Unmanned Aircraft System (UAS) Operator Error Mishaps: An Evidence-based Prioritization of Human Factors Issues

Anthony P. Tvaryanas, Maj, USAF, MC, FS
311th Performance Enhancement Research Division
2485 Gillingham Drive
Brooks City-Base, TX 78235-5015

anthony.tvaryanas@brooks.af.mil

William T. Thompson, MA
United States Air Force School of Aerospace Medicine Clinical Sciences Division
2507 Kennedy Circle
Brooks City-Base, TX 78235-5015

bill.thompson@brooks.af.mil

ABSTRACT

The validity of previous human factors data may be called into question when technology changes rapidly or new and radical designs are introduced as with the advent of unmanned aircraft systems (UASs). The purpose of this study was to analyze the role and pattern of active and latent human failures in USAF MQ-1 Predator UAS mishaps using the Human Factors Analysis and Classification System. A mishap database was constructed and a factor analysis performed to detect structure in the relationships between latent and active failures and hence mishaps. The linkages between latent ant active failures identified from the factor analysis were used to construct a decision tree, allowing a quantitative comparison of the utility of addressing specific latent failures. Additionally, three cross sectional analyses were conducted to determine the prevalence odds ratios for human causal factors and phase of flight, mission type, and crew composition. Overall, human error was the most common cause of MQ-1 Predator UAS mishaps and four recurring patterns of error were identified. Based on the utility analysis, preventing mishaps is best accomplished by addressing latent failures involving organizational factors and the technological environment. There was a greater likelihood for mishaps to involve perceptual factors and perceptual errors during launch and recovery operations and training operations and organizational climate factors and violations during operations other than training.

1.0 INTRODUCTION

> *We cannot change the human condition, but we can change the conditions under which humans work - James Reason.*

Since humans are a system of chronobiological systems, human performance is inherently unstable and varies both predictably and unpredictably over time based on a variety of intrinsic and extrinsic factors. It should not be surprising then that human error is implicated in a variety of occupational accidents, including

20-70 percent of United States (US) military unmanned aircraft system (UAS) mishaps.[9] If the Department of Defense (DOD) is to achieve its goal of reducing mishap rates by 50 percent, the primary causes of UAS mishaps must be addressed. However, simply increasing the allocation of resources for UAS research and development is not the answer to this problem. The solution is to refocus existing efforts so they address the most important safety issues, which obviously presumes these issues are known. Therefore, the initial step in this process is to conduct a comprehensive review of existing mishap databases to determine the factors responsible for UAS mishaps.[11]

Within the US DOD, the Human Factors Analysis and Classification System (HFACS) is the general human error framework around which current mishaps are investigated and existing mishap databases are being restructured.[1] HFACS is based on James Reason's "Swiss cheese" model of system mishaps (Figure 1). According to this metaphor, hazards are prevented from causing mishaps in complex systems by a series of defenses (e.g., the layers of cheese). Each layer of defense has unintended weaknesses or vulnerabilities (e.g., the holes in the cheese), which are dynamic and vary in size and location over time. The holes in the defenses arise for one of two reasons: active or latent failures. Active failures are the acts committed by those in direct contact with the system (e.g., UAS crewmembers and maintainers). Latent failures, on the other hand, are the inevitable "resident pathogens" within the system, arising from decisions made by designers, procedure writers, and all levels of management. When by chance the holes in the defenses align, a mishap trajectory occurs, and a hazard is allowed to cause a mishap.[1,6,10]

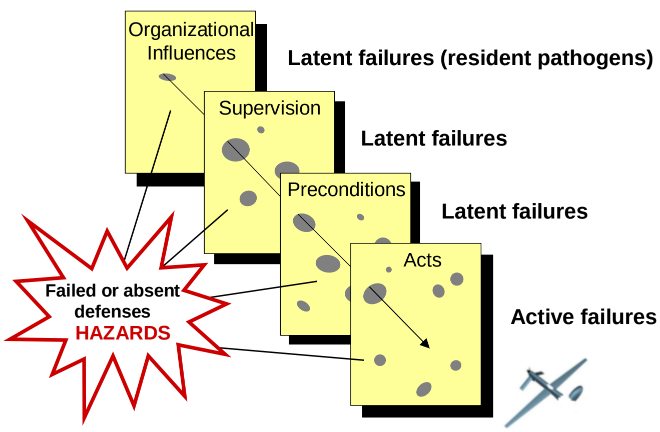

Figure 1: Reason's "Swiss cheese" model of system mishaps.

