



AEROSPACE RECOMMENDED PRACTICE

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Sizing Criteria for Stored Energy Systems Used for Emergency Braking

RATIONALE

This SAE Aerospace Recommended Practice (ARP) fulfills the need to recommend a process to determine whether a transport category aircraft should include a stored energy system for emergency braking, and—if so—its size and minimum brake control functionality.

FOREWORD

Braking systems on transport category aircraft (i.e., 14 CFR/CS Part 25 aircraft) include a stored energy system—accumulator(s) for hydraulic brakes or battery(s) for electric brakes. The stored energy system serves two primary purposes. It applies and holds the park brake when the active power sources have been shut off, and it provides a power source for emergency braking when all the active sources have been lost. A system safety assessment (SSA) is performed on each aircraft model to determine if one or more failure conditions exist which would rely on the stored energy system to meet 14 CFR/CS Part 25 safety requirements. If so, then that will almost certainly size it. Among the regulatory requirements is one for six brake applications that applies only if certain single failure conditions exist. This is a very old requirement, and its applicability to modern brake control systems is discussed. This ARP discusses the applicable Part 25 requirements, recommends guidance for sizing the stored energy system, and recommends a standard methodology for demonstrating compliance with the applicable Part 25 requirements.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) presents the regulatory requirements for transport category aircraft that may necessitate a stored energy system for emergency braking and discusses various scenarios that should be considered for sizing it. Since the vast majority of brake control systems are hydraulic, a simulator-based compliance demonstration is recommended to substantiate that the accumulator in hydraulic braking systems meets all 14 CFR/CS Part 25 requirements. As the need arises, this ARP can be revised to add recommendations for the battery in electric braking systems. This Recommended Practice is intended to apply to all FAR/CS Part 25 brake control systems created after release of this document.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP1070 Design and Testing of Antiskid Brake Control Systems for Total Aircraft Compatibility

2.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 25 (Amendments 25-23, 25-78, 25-108, 25-123, and 25-140)

2.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

CS-25 Large Aeroplanes, Amendment 21

AMC 25.734 Protection against wheel and tire failures

2.4 Additional References

Accident Investigation Final Report, All Engines-Out Landing Due to Fuel Exhaustion, Air Transat Airbus A330243 marks C-GITS, Lajes, Azores, Portugal 24 August 2001. Available at <http://www.fss.aero/accident-reports/dvdfiles/PT/2001-08-24-PT.pdf>.

Accident involving Boeing 767-332ER, registration N-182DN, operated by Delta Airlines at the Madrid Barajas airport (Madrid Spain) on 5 December 2013. Available at https://reports.aviation-safety.net/2013/20131205-0_B763_N182DN.pdf.

Aircraft Accident Report 1/2010, Report on the accident to Boeing 777-236ER, G-YMMM, at London Heathrow Airport on 17 January 2008. Available at <https://www.gov.uk/aaib-reports/1-2010-boeing-777-236er-g-ymmm-17-january-2008>.

Final Report of the Board of Inquiry, Air Canada Boeing 767 aircraft C-GAUN, emergency landing at Gimli, Manitoba, 23 July 1983. Available at https://reports.aviation-safety.net/1983/19830723-0_B762_C-GAUN.pdf.

Loss of Thrust in Both Engines After Encountering a Flock of Birds and Subsequent Ditching on the Hudson River, U.S. Airways Flight 1549, Airbus A320-214, N106US, Weehawken, New Jersey, 15 January 2009. Available at <https://www.nts.gov/investigations/AccidentReports/Reports/AAR1003.pdf>.

2.4.1 Applicable FAA and EASA Requirements for Transport Category Aircraft (i.e., 14 CFR Part 25 Aircraft) and CS Part 25 EASA Regulations

14 CFR/CS Part 25.125: Landing. (Referred to in 25.735 below, this is a fairly lengthy paragraph that defines the dry runway performance landing certification requirements.)

14 CFR Part 25.671: General - Control Systems. (Relevant parts only.)

- (d) The airplane must be designed so that it is controllable if all engines fail. Compliance with this requirement may be shown by analysis where that method has been shown to be reliable.

EASA CS Part 25.671 Amendment 24:

- (d) The aeroplane must be designed so that it is controllable, if all engines fail at any time of the flight:

- (1) it is controllable in flight;
- (2) an approach can be made;
- (3) a flare to a landing, and a flare to a ditching can be achieved; and
- (4) during the ground phase, the aeroplane can be stopped.

