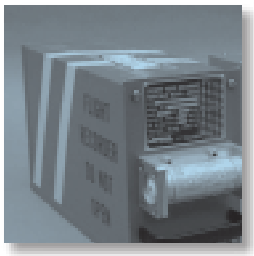


Aviation Recorder Overview

Dennis R. Grossi, National Transportation Safety Board

INTRODUCTION

A wide variety of airborne and ground-based aviation recording devices are available that can provide vital information for accident prevention purposes. The primary information sources include the mandatory crash-protected flight recorders, airborne quick access data recorders, and ground-based recordings of air traffic control (ATC) radar returns and radio communications. Other sources of recorded information, such as aircraft system internal memory devices and recordings of airline operational communications, have also provided vital information to accident investigators. These devices can range from nonvolatile memory chips to state-of-the-art solid-state flight recorders. With the exception of the mandatory flight recorders, these devices were designed primarily to provide recorded information for maintenance troubleshooting or specific operational requirements. Regardless of their original purpose, they have all been used in one form or another to investigate aviation accidents. This paper will give an overview of the evolution of flight recorder technology and regulatory requirements, and will describe the capabilities and limitations of the various types of recorded information available to the aviation community for accident prevention and, in particular, accident/incident investigation.

CRASH-PROTECTED FLIGHT RECORDERS

Evolution of Regulatory Requirements

First Flight Data Recorder

The need for a crash-survivable recording device became apparent following a series of airline crashes in the early 1940s. This spurred the Civil Aeronautics Board (CAB) to draft the first Civil Aviation Regulations calling for a flight recording device for accident investigation purposes. However, recorder development was delayed by shortages brought about by World War II. As a result, such a device was not available, and after extending the compliance date three times, the CAB rescinded the requirement in 1944. The CAB issued a similar flight recorder regulation in 1947, after the war, but a suitable recorder was still not available and the regulation was rescinded the following year.

During the 9 years that followed, the Civil Aviation Authority (CAA), the CAB, and aviation industry representatives studied the capabilities of recorder technology in an effort to develop new recorder requirements. Finally in 1957, after determining that suitable recording devices were available, the CAA issued a third round of flight recorder regulations. These regulations called for all air carrier airplanes over 12,500 pounds that operated above 25,000 feet to be fitted with a crash-protected flight recorder by July 1, 1958, that recorded altitude, airspeed, heading, and vertical accelerations as a function of time. This marked the introduction of the first true crash-protected flight data recorder in the U.S.

First Cockpit Voice Recorder (CVR)

As a result of a CAB recommendation to record flight crew conversation for accident investigation purposes, the Federal Aviation Administration (FAA) conducted a study in 1960 that established the feasibility of CVRs. The FAA produced airworthiness installation approval criteria and operating rules that called for the installation of a CVR in transport-category aircraft operated in air carrier service. The compliance dates were July 1, 1966, for all turbine-powered aircraft, and January 1, 1967, for all pressurized aircraft with four reciprocating engines.

1972 Flight Data Recorder Rule Change

FDR requirements remained virtually unchanged until December 10, 1972, when the rules for transport-category airplanes that received type certification after September 30, 1969, were amended to require an expanded parameter digital flight data recorder (DFDR) system. The expanded parameter requirements included existing parameters plus parameters for pitch and roll attitude, thrust for each engine, flap position, flight control input or control surface position, lateral acceleration, pitch trim, and thrust reverser position for each engine. Unfortunately, this rule change, which was retroactive to include the Boeing 747, did not affect airplanes like the Boeing 707, 727, and 737, and the McDonnell Douglas DC-8 and DC-9, all of which had type certificates issued before 1969. Therefore, existing and newly manufactured versions of these older aircraft types could be operated under the same FDR rules established in 1957. Flight recorder requirements remained essentially unaltered until the rule changes in 1987 and 1988.

1987 and 1988 Flight Recorder Rule Changes

During the 30 years following issuance of the original 1957 FDR regulations, the National Transportation Safety Board and its predecessor, the CAB, issued numerous safety recommendations to the FAA requesting upgraded recorder standards to meet the needs of accident investigators. The recommendations called for the following:

1. Replace original foil-type oscillographic recorder with digital recorders.

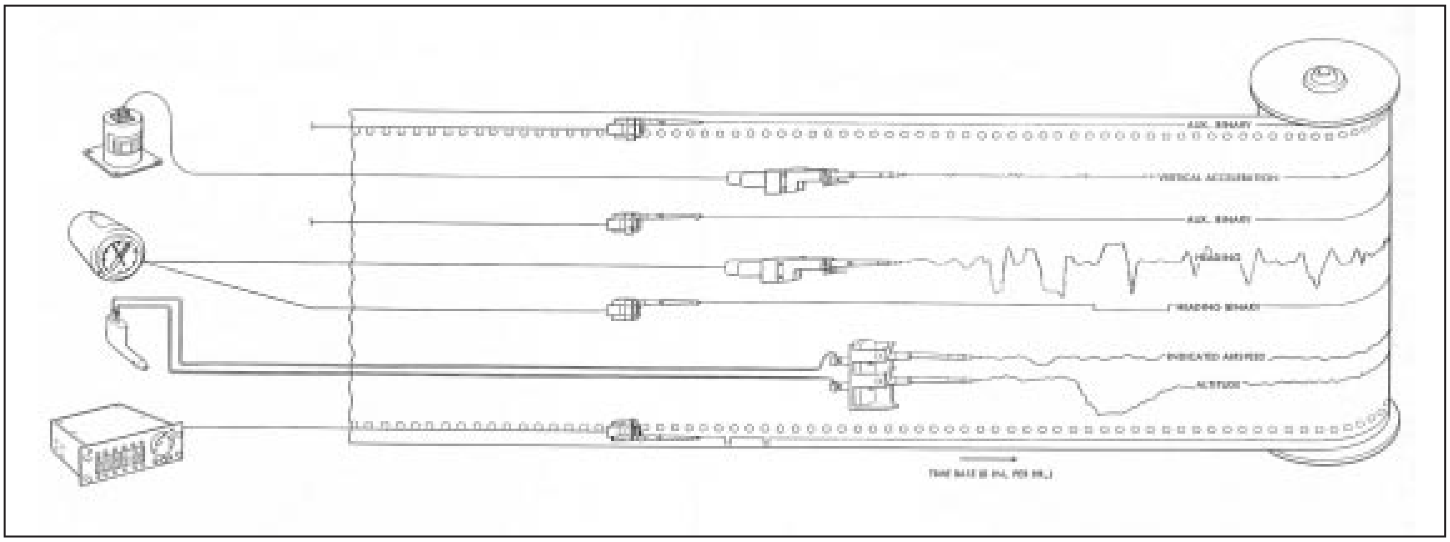


Figure 1. System schematic for a typical oscillographic foil recorder.

2. On existing transport-category airplanes, retrofit five-parameter FDRs with six additional parameters.

3. Expand parameter requirements for newly manufactured transport-category airplanes.

4. Require the flight crew to use hot-microphones below 18,000 feet.

5. Record hot-microphone channels on CVRs.

6. Require CVRs and FDRs for some air taxi and corporate executive aircraft.

The FAA repeatedly cited cost as the primary reason for not adopting the recommendations.

Following a series of high visibility accidents in the early 1980s, the FAA issued flight recorder rule changes in 1987 and again in 1988. These rule changes called for the following:

1. Replace oscillographic foil-type FDR digital recorders by May 26, 1989.

2. Increase the number of mandatory parameters for airplanes type-certificated before October 1969 to include pitch and roll attitude, longitudinal acceleration, thrust of each engine, and control column or pitch control surface position. (The original compliance date, May 26, 1994, was extended by 1 year to May 26, 1995.)

3. Require transport-category airplanes (20 or more passengers) manufactured after October 11, 1991, to record 28 parameters in a digital format.

4. Require existing transport-category airplanes (20 or more passengers) fitted with a digital data bus to record 28 parameters in a digital format.

5. Require all multiengine turbine-powered air taxi aircraft capable of carrying 10-19 passengers and manufactured after October 11, 1991, to have a 17-parameter FDR.

6. Extend the CVR requirements to multiengine turbine-powered aircraft capable of carrying six or more passengers and requiring two pilots.

7. Require flight crews to use existing CVR hot-microphone systems below 18,000 feet.

1997 Flight Data Recorder Rule Changes

Following two fatal Boeing 737 accidents (United flight 585, Colorado Springs, Colorado, July 1989, and USAir flight 427, Pittsburgh, Pennsylvania, September 1994), the Safety Board reexamined FDR parameter requirements, and as a result, made safety recommendations to the FAA that called for the following:

1. Require additional parameters for most existing air transports that focused on recording crew flight control inputs and the resulting control surface movements, with parameter retrofits to be completed by January 1, 1998.

2. Increase parameter requirements for transport airplanes manufactured by January 1, 1996.

3. Urgent retrofit of all Boeing 737 airplanes with FDR parameters to record lateral acceleration, crew flight control inputs, and the resulting control surface movements by the end of 1995.

The FAA responded by issuing a notice of proposed rulemaking (NPRM) in August 1996 and a final rule on August 18, 1997. Although the final rule generally met the requirements of the safety recommendations, the compliance dates were significantly relaxed from those recommended by the Safety Board. In addition, the FAA did not agree with the urgent recommendation to retrofit Boeing 737s by the end of 1995. However, the final rule did require that air transports record flight control crew inputs and control surface position. The final rule called for the following:

1. Transport airplanes type certificated before October 1, 1969, and manufactured before October 11, 1991, must record as a minimum the first 18 to 22 parameters listed in the rule by August 18, 2001.

2. Transport airplanes manufactured after October 11, 1991, and before August 18, 2001, must record as a minimum the first 34 parameters listed in the rule by August 18, 2001.

3. Transport airplanes manufactured after August 18, 2000, must record as a minimum the first 57 FDR parameters listed in the rule.

4. Transport airplanes manufactured after August 18, 2002, must record as a minimum all 88 FDR parameters listed in the rule.