When HFACS is used as a primary tool to investigate and document an individual mishap, the end result is a case study of system failure. However, HFACS can also be used as a secondary tool to evaluate a collection of mishaps, analogous to the approach used in the medical case series or the epidemiological cross sectional study. The results of such mishap analyses are often lists or tables of observed frequencies or prevalences of active and latent failures. While such methods are useful for cataloguing the holes in the defenses, they fail to capture the linkages between active and latent failures as depicted by the mishap trajectory (e.g., the arrow representing the path from hazard to mishap) in Reason's model. This is important because, far from being random, mishaps tend to fall into recurrent patterns. Thus, the same set of circumstances tend to provoke similar errors regardless of the individuals involved.[6] Identification of these recurring patterns would capture another data element present in mishap databases as well as allow for a more systematic and potentially synergistic approach to planning human factors interventions. The purpose of the present study was to determine if it was possible to identify recurring mishap trajectories within a database of MQ-1 Predator mishaps.

2.0 METHODS

2.1 Data

The study protocol was approved by the Brooks City-Base Institutional Review Board in accordance with federal and United States Air Force (USAF) regulations on the protection of human subjects in biomedical and behavioral research. A comprehensive review of all MQ-1 Predator UAS mishaps between October 1996 and September 2005 was conducted using database records maintained by the Air Force Safety Center. The USAF defines a mishap as an unplanned occurrence, or series of occurrences, resulting in damage or injury. The USAF classifies a mishap based on the total direct mishap cost and the severity of any injury/occupational illness. Since no UAS mishaps involved injury/occupational illness, only mishap cost was a factor in classifying mishaps. All mishaps with direct costs totalling $20,000 or more require a safety investigation and report and were included in this analysis. Of particular interest to this study were occurrences not meeting reportable mishap classification criteria, but which were deemed important to investigate and report for mishap prevention. Such "near misses" included hazardous air traffic report (HATR) events, high accident potential (HAP) events, and wildlife strike events. These event reports were also included in this analysis. A total of 95 reports were identified of which 51% involved crew acts.

2.2 HFACS Classification

The 95 mishap reports were reviewed and 433 causal human factors were identified for further analysis. Each of these factors was subsequently coded independently by an aerospace medicine specialist and a research physiologist using the DOD HFACS version 6.2 framework.[1] Disagreements among the raters were noted during the coding process and ultimately resolved by discussion. No new factors were identified or mishaps reinvestigated. However, in cases where an inference could reasonably be made as to embedded human causal factors based on the mishap narrative, findings, or recommendations, codes were assigned accordingly.

2.3 Statistical Analysis

Each mishap was entered into a database regardless of causal factors along with any associated HFACS nanocodes. For each mishap, data was aggregated at the category level of HFACS to decrease the total number of cells. Statistical Package for the Social Sciences (SPSS Inc, Chicago, IL) version 11.5 principal component analysis (PCA) with varimax rotation was performed to detect structure in the relationships between HFACS categories of latent and active failure.

A decision tree was created to examine the utility of mitigating specific categories of latent failure. The results of the PCA were used to define the possible pathways from latent to active failure and hence mishaps. Proceeding from left to right through the decision tree, first the branches for categories of acts were assigned values based on their observed probabilities as calculated from the mishap database. Then the subsequent branches for categories of latent failure were assigned values based on the observed probability of their being associated with the preceding category of acts. Finally, a weighted measure of utility (e.g., probability of mishap), was calculated for each category of latent failure by multiplying the observed probabilities across the decision tree. In addition to acts, other undesirable active failures such as electromechanical failures were included in the decision tree to allow a direct comparison of the utility of addressing these causes of mishaps as well.

