots during actual flight, which averaged 1.72 kcal/min (120 watts). Pilots wore a standard flight suit with a rubber mask. No significant differences were found in the metabolic rates of pilots flying in the observation, utility, and cargo helicopters studied. Experienced pilots showed no gross difference in the metabolic rates of piloting such aircraft. In 1970, studies by Kaufman *et al.* (34) and Billings *et al.* (4) were performed in older helicopters models: J-CH3 (gas turbine-powered) and Hiller 12-E/12-EL (reciprocating engine utility model). Clothing descriptions were not reported in either study. Kaufman *et al.* (34) reported military pilots flying in the heaviest aircraft of 1970 had relatively low metabolic rates, and the metabolic requirements of operating modern aircraft were not markedly different from older aircraft. They concluded that even with the pilot assist systems inoperative, pilots worked only about as hard as truck drivers (80 kcal/m^{2}hr). This is the equivalent of approximately 148 watts, which is achieved during emergency flight in a J-CH3 helicopter. They also stated that experienced and inexperienced test pilots did not show statistically significant differences in metabolic requirements. Billings *et al.* (4) concluded that metabolic rate in some flight patterns were 70% higher than at rest, and crosswind hovering in strong winds required double the resting metabolic rate.

Since 1970, all studies listed in **Table 1** involved chemical defense clothing ensembles, and most were simulated flight. Metabolic rates during flight ranged from 90-240 watts. According to USARIEM Technical Report 91-2 (56), this is considered to be very light to light metabolic work. Thornton *et al.* (49) stated that the metabolic rate during flight is 50% greater than sitting at rest. Investigation of the literature indicates Thornton *et al.* (48) are the first to distinguish differences in the metabolic rates of pilots and crewmembers. Crewmembers metabolic rates were determined to be approximately 330 watts, which is considered moderate metabolic intensity (56). Preflight metabolic rates range from 206-490 watts. This would be classified as light to moderate metabolic intensity (56). Bjorn *et al.* (5) stated that aircrew metabolic requirement during preflight is double the metabolic requirement of flight. The metabolic rates shown in **Table 1** seem to confirm these findings.

HEAT STRESS CONDITIONS

In review of the literature, it appears that a great deal of effort has been made to assess helicopter cockpit temperature and aviator performance. A U.S. Army Engineer Research and Development Laboratories Conference (55) set wet bulb globe temperature (WBGT) limits for aircraft at 88°F for pre-flight activities and 85°F for in-flight operations. Simulated studies by Bell Helicopters (31) reported cockpit temperatures in bright sunlight will be at least 10°F above ambient temperatures. Breckenridge and Levell (7) studied heat stress in the cockpit of the AH-1G Huey Cobra helicopter parked in direct sunlight using a "sweating" copper manikin. They found a relationship which indicated that a pilot would store heat at an ambient WBGT above 80°F. Cockpit temperatures as high as 134°F were reported.

Moreland and Barnes (41) found pilot performance decreased and performance variability increased above an ambient WBGT of 85°F. Belyavin *et al.* (3) used a mathematical model to predict aircrew flying at a WBGT of 28.9°C (84°F) in chemical defense clothing may reach an unacceptable level of mean body temperature within 40 minutes, and deep body temperature will rise at 1°C per hour with no plateau in rise noted. Froom *et al.* (23,24) concluded the greenhouse effect results in a cockpit WBGT which is significantly higher than ambient conditions. Studies such as these warranted further investigation and development of cockpit temperature control devices.

Army aviators often fly in a hot environment while wearing chemical protective clothing (CPC). Several studies show pilot performance decrements while wearing various configurations of CPC during actual and simulated helicopter missions (1,27,35,36,38,44,45,46,50,53). Microclimate cooling devices in conjunction with CPC have shown improvement in aviator performance (2,8,28,40,47,51).

Guidance for operation of fighter aircraft at low altitude in hot weather was conducted by Nunneley and Stribley (42) for the U.S. Air Force. The Fighter Index of Thermal Stress (FITS) table yields an estimate of cockpit thermal stress in fixed-wing aircraft. Manton and Hendy (39) document thermal stress in aircrew operating in the cabin and cockpit of the Royal Australian Navy (RAN) Sea King helicopter. The Sea King Index of Thermal Stress (SKITS) provides guidelines for the tolerable exposure of RAN Sea King aircrew during low level operations. Guidelines such as FITS and SKITS are necessary for field commanders to assess heat stress risks while planning and implementing flight missions. A comprehensive study by Thornton *et. al* (52) in the

Blackhawk helicopter provides equations for use in further thermal modeling studies of helicopter simulators. Further assessment of cockpit temperature and heat stress indices for aviators is necessary to improve the helicopter cockpit environment.

CONCLUSION

Although the metabolic rates of helicopter crewmembers is very light to moderate, the potential greenhouse effect of the helicopter cockpits may create debilitating heat stress situations for Army aviators. The continuous improvement of cockpit climate and microclimate cooling devices warrants further research efforts to provide heat stress indices and guidelines for Army aviators.

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