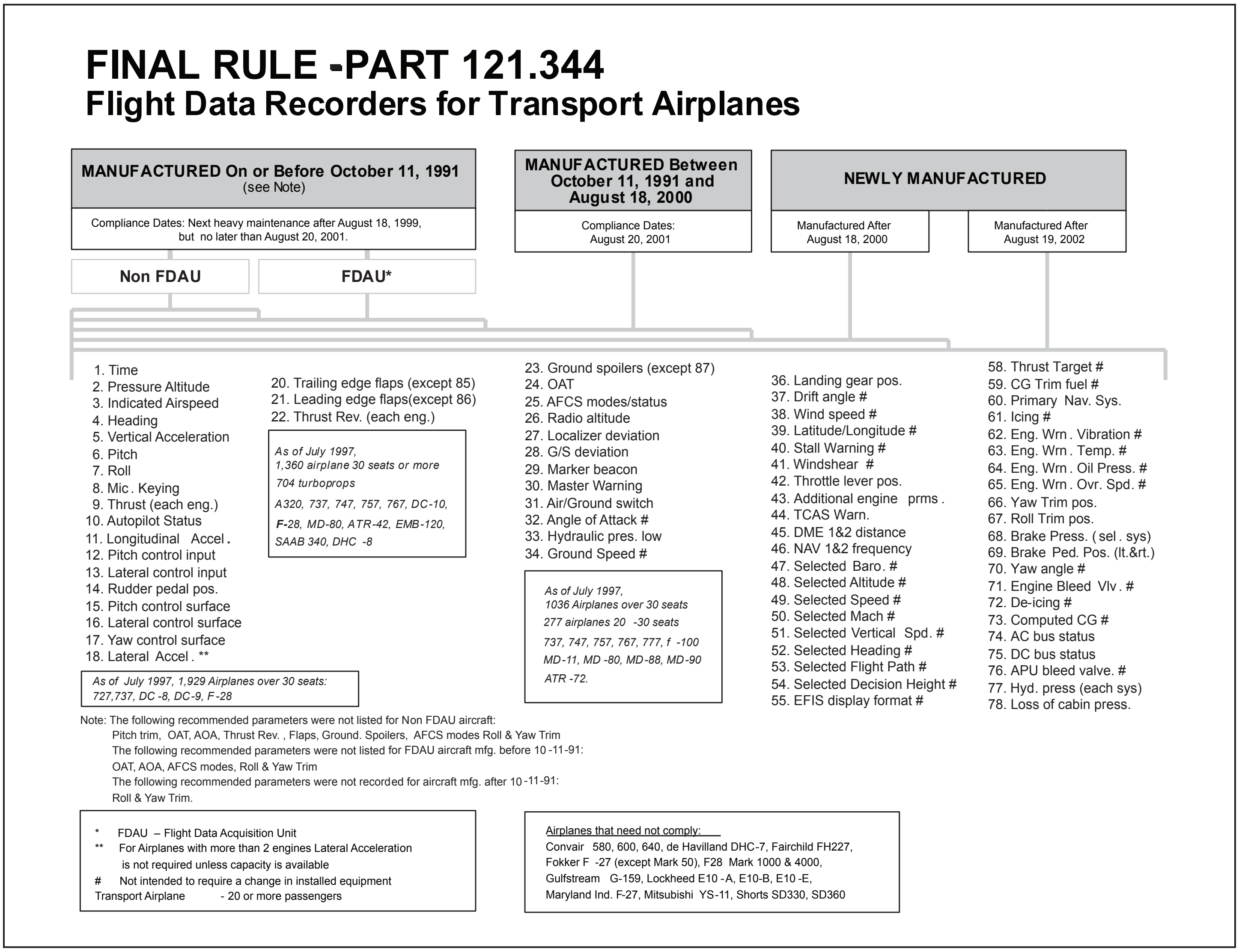
The specific parameter requirements are contained in table 1.

March 9, 1999
NTSB and TSB Flight Recorder Recommendations

The Transportation Safety Board of Canada (TSB) and the Safety Board worked together to develop the March 9, 1999, recommendations following the September 2, 1998, accident of Swissair flight 111, an MD-11. The regularly scheduled passenger flight from New York to Geneva, Switzerland, diverted to Halifax after the crew reported smoke in the cockpit. The airplane crashed into the waters near Peggy's Cove, Nova Scotia, killing all 229 passengers and crew on board. The investigation was severely hampered by the lack of data from the CVR and FDR, which stopped nearly 6 minutes before the airplane hit the water.

The Swissair accident was another in a long history of accident and incident investigations that were hindered by the loss of flight recorder information due to the interruption of aircraft electrical power to the flight recorders. However, innovations in recorder and power supply technologies have resulted in the development of an independent power source that would provide sufficient power to operate a solid-state flight recorder for 10 minutes. In addition, the availability of combined voice and data recorders has introduced the possibility of fitting two combined recorders on newly manufactured airplanes, with one recorder near the cockpit to reduce the probability of a mechanical or electrical interruption of the signals and power supply, and the second recorder as far aft as practical to enhance survivability. The Embraer-170, a recently introduced regional jet (RJ), is the first aircraft to be fitted with fore and aft "combi" recorders.

Table 1. Parameter requirements for air carrier flight data recorders.



As a result of the Swissair accident, the Safety Board and the TSB issued safety recommendations on March 9, 1999, to require the following:

1. By January 1, 2005, retrofit aircraft with a 2-hour solid-state CVR that is fitted with an independent power supply capable of operating the CVR and area microphone for 10 minutes when aircraft power to the CVR is lost.

2. By January 1, 2003, fit all newly manufactured airplanes that are required to carry both a CVR and FDR with two combined voice and data recorders, one recorder located as close to the cockpit as practical and the other as far aft as practical.

3. Amend Title 14 U.S. *Code of Federal Regulations* to require that CVRs, FDRs, and combination flight recorders be powered from separate generator buses with the highest reliability.

