Note. This document represents an update of an earlier review of 15 select NTSB maintenance mishaps. The previous version focused entirely upon primary and contributing factors listed in the executive summary and conclusion sections. This review considers all of the evidence in the reports as written.

HUMAN FACTORS ANALYSIS & CLASSIFICATION SYSTEM – MAINTENANCE EXTENSION (HFACS-ME) REVIEW OF SELECT NTSB MAINTENANCE MISHAPS: AN UPDATE

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1. EXECUTIVE SUMMARY

To study maintainer error, the Naval Safety Center's Human Factors Analysis & Classification System (HFACS) was adapted for maintenance mishaps. The HFACS Maintenance Extension (ME) successfully profiled the latent supervisory, maintainer, and working conditions that "set the stage" for subsequent unsafe maintainer acts in Naval Aviation mishaps. In order to assess its suitability for analyzing major commercial airline accidents, a post hoc analysis was conducted on 15 National Transportation Safety Board (NTSB) reports. Two judges separately coded the mishaps, and a Cohen’s kappa of .85 was achieved, indicating an “excellent” level of agreement. Generally, HFACS-ME was able to profile maintainer errors and the factors that contribute to them. Major issues include inappropriate processes and operations, inadequate supervision and documentation, failed crew coordination, training and preparation shortcomings, judgment and decision making errors, and minor procedural violations.

2. INTRODUCTION

Marx[7] in a comprehensive review of maintenance error investigation and analysis systems, states that human error is “under-served” by traditional event investigation methods. He contends that investigations effectively end with the identification of a human error without an effort to determine why it occurred. Many have previously observed this same problem and attributed it to several factors: 1) reporting criteria, 2) investigator biases, 3) report scope, depth, and quality, 4) reporting system design, and 5) database construction[2,3,4,5,6,7]. Marx[7] reflects that many argue that through a human factors oriented investigation and reporting process “industry can now begin to understand why people make certain mistakes.”

Harle[8] posits: “accident prevention is critically linked to the adequacy of the investigation of human factors.” However, such systems can be plagued by the same issues as traditional systems if not properly designed, implemented, and supported. Zotov[9], in reflecting on the standard International Civil Aviation Organization (ICAO) reports involving human factors, states they "frequently generated more heat than light." Further, Bruggink[10] finds the reactive use of human factors accident data fails to "exploit the preventive potential of the human element that safeguards the system."

Even though there is general agreement throughout the aviation industry that human factors based investigation methods are better, they are not being widely used. Marx[7] cited that of 92 carriers trained to use the Maintenance Error Decision Aid (MEDA), only six were in the United States. He notes that this was in spite of the fact that 15 percent of air carrier mishaps are attributed to maintenance error at an annual cost of over a billion dollars. Some of the reasons cited were their tendency to place blame, not transcend the proximate causes, emphasize static who, what, and when variables and not dig for underlying causes

A conceptual framework of human error that had gained fairly wide acceptance across the government, military, and commercial sector is that established by Reason's model[11,12]. It shows unsafe individual acts were not the only accident-generating agent, and that organization processes and task/environment conditions "set the stage" for their occurrence (see Figure 1). Marx[7] lamented that despite this acceptance, the model does not provide for the identification precursors to accidents.