Three cross sectional analyses were conducted to determine the prevalence odds ratios (PORs) for causal human factors based on phase of flight, mission type, and crew composition. In the first analysis, mishaps occurring during launch and recovery operations (e.g., ground operations, takeoff, or landing), a period when the unmanned aircraft is typically operated by direct remote versus supervisory control, were compared to mishaps during enroute mission control operations. In the second analysis, training mishaps were compared to all non-training mishaps. In the third analysis, mishaps involving civilian crews were compared to mishaps involving military crews. All mishaps involving mixed crews (e.g., a combination of civilian and military crewmembers) were excluded from this last analysis. Odds ratios and 95 percent confidence intervals (95% CI) were calculated using SPSS. For any contingency table with a cell count of zero, 0.5 was added to all cell frequencies.

3.0 RESULTS

Using an exploratory factor analysis, it was possible to reduce the relatively large HFACS dataset to eight factors while still accounting for 72 percent of the variance in the original dataset (Table 1). It is important to note a factor analysis only uncovers latent mathematical structure within a set of variables. Thus, it is necessary for the researchers to verify the results are not spurious and to correctly infer the meaning of the factors. Based on the underlying premises of HFACS (e.g., the combination of an active failure and several latent failures yields a mishap trajectory and such mishap trajectories tend to recur), it was hypothesized active failures and their associated latent failures would segregate into factors representing mishap trajectories. Consistent with this hypothesis, the four categories of active failures resolved into separate factors (factors 1, 3, 4, and 6) with associated latent failures. Additionally, the latent failures technological environment, organizational processes, and resource/acquisition management resolved into a separate factor (factor 2) without any associated category of active failure. This was surprising to the researchers since these latent failures were common, were shown to be strongly associated with crew error in a prior study,[9] or both. Based on a subsequent correlation analysis, it was found factor 2 was nearly equally correlated ($p \leq 0.05$) with two factors containing active failures (factors 1 and 4). This was postulated as the cause for these latent failures not resolving into a specific factor containing an active failure. No other factors were correlated at the $p \leq 0.05$ level. Based on the results of this analysis, four recurring mishap trajectories were identified (Figure 2) accounting for 68 percent of the variance explained by the factor analysis and half the variance in the original mishap database. Table 2 summarizes the nanocodes associated with these mishap trajectories. Figure 3 diagrammatically summarizes the observed frequencies of active and latent failures as related to these mishap trajectories along with a weighted measure of utility for addressing each latent failure. The branches in the figure reflect the linkages between active and latent failures (e.g., the underlying structure) identified in the factor analysis and the values assigned to each branch reflect the observed probabilities calculated from the original dataset. The “probability of mishap” is the measure of utility, expressed as an undesirable outcome, in addressing categories of latent failure. It was calculated by multiplying from left to right across the branches of the decision tree.

Table 1: Results of the factor analysis of the mishap dataset.

Factor	Component(s)	Factor loadings	Cumulative % variance
1	*Perception error*[†]	0.943	11.757
	Perceptual factors	0.943	
2	Technological environment	0.748	22.321
	Organizational processes	0.742	
	Resource/acquisition management	0.706	
3	*Violations*	0.848	31.640
	Supervisory violations	0.685	
	Organizational climate	0.565	
4	*Skill-based error*	0.848	40.761
	Cognitive factors	0.671	
5	Self-imposed stress	0.820	49.447
	Adverse physiological states	0.680	
6	*Judgment and decision-making error*	0.869	58.095
	Planned inappropriate operations	0.594	
	Coordination/communication/planning factors	0.593	
7	Failure to correct known problem	0.868	65.059
8	Psycho-behavioral factors	0.855	71.950
	Inadequate supervision	0.491	

[†]Acts highlighted in italics.