In a March 19, 1999, letter, the FAA agreed to the recommendations without revision and promised to issue an NPRM by the end of the summer. However, the promised NPRM was not released until February 2005, and the Safety Board made additional flight recorder recommendations in the interim. These recommendations were prompted by the lack of recorder data for some air taxi accidents involving aircraft not required to have a recorder, the need for cockpit image recordings for a series of air carrier accidents, and the need for increased sampling rates for some FDR parameters. These recommendations if adopted would require the following:

1. Issue an image recorder technical standard order (TSO), followed by installation of an image recorder on existing and newly manufactured turbine-powered aircraft engaged in Part 121, Part 135, and commercial or corporate Part 91 operations not currently required to have a flight recorder.

2. Retrofit all turbine-powered aircraft that have the capability of carrying six or more passengers engaged in Part 121, 135, or 91, with a 2-hour CVR.

3. Equip existing and newly manufactured Part 121, 125, and 135 aircraft required to have a CVR and FDR with a 2-hour crash-protected image recorder capable of recording a color image of the entire cockpit.

4. Require that all transport-category aircraft FDRs be capable of recording values that meet the accuracy requirements through the full dynamic range of each parameter at a frequency sufficient to determine a complete and unambiguous time history of the parameter.

The February 2005 NPRM addressed most of the Safety Board's recommendations for flight recorder enhancements, proposing that CVR duration be increased to 2 hours, that the sampling rate for some FDR parameters be increased, and that physical separation of the CVR and FDR be required. The NPRM also allowed a single combined CVR/FDR on some rotorcraft, improved power supply reliability including a 10-minute independent power supply, and the recording of data-link communications when so equipped. The NPRM did not address cockpit image recorders or the installation of forward- and aft-mounted combined FDR/CVR recorders on newly manufactured transports.

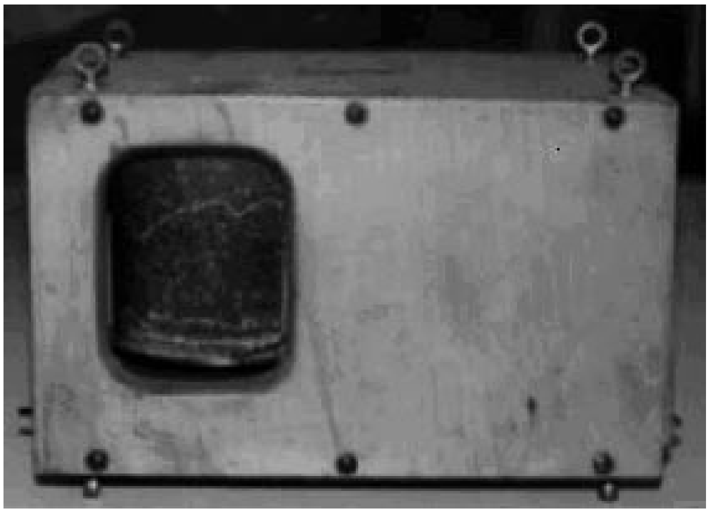


Figure 2. Spirit of St. Louis flight recorder.

EVOLUTION OF FLIGHT RECORDERS

Flight data recorders can be traced back to the origins of power flight. Wilbur and Orville Wright's historic first flight was documented by the first flight data recorder. This rudimentary device recorded propeller rotation, distance traveled through the air, and fight duration. Charles Lindbergh's airplane the *Spirit of St. Louis* was also fitted with a flight-recording device. Lindbergh's recorder was a bit more sophisticated, employing a barograph that marked changes in barometric pressure or altitude on a rotating paper cylinder (see figure 2).

These early recordings survived because they were designed to record historical events, not mishaps. The first practical crash-protected flight data recorder was not introduced until 1953. This recorder used styli to produce individual oscillographic tracings for each parameter on metallic foil. Time was determined by foil movement, which typically advanced at a rate of 6 inches per hour. This often resulted in an entire accident sequence being recorded within a 0.1 inch of foil movement. Investigators recovered the recorded information by optically reading the scribed markings through a microscope, and then converting the displacement of the scribed marks from the reference line to engineering units. This process was very time consuming and required a significant amount of reader interpretation.

The 1957 regulations that mandated the installation of FDRs by July 1958 created a market for FDRs that attracted other manufacturers who also used the metal foil oscillographic technique (see figures 3 and 4). The regulations also required compliance with TSO C-51. This TSO defined range accuracy, sampling interval, and type parameters to be recorded (altitude, airspeed, heading, vertical acceleration, and time) and specified the requirement to survive a crash shock of 100 g and envelopment in an 1100° C flame for 30 minutes. The TSO also defined three basic types of flight recorders:

Type I: a non-ejectable recorder, unrestricted location

Type II: a non-ejectable recorder, subjected to a minimum 15-minute fire test, restricted to any location more than ½ of the wing root chord from the main wing structure through the fuselage and from any fuel tanks

Type III: an ejectable recorder, minimum 1.5 minutes fire test, unrestricted location.

Figure 3. Early Lockheed model 109.