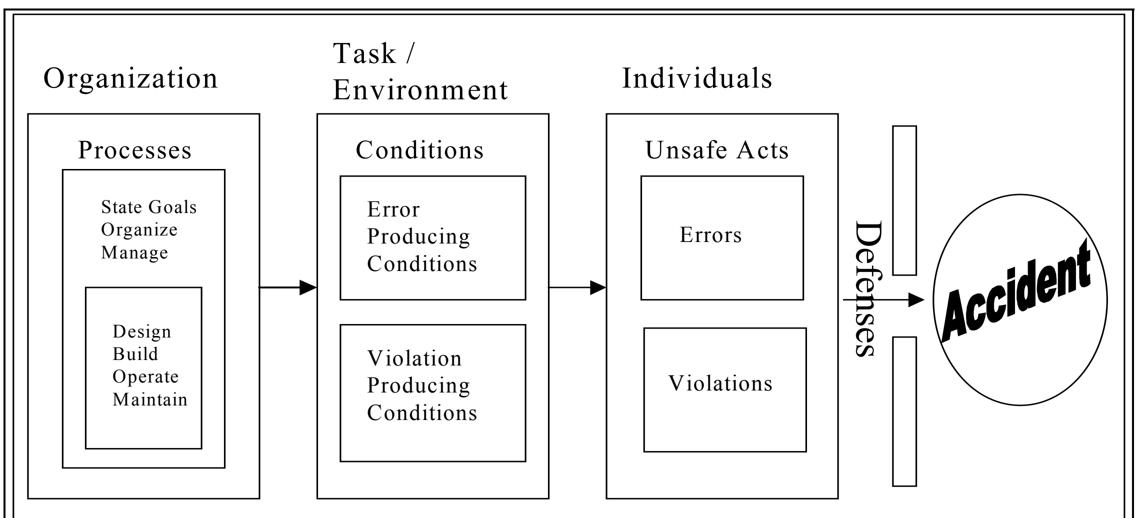

Figure 1. Reason's Model

3. HUMAN FACTORS ANALYSIS & CLASSIFICATION SYSTEM - MAINTENANCE EXTENSION

The Human Factors Analysis & Classification System (HFACS) was developed by the Naval Safety Center to analyze human errors contributing to Naval Aviation mishaps. It incorporates features of Heinrich's “Domino Theory”[13] and Edward's “SHEL Model”[14] as well as Reason's model to fully depict factors that are precursors to accidents. Latent conditions and active failures are partitioned into one of three categories (see Figure 2). These categories enable an analyst to identify failures at three levels historically related to accidents: supervisory conditions, operator conditions, and operator acts. These classifications can then be used to target appropriate intervention strategies.

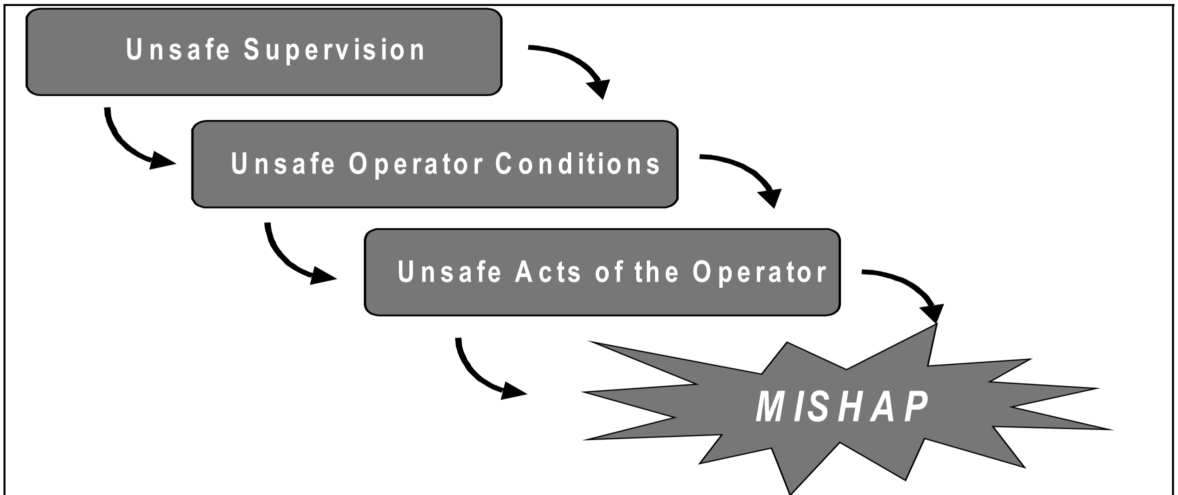

Figure 2. HFACS Component Levels

The original HFACS framework was adapted to classify human errors and other factors that contribute to Mishaps. The HFACS addition, termed “Maintenance Extension” (ME), consists of four error categories: Management Conditions (latent), Maintainer Conditions (latent), Working Conditions (latent), and Maintainer Acts (active). The three maintenance error orders reflect a shift from a molar to a micro perspective (see Table 1).