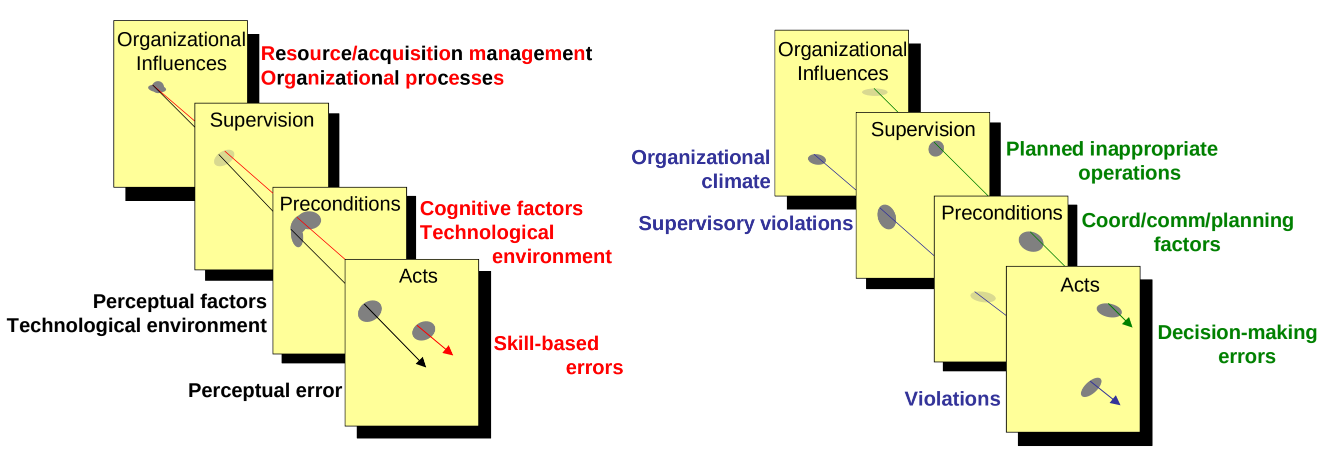

Figure 2: Pictorial representations of the recurring mishap trajectories identified from the factor analysis.

Table 2: Nanocodes associated with the recurring mishap trajectories identified in the factor analysis.

Factor	Active/latent failures & nanocodes
1	Perception error
	Perceptual factors
	Misperception of operational conditions
	Spatial disorientation (type 1) - unrecognized
2	Technological environment
	Instrumentation & sensory feedback systems
	Automation
	Controls & switches
	Communications - equipment
	Visibility restrictions
	Organizational processes
	Procedural guidance & publications
	Organizational training issues/programs
	Program & policy risk assessment
	Ops tempo/workload
	Program oversight/program management
	Resource/acquisition management
	Acquisition policies/design processes
	Personnel resources
	Air traffic control resources
	Operator support
	Airfield resources
3	Violations
	Violation - routine/widespread
	Violation - lack of discipline
	Violation - based on risk assessment
	Supervisory violations
	Supervision - discipline enforcement
	Supervision - defacto policy
	Organizational climate
	Unit/organization values/culture
	Perceptions of equipment
	Organizational structure
4	Skill-based error
	Procedural error
	Breakdown in visual scan
	Overcontrol/undercontrol
	Checklist error
	Cognitive factors
	Channelized attention
	Inattention
	Distraction
	Confusion
	Cognitive task oversaturation
	Negative transfer
	Checklist interference
6	Judgment & decision-making error
	Risk-assessment during operations
	Necessary action - delayed
	Decision-making during operation
	Task misprioritization
	Caution/warning ignored
	Planned inappropriate operations
	Limited total experience
	Risk assessment - formal
	Crew/flight makeup/composition
	Proficiency
	Limited recent experience
	Coordination/communication/planning factors
	Cross-monitoring performance
	Communicating critical information
	Mission briefing
	Rank/position authority gradient
	Task/mission-in-progress re-planning
	Miscommunication
	Standard/proper terminology
	Crew/team leadership
	Mission planning