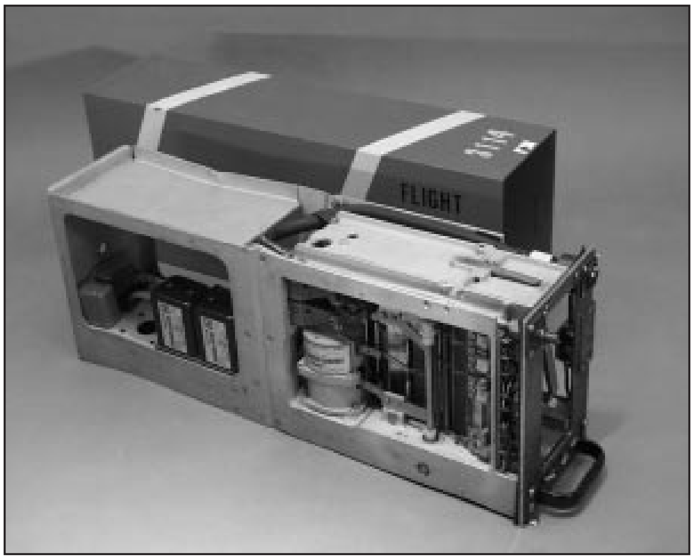


Figure 4. Sundstrand Model 542 FDR, 1/2 ATR long format.

The early recorders were all of the Type I design and most were mounted in the cockpit area or in the main gear wheel well. Unfortunately, these locations subjected the recorders to fire and impact forces that destroyed or severely damaged the recording medium. Type II and III recorders were never fitted to commercial air carriers; however, type III ejectable recorders are currently in use on some military aircraft.

In the early 1960s, the CAB made a series of recommendations to the FAA that called for additional protection for FDRs against impact force and fire damage, and also recommended relocating the recorders to the aft area of the fuselage to provide maximum protection of the recording media. As a result, the FAA issued rule changes that specified the location of the recorder as far aft as practical and upgraded the performance standards in TSO C-51, reissuing it as C-51a. The upgraded TSO specifications increased the impact shock test from 100 g to 1,000 g and introduced static crush, impact penetration, and aircraft fluid immersion tests. The fire test was not changed. Unfortunately, neither TSO contained an adequate test protocol to ensure uniform and repeatable test conditions.

At about the same time as the foil recorders were being developed in the United States, recorders that used magnetic steel wire as a recording medium were being developed in the United Kingdom. The wire recorders were the first to use digital pulse coding as a recording method. The robust design of the wire recorder made it a fairly reliable recorder for its time. Although the wire-recording medium was fairly impervious to postimpact fires, it did not fare as well with impact shock. The wire would often brake into several sections and become tangled, making it difficult and tedious to reassemble in the proper sequence.

In the late 1940s, the French developed an FDR that used a photographic system that recorded data on light-sensitive paper.

Table 2. Early flight recorder crash/fire survivability standards.

	TSO C84 CVR Requirements	TSO C-51 FDR Requirements	TSO C-51a FDR Requirements
Fire	1100°C flame covering 50% of recorder for 30 minutes	1100°C flame covering 50% of recorder for 30 minutes	1100°C flame covering 50% of recorder for 30 minutes
Impact Shock	100 g	100 g	1000 g for 5 ms
Static Crush	None	None	5,000 pounds for 5 minutes on each axis
Fluid Immersion	None	None	Immersion in aircraft fluids (fuel, oil, etc.) for 24 hours
Water Immersion	Immersion in sea water for 48 hours	Immersion in sea water for 36 hours	Immersion in sea water for 30 days
Penetration Resistance	None	None	500 pounds dropped from 10 feet with a ¼-inch-diameter contact point

Its obvious disadvantages were flammability and the tendency of the recording to disappear when subjected to light. The French later adopted the metal foil oscillographic recorder.

Cockpit Voice Recorder

In response to CAB recommendations, the FAA conducted a study in 1960 to determine the feasibility of recording the spoken words of the flight crew for accident investigation purposes. Although cockpit ambient noise levels posed a significant obstacle to 1960 recording technology, the study showed that recording crew conversation was feasible. The following equipment capabilities were initially proposed:

1. Record each crewmember's conversation, both transmitted and received, with ground facilities and on the airplane's intercommunication system. Also, record other conversation in the cockpit not conducted over those media. Provide sufficient channels to preclude the possibility of more than one crewmember recording on a channel at one time.
2. Retain the last 30 minutes of the crew's conversation.
3. Provide for stopping the recorder in the case of a crash so that the last 30 minutes of conversation is not erased or overwritten.
4. Ensure that recorder can withstand the crash conditions required in TSO-C51.
5. Ensure that recording is intelligible over the ambient noise of the cockpit or that unwanted noise can be filtered from the record with appropriate ground equipment.
6. Ensure that recorder is capable of recording crew voices, other than on the communication and intercommunication systems, without the use of lip or throat microphones.
7. Inform the crew when the recorder is operating properly.

As a result, the FAA issued rules mandating the use of CVRs on all transport-category aircraft and issued TSO C-84, which established crash fire survivability and equipment approval standards.

Magnetic Tape Flight Recorders

The introduction of the CVR in the late 1960s and DFDRs in the early 1970s made magnetic tape the recording medium of choice until the introduction of solid-state flight recorders in the late 1980s. Recorder manufacturers used a variety of tapes and tape transports. The most widely used tapes were Mylar®, kapton, and metallic. The tape transports were even more varied, using designs such as coplaner reel-to-reel, coaxial reel-to-reel, endless loop reel packs, and endless loop random storage.

