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Cover photo: *787 wing assembly.*

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BOEING EDGE

AERO magazine is published quarterly by Boeing Commercial Airplanes and is distributed at no cost to operators of Boeing commercial airplanes. *AERO* provides operators with supplemental technical information to promote continuous safety and efficiency in their daily fleet operations.

The Boeing Edge supports operators during the life of each Boeing commercial airplane. Support includes stationing Field Service representatives in more than 60 countries, furnishing spare parts and engineering support, training flight crews and maintenance personnel, and providing operations and maintenance publications.

Boeing continually communicates with operators through such vehicles as technical meetings, service letters, and service bulletins. This assists operators in addressing regulatory requirements and Air Transport Association specifications.

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Boeing 777X: Advancing the World's Most Efficient, Flexible Twin-Aisle Family

BOB FELDMANN
Vice President and General Manager,
777X Program
Boeing Commercial Airplanes

Last fall, we were very excited to officially introduce the new 777X, Boeing's newest family of twin-aisle airplanes, at the Dubai Airshow. The record-breaking launch for 259 airplanes from four customers across Europe and the Middle East propelled the program to an outstanding start.

This new airplane builds on the passenger-preferred and market-leading 777 while offering more market coverage and revenue capability than the competition. The 777X will include new engines and an all-new composite wing and will leverage technologies from the 787 Dreamliner.

The 777X introduces the latest innovative technologies, including the most advanced, fuel-efficient commercial engine ever. Engine supplier GE was the first partner announced on the program, and its GE9X engine will be greater than 5 percent more efficient than anything in its class.

In addition, the fourth-generation 777X composite wing has a longer span than today's 777. Its folding, raked wingtip and optimized span deliver greater efficiency, significant fuel savings, and complete airport gate compatibility.

Finally, the 777X leverages the latest technologies from the 787 Dreamliner to the proven and reliable 777. The 777X implements 787 technologies aimed at adding maximum value to our customers. These include the wing, flight controls, flight deck, and other systems. Ultimately, these innovations make the 777X the most advanced and fuel-efficient commercial airplane.

The 737 MAX incorporates new features that improve fuel efficiency and operations for airlines.

New 737 MAX: Improved Fuel Efficiency and Performance

Boeing's newest airplane family incorporates improvements that increase fuel efficiency, payload, and range and reduce emissions and noise.

By Michael Teal, Vice President and Chief Project Engineer, 737 MAX

Boeing's 737 MAX family of airplanes offers airlines improved fuel efficiency and reduced emissions and noise while extending the 737's reputation for reliability and retaining commonalities with the current 737 fleet.

The 737 MAX, which is scheduled to begin delivering to customers in 2017, has more than 1,700 orders since its 2011 launch.

This article provides details about the improvements and new technologies incorporated in the 737 MAX and how the new model's improved fuel efficiency will reduce operating costs, increase payload, and improve revenue for operators.

EXTENDING THE BOEING 737 FAMILY

Boeing's newest single-aisle airplanes — 737 MAX 7, 737 MAX 8, and 737 MAX 9 — build on the Next-Generation 737's popularity and reliability while delivering a new level of fuel efficiency for single-aisle airplanes.

Commonality with current 737 models. The 737 MAX builds off the industry-leading Next-Generation 737, allowing the 737 MAX to retain operational commonality while achieving new levels of efficiency. For example, the fuselage and wings are similar in both models, but they will be strengthened to support the increased engine weight of the 737 MAX. The 737 MAX will fit into customers' existing 737 fleets using the same support system and maintenance program as the Next-Generation 737 airplane. The 737 MAX also will retain significant spares commonality with the Next-Generation 737.

Fuel efficiency. The 737 MAX will be 14 percent more fuel efficient than today's most efficient single-aisle airplanes. When compared to a fleet of 100 of today's most fuel-efficient airplanes, the 737 MAX will emit over 310,000 fewer tons of carbon dioxide and save more than 215 million pounds of fuel per year, translating into more than $112 million in annual cost savings.

Environmental improvements. The 737 MAX will be cleaner, quieter, and more efficient than its predecessor, the Next-Generation 737. In addition to 14 percent less fuel and carbon emissions, the 737 MAX has up to a 40 percent smaller operational noise footprint and approximately 50 percent lower nitrogen oxide emissions than the International Civil Aviation Organization's Committee on Aviation Environmental Protection (i.e., CAEP/6) limits.