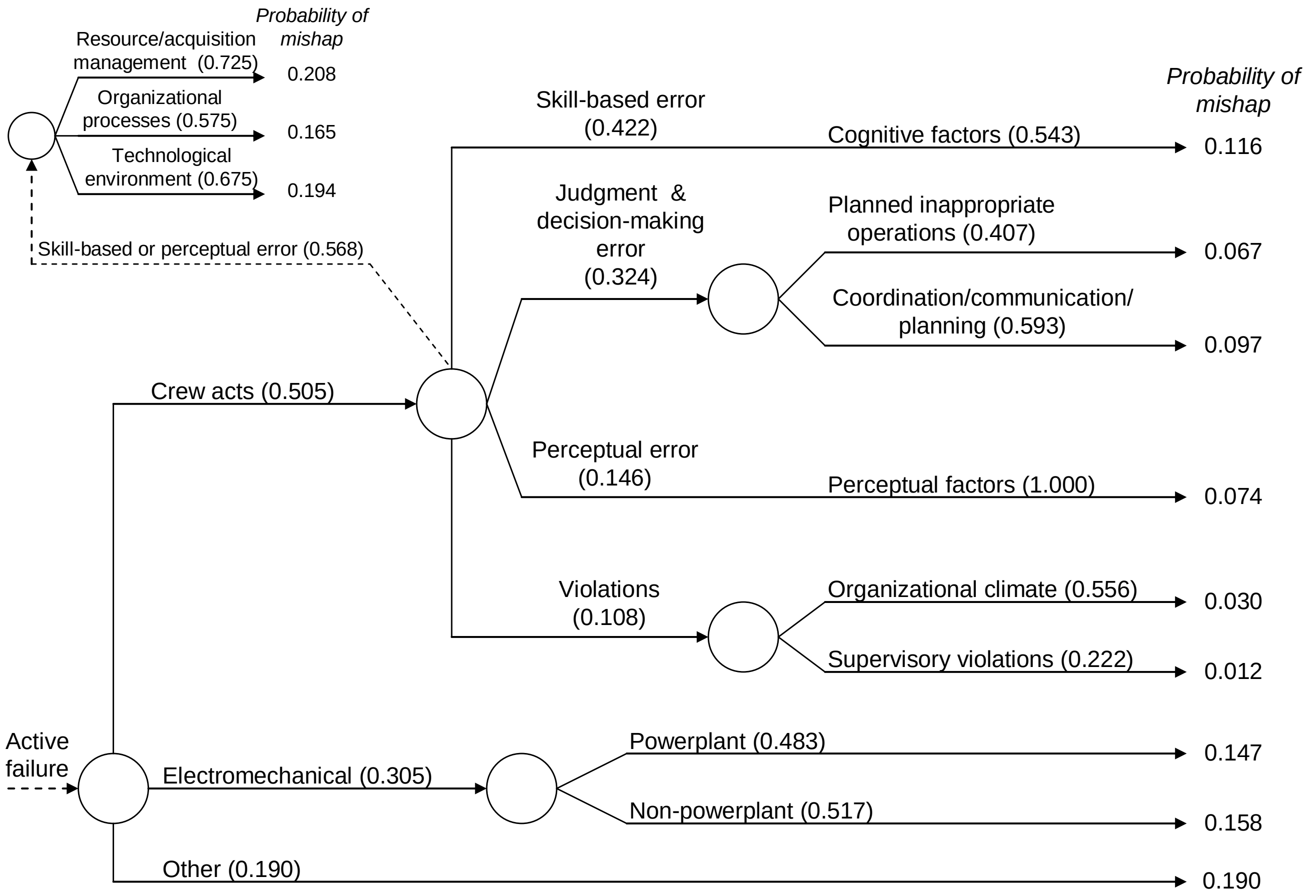

Figure 3: A decision tree concerning the utility of mitigating various latent failures contributing to MQ-1 Predator UAS mishaps.

The cross sectional analyses were limited to the subset of mishaps (n = 48, 51%) involving crew acts. In the phase of flight analysis, there were 31 (65%) launch and recovery mishaps (ground ops: n = 6, 13%; landing: n = 24, 50%; takeoff: n = 1, 2%) and 17 (35%) enroute mission control mishaps. In the mission type analysis, there were 20 (42%) training mishaps and 28 (58%) non-training mishaps (combat support: n = 23, 48%; test: n = 5, 10%). The significant causal human factors PORs for both of these analyses are summarized in table 3. In the crew composition analysis, there were 5 (10%) mishaps involving only civilian crewmembers and 24 (50%) mishaps involving only military crewmembers. Nineteen mishaps (40%) were excluded from this analysis because either the crew composition was not adequately documented in the original mishap report or the crew was composed of a mixture of civilian and military members. There were no differences in the PORs (95% CI inclusive of 1.00) for any category of active or latent failure.

Table 3: Results of cross sectional analyses for phase of flight and mission type.

Human factors	No.	%	No.	%	Odds ratio	95% CI
Phase of flight	L&R		EMC			
Perceptual error	11	35.5	1	5.9	8.80	1.03, 75.55
Perception factors	11	35.5	1	5.9	8.80	1.03, 75.55
Mission	Training		Non-training			
Perceptual error	9	45.0	3	10.7	6.82	1.54, 30.15
Violations	0	0	9	32.1	0.05	<0.01, 0.92
Perceptual factors	9	45.0	3	10.7	6.82	1.54, 30.15
Organizational climate	0	0	10	35.7	0.04	<0.01, 0.79

L&R = launch and recovery operations, EMC = enroute mission control operations.