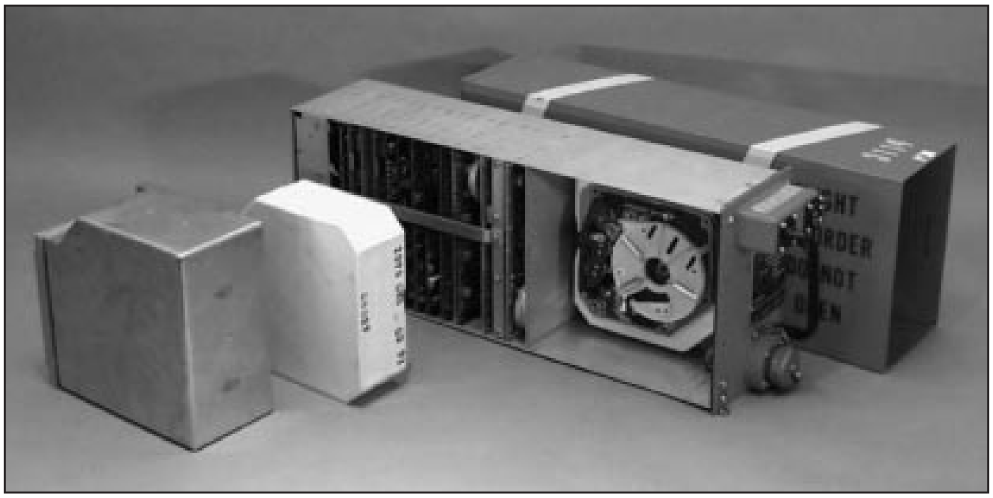


Figure 5. Fairchild model F800 DFDR, 1/2 ATR long format.

Tape CVRs recorded four channels of audio for 30 minutes, and the DFDR recorded 25 hours of data. CVRs and FDRs recorded over the oldest data with the newest data in an endless loop-recording recording pattern. The DFDR tape transport and protective enclosure shown in figure 5 is an endless loop real pack design adapted from a 1960s CVR.

All of the magnetic tape flight recorders, including the units that used metallic tape, were found to be susceptible to thermal damage during postcrash fires. Although the TSOs called for a high-intensity fire test, the lack of a detailed test protocol allowed for a less than adequate design to be approved. In addition, the real world experience would show magnetic tape flight recorders to be most vulnerable when exposed to long duration fires, a test condition not required at the time tape flight recorders received TSO approval. In addition, metallic tapes were found to be vulnerable to impact shock, which tended to snap the tape, releasing the spring tension and unwinding the tape, causing further tape damage and loss of data.

Digital Recording Method

The DFDR and its companion recorder, the quick access recorder (QAR), were introduced about the same time. DFDRs and QARs use the same recording techniques, but as the name implies, the QAR can be quickly accessed and downloaded. Most early model QAR systems recorded far more parameters than the mandatory DFDR systems. As nonmandatory recorders, QARs were not designed to survive a crash impact and postimpact fire, although a number have survived fairly significant crashes.

Most DFDRs and QARs require a flight data acquisition unit (FDAU) to provide an interface between the various sensors and the DFDR. The FDAU converts analog signals from the sensors to digital signals that are then multiplexed into a serial data stream suitable for recording by the DFDR. Industry standards dictate the format of the data stream, which for the vast majority of tape-based DFDRs is 64 12-bit data words per second. The recording capacity of the tape DFDR is limited by the length of tape that can be crash-protected and the data frame format. The capacity of the tape DFDRs was adequate for the first generation of wide-body transports, but was quickly exceeded when aircraft like the Boeing 767 and Airbus A320 with digital avionics were introduced.

Digital Avionics Systems

The introduction of digital avionics systems into commercial aviation in the early 1980s significantly increased the amount of information available to DFDRs and QARs. Digital avionics also brought about digital data buses, which carry digital data between systems. This made vast amounts of critical flight and aircraft system information available to the DFDR and QAR simply by tapping into the buses. The introduction of digital data buses also brought about digital FDAUs (DFDAU). The FDAU and DFDAU perform the same function except that DFDAUs can interface with the data buses and analog sensors.

Solid-State Flight Recorders

The introduction of solid-state flight recorders in the late 1980s marked the most significant advance in evolution of flight recorder technology. The use of solid-state memory devices in flight recorders has expanded recording capacity, enhanced crash/fire survivability, and improved recorder reliability. It is now possible to have 2-hour CVRs and DFDRs that can record up to 256 12-bit data words per second, or 4 times the capacity of magnetic tape DFDRs. Survivability issues identified over the years have been addressed with new crash/fire survivability standards developed in close cooperation between accident

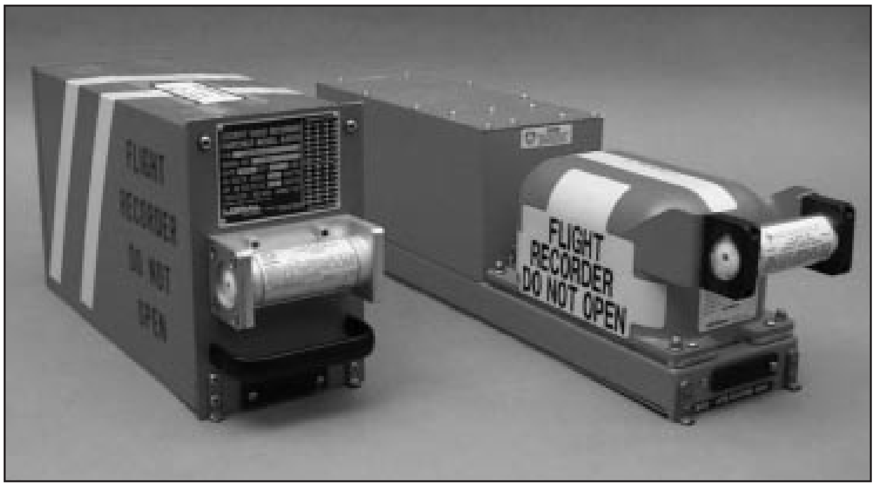


Figure 6. Typical solid-state CVR and DFDR.

investigators and the recorder industry (see table 3). The lack of moving parts in solid-state recorders has greatly improved recorder reliability.