Increased payload or range. The new airplane will extend the Next-Generation 737 range advantage with the capability to fly more than 3,500 nautical miles (nmi) (6,482 kilometers [km]), an increase of 405 to 580 nmi (750 to 1,074 km) over the Next-Generation 737. With better efficiency than competing airplanes, the 737 MAX will enable operators to fly farther or carry more payload than the competition.

Lower operating costs. The more efficient structural and aerodynamic design, lower engine thrust, and reduced required maintenance of the 737 MAX will offer customers large cost advantages. Depending on the model, the 737 MAX will be up to 8 percent lighter per seat than competing airplanes. Its reduced weight, combined with its new aerodynamic features, means the more efficient design of the 737 MAX will have the lowest operating costs in the single-aisle market segment with an 8 percent per-seat advantage over competing airplanes.

The 737 MAX requires less maintenance less often — with longer check intervals than competing airplanes. This means that rather than being in the hangar undergoing frequent checks, the 737 MAX is more available for revenue service. The 737 MAX maintenance program is based on experience gained from the worldwide fleet of Next-Generation 737s, and airframe and engine maintenance costs are expected to be the same while providing greater fuel and operating efficiency.

DESIGNED FOR OPERATIONAL EFFICIENCY

The 737 MAX family achieves its efficiency through a combination of design innovations.

New advanced technology winglet. The 737 MAX features the most advanced winglet technology currently available. The advanced technology winglet contributes about 1 percent to the airplane's efficiency on 500-nmi missions. At longer ranges, customers will see more than 1.5 percent improvement over today's winglet technology. The unique up-and-down configuration and natural laminar flow enabled by the winglet design are the innovations that make this feature so efficient (see fig. 1).

Enlarged flight deck displays for enhanced visuals, improved reliability, lower spares and maintenance costs, lower weight, and lower upgrade costs over the life of the airplane. As pilot and training needs evolve, Boeing will be able to incorporate future functionality into the 737 MAX flight deck (see fig 2).

Revised tail design. Aft body aerodynamic improvements include a redesigned auxiliary-power-unit (APU) inlet, extended tail cone, and a thickening of the tail cross-section above the elevator to improve the steadiness of air flow. These changes eliminate the need for vortex generators on the tail and reduce drag by 1 percent, contributing to fuel efficiency (see fig. 3).

New engines optimized for the 737 MAX. The 737 MAX will be powered by CFM International LEAP-1B engines with an optimized, more efficient core and increased fan diameter (see fig. 4) from 61 inches (in) (155 centimeters [cm]) to 69.4 in (176 cm). The new engines are the major driver for fuel-efficiency on the new airplane — contributing about 11 percent fuel-use reduction after drag is calculated. The LEAP-1B engine is derived from a suite of advanced technologies that encompass a carbon fiber composite fan and fan case; fourth-generation three-dimensional aerodynamic airfoil designs; the twin-annular, pre-swirl combustor; advanced cooling and

Figure 1: Advanced technology winglets reduce fuel use

The winglets' innovative up-and-down configuration and laminar flow improve fuel efficiency.