Table 1. Error Categories of HFACS-ME Framework		
First Order	***Second Order***	***Third Order***
Management Conditions	***Organizational***	***Inappropriate Processes*** ***Inadequate Documentation*** ***Inadequate Design*** ***Inadequate Resources***
	Supervisory	***Inadequate Supervision*** ***Inappropriate Operations*** ***Uncorrected Problem*** ***Supervisory Misconduct***
Maintainer Conditions	***Medical***	***Adverse Mental State*** ***Adverse Physical State*** ***Physical/Mental Limitation***
	Crew Coordination	***Inadequate Communication*** ***Inadequate Assertiveness*** ***Inadequate Adapt/Flexibility***
	Readiness	***Training/Preparation*** ***Certification/Qualification*** ***Infringement***
Working Conditions	***Environment***	***Inadequate Lighting/Light*** ***Unsafe Weather/Exposure*** ***Unsafe Environmental Hazards***
	Equipment	***Damaged/Unserviced*** ***Unavailable/Inappropriate*** ***Dated/Uncertified***
	Workspace	***Confining*** ***Obstructed*** ***Inaccessible***
Maintainer Acts	***Error***	***Attention/Memory*** ***Knowledge/Rule Based*** ***Skill/Technique Based*** ***Judgment/Decision-making***
	Violation	***Routine*** ***Infraction*** ***Exceptional*** ***Flagrant***

The following paragraphs provide a brief illustration of the HFACS-ME taxonomy levels (see the Naval Aviation Safety Program OPNAVINST 3750.6R Appendix O for a complete listing):

Latent Management Conditions that can contribute to an active failure includes both "Organizational" and "Supervisory."

Examples of Organizational Conditions include:

- A manual omits a step calling for an o-ring to be installed (Inadequate Processes)
- A technical publication does not specify torque requirements (Inadequate Documentation)
- A poor component layout prohibits direct viewing during inspection (Inadequate Design)
- A shortage of tools leads to using what is immediately available (Inadequate Resources).

Examples of Supervisory conditions include:

- A commander does not ensure that personnel wear required protective gear (Inadequate Supervision);
- An engine change is performed in a high sea state despite the risk (Inappropriate Operations)
- a supervisor does not correct cutting corners in a procedure (Uncorrected Problem)
- A supervisor orders personnel to wash an aircraft without training (Supervisory Misconduct).

Latent Maintainer Conditions that can contribute to an active failure include "*medical*," "*crew coordination*," and "*readiness.*"

Examples of maintainer medical conditions include:

- A maintainer who has marital problems and cannot focus on their work (Mental State)
- A maintainer who worked for 20 hours straight and suffers from fatigue (Physical State)
- A short maintainer who cannot visually inspect aircraft before a launch (Physical Limitation).

Examples of maintainer crew coordination conditions include:

- A maintainer who taxis an aircraft into another due to poor hand signals (Communication)
- A maintainer who signs off an inspection due to perceived pressure (Assertiveness)
- A maintainer who downplays a discrepancy to meet the flight schedule (Adaptability)

Examples of maintainer readiness conditions include:

- A maintainer who is working on an aircraft skipped the requisite OJT evolution (Training)
- A maintainer who engages in a procedure they are not qualified to perform (Certification)
- A maintainer who is intoxicated on the job (Infringement)

Latent Working Conditions that can contribute to an active failure include "*environmental*," "*equipment*," and "*workspace.*"

Examples of environmental working conditions include:

- A maintainer who is working at night does not see a tool he left behind (Lighting)