4.0 DISCUSSION

Given the relatively large number of causal mishap factors contained in the dataset vice the total number of mishaps, each mishap would appear at first glance to be relatively unique. However, as suggested by Reason,[6] it was possible to identify recurring patterns of active and latent failures within this collection of mishaps. Additionally, it was possible to gain an appreciation of the relative importance of these common mishap trajectories. Since many non-data-driven human factors safety programs produce only marginally effective intervention strategies for reducing the occurrence and consequences of human error, the potential merits of the approach demonstrated in this study should be obvious. With that said, what does the data suggest?

First, two of the recurring mishap trajectories identified in this study are suggestive of situation awareness (SA) problems. As defined by Endsley,[2] SA involves the perception of the elements in the environment within a volume of time and space (level 1 SA), the comprehension of their meaning (level 2 SA), and the projection of their status in the near future (level 3 SA). Thus, the perceptual errors resulting from perceptual failures and skill-based errors resulting from cognitive failures related to attention issues are largely consistent with level 1 SA errors. That these mishap trajectories also included latent failures related to system design should not be surprising since SA problems are frequently caused by data overload, non-integrated data, automation, complex systems that are poorly understood, and excess attention demands.[3] It is noteworthy these two mishap trajectories were responsible for only 64 percent of crew error-related mishaps as Jones and Endsley[5] found 76 percent of pilot errors could be traced to problems with level 1 SA. Nevertheless, as with manned aviation, problems with level 1 SA were the most common cause of Predator UAS crewmember error-related mishaps. This fact is of obvious importance since work is already being devoted to level 3 SA for UAS crewmembers,[4] which presupposes crewmembers have level 1 and 2 SA. However, the major challenge in UAS operations may very well be providing sufficient information through a geographically remote interface to compensate for the cues once perceived directly.[3]

Second, three latent failures are ripe targets for intervention. These involve the HFACS categories of resource/acquisitions management, organizational processes, and technological environment. *Resource/acquisitions management* encompasses the realm of top-level decision-making regarding the allocation and maintenance of organizational assets such as equipment, personnel, and facilities. Resident pathogens are introduced into systems at this level when senior managers must make tradeoffs between the potentially conflicting goals of safety and cost.[10] Latent failures observed within this category often involved acquisition policies and design processes such as poor ground control design and failure to correct known design flaws. The *organizational processes* category refers to top-level decisions and rules which govern routine activities within an organization. It includes latent failures related to daily operations, establishment and use of standard procedures, and formal methods for providing oversight.[10] Issues observed from this category involved operational tempo, procedures and performance standards, and program and policy risk assessment. Finally, the *technological environment* category encompasses a variety of issues pertaining to cockpit or work station design.[10] Latent failures observed from this category included the design of equipment and controls, display/interface characteristics, and automation. Collectively, these latent failures had two kinds of adverse effects. They created error provoking conditions as evidenced by their association with two categories of active failures (e.g., perception and skill-based errors). They also created long lasting holes or weaknesses in mishap defenses. These latent failures were present for many years and contributed to numerous mishaps. Since human factors interventions are often constrained by the limited improvements achievable in human performance capabilities,[10] it was important to identify the association between these latent failures in order to gain synergistic effects through coordinated interventions.