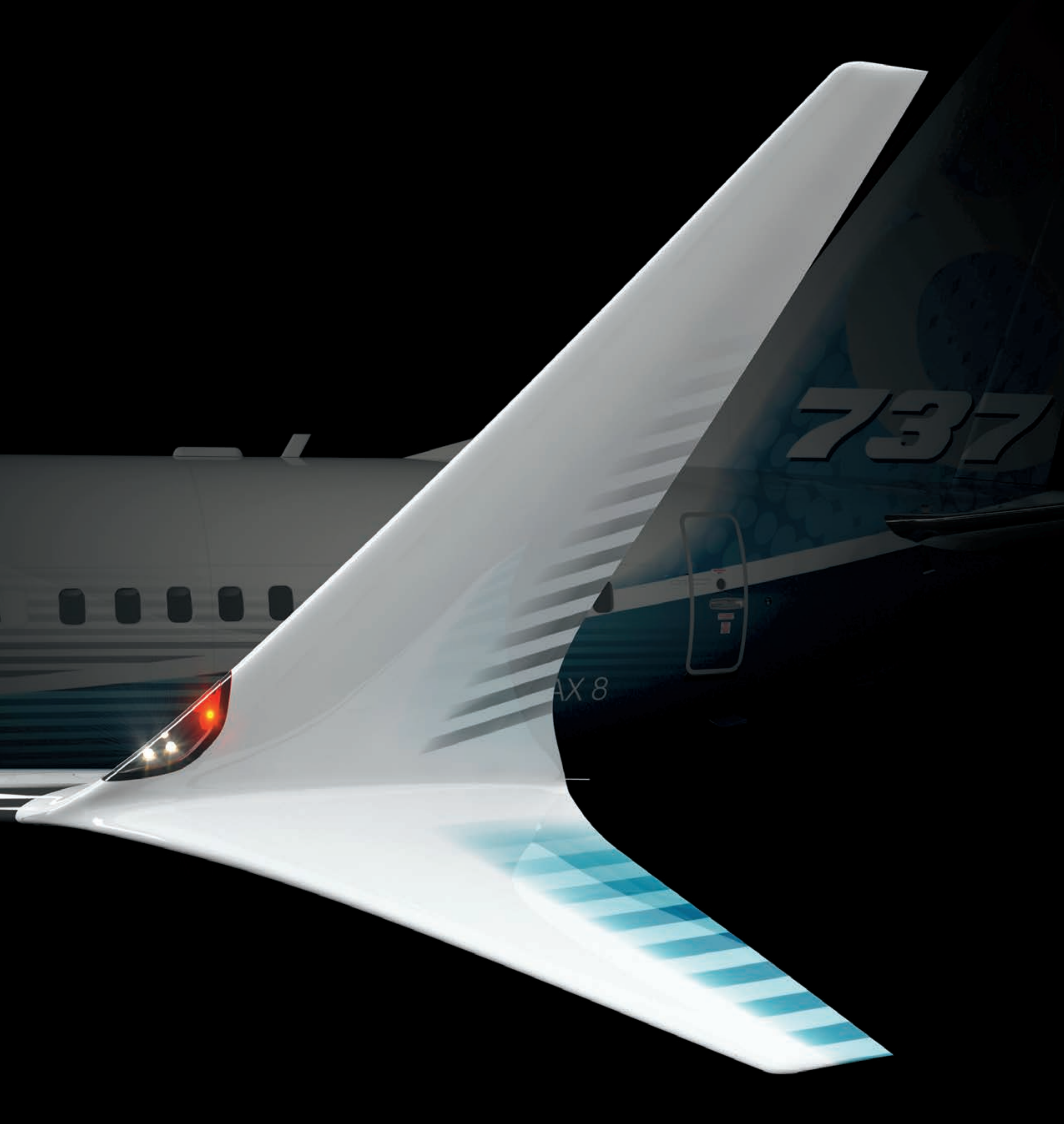


Figure 2: Updated flight deck displays

The 737 MAX flight deck will have four new large displays with significant growth capability while maintaining a common look-and-feel with the Next-Generation 737 display formats that preserves commonality with training across the 737 family.