- A maintainer who is securing an aircraft in a driving rain fails to properly secure it (Weather)
- A maintainer who is working on a pitching deck falls from a ladder (Environmental Hazard)

Examples of equipment working conditions include:
- A maintainer who is using a defective test set does not precheck it before use (Damaged)
- A maintainer who works on landing gear without a jack because all in use (Unavailable)
- A maintainer who uses an old manual because a CD-ROM reader is not available (Dated)

Examples of workspace working conditions include:
- A maintainer who is working in a hangar bay cannot properly position a maintenance stand (Confining)
- A maintainer who is spotting an aircraft with his view obscured by catapult steam (Obstructed)
- A maintainer who is unable to perform a corrosion inspection that is beyond his reach (Inaccessible)

Maintainer Acts are "*active failures*," which directly or indirectly cause mishaps, or lead to **Latent Maintenance Condition**; this category includes errors and violations.

Examples of errors in maintainer acts include:
- A maintainer who is familiar with a procedure may reverse steps in a sequence (Memory)
- A maintainer who inflates an aircraft tire to a pressure required by a different aircraft (Rule)
- A maintainer who roughly handles a delicate engine valve causing damage (Skill)
- A maintainer misjudges the distance between a tow tractor and an aircraft wing (Judgment)

Examples of violations in maintainer acts include:
- A maintainer who engages in rule bending that is condoned by management (Routine)
- A maintainer who strays from accepted procedures to save time, bending a rule (Infraction)
- A maintainer due to perceived pressure omits an inspection and signs off (Exceptional)
- A maintainer willfully breaks standing rules disregarding the consequences (Flagrant).

Following the HFACS-ME, **Management, Maintainer**, and **Working Conditions** are latent factors that can impact a maintainer's performance and can contribute to an active failure, an **Unsafe Maintainer Act**. An **Unsafe Maintainer Act** may lead directly to a mishap or injury. For example, a maintainer runs a forklift into the side of an aircraft and damages it. The **Unsafe Maintainer Act** could also become a latent **Maintenance Condition**, which the aircrew would have to deal with on take-off, in-flight, or on landing. For example, an improperly rigged landing gear that collapses on touchdown or an over-torqued hydraulics line that fails in flight causing a fire. It is important to note that **Management Conditions** related to design for maintainability, prescribed maintenance procedures, and standard maintenance operations could be inadequate and lead directly to a **Maintenance Condition** (see Figure 3).