EASA CS Part 25.734: Protection against wheel and tire failures. (Refer to AMC 25.734.)

The safe operation of the aeroplane must be preserved in case of damaging effects on systems or structures from: tire debris, tire burst pressure, flailing tire strip; and wheel flange debris.

14 CFR/CS Part 25.735: Brakes and Braking Systems. (Relevant parts only.)

- (b) Brake system capability: The brake system, associated systems, and components must be designed and constructed so that:
 - (1) If any electrical, pneumatic, hydraulic, or mechanical connecting or transmitting element fails, or if any single source of hydraulic or other brake operating energy supply is lost, it is possible to bring the airplane to rest with a braked roll stopping distance of not more than two times that obtained in determining the landing distance as prescribed in Part 25.125 (see above).
- (h) Stored energy systems: An indication to the flightcrew of the usable stored energy must be provided if a stored energy system is used to show compliance with (b)(1) of this section. The available stored energy must be sufficient for:
 - (1) At least six full applications of the brakes when an antiskid system is not operating; and
 - (2) Bringing the airplane to a complete stop when an antiskid system is operating, under all runway surface conditions for which the airplane is certificated.

14 CFR/CS Part 25.1309: Equipment, Systems, and Installations. (Relevant parts only.)

- (a) The airplane equipment and systems must be designed and installed so that:
 - (1) Those required for type certification or by operating rules, or whose improper functioning would reduce safety, perform as intended under the airplane operating and environmental conditions.

- (2) Other equipment and systems do not adversely affect the safety of the airplane or its occupants, or the proper functioning of those covered by (a)(1) of this section.

- (b) The airplane systems and associated components, considered separately and in relation to other systems, must be designed and installed so that:
 - (1) Each catastrophic failure condition:
 - (i) is extremely improbable; and
 - (ii) does not result from a single failure; and
 - (2) Each hazardous failure condition is extremely remote; and
 - (3) Each major failure condition is remote.
- (c) Information concerning unsafe system operating conditions must be provided to the crew to enable them to take appropriate corrective action. A warning indication must be provided if immediate corrective action is required. Systems and controls, including indications and annunciations, must be designed to minimize crew errors which could create additional hazards.

3. REVIEW OF INCIDENTS RELEVANT TO A STORED ENERGY SYSTEM FOR EMERGENCY BRAKING

There have been several incidents where a stored energy system has been used to bring an airplane to a stop following failures outside of the brake system. These incidents, along with others that well could have used a stored energy system, are discussed below with an analysis of the adequacy of the stored energy system to bring the airplane to a stop.

3.1 Air Canada Flight 183, Boeing 767-200, Registration Number C-GAUN, Landing at Gimli, Manitoba, Canada on July 23, 1983

This incident is known as the “Gimli Glider,” where a Boeing 767-200 made an emergency landing at Gimli, Manitoba, Canada following loss of all engines due to fuel exhaustion. With the loss of all active hydraulic power, the hydraulic accumulator was used for emergency braking to bring the airplane to a stop. Because generator electrical power was lost to the antiskid system, only four of the eight wheels had antiskid protection from battery power. When the pilot applied brakes following touchdown on a dry runway, four of the wheels locked up due to loss of antiskid protection and two tires burst. The nose gear collapsed which increased drag on the runway to stop the airplane. The airplane was steered using differential braking so that the right main landing gear intentionally overran a barrier that had been constructed on the centerline of the abandoned runway, which was being used for automobile racing. This also increased airplane deceleration independent from braking. This incident then did not require a properly sized brake accumulator with only four of the eight brakes requiring antiskid flow demand from the hydraulic brake accumulator to bring the airplane to a stop.

3.2 Air Transat Flight TSC236, Airbus A330-243 Marks C-GITS, Lajes, Azores, Portugal, August 24, 2001

Air Transat flight TSC236 made an emergency landing at Lajes, Azores, Portugal following loss of all engine power due to fuel exhaustion. Due to the engines-out condition, the landing was conducted without the brake antiskid and normal braking systems functioning and without most of the spoilers and nose wheel steering. Because the emergency brake accumulator only provides for a limited amount of brake applications, full braking was applied and maintained after touchdown on a dry runway. All eight main landing gear tires burst following brake application and wheel lockup and the airplane came to a stop 7600 feet from the approach end of the 10000-foot runway. The segments of the main wheels contacting the pavement were worn down to the bearing journals, the left, rear, inboard wheel detached from the axle. Both left and right brake torque links attachment horns on the bottom segments of the main oleos also contacted the pavement. This incident required only one full brake application from the accumulator to stop the airplane with no directional control.