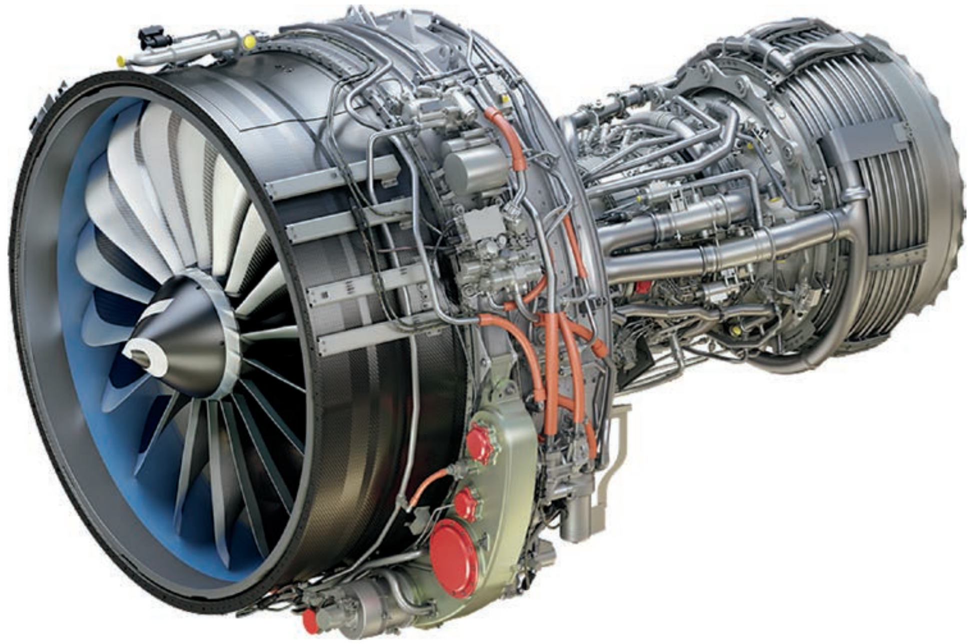

Gate 8

Figure 3: Revised tail design reduces drag

The 737 MAX features a number of aft body aerodynamic improvements that reduce drag by 1 percent.

Figure 4: LEAP-1B engine

The 737 MAX uses LEAP-1B engines that combine long-range fuel-efficiency performance with high-cycle reliability and durability.



coatings in the high-pressure turbine; and state-of-the-art materials, such as ceramics matrix composites and titanium aluminide. The result is a low-weight, high-performance engine that is optimized for the 737 MAX. Thrust ratings on the 737 MAX are about 1,000 pounds (lbs) (454 kilograms [kg]) higher than the same ratings on the Next-Generation 737 and range between 20,000 lbs (9,072 kg) to 28,000 lbs (12,701 kg).

The engine and wing integration has also been improved, moving the engine up and forward on the wing while keeping ground clearance the same as that of the Next-Generation 737. This improved integration also reduces drag, contributing about a half a percent of fuel efficiency.

ADDITIONAL IMPROVEMENTS

In addition to its features that enhance fuel efficiency, the 737 MAX incorporates a number of other improvements, including:

- Fly-by-wire spoiler system to improve reliability, reduce weight, and improve stopping distances.
- Electronic bleed air system that allows for increased optimization of the cabin pressurization and ice protection systems. This also contributes to fuel efficiency.
- Onboard network system. The 737 MAX will include an enhanced onboard network system comprising a Network File Server and an enhanced Digital Flight Data Acquisition Unit. These systems will provide a new set of capabilities, including advanced data collection, onboard repository of loadable airplane software parts, and real-time data processing. The system will also leverage available connectivity for secure communications with ground-based systems to support airline operations such as remote software part transferring from the airline back office or analytic capabilities with Boeing airplane health management and electronic logbook. The 737 MAX will build on the 737's enhanced connectivity to provide real-time data about airplane systems to the ground during flight. These changes are designed to make it easier for airlines to make more timely operational decisions about maintenance.
- Built-in test equipment in flight deck. The 737 MAX will feature a more centralized Built-in Test Equipment system that will give maintenance technicians better access to maintenance information. Today some fault information is accessed from the forward electronic equipment bay of the airplane, which takes additional time. On the 737 MAX, maintenance technicians will be able to access this data from the flight deck, speeding up their ability to assess dispatch limitations and perform maintenance actions.
- Boeing Sky Interior is standard on the 737 MAX. (For more information about the Boeing Sky Interior, see *AERO* second-quarter 2013.)

SUMMARY

The 737 MAX extends the 737 family of airplanes by incorporating new features that improve fuel efficiency and operations for airlines. The airplane's commonalities with previous 737 models will allow for easy integration into existing 737 fleets.

An effective safety culture focuses on understanding and addressing safety issues instead of blaming technicians.

Creating a More Effective Safety Culture

Airlines seeking ways to create safety cultures should clearly distinguish between acceptable and unacceptable behavior. A good safety culture facilitates the implementation of a Safety Management System (SMS) through encouraging collaborative participation in event investigation and the reporting of important safety-related information.

By Maggie J. Ma, Ph.D., Certified Human Factors Professional, Systems Engineer, Maintenance Human Factors, and
William L. Rankin, Ph.D., Boeing Technical Fellow, Maintenance Human Factors

The Boeing Maintenance Human Factors team provides implementation support to customer airlines on a wide array of maintenance human factors safety processes and programs. Operators often ask the team how to promote or facilitate a good safety culture in order to implement these processes and programs.