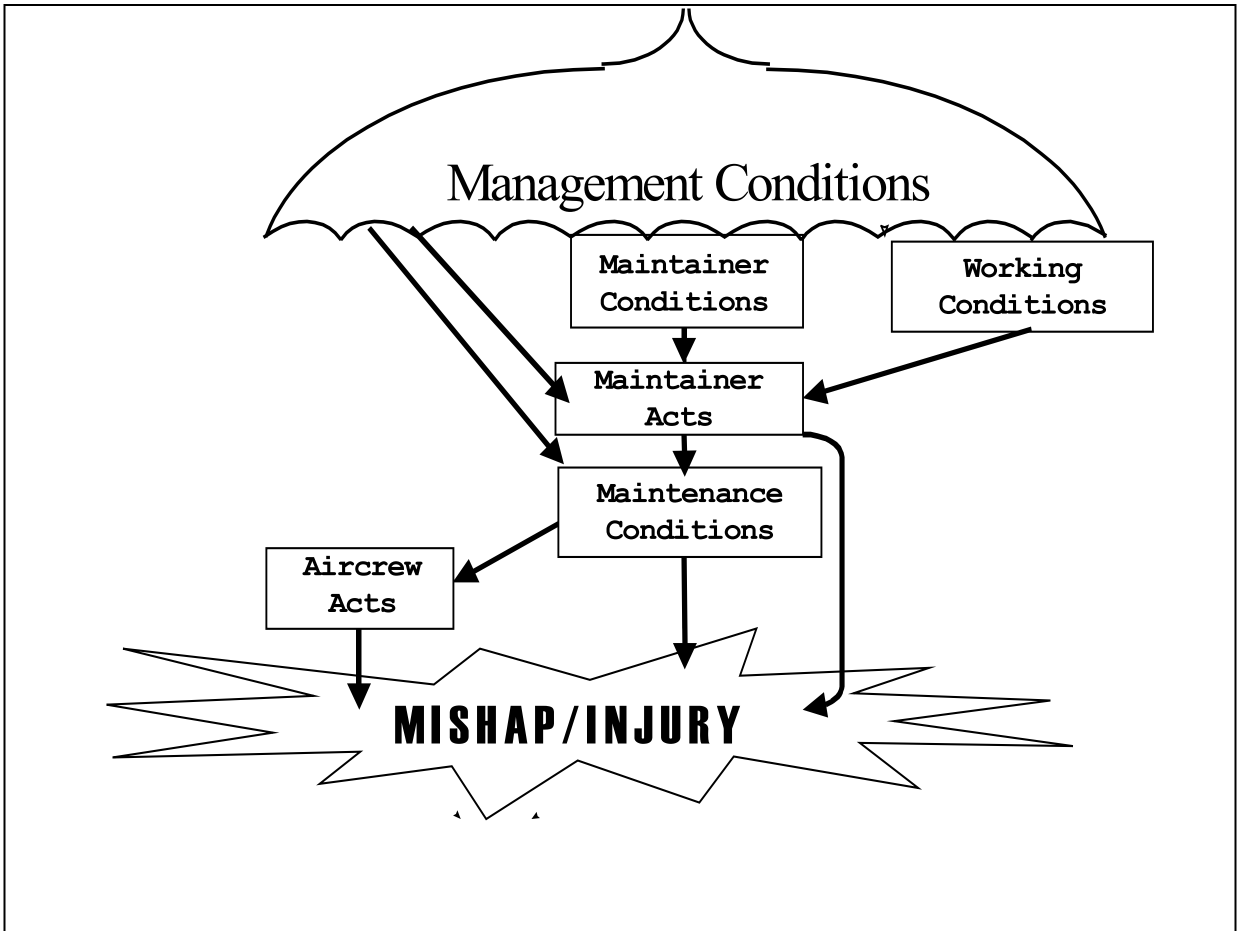

Figure 3. HFACS Maintenance Extension Model

HFACS-ME was effective in capturing the nature of and relationships among latent conditions and active failures present in Naval Aviation Class A mishaps[15]. The insights gained provide a solid perspective for the development of potential intervention strategies. The major mishaps analyzed were primarily Flight Mishaps (FMs,) meaning that many imposed in-flight Maintenance Conditions on aircrew. Subsequent analyses of Naval Aviation major and minor maintenance mishaps[16] as well as maintenance incidents and injuries[17] demonstrated the ability of HFACS-ME to capture factors leading to maintenance error.

4. OBJECTIVE

The Federal Aviation Administration (FAA) has displayed a continuing interest in the application of human error models and taxonomies to mishaps. This interest is maintained in order to facilitate the identification of human factors problem areas as well as to provide a basis for the development of tailored intervention strategies. Given a stated desire to uncover all levels of human error that contribute to a mishap and to proactively use such an analysis in prioritizing and focusing safety efforts, the FAA Office of Aviation Medicine requested that the HFACS-ME be applied post hoc to several commercial airline mishaps. In addition, the HFACS-ME was characterized according to the criteria laid outlined in the Marx report[7].

4.1 Methods

Database. The NTSB/FAA Maintenance Accident Report Infobase constructed by Galaxy Scientific Corporation for the FAA Office of Aviation Medicine contains a total of 24 NTSB accident investigation reports. The Honorable John Goglia of the NTSB provided the reports. The reports examined all had maintenance as a contributing causal factor. Infobase offers full-text search and hyperlinking capabilities that are invaluable tools for researchers and users to review past mishaps. This database provided the source of information used for this assessment.