Future Flight Recorder Capabilities Requirements

As proposed in the Safety Board's March 9, 1999, recommendation letter to the FAA, two combination voice-data recorders built to TSO C123a and C124a standards will provide the redundant recording capabilities that separate CVRs and DFDRs cannot. Locating one recorder in the nose of the aircraft and the other in the tail will further enhance the probability of capturing catastrophic events that would otherwise compromise the CVR and DFDR when they are colocated. The forward-mounted flight recorder will be close to the cockpit and the avionics compartment, which reduces the possibility of signal loss. The addition of a 10-minute, independent alternate power supply adjacent to the flight recorder will further enhance the possibility that the recorder will be powered and critical data will be recorded until the end of the flight.

The next-generation combination flight recorders will be required to record more than the traditional voice and data parameters. The FAA's February 2005 flight recorder NPRM calls for the recording of Controller Pilot Data Link (CPDL) messages if an aircraft is equipped to use data-link communications. Recent advancements in video technology have made video recording a distinct possibility in the not-too-distant future. The International Civil Aviation Organization (ICAO) Flight Recorder Panel has concluded that video technology has matured to the point that specific technical aspects must be determined. The European Organization for Civil Aviation Equipment (EUROCAE) has since issued its image recorder standard, which was recently incorporated into a notice of proposed technical standard order C176, *Aircraft Image Recorder Systems.*

Table 3. Current flight recorder crash/fire survivability standards.

	TSO C123a (CVR) and C124a (DFDR)
Fire (High Intensity)	1100°C flame covering 100% of recorder for 30 minutes. (60 minutes if ED56 test protocol is used)
Fire (Low Intensity)	260°C Oven test for 10 hours
Impact Shock	3,400 g for 6.5 ms
Static Crush	5,000 pounds for 5 minutes on each axis
Fluid Immersion	Immersion in aircraft fluids (fuel, oil etc.) for 24 hours
Water Immersion	Immersion in sea water for 30 days
Penetration Resistance	500 pounds dropped from 10 feet with a ¼-inch-diameter contact point
Hydrostatic Pressure	Pressure equivalent to depth of 20,000 feet

AIR TRAFFIC CONTROL RADAR AND AUDIO RECORDINGS

Ground-based recordings of the air traffic control (ATC) radar and radio transmissions provide aircraft communication and position time history information. The FAA records all radio communications between controllers and pilots, and also landline communications between controllers. Air Route Traffic Control Centers (ARTCC) provide complete radar coverage of the United States and parts of Canada and Mexico. In addition, most ATC airport approach radar facilities also record.

ATC Communication Recordings

Recordings of the two-way radio communications between controllers and pilots and inter-controller communications via landlines are maintained for 30 days. In the event of an accident or incident, the original recording of the event can be set aside and retained for investigators; otherwise, the recording medium will be reused and the information lost.

The ATC communications recordings have provided vital information to investigators. In instances where the aircraft are not fitted with a CVR, these recordings provide the only record of flight crew communications and have at times provided background sounds (for example, wind noise, rotor speed, sounds of cockpit warnings) that have proven to be vital to the investigations. A time code is also recorded with the audio communications to provide a time reference independent of any subtle recording anomalies.

ATC and Other Radar Recordings

Recorded radar data can provide aircraft position time history information by recording the position coordinates of individual radar returns, time, and when available, altitude and identification information transmitted from the aircraft. Altitude and identification data are produced by a transponder[1] fitted to the aircraft that also reinforces the radar return.

The rate at which the radar antenna rotates will determine the sampling interval between returns. ARTCC rotates at between 5 to 6 revolutions per minute (that is, generating radar returns every 10 to 12 seconds), whereas airport approach radar antennas do a complete rotation every 4.8 seconds. The most accurate position coordinates recorded by the ARTCC are in latitude and longitude, whereas approach radar records position coordinates as range and azimuth values, and both record the transponder-generated altitude values.

Military and private radar facilities can provide similar position time history information. Military aircraft Airborne Warning and Control Systems (AWAC) and naval vessel radar data are also recorded and are available to investigators upon request.

Use of ATC Recordings by Accident Investigators

The importance of ATC recorded data is determined by the circumstances surrounding an accident or incident. Accidents or incidents involving very dynamic conditions, such as aerodynamic stall and loss of control, are difficult to evaluate with ATC data alone. ATC data are more significant for less dynamic accidents, such as controlled flight into terrain, or when used in conjunction with FDR and CVR data.

Correlation of events common to the ATC recordings and the FDR and CVR recordings can provide a very accurate local time reference. This can become critical because the FDR and CVR are only required to record relative time, and the local time reference may vary from one ATC facility to the next. ATC radar and FDR data can be correlated by comparing the altitude time histories, and ATC communication recordings can be correlated by the radio transmission time histories recorded by the various ATC facilities and the CVR and FDR.

In addition to a time reference, ATC-recorded information also provides ground track reference, which is essential in performance-related accidents. A wind model can be developed when radar flight path data are combined with FDR parameters, such as altitude airspeed and heading and airplane acceleration parameters. This is particularly useful in accidents or incidents involving dynamic meteorological conditions, such as wind shears or crosswind and turbulence conditions.