3.3 Delta Airlines Flight DAL415, Boeing 767-300ER, Registration Number N-182DN, Barajas, Madrid, Spain, December 5, 2013

Delta flight DAL415 made an emergency landing following a tire burst on takeoff, which caused substantial damage to airplane systems and structure and resulted in the flight crew electing to immediately return to the airfield and land. Tire debris from the tire burst resulted in loss of two of the three hydraulic systems on the airplane, and the brake hydraulic accumulator was used as the source of pressure to the brakes. Fuel was not jettisoned prior to the landing. The airplane touched down on a dry runway with flap setting 20 degrees at 172 knots groundspeed with a weight of 368000 pounds (44000 pounds below maximum takeoff weight). Only three of the 12 speedbrake panels deployed 6 seconds after touchdown to provide aerodynamic drag and reduce lift because of the loss of hydraulic systems. The right thrust reverser was inoperative so the left thrust reverser was deployed 9.5 seconds after touchdown to slow the airplane with the rudder used to maintain airplane heading on the runway centerline. The brakes were fully applied to slow the airplane beginning at 11.5 seconds and 3400 feet distance traveled after touchdown (5539 feet of runway remaining). The airplane speed was approximately 170 knots at brake application. Both antiskid and differential braking capability were available, and the average airplane deceleration during braking was approximately 5.8 ft/s/s. Forty seconds after brake application, at 32 knots and 9000 feet after touchdown, the brake accumulator was depleted of hydraulic fluid and all airplane deceleration capability was lost. It departed the left side of the runway onto a taxiway at 40 knots with 450 feet of runway remaining. This occurred due to left engine reverse thrust and loss of effectiveness of the rudder to maintain airplane directional control. Nose gear steering was also not available due to the loss of hydraulic systems and the airplane was uncontrollable at this point. The airplane came to rest in a grassy area after striking some lights and signs 600 feet left of the runway centerline and 9400 feet after touchdown. There were no fatalities or injuries to passengers or crew. This incident shows that sizing the brake accumulator to six-brake applications is not adequate to stop on the runway, and the exit speed would have been greater if landing on a wet runway because the increased antiskid activity during braking would have fully depleted the brake accumulator at a higher airplane velocity.

3.4 British Airways Flight 38, Boeing 777-236ER, Registration Number G-YMMM, London Heathrow Airport, January 17, 2008

In this incident a Boeing 777 lost all engine power on final approach to the runway due to accreted ice from within the fuel system being released, causing a restriction to the engine fuel flow to both of the engines. Engine thrust was lost from both engines at 700 feet altitude on final approach to the runway. The airplane could not maintain the approach path to landing on the runway and touched down short of the runway in a grassy area. It slid to a stop after all landing gear collapsed. Braking was not used during this incident however if the airplane had landed on the runway it would have used the hydraulic brake accumulator as the source of hydraulic fluid to the brakes. The runway was dry during this incident.

3.5 U.S. Airway Flight 1549, Airbus A320-214, Registration Number N-106US; Loss of All Engines and Landing in the Hudson River on January 15, 2009

This incident involved an Airbus A320 that lost all engine thrust after encountering a flock of birds that were ingested into both engines after takeoff from LaGuardia Airport in New York, NY. Engine thrust was lost at 2800 feet altitude after takeoff. The flight crew's first choice was to return to LaGuardia Airport for an emergency landing. If this had been possible the hydraulic brake accumulator would have been the source of stored energy to the brake system. The airplane weight was 151510 pounds at takeoff which is almost at the maximum takeoff weight limit of 151600 pounds for the A320-200 aircraft model. If the airplane had landed, the brake accumulator would have been required to provide enough hydraulic fluid to bring the airplane to a stop at near its maximum takeoff weight. Teterboro airport in New Jersey was also considered by the flight crew as an emergency landing site, but they were not able to make it to this airport. The flight crew ultimately decided to ditch the aircraft in the Hudson River.

