# Friendlier Skies: Development of Electronic Checklists for Emergency Procedures for the KC-135 Stratotanker

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The KC-135 Stratotanker has been a workhorse aircraft for the U.S. Air Force and Air National Guard for over 60 years. The aircraft and its technologies have had many modifications and updates over the decades, but the Emergency Procedures (EPs) section of the KC-135 In-Flight Manual has only been updated based on engineering modifications and incident and accident reports. The goal of this project was to systematically assess, identify, and document issues in the KC-135 EPs using aviation checklist design guidance and a crew-centric human factors approach. Electronic checklists were then created to address the issues in the KC-135 EPs. The number of emergency procedures was reduced by over 50%: 351 KC-135 EPs were streamlined into 154 electronic checklists. The revised electronic checklists for emergency procedures will optimize KC-135 crew responses to non-normal situations and ensure safe and efficient operation of the KC-135 beyond its projected sunset in 2040.



## INTRODUCTION

### KC-135 Stratotanker: A Brief History

For over 60 years, the KC-135 Stratotanker has provided aerial refueling capability for the United States Air Force, Navy, Marine Corps, and allied nation aircraft. In-air refueling creates a global reach for the U.S. military in the skies. Additionally, the KC-135 can transport cargo, troops, and/or ambulatory patients. Throughout its lifetime, the KC-135 has been upgraded many times to expand its capabilities and update its technology to meet the demands of military missions. Analog flight deck instruments have been replaced with digital instruments; communication, navigation, and autopilot systems are just a few of the systems that have been updated.

The KC-135 is operated by a three-person crew: pilot, co-pilot, and boom operator. The team works together to fly the aircraft and refuel receiver aircraft as missions demand. Fuel is transferred via the flying boom, which is controlled by the boom operator stationed at the rear of the aircraft during in-flight air refueling (Retrieved 2/28/20 from https://www.af.mil/About-Us/Fact-Sheets/Display/Article /1529736/kc-135-stratotanker/).

*KC-135 Flight Manuals.* Although the KC-135 aircraft itself has been modified and updated many times throughout its lifetime, the KC-135 In-Flight Manual has not received the same level of attention as the physical aircraft. The Flight Manual USAF Series KC-135R/T Aircraft (T.O. 1C-135(K)R(II)-1 Inflight Data) is a paper or PDF document that is over 1,000 pages long. It contains seven sections (Section II-VIII): Normal and Alert Procedures, Emergency Procedures (EP), Crew Duties, Limitations, Flight Characteristics, Adverse Weather Operation, and Air Refueling (Receiver). Section I is contained in a separate document, T.O. 1-135(K)(I)-1 Reference Data; it contains Section 1 – Systems Description and is over 1500 pages long.

Over the decades, procedures have been revised, modified, added, or removed as needed to align with engineering technological changes or with current aviation practice, or to address flight incidents or accidents. Specifically, the emergency procedures present a challenge to crews: Section III – Emergency Procedures is 367 pages long and lists 343 emergency procedures in the table of contents. Air National Guard (ANG) aircrews have long recognized the inadequacies of the KC-135 emergency procedures; the existing T.O. 1C-135(K)R(II)-1 does not support quick and easy access to these procedures.

*Line Oriented Safety Audit (LOSA) and Shell 77 Accident.* In 2013, Air Mobility Command (AMC) commissioned a LOSA of KC-135 aircrew operations. The LOSA was conducted over a 60-day period by instructor pilots and boom operators trained by industry experts in error analysis. The LOSA data indicated that KC-135 aircrews accomplished normal and abnormal procedures at grossly high error rates. A significant percentage of the errors went undetected and sometimes led to undesirable aircraft states.

Approximately six to eight use errors in normal situations were identified for each flight. A common example of such errors was that aircrews were not using checklists during indicated normal situations. Additionally, approximately 40% of flights experienced non-normal situations during which crews should have referred to the EP section of the flight manual. However, non-normal situations were so common for crews, that for the majority of those situations, the crews accomplished non-normal procedures from memory. Crews explained during post-flight interviews that they did not reference the EPs because the manual and procedures are so cumbersome they did not want to bother with it. The LOSA safety investigation board (SIB) recommended the development of a KC-135 Quick Reference Handbook (QRH), which is standard practice in aviation. A QRH is "a handbook containing checklists which may need to be referenced quickly or frequently, including emergency and abnormal checklists. The checklists may be abbreviated for ease of reference (although must reflect the procedures contained in the Flight Manual)" (Civil Aviation Authority, 2005; p. xi; see also QRH Description, https://www.skybrary. aero/index.php/ Quick_Reference _Handbook_(QRH), 2017).

