

Emergency and Abnormal Checklist Design Factors Influencing Flight Crew Response: A Case Study

Barbara K. Burian

SJSUF / NASA Ames Research Center

IHS, MS 262-4

Moffett Field, CA 94035, USA

bburian@mail.arc.nasa.gov

ABSTRACT

There are a number of different factors that go into the design of emergency and abnormal checklists. How these factors may relate to checklist use and errors made when completing them is often under-appreciated. A variety of checklist design features are discussed with an emphasis on those that may have influenced a flight crew's checklist use in response to an in-flight fire.

Keywords

Emergency checklist, abnormal checklist, non-normal checklist, checklist design, checklist use, aviation accidents

INTRODUCTION

Emergency and abnormal checklists are essential tools flight crews use to respond appropriately to situations that can be very serious and time critical. Therefore, it is crucial that these checklists be complete, clear, and easy for the crews to use. Designing such emergency and abnormal checklists is not a simple task, however. In one study, 65% of the pilots surveyed said that certain procedures they were to use to respond to emergency and abnormal situations were complicated and difficult to use [4]. It is possible that design features of these checklists accounted for some of the difficulty the pilots encountered.

Only a few of the factors related to the design of emergency and abnormal checklists have been identified and discussed by the research and operational communities. The factor most commonly addressed is checklist typography [1, 3, 5, 8, 12], which includes aspects such as font type and size, the use of capital and/or lowercase letters, the use of boldface and italics, horizontal spacing between letters and words, vertical spacing between lines, and the like.

Other design factors that have been addressed to some degree are checklist layout and formatting [1, 3], immediate action items (also called memory or recall items) [3, 8], nomenclature (i.e., the names given to various switches, knobs, dials, etc.) [8, 12], and the order in which items on a checklist are presented [3, 6, 12]. Unfortunately, these factors have not been fully addressed and other factors, such as progression within and between checklists, have rarely been discussed at all.

The importance of checklist design as it relates to crew behavior in non-normal situations cannot be over-emphasized. Information contained in the accident report regarding an in-flight fire, described below, clearly illustrates this point and can be used to examine a few checklist design factors in more detail. (A more complete discussion of emergency and abnormal checklist design factors can be found in other work currently in progress [2].)

The following discussion will be limited to an analysis of checklist design features and flight crew response. I will not discuss the role that workload, stress, prior training, experience, fatigue or many external factors, such as visibility or time of day, may have had in how the crew responded to this situation, although many of these factors, and others, likely influenced the crew's behavior.

It should be noted that although the fire eventually destroyed the airplane and therefore the event was classified as an accident by the National Transportation Safety Board (NTSB), the agency did not cite checklist design, the performance of the flight crew, or any other operational factor as a causal element in the accident. In fact, the crew performed quite well in circumstances that could have led any crew to make errors. Thus, this review of the crew's actions and use of the checklists is not intended to be critical of the persons involved. Further, it should be emphasized that all of the checklists discussed in this paper have undergone several revisions since the time of the accident. Nonetheless, many of the design features discussed below are still commonly seen in emergency and abnormal checklists used by air carriers around the world, and thus bear examination.

OVERVIEW OF THE ACCIDENT

In 1996, a U.S. cargo carrier experienced an in-flight cargo fire while cruising at 33,000 feet MSL. The flight, a DC-10-10CF aircraft with three flight crew members and two jumpseat passengers on-board, made an emergency landing at 0554 eastern daylight time. All aboard barely escaped the burning aircraft, which was eventually destroyed by the fire [9].

The event began when the cabin/cargo smoke warning light illuminated on the flight deck 18 minutes before their emergency landing. The flight engineer announced the memory items from the FIRE & SMOKE checklist and the crew completed them. While completing the rest of this

checklist, the flight engineer accomplished the items related to the conditional checklist branch for “If Descent is NOT Required,” apparently without input from the captain [9].