ATC radar data are particularly useful in evaluating the relative position of aircraft when multiple aircraft are involved. Investigations of mid-air collisions and wake turbulence encounters rely heavily on this information.

Significant accuracy and resolution limitations must be considered when using recorded radar data. The accuracy limitations are known and should be factored into the ground track calculations. The sampling intervals of 4.7 to 12 seconds present a significant limitation on usefulness of recorded radar data.

NONVOLATILE MEMORY DEVICES

Modern aircraft use an increasing number of microprocessor-based electronic devices for operational and maintenance purposes. As a result, aircraft are fitted with nonvolatile memory (NVM) to store information, such as flight

1 A transponder is a receiver/transmitter that generates a reply signal upon proper interrogation from a radar facility.

crew entries to the navigation database, system fault messages generated by electronic control devices, and system status messages. These devices, generally known as electronically erasable read-only memory (EEROM), provide temporary storage of transitional information during power interruptions. The term "nonvolatile" implies that the stored information will be available if the system is electrically powered or not.

Accident investigators have found NVM to be a valuable source of information. However, because NVM is not crash- or fire-protected, there is no assurance that it will be available following a catastrophic accident. That said, NVM has survived severe impacts and postimpact fires in a significant number of cases.

The recovery of information from undamaged NVM systems can be as simple as powering the system and reading or downloading the information. Damaged units may require system experts at the manufacturer's facility to disassemble the unit to recover the information using specialized equipment and software.

The amount of effort and technical expertise needed to recover information from NVM is generally determined by the amount of damage and system complexity. The first step in the recovery process is a visual inspection of the disassembled unit to determine the amount of damage. It may be possible to simply replace a damaged connector or place the circuit board containing the memory device in a serviceable unit to recover the data. However, extreme caution must be taken when applying power to units that are suspected of receiving impact shocks that exceed the normal design requirements: an undetected short or open circuit might result in the loss of the stored data.

Example: Lauda Air, Flight NG004, May 26, 1991

The May 26, 1991, fatal accident of Lauda Air flight NG004, a Boeing 767 that crashed in Suphan-Buri Province, Thailand, demonstrated the importance of NVM. The aircraft departed controlled flight while climbing through 24,000 feet and experienced an in-flight breakup during the recovery maneuver and subsequently crashed in the jungle. The FDR magnetic tape recording medium was destroyed by the postcrash fire and provided no data. However, crew comments recorded by the CVR indicated a problem with an engine thrust reverser just before the loss of control.

The electronic engine control (EEC) units for both engines were removed from the aircraft wreckage and brought to the manufacturer's facility in Windsor Locks, Connecticut, to recover the fault messages stored in the NVM. The EECs showed signs of severe impact shock. As a result, the EEROMs containing the NVM were removed from the circuit board and mounted on an identical laboratory test unit. A normal fault message download was performed and the data were subsequently processed using the manufacturer's proprietary software.

Each time an EEC fault message was generated, the following information was captured and stored in NVM:

- diagnostic fault messages codes
- values for N1 (high pressure compressor rotation speed), P2 (fan inlet total pressure), mach number, temperature (cold junction compensation)
- fault time in elapsed hours
- logging of flight and leg cycles

The recovered data contained diagnostic messages from the last 390 hours of operation, which spanned 95 flights. The EECs from the left engine, which experienced the uncommanded thrust reverser deployment, provided a significant amount of information specifically relating to the faulty thrust reverser and ancillary altitude, airspeed, and engine thrust values provided key reference values, which gained significance in light of the loss of the FDR data. The EEC from the right engine, which did not record any faults during the accident flight, yielded little additional information.

CONCLUSIONS

As far back as the early 1940s, the aviation community realized that, if commercial aviation were to prosper, public confidence must be gained and maintained through a quick and accurate determination of probable cause of any aviation mishap. It was also obvious that the nature of aviation accidents would require the use of recording devices to provide accident investigators with the information needed to determine the cause of a mishap and take the proper corrective action to prevent a similar mishap from recurring.

The first flight recorders introduced over 40 years ago gave accident investigators their first appreciation of the recorder's safety potential. However, the data provided by these early recorders were limited and often of such poor quality that investigators could at best determine what happened, but not with a high degree of certainty as to why it happened.

Flight recording technology has had to adapt to a rapidly evolving commercial aviation industry and the corresponding needs of accident investigators. One of the most significant changes in recorder technology occurred in the early 1970s with the introduction of digital data recorders. The amount and quality of data provided by DFDRs, CVRs, and other recorded data, like ATC radar, gave accident investigators their first real opportunity to pursue an in-depth evaluation of the facts, conditions, and circumstances surrounding an occurrence. The introduction of digital recordings also made it practical to use flight recorder data proactively.

The introduction of digital avionics and fly-by-wire technologies in the 1980s provided investigators with challenges and opportunities. This new technology eliminated some well-established investigative techniques while offering an opportunity to record and recover vast amounts of previously unattainable information. Indeed, the amount of available information overwhelmed early-model DFDRs. However, the advent of solid-state recorders has solved the recorder capacity problem while improving survivability and reliability.

The future of flight recording is promising. Advances in recorder and aircraft systems will allow for the introduction of recording techniques to record video images of the cockpit and data link messages, as well as providing more opportunities for the proactive use of flight data to prevent accidents.

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