Third, there were differences in the likelihood for specific categories of latent and active failures based on mishap phase of flight and mission type, but not crew composition. There was a greater likelihood for perceptual failures and perceptual errors in launch and recovery vice enroute mission control mishaps. This is not surprising since launch and recovery operations involve direct remote control of the aircraft, providing an opportunity for latent perceptual failures to manifest as perceptual errors. In contrast, enroute mission control generally involves a higher level of supervisory control, as in the use of autopilot hold modes and pre-programmed waypoints, where there is less opportunity for latent perceptual failures to be translated into acts and thus perceptual errors. Additionally, the launch and recovery task environment places greater perceptual demands on the crew, such as judging distance above the runway using a 30 degree field-of-view camera image. Likewise, training mishaps were more likely than combat support or test mishaps to involve latent perceptual failures and perceptual errors. This is expected since training missions involve inexperienced crewmembers who may still be learning where to best focus their attention for the necessary perceptual cues or who have inadequate mental models for the relatively sensory deprived UAS task environment. Nevertheless, perceptual errors overall comprised a relatively small percentage of crewmember errors. This suggests launch and recovery and training operations, rather than being relatively distinct cases, instead largely share the same vulnerabilities (e.g., organizational factors and the technological environment) as other types of operations. In contrast, there was a decreased likelihood for training operations to involve latent organizational climate failures and violations. This likely reflects the greater tendency for crews participating in combat support operations to "bend the rules" in order to accomplish mission objectives. Fortunately, violations were relatively infrequent compared to errors as a cause of crew-related mishaps.

Although a great deal of resources and effort are currently being expended to address the UAS technological environment, it is crucial this work occur in conjunction with efforts to address the other latent failures at the organizational level. For example, little will be gained by improving our understanding of how best to design UAS controls, format displays and interfaces, and implement automation if organizational planners cannot write system specifications or contractual mechanisms which incorporate these improvements. Likewise, it does little to mitigate errors by redesigning a UAS control station while not purchasing and maintaining checklists and procedural manuals as well as procuring related training devices. Thus, information regarding the technological environment needs to be appropriately communicated within the organization to top-level decision-makers. However, it is equally important those working on the technological environment seek out information on strategic decisions having the potential for introducing pathogens into the system. For example, other organizational factors such as operational tempo, time pressure, and work schedules are all variables which have been shown to adversely affect UAS crewmember performance.[7,8] Therefore, those seeking to improve UAS crewmember performance must take a broader socio-technical perspective of UASs, focusing on the technology, the organization which acquires and employs it, and their interaction.

5.0 REFERENCES

[1] Aviation Safety Improvement Task Force. Department of Defense human factors analysis and classification system: a mishap investigation and data analysis tool. Retrieved February 5, 2006, from the World Wide Web: http://afsafety.af.mil/SEF/Downloads/ hfacs.pdf

[2] Endlsey MR. Design and evaluation for situation awareness enhancement. Proceedings of the Human Factors Society 32nd Annual Meeting; 1988 Oct 24-28; Anaheim. Santa Monica: Human Factors Society; 1988.

[3] Endsley MR. Theoretical underpinnings of situation awareness: a critical review. In: Endsley MR, Garland DJ, eds. Situation awareness analysis and measurement. Mahwah: Lawrence Erlbaum; 2000:3-32.

[4] Goossens AAHE, Koeners GJM, Theunissen E. Development and evaluation of level 3 situation awareness support functions for a UAV operator station. Proceedings of the 23rd Digital Avionics Systems Conference; 2004 Oct 24-28; Salt Lake City. Los Alamitos: Institute of Electrical and Electronics Engineers Press; 2004.

[5] Jones DG, Endsley MR. Sources of situation awareness errors in aviation. Aviat Space Environ Med 1996; 67(6):507-512.

[6] Reason J. Human error: models and management. BMJ 2000; 320(7237):768-770.

[7] Tvaryanas AP, Lopez N, Hickey P, et al. Effects of shift work and sustained operations: operator performance in remotely piloted aircraft (OP-REPAIR). Brooks City-Base, TX: United States Air Force, 311th Human Systems Wing; 2006 Jan. Report No.: HSW-PE-BR-TR-2006-0001.

[8] Tvaryanas AP, Thompson WT. Fatigue in military aviation shift workers: survey results for selected occupational groups. Aviat Space Environ Med. (In press.)

[9] Tvaryanas AP, Thompson WT, Constable SH. Human factors in remotely piloted aircraft operations: HFACS analysis of 221 mishaps over 10 years. Aviat Space Environ Med 2006; 77(7):724-732.

[10] Wiegmann DA, Shappell SA. A human error approach to aviation accident analysis, the human factors analysis and classification system. Burlington: Ashgate, 2003.

[11] Wiegmann DA, Shappell SA. Applying the human factors analysis and classification system (HFACS) to the analysis of commercial aviation accident data. Proceedings of 11th International Symposium on Aviation Psychology; 2001 Mar 5-8; Columbus. Association for Aviation Psychology; 2001.