On the second emergency and abnormal checklist he completed (CABIN CARGO SMOKE LIGHT ILLUMINATED), the flight engineer did not perform two steps and did not perform the actions necessary for proper completion of a third step. The captain did not call for and the crew did not complete emergency descent or evacuation checklists and, upon landing, the aircraft was still partially pressurized which delayed their evacuation [9].

CHECKLIST DESIGN ANALYSIS

Six DC-10 emergency and abnormal checklists were included in the NTSB docket for the accident:

- FIRE & SMOKE
- CABIN CARGO SMOKE LIGHT ILLUMINATED
- COCKPIT / CABIN SMOKE REMOVAL
- AIR CONDITIONING SMOKE
- CARGO FIRE LIGHT ILLUMINATED (FWD OR AFT)
- DC-10 EMERGENCY EVACUATION (LAND)

A number of features pertaining to typography and layout in these checklists conform with current “best practices” in checklist design [5]. These include the use of a sans-serif font, a mixing of lowercase with uppercase letters for portions of checklist items, checklist titles that are clearly distinguished from checklist items, an indication marking the end of a procedure, good use of white (blank) space in relation to printed text, and good legibility and readability.

However, some deficiencies related to typography and layout also occur. For example, it is desirable to present smoke and fire checklists in a larger than normal font size to increase readability of the items in low visibility conditions [10]. The font size used for the accident aircraft smoke and fire checklists appears to be rather small. However, the move in the industry to use a larger font size for these types of checklists is fairly recent, and has not yet been uniformly adopted.

The following analysis will focus on concerns with the design of these checklists rather than on checklist items or features that were good. Except for the three items that were not completed properly, the crew responded as the checklist designers intended despite some of the checklist design issues described below. Additionally, a few other checklist design concerns that were not related to this accident will also be discussed. Portions of these checklists, as they appeared in the NTSB docket, are re-created below. On the original checklists included in the docket, the items were printed using the entire width of the page, rather than being condensed horizontally to fit into columns, as they are in this paper. Other than this “horizontal condensation,” each item printed below replicates as accurately as possible its presentation in the checklists included in the docket – this includes vertical spacing, size and type of font, indentation, etc.

The FIRE & SMOKE Checklist

The FIRE & SMOKE checklist was the first emergency and abnormal checklist the crew accessed following the illumination of the cabin cargo smoke warning light. Although it did not appear to cause the crew any problems, the title of this checklist does not match the name of the warning light that was illuminated. At the time of this accident, crews at this air carrier were to access the FIRE & SMOKE checklist first when confronted with smoke or fire. This checklist then served as a gateway and directed crews to other smoke or fire checklists based upon the source of smoke or fire (engine or APU fires were an exception to this procedure). Common practice today is for crew alert messages and/or illuminated warning lights and the titles of their associated checklists to match word-for-word. This helps, in most circumstances, to ensure that crews access the correct checklist for their situation.

When the flight engineer (FE) came to steps 4 and 5 on the FIRE & SMOKE checklist, he apparently did not consult the captain about which of these two exclusive conditionals should be chosen and selected step 5 [9]. (A set of conditionals are considered “exclusive” when only one in the set can be true, and thus, chosen for completion.)

- 4. If Descent is required.....PROCEED TO STEP 6
- or
- 5. If Decent is NOT Required.....PROCEED TO STEP 14

Clearly, the captain should have been involved in this type of decision but there is nothing in these items to indicate this. The items are formatted the same way as all other items that the flight engineer was expected to complete on his own without direction from the captain.

It is very understandable that the FE might have used the checklist in a “cookbook” fashion [7] and, as long as the reason for the step was clear [4], simply proceeded from one item to the next without cognitively processing very much what he was being directed to do. The goal of many emergency checklist designers may be to allow pilots to use these checklists in exactly this way to minimize the need for a lot of effortful analysis when time may be limited and workload is high. Therefore, although what really occurred is unknown, it would not be surprising if the FE had come to these items, looked up and saw that they were not descending and then had chosen item 5 accordingly. The captain did initiate a descent not long after this checklist was completed.