During the 60-day LOSA period, a KC-135 (Shell 77) supporting Operation Enduring Freedom broke up in flight over Kazakhstan resulting in the complete loss of crew and aircraft. The accident investigation discovered a minor aircraft flight control malfunction that was misdiagnosed by the aircrew. The aircraft broke up in flight six minutes after the crew became aware of the problem. Due to the ambiguous guidance of the KC-135 EPs, the crew selected the wrong procedure. The Shell 77 Accident Investigation Board (AIB) concluded the crew was unable to determine the correct emergency procedure due to the lack of clear and concise guidance provided by the KC-135 Flight Manual.

The Shell 77 AIB recommended the Flight Manual be re-written to provide clear and concise guidance to lead the crew to the correct procedure. The Shell 77 aircrew lacked the experience to overcome the ambiguity inherent to the EPs. Although the AIB did not recommend a QRH by name, the description of the recommended solution described a procedural format consistent with all modern aircraft manufacturers' QRH format. The subsequent LOSA Safety Investigation Board did recommend the development of a KC-135 QRH to reduce aircrew procedural error.

**Emergency and Abnormal Checklist Design**

As illustrated by the LOSA and the Shell 77 accident, flight crews must have checklists that can be easily accessed during stressful non-normal situations, that quickly stabilizes the aircraft, and ideally, resolves the problem. Leveraging extant guidance on electronic checklist design and emergency checklist design for aviation, as well as using a human factors crew-centric approach, the KC-135 EPs were evaluated and re-designed.

Three high-level factors were identified by Burian (2006) to guide emergency and abnormal checklist design, content, and use: internal factors, external factors, and overall purpose.

Fourteen sub-factors comprise the internal factors and are as follows: Physical properties and interface; organization and access; typography and use of symbology; layout, format, and display; length and workload; navigation, progression, and jumping; nomenclature and abbreviations; language, grammar, and wording; purpose; objective(s); level of detail; engineering completeness; engineering coherence; and logical coherence. There are seven sub-factors that comprise the external factor of EP checklist design: specific aspects of emergency or abnormal situations; standard operating procedures (SOPs) and aviation regulations; operational requirements; human performance capabilities and limitations under high workload and stress; social and cultural influences on crew performance, behavior and checklist usage; aircraft systems requirements; philosophies and policies; flight crew training; economic constraints; and level of detail. The overall purpose represents the 35,000 foot view of the checklist: To what degree does the checklist guide and direct crew response to a non-normal situation?

Snead, Militello, and Ritter (2004) assessed B-2 (stealth bomber) crew behaviors using paper checklists via post-flight interviews and crafted guidelines for developing electronic checklists for military aviation. A summary of the guidelines are as follows:

- Reduce pilot and crew cognitive load and enable quick and easy access to all flight information,
- Consider advanced electronic checklist features in a multi-crewmember aircraft,
- Support crew's troubleshooting processes,
- Consider leveraging technologies that can support system-level assessment during multi-component malfunction situations,
- Consider passive collection of information from the aircraft to guide crews in selecting appropriate checklists,
- Hyperlinks can facilitate accessing related documents to support troubleshooting.

**Project Goal**

The goal of this project was to systematically assess, identify, and document issues in the KC-135 Flight Manual, Section III – Emergency Procedures using aviation checklist design guidance, referring to QRHs currently used by the military, and employing an overall human factors approach. The electronic checklists were developed to implement solutions that addressed weaknesses in the KC-135 EPs.