Judges. A Navy human factors expert and a Navy Maintenance Officer, both experienced in maintenance operations and well versed in the HFACS-ME taxonomy, reviewed the Infobase reports and selected 15 (63%) as clearly having maintenance as a contributing causal factor (see Table 2). Those excluded involved an inflight lavatory fire, a lightning strike followed by a fuel cell explosion, a fatality from malfunctioning inflight service equipment, incorrect take-off/approach procedures, and catastrophic engine failures. Two judges independently coded the cases, and Cohen's kappa was calculated as a measure of agreement and reliability. A kappa of .85 was achieved, indicating an "excellent" level of agreement between the raters.

Table 2. NTSB Accident Reports Selected for Analysis

Date	Aircraft	Company
01/07/96	DC-9	ValuJet Airlines
08/21/95	EMB-120RT	Atlantic SE Airlines
06/08/95	DC-9	ValuJet Airlines
12/14/94	Learjet 35A	Phoenix Air Group
03/01/94	B747	Northwest Airlines
09/11/91	EMB-20RT	Britt Airways/Cont.Exp
07/19/89	DC-10	United Airlines
03/18/89	DC-9	Evergreen Int'l Airlines
02/24/89	B747	United Airlines
04/28/88	B737	Aloha Airlines
05/05/83	L1011	Eastern Airlines
09/22/81	L1011	Eastern Airlines
09/22/81	DC-10	Air Florida Airlines
05/25/79	DC-10	American Airlines
02/08/76	DC-6	Mercer Airlines

Procedure. Each mishap case was independently reviewed and the HFACS-ME codes for each case were entered into a spreadsheet for subsequent tabulation. Each causal factor was assigned only one HFACS-ME code, and codes were only assigned to issues clearly identified as having had contributed to the mishap. Codes that were disputed were discussed and resolved on the spot or after conferring with a third party.

Analysis. Each HFACS-ME category level was totaled and frequencies were either entered into a chart for subsequent inspection.

4.2 Results

The percentage involvement of each second level HFACS-ME factor for the 15 mishaps provided in the NTSB database is presented below (see Figure 4). There were a total of 36 maintenance causal factors taken from the 15 Mishaps, averaging 2.4 factors per case. The updated analysis (see Figure 5), which carefully sifted through all of the cases came up with 150 latent conditions (average 10 per case) that set the stage for 55 unsafe acts (average 3.7 per case). This indicates that the reports do not consistently call out all potential contributing factors that are identified during an investigation. Though these may not be major factors, their potential for reducing the chances of an incident or mitigating its consequences is not to be underrated.