As a side issue, it is worth noting that crews were prompted to consider descending quite early in this checklist (step 4). When an aircraft is on fire, it is crucial that an emergency descent is initiated early enough to complete an emergency landing before crew incapacitation or systems failures cause control of the aircraft to be lost. However, many smoke and fire checklists that are in current use by other air carriers provide such guidance or direction to crews as the very last

step in a checklist, if it is given at all. There is a great deal of disagreement within the industry about whether this direction should be given to flight crews and, if so, where in smoke and fire checklists it should appear.

Although it was not pertinent to this accident, notice that the location of the Warning Statement following item 5 relative to the surrounding items (see below) makes it unlikely that the Warning Statement would have consistently been read by crews using this checklist. If a descent was required and step 4 was selected, the user would go to step 6, thereby jumping over the Warning Statement. If a descent was not required and step 5 was selected for completion, the pilot would jump to step 14, again missing the Warning Statement.

- 4. If Descent is required.....PROCEED TO STEP 6
- or
- 5. If Decent is NOT Required.....PROCEED TO STEP 14

WARNING

Should structural damage be suspected, limit airspeed. Gear and / or Speed Brakes may be used depending on type of damage.

- 6. Autopilot.....AS REQUIRED
- 7. Throttles.....IDLE
- 8. Speed Brake.....FULL
- 9. Airspeed.....MACH .82 TO .85 (320 TO 350 KIAS)
- NOTE**
- If structural damage is known or suspected, use appropriate turbulence penetration speed.
- 10. ATC.....NOTIFY
- 11. Transponder (if no contact with ATC).....7700
- 12. Tank Pumps.....ALL ON
- 13. Altimeter.....SET

Also, although it may be unavoidable, checklist designers should be aware that requiring crews to jump around within (or between) checklists can be problematic for a variety of reasons, the least of which is that it is easy to lose one's place or jump to the wrong item or checklist.

There is also a problem with how the Note is presented relative to the item it relates to: step 9. There is a gap between the Note and item 9 and the text of the Note is presented in normal type rather than boldface (as the checklist steps are). These two factors make it more likely that the Note will be skipped over or that actions specified in step 9 will be completed in a way contrary to what is specified in the Note.

This is a common problem with the way many current emergency and abnormal checklist items are formatted. There are also a few design issues with the final item on the FIRE & SMOKE checklist.

14. Type of Smoke or Fire....DETERMINE AND PROCEED TO APPROPRIATE PROCEDURE, THIS CHAPTER

- A. **ELECTRICAL FIRE & SMOKE**: Can best be determined by smell or visible smoke from electrical components (e.g., circuit breaker, radio)
- B. **AIRCONDITIONING SMOKE**: Can best be recognized by smoke emanating from overhead air conditioning outlets.
- C. **CABIN CARGO SMOKE**: Can best be recognized by checking smoke detectors on the Second Officers panel, or by observing smoke or fire in the main deck cargo area.

It appears that choices A, B, and C are part of an exclusive set, but this was not made explicit in how they were formatted. In contrast to items 4 and 5 earlier in the checklist, where the word "or" was used with lines pointing to the various options, the formatting of step 14 does not help crews recognize that they must choose among the three possibilities. This was likely not a problem for this crew but it is an inconsistency in formatting, and consistency is the hallmark of good checklist design.

The titles of the checklists in the NTSB docket for this accident were all formatted the same way: all capital letters were used, printed in white type against a black background. Thus, based upon similarities in typography, it appears at first glance that the three choices given under this step (A, B, and C) refer to the titles of checklists. If this was the case, then these titles did not exactly match the titles of the actual checklists. CABIN CARGO SMOKE might easily be misread (or mis-remembered) as COCKPIT / CABIN SMOKE, and the crew might then mistakenly complete the COCKPIT / CABIN SMOKE REMOVAL checklist instead of the CABIN CARGO SMOKE LIGHT ILLUMINATED checklist, as was intended by the checklist designers. Entire (and exact) titles should be used throughout a Quick Reference Handbook (QRH).