## METHOD

Aviation checklist design guidance, current QRHs, and general human factors tenets (recognizing the interaction between human capabilities and limitations, task demands, and environmental conditions) were used to guide the assessment of the KC-135 EPs. A team of human factors professionals and a team of four KC-135 pilot and boom operator subject matter experts (SMEs) conducted the assessments and developed the checklists. Collectively, the KC-135 SMEs brought the following experience to this project:

- 51 years of KC-135 pilot experience
- 25 years of KC-135 boom operator experience
- 8 years of RC-135 navigator experience (Reconnaissance aircraft similar to KC-135)
- 11 years of KC-135 maintenance experience
- 40 years of training instructor experience for pilots and boom operators
- 17 years of aviation safety consulting experience
- 12 years of pilot experience in private industry/commercial airlines.

Over a 15-month period, the dyads of SMEs and human factors experts met multiple times per week to review the existing KC-135 EPs and draft the content for the electronic checklists. Meetings with all team members were regularly held to discuss overall issues or direction of the non-normal procedures. Issues were identified and documented; streamlined electronic procedures were created. All issues and solutions were documented, and a style guide was created to support the development of the emergency checklists.

## RESULTS

The table of contents (TOC) for Section III – Emergency Procedures of the KC-135 In-Flight Manual listed 343 emergency procedures. However, 43 additional emergency procedures were identified in the body of the document itself that were not listed in the TOC. This yielded 386 emergency procedures to be reviewed and evaluated. As of March 1, 2020, 351 procedures (91%) had been reviewed, and a total of 154 electronic checklists for emergency procedures had been created. Seventy-nine KC-135 EPs have been removed from the electronic checklists due to the procedures deemed irrelevant, redundant, as training material only, or as maneuvers. Thirteen new checklists were created that do not directly map to a KC-135 EP but were identified by the SMEs as critical to include for crew safety.

The following examples provide an overview of the issues identified and solutions implemented as a function of the relevant aviation checklist guideline.

**Reduce pilot and crew cognitive load and enable quick and easy access to all flight information**

**Issue**: Of the 343 emergency procedures listed in the KC-135 EP table of contents, many had similar titles.

**Solution**: Procedures with similar titles were consolidated into fewer checklists. For example, six variations of the procedure, “Landing With Inoperative Engines” were identified in the KC-135 EPs:

- Landing With One Engine Inoperative, Rudder Power Operative
- Landing With One Engine Inoperative, Rudder Power Inoperative
- Landing With Two Engines Inoperative (One On Each Wing), Rudder Power Operative or Inoperative
- Landing With Two Engines Inoperative On The Same Wing, Rudder Power Operative
- Landing With Two Engines Inoperative On The Same Side, Rudder Power Inoperative

To reduce crew cognitive load and enable quick and easy access to relevant information, these procedures were consolidated into a single checklist called, “Engine Inoperative Landing.” Crews will select which engine(s) are inoperative and if rudder power is available as prompted in the electronic checklist.

**Issue**: Selecting the correct KC-135 EP is challenging because the conditions under which the procedure should be used is often buried in paragraphs of text.

**Solution**: Every checklist now includes a condition statement that helps users determine if they are using the correct checklist. For example, in “Engine Oil Pressure Abnormal” checklist, the condition statement states the following:

One or more of the following occur:

- Oil pressure low (less than 11 psi)
- Oil pressure high (greater than 92 psi)

• Oil pressure fluctuating or erratic
• ENG # LOW OIL PRESS illuminated.

**Human performance capabilities and limitations under high workload and stress**

**Issue**: The current KC-135 EPs are available to crews in paper format or as a PDF on a mobile device (i.e., iPad). If more than one procedure must be performed, the crewmember running the procedure must keep track of where the crew is in completion of each procedure. This situation places high demand on a crewmember's working memory.

**Solution**: Electronic checklists allow users to open as many checklists as needed. The checklists retain the last step completed by the crew, and all checklists are marked as "In Progress" or "Complete." Electronic checklists support task management and completion by reducing the working memory demands on the users.

**Issue**: In some cases, after a non-normal situation has occurred and the emergency procedure completed, the aircraft is functioning but with certain limitations. The current KC-135 EP does not summarize such aircraft limitations upon completion of an EP.