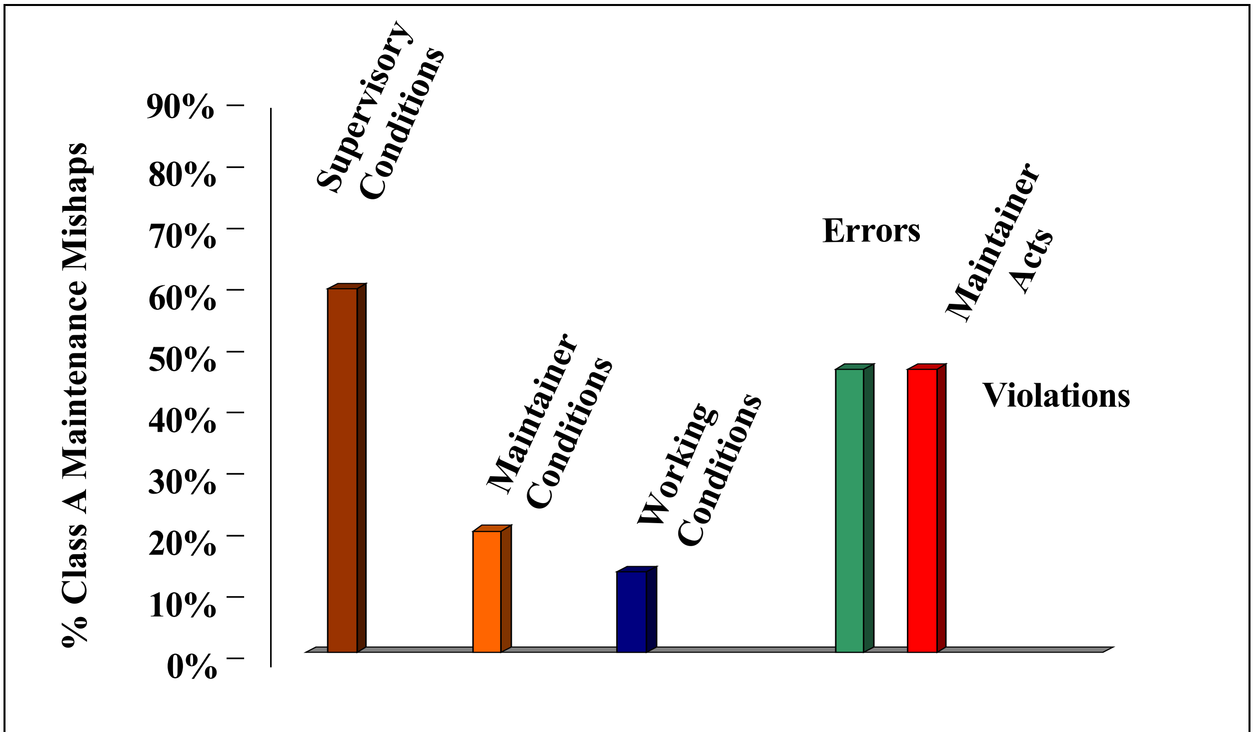

Figure 4. Original HFACS-ME Profile of 15 Select NTSB Mishaps

Supervisory Conditions – 60.0% of the 15 NTSB mishaps reported Supervisory Conditions, whereas 26.7% had Organizational Conditions (not shown).

Maintainer Conditions – 20.0% of the 15 NTSB mishaps reported primarily Crew Coordination issues. *Note: Maintainer Conditions were under reported.*

Working Conditions – 13.3% of the 15 NTSB mishaps reported primarily Environment and Workspace Conditions. *Note: Workspace Conditions were under reported.*

Maintainer Acts – 46.7% of the 15 NTSB mishaps reported Maintainer Errors, whereas 46.7% had Violations.