It is also possible that the three choices given under step 14 were presented to help the crews determine what type of smoke or fire they were dealing with and were not checklist titles. In this case, crews were left to determine on their own which other checklist(s) were appropriate to complete.

In either case, be they checklist titles or types of smoke and fire, the exact location (i.e., page numbers) of the subsequent checklists the crew were to complete were not provided. Providing page numbers speeds locating the proper checklist. Indicating that the desired checklist can be found in "THIS CHAPTER" is somewhat helpful but not sufficient.

The CABIN CARGO SMOKE LIGHT ILLUMINATED Checklist

This was the second emergency checklist used by the crew and its overall purpose was to depressurize the aircraft and minimize the amount of oxygen available to feed the fire. Nowhere was this said or indicated in this checklist. Having such information might have helped eliminate some of the confusion the flight engineer in this accident reported having when completing this checklist [9].

CABIN CARGO SMOKE LIGHT ILLUMINATED

1. Pack Function Control Selectors....TWO PACKS OFF

NOTE

Operate the No. 1 Pack only, if available.

Step 1 in this checklist is another instance in which elaboration text in the form of a Note is not integrated well enough with the step and consequently crews may complete the required action before seeing the information included in the Note. Here, this might lead a crew to turn off the wrong pack(s), which would then require them to go back and reconfigure the pack switches, unnecessarily taking time and diverting the crew's attention from other tasks.

The next set of issues with the design of this checklist pertain to steps 4, 5, 6, and 7 and, from a usage perspective, are among the most serious. The FE did not perform steps 6 and 7 when conducting this portion of the checklist and did not carry out actions sufficient to complete step 5 [9]. Checklist design factors may have contributed to these errors, and the design of these four items should be considered together. The actions specified pertain to adjusting the aircraft pressurization and reducing the amount of oxygen in order to slow the rate that a fire in the cabin might spread.

4. Airplane Altitude.....CAPTAIN'S DISCRETION

- A. Land as soon as possible.
- or**
- B. If above FL 270, consider descent to FL 270. Manually raise cabin altitude to 25,000 ft.
- or**
- C. If below FL 270, and an immediate landing is not possible, climb to FL 270. Manually raise cabin altitude to 25,000 ft. using the MANUAL CAB ALT CONTROL WHEEL.

5. If unable To Extinguish Fire/Smoke.....MANUALLY RAISE CABINALTITUDE TO 25,000 FEET

6. Cabin Air Shutoff T-Handle.....PULL

7. Maintain 0.5 PSI Diff Pressure Below FL 270, Or 25,000 Ft. Cabin Altitude Above FL 270.

The first difficulty is that item 4 is written with three exclusive conditional choices for the crew to choose from, but the three choices presented are really not mutually exclusive. Choice A may be pursued (landing as soon as possible) at the same time choice B or C is being pursued. What was likely intended by the checklist designer was that choice A was to be selected if an *immediate* landing could be undertaken (though it isn't worded this way). Relatedly, it appears that choice B is to be selected if the aircraft is above FL 270 and an immediate landing is *not* possible (although, again, this is not stated).

Very important issues concerning the design of items 4 through 7 relate to the presentation of similar directions and the order in which these directions are encountered as the items are completed. Directions to manually raise the cabin altitude to 25,000 feet (or maintain it at 25,000 ft.) are presented in four different locations within these four checklist items: exclusive conditional choices B and C in step 4, and in steps 5 and 7. As will be shown below, presenting these directions so many times in so many places can be quite confusing. Additionally, imbedded within all of this information was step 6 (pulling the T-handle) which does not involve information or directions pertaining to the cabin altitude setting or flight level and, therefore could be easily missed. In fact, the flight engineer in the accident did miss this crucial step [9].