3.6 Discussion of Accident History

Of the incidents requiring a stored energy system to stop the airplane, the most significant one for sizing the stored energy system is the Boeing 767-300ER landing at Madrid in 2013 (see 3.3) since the brake accumulator was relied upon as the energy source to the brakes used to stop the airplane. The airplane was traveling at 32 knots when the stored energy system was fully depleted by the demands of the brake system. The weather conditions were favorable during this incident. Both antiskid and differential braking capability were available. Since the runway was dry the antiskid system demands on the brake accumulator were reduced because the accumulator pressure quickly dropped below the skid threshold. Had the runway been wet or icy during this incident the antiskid flow demands on the accumulator would have been greater and the brake accumulator would have been exhausted at a higher speed. The brake accumulator was sized to provide six brake applications, yet it was not sufficient to stop the airplane on the runway during this incident.

Both antiskid and differential braking capability were available during the landing to provide directional control from tire cornering force. If antiskid had not been available and the tires had burst, they would not have provided tire cornering to provide directional control which was required following failure of one of the thrust reversers. The airplane rudder is effective for directional control at high speeds down to approximately 60 to 80 knots. Steering and/or differential braking are required at low speed for lateral directional control, so the stored energy system must be relied upon to maintain directional control at all times, especially at lower speeds.

The point of citing the “Sully” Sullenberger Airbus A320 ditch in the Hudson River is to illustrate that a 25.671(d) loss of all engines can occur at max takeoff weight, and as such the stored energy system for braking should be sized considering the loss-of-all-engines landing may occur at maximum takeoff weight. In this incident, the airplane hit a flock of birds on takeoff and lost all engines. The pilot tried to make it to a runway but decided he couldn't quite make it, so he landed in the Hudson River instead. Had he been able to make it to the runway, he would have had to make a stop with multiple airplane systems lost or seriously degraded and using the stored energy system for braking.

4. ASSESSING THE NEED FOR A STORED ENERGY SYSTEM FOR EMERGENCY BRAKING

4.1 The Three Applicable Requirements

There are three requirements for transport category airplanes that are applicable to assessing the need for and sizing of a stored energy system for emergency braking—25.1309, 25.671, and 25.735 (relevant parts reproduced in 2.1).

The first two requirements are 25.1309, which contains a general safety requirement that applies to airplane systems and 25.671, which contains a general safety requirement that applies in the event all engines fail. If a stored energy system is required for emergency braking, then it will almost certainly be sized to meet one or both of these requirements.

The third requirement is 25.735, which contains a safety requirement specific to single failures of the braking system itself or the loss of a single source of power to it. Transport category braking systems are typically designed such that a stored energy system for braking is rarely, if ever, required to meet the limited single failure requirements of 25.735.

4.1.1 25.1309(b)(1) and 25.671(d) Establish the Need

25.1309(b)(1) requires that “The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that (1) Any catastrophic failure condition (i) is extremely improbable and (ii) does not result from a single failure.” A failure condition is a condition, caused or contributed to by one or more failures or errors that has either a direct or consequential effect on the airplane, its occupants, and/or other persons, considering: flight phase, relevant adverse operational or environmental conditions, and external events.

25.1309(b)(1) is the basis for conducting an airplane-level system safety assessment (SSA) to determine if there is any single failure condition, or any combination of failure conditions that is not extremely improbable, that would require a stored energy system for emergency braking to achieve continued safe flight and landing. This includes common mode and particular risk failure conditions external to the braking system itself that would take out all active power sources to the braking system, thus placing reliance on a stored energy system to complete a safe flight and landing. Particular risks are defined as events or influences which are outside the systems concerned. Particular risks such as multiple failures resulting from a single cause are considered to be a single failure (e.g., fracture of two or more hydraulic lines as a result of a single tire failure should be considered a single failure). Examples of particular risks are fire, leaking fluids, bird strike, high intensity radiated fields exposure, lightning, uncontained failure of high energy rotating machines, and wheel/tire failures as defined in EASA CS 25.734.

Section 2.3: “25.671(d) requires that “The airplane be designed so that it is controllable if all engines fail.” FAA and EASA have different versions of 25.671(d), which are given in 2.2 and 2.3 respectively. EASA CS 25.671(d)(4) also requires that the airplane come to a complete stop, assuming it can reach a usable runway. This event should be included in the SSA. Compliance with this requirement should include which portions of the flight controls, hydraulic, and braking systems are available with an all engine failure and to what extent control is limited or restricted.