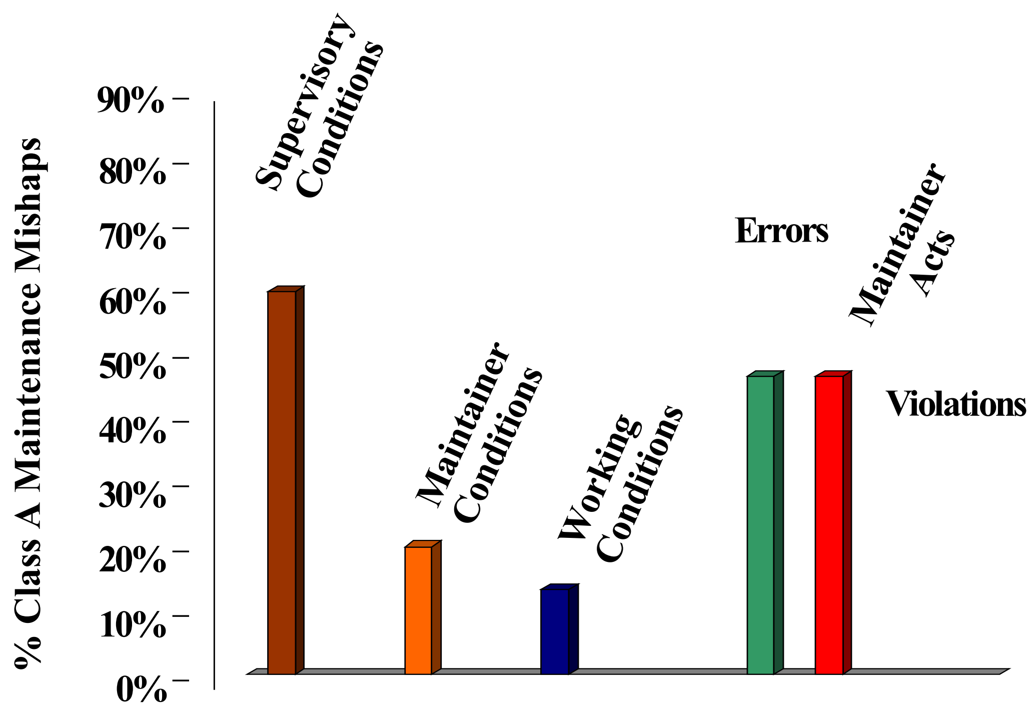

Figure 5. Updated HFACS-ME Profile of 15 Select NTSB Mishaps

Management Conditions – All of the 15 NTSB mishaps reported both having a Management Conditions that set the stage for an unsafe act and/or maintenance condition. The majority of management issues involved inadequate procedures, documentation, design, supervision, and operations.

Maintainer Conditions – 73% of the 15 NTSB mishaps reported Maintainer Conditions. The majority of maintainer issues encompass inadequate communication, adaptability/flexibility, and training/preparation.

Working Conditions – 67% of the 15 NTSB mishaps reported Working Conditions. The majority of maintainer issues cover inadequate lighting/light, unavailable/inappropriate equipment, and confining/obstructed workplace.

Maintainer Acts – 87% of the 15 NTSB mishaps reported Maintainer Errors, whereas 47% had Violations. Errors were fairly equally divided among all categories, and most violations were minor.

5. CONCLUSIONS

The HFACS-ME was effective in capturing the nature of, and relationships among, latent conditions and active failures present in NTSB mishaps. The insights gained provide a solid perspective for the development of potential intervention strategies. These major mishaps primarily occurred in-flight, meaning they imposed Unsafe Maintenance Conditions on the aircrew. Observed elements of inadequate supervision, procedures, and training, communication breakdowns on procedural changes, inspection and omission errors, and procedural violations make up the bulk of the observed human error causal factors. Based upon these findings, the primary errors sources can be prioritized and then targeted for intervention.

Since most major mishaps involve only flight operations, it is essential to evaluate the more minor ones that occur on the ramp and in the hangar. Such mishaps involve activities that can lead directly to damage to the aircraft or injury to the maintainer. Consequently, the present profile for major mishaps cannot be generalized to all mishaps of lesser severity. It is essential to apply HFACS-ME to minor incidents to get at the whole maintenance-related mishaps picture. Further, it can be contended that interventions developed for major mishaps involving maintenance activities, such as engine repair, are not likely to be appropriate for ones of lesser severity that involve other activities such as cargo loading or aircraft towing.

5.1 System Comparison Criteria

Using the criteria provided in the Marx report[7] on maintenance error investigation and analysis systems, the HFACS-ME is classified as follows:

Name:	Human Factors Analysis & Classification System-Maintenance Extension (HFACS-ME)
Characterization:	Error Investigation and Analysis Methodology
Owner:	Dept. of the Navy; U. S. Government
Scope of Investigation:	Major/Minor Events and Potential Discrepancies
Investigative Approach:	Assigned Investigators

Structured Data Analysis:	Single Event; Graphical, Aggregate Profile,Trend, & Comparative Analysis; used w/ Categorical Data Analysis, Logistical Regression, & Stochastic Modeling
Structured Prevention/ Strategy Development:	Operational Risk Management
Structured Monitoring and Feedback:	Event, Cost, & Risk Trending

The information provided depicts both the current, as well as projected attributes of HFACS-ME. To date, HFACS has been successfully applied to study major and minor mishaps, maintenance related incidents and injuries, trend and cost analysis, models of future event frequencies, and statistically significant human error patterns.

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