Let us imagine working our way through these four checklist steps (4 through 7) using the various conditional choices available to the pilots to identify how this organization and presentation could be quite confusing.

First, imagine that, as was the case for the accident crew, choice A was selected in step 4: "Land as soon as possible." A landing is assumed to be imminent and the aircraft is either descending at this point or a descent is initiated at this point. The FE, after reading choice A would then proceed to step 5.

The first portion of step 5 might be rather puzzling: "If unable To Extinguish Fire/Smoke..." At this point in the checklist (even assuming that the FIRE & SMOKE checklist has also previously been completed), the crew have not done anything yet that *would* have extinguished the fire or smoke – no direct steps have been taken (such as using a fire suppressant agent) nor have any indirect steps been taken (such as starving the fire of oxygen). Assuming that the FE is not confused by this, he or she then completes the action specified by step 5 and manually raises the cabin altitude to 25,000 feet – which *is* an indirect method of trying to at least contain the fire. Now, after completing step 6, one comes to step 7 which states:

7. Maintain 0.5 PSI Diff Pressure Below FL 270, Or 25,000 Ft. Cabin Altitude Above FL 270.

If the aircraft is above FL 270, this checklist step serves as a reminder to the checklist user to monitor and maintain the cabin altitude setting that had been adjusted in step 5. If the

aircraft is below FL 270, however, the checklist user must abandon the action he or she had just completed in step 5 and now must work to maintain a 0.5 PSI differential pressure. (If the aircraft is descending, maintaining the desired differential pressure will require continual readjustment of the manual cabin altitude control wheel.)

In this scenario, since we are assuming that the aircraft is descending, it might be possible that the aircraft is still above FL 270 when checklist step 7 is reached and only descends below FL 270 later, perhaps even after the entire checklist has been completed. Whenever the descent through FL 270 occurs, the FE will have to remember to adjust for a 0.5 PSI differential pressure and then continue to maintain it instead of maintaining a cabin altitude of 25,000 ft. There is a serious danger that, under stress and high workload, the FE will not remember to refer to these gages or make readjustments to the control wheel later on as the situation unfolds [11] unless specifically prompted to do so.

Now, let's imagine a different scenario and go through these four checklist steps again. In this instance, let's imagine that an immediate landing is not possible (perhaps they are flying over the ocean) and the aircraft is above FL 270.

In this case, choice B in step 4 would be selected so the crew would likely descend to FL 270 and the FE would manually raise the cabin altitude to 25,000 ft. He or she would then proceed to step 5 which, in this case, is pointless – it directs the pilot to repeat an unrepeatable action that has just been taken in step 4 (raising the cabin altitude to 25,000 feet). After completing step 6, the FE reads step 7 and finds that, if they had descended to FL 270 as was suggested in choice B of step 4, neither of the options given in step 7 applies: they are neither below nor above FL 270, but instead are *at* FL 270. This may not have much practical difference as a PSI differential pressure of 0.5 is likely not too different from what it would be if the cabin altitude were set at 25,000 ft. and the aircraft was flying at FL270. However, it is an oversight in the design/wording of the checklist item and might cause a moment's hesitation on the part of the FE while he or she tries to decide whether to set the cabin altitude or focus on the differential pressure. The observations made earlier about the difficulty in remembering to monitor these settings or change approaches to dealing with the aircraft pressurization after this item has been completed, also apply in this scenario.

In the third possible scenario involving these four checklist items, one in which an immediate landing isn't possible and the aircraft is below FL 270, choice C under item 4 would be selected and the aircraft would climb to FL 270 and the FE would manually raise the cabin altitude to 25,000 feet. All the observations about design concerns pertaining to steps 5 through 7 in the second scenario above (when item 4, choice B was selected) also apply here.