**Solution**: An operational limitation summary page was created for the electronic checklist to provide the crew with the current operational conditions of their aircraft. For example, in "Hydraulic Pressure Abnormal," if the right hydraulic system has been restored by crossing over from the left hydraulic system, the following components are not restored and are listed in the operational limitation summary page:

• Leading edge flaps
• OUTBOARD spoilers
• Nose gear steering
• Copilot brakes.

**Support crew's troubleshooting processes**

**Issue**: Many KC-135 EPs were written in prose with action steps embedded within the text. The EPs are a combination of troubleshooting steps, notes, cautions, warnings, and background and training material that does not always directly relate to the non-normal situation.

**Solution**: In collaboration with the SMEs, actions, notes, cautions, and warnings were extracted and proceduralized into checklist format to support crew troubleshooting during a malfunction. Checklists contained the following types of steps:

- Action = Noun…Action
- Caution = Notifying crew of potential damage to aircraft
- Choice = Question with up to six choices
- Navigate = Takes user from one checklist to another
- Note = Additional information that would support an action or decision
- Operational Limitation (OpLimit) = Summarizes any aircraft limitation due to a malfunction.
- Warning = Notifying crew of potential harm to crew

**Issue**: Many instances were identified in the KC-135 EPs in which an action was provided but then a note, caution, or warning appeared after the action that described the conditions under which that action should not be taken. For example, in the "Boom Hoist Cable Broken" procedure, the crew was instructed stow the boom but then provided a warning after the action that stated, "Do not stow boom when broken cable extends past ruddevators or extensive damage to airplane elevators can occur."

**Solution:** All relevant notes, cautions, and warnings were provided before the associated action. In the electronic checklist, "Hoist Cable Broken," a warning is provided about not stowing the boom if the cable extends past the ruddevators, then asks about the position of the cable, and then provides the appropriate action based upon the crew's response.

**Nomenclature**

**Issue**: Terms used in the KC-135 EPs were not consistent with crew vernacular. For example, *"[With TCTO 1823]"* and *"[Without TCTO 1823]"* were commonly used in the EPs. These are the engineering technical change designations that indicate whether the aircraft has been upgraded to the most current glass flight deck.

**Solution**: Crews refer to the aircraft as either a Block 40 [B40] or a Block 45 [B45] configuration. Therefore, all references to "TCTO 1823" were replaced with [B40] or [B45] to be consistent with crew vernacular. Crews are trained to fly both configurations of the aircraft; there are specific and critical differences between these configurations.

## DISCUSSION

The overarching goal of the electronic checklist is to provide quick, actionable steps for the crew to maintain aircraft control, identify and rectify the non-normal situation if possible, and provide guidance on how to configure the aircraft for landing if necessary. By consolidating procedures with similar actions, the number of emergency procedures was reduced by over 50%: 351 KC-135 EPs were streamlined into 154 electronic checklists. Titles were revised to describe symptoms of malfunctions to make it easier for crews to access the correct procedures. The new format follows the streamlined QRH format and presents only relevant information to crews as they need it. The checklists are searchable, reliable, and provide consistent information to the crews. Initial pilot testing of the electronic checklists with ANG crews has yielded positive feedback.

The strength of this project lies in the approach taken to address the issue of inadequate and difficult to use KC-135 EPs. Aviation checklist guidelines were leveraged and close collaboration with KC-135 SMEs was maintained throughout the duration of the project. The revised checklists were developed by KC-135 pilots and boom operators for KC-135 pilots and boom operators. The revised electronic checklists for emergency procedures will optimize KC-135 crew responses to non-normal situations and keep crews safe.

Much work must still be done as the KC-135 QRH continues to grow and mature. Verification of non-normal checklist content continues, and formal user testing with crews in simulators is planned. Testing protocols have been drafted and data collection mechanisms have been established (Krutein & Boyle, 2019). Training protocols must also be developed, tested, and implemented (see Landman et al., 2018).

This is a first step in the long-term project to develop a well-designed QRH that will guide aircrews through the diagnostic process to ensure correct selection of the emergency procedure, significantly reducing error and cockpit workload during execution, and mitigating dependency on aircrew experience. Using this approach will deliver a top-of-the-line QRH that will ensure safe and efficient operation of the KC-135 beyond the year 2040, its projected sunset.

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