Before, moving on, there are a couple of other observations to make regarding these four checklist steps. Note that only once in the three locations where the direction is given to raise the

cabin altitude to 25,000 is there a bit more information provided about how to actually do this ("using the MANUAL CAB ALT control wheel"). If this information is desired or required in one location, consistency would dictate that it should be included in all locations where this checklist action occurs. It turns out that even this additional information was not sufficient in guiding the crew to accurately complete this action, however. The FE reported having "cranked it open a couple of times." During the accident investigation however, the NTSB determined that 16 cranking motions would have been needed to complete this step [9].

There were also a few difficulties with the design of the next step on the CABIN CARGO SMOKE LIGHT ILLUMINATED checklist, step 8. This item directed the crew to check if the fire had been extinguished. To accomplish this step, one might feel the need to open the cockpit door or even leave the flight deck. However, doing that would be in direct contradiction with the instructions given in the third checklist step on the FIRE & SMOKE checklist, which would have been completed earlier. This step stated, in part, "...Leave [cockpit] door closed unless opening it is dictated by a greater emergency, and then at Captain's discretion."

9. If It is Necessary to Leave The Cockpit to Fight A Fire:

- A. Protective Breathing Equipment.....DON/ACTIVATE

NOTE

The PBE is located in a container in the coat closet and should be worn when fighting an actual fire. The walk-around O₂ bottle is also available in the cockpit.

- B. Fire extinguisher.....OBTAIN
- C. Fire or smoke source.....EXTINGUISH

10. Land At Nearest Suitable Airport.

Finally, item 10 on the CABIN CARGO SMOKE LIGHT ILLUMINATED checklist directed the crew to land at the nearest airport that was suitable. It could be possible that a crew might get involved in fighting a fire, as described in step 9, and as a result delay their descent and landing, if they are not prompted to consider landing at the nearest suitable airport until reaching step 10.

The Emergency Descent and Evacuation Checklists

Recall that the crew did not complete either the emergency descent checklist or the evacuation checklist, although the captain stated that he thought they had completed most of the items on these checklists from memory [9]. There are a variety of reasons why these checklists may not have been completed. Related to checklist design, it is possible that the inclusion of "rapid depressurization" in the title of the descent checklist (RAPID DEPRESSURIZATION / EMERGENCY DESCENT) may have caused the captain to not think of it as they were

descending, because they had not experienced a rapid depressurization.

Two issues with the design of the evacuation checklist were that it was quite lengthy (almost two full pages of items and information) and several of the items were supposed to be completed during the descent and approach phases of flight. Placing these items on the evacuation checklist instead of an earlier checklist reduces the likelihood that crews will be prompted to perform the items before landing. For that reason most companies' evacuation checklists only contain items that are to be completed once the landing is finished and the aircraft has stopped.

CONCLUSION

This case study has demonstrated the importance of various checklist design factors as they may influence flight crew checklist use and response to emergency and abnormal situations. Only a few of the many non-normal checklist design features that exist have been addressed here [2]. The most commonly identified design issue discussed in this case study was the *formatting, layout, and organization* of checklist items on the page. The *level of detail* of the information provided to the crews within some of the items was also discussed. Concerns regarding *wording, grammar and nomenclature* were identified particularly related to the names given to checklist titles, as well as the process crews were to follow to *access* the correct checklists.

Another checklist design issue discussed was the lack of *logical coherence* in places. Logical coherence can only be evaluated across two or more items within a checklist and means that the directed actions across those items make logical sense to someone using the checklist. Logical coherence can be especially difficult to ensure when a checklist contains conditional statements. *Progression*, another significant checklist design factor, refers to a user's movement from item to item within a checklist, as well as directed movement among multiple checklists.

Although I have discussed only a small fraction of the factors that should be considered when designing emergency and abnormal checklists, I hope this brief treatment makes it clear how important these issues are to address to provide maximum support to crews facing potentially life-threatening situations, often under conditions of high workload and stress.

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