This article defines a good safety culture in the context of implementing an SMS, outlines the limitations of discipline, provides practical steps on how to establish an effective safety culture, and recommends strategies for dealing with ineffective norms in the workplace.

ESTABLISHING AN SMS

Most civil aviation authorities around the world either already require or will soon require airlines to have an SMS (see Federal Aviation Administration [FAA] Order VS 8000.367A - Aviation Safety (AVS) Safety Management System Requirements). An SMS involves using reactive, proactive, and predictive hazard identification processes.

Reactive. Accidents and serious incidents are investigated based on the belief that organizations should learn from their mistakes, which provide valuable information. An example of a reactive hazard identification process for maintenance is the Maintenance Error Decision Aid (MEDA) process. (For more information about MEDA, see *AERO* second-quarter 2007.)

Proactive. An organization's activities to identify safety risks are analyzed based on the belief that system failures can be minimized by identifying safety risks within the system before failure occurs. Examples include quality assurance audits and voluntary reporting systems, such as hazard reporting systems and the Aviation Safety Action Program (ASAP).

Predictive. This approach/process captures system performance as it happens in real-time normal operations, based on the belief

Figure 1: Three interrelated aspects of a safety culture

Safety Culture

"The product of individual and group values, attitudes, perceptions, competencies, and patterns of behavior that can determine the commitment to and the style and proficiency of an organization's health and safety management system."

Psychological Aspects

How people feel

Can be described as the "safety climate" of the organization, which is concerned with individual and group values, attitudes, and perceptions.

Behavioral Aspects

What people do

Safety-related actions and behaviors.

Situational Aspects

What the organization has

Policies, procedures, regulation, organizational structures, and the management systems.

A Three Aspect Approach to Safety Culture (adapted from the U.K. Health and Safety Executive Research Report 367, 2005)

that safety management is best accomplished by aggressively seeking information from a variety of sources that may predict emerging safety risks. Examples of these sources include maintenance reliability programs, airplane health management program, and maintenance line operations safety assessment (LOSA). Maintenance LOSA is a tool for collecting safety data by observing maintenance technician behavior during normal maintenance operations. (For more information about LOSA, see *AERO* second-quarter 2012.)

An SMS is much more effective when it is implemented within an appropriate safety culture. The European Aviation Safety Agency first promoted "Culture of Safety" in its basic regulation (EDC 216/2008) that reporting of incidents and other safety occurrences should be facilitated by the establishment of a non-punitive environment in order to encourage reporting of safety information. A U.K. Health and Safety Executive Research Report reviewed safety culture and safety climate literature and identified three interrelated aspects of safety culture (see fig. 1). The International Civil Aviation Organization discusses "non-punitive reporting systems" in its SMS training. "Non-punitive" means that employees should not be disciplined for reporting bad news (e.g., incidents and safety hazards).

DEFINING A GOOD SAFETY CULTURE

In the 1997 book *Managing the Risks of Organizational Accidents*, James T. Reason wrote that a good safety culture comprises five elements:

- Informed Culture. Those who manage and operate the system have current knowledge about the human, technical, organizational, and environmental factors that determine the safety of the system as a whole.
- Reporting Culture. People are willing to report errors and near misses.
- Learning Culture. People have the willingness and competence to draw the right conclusions from their safety information system and the will to implement major reforms when the need is indicated.
- Flexible Culture. Organizational flexibility is typically characterized as shifting from the conventional hierarchical structure to a flatter professional structure.
- Just Culture. An atmosphere of trust is present and people are encouraged or even rewarded for providing essential safety-related information, but there is also a clear line between acceptable and unacceptable behavior.

Of these elements, Just Culture is critical and lays the foundation for the other elements. Just Culture refers to how a company deals with the issue of discipline and is not equivalent to an absence of disciplinary action.

A Just Culture emphasizes shared accountability between the organization and its employees. In the Just Culture, an individual employee is not held accountable for system failures over which he or she has no control, but it does not tolerate conscious disregard of rules, reckless behavior, or gross misconduct. In a Just Culture, event investigation looks beyond the "who" and searches for the "why" so that system issues that lead to errors and violations can be fixed. A Just Culture recognizes that a large proportion of unsafe acts are honest errors, and there is not much corrective or preventative benefit from discipline. According to Reason, only about 10 to 20 percent of actions

Developing an effective safety culture

According to Heather Baldwin in the article "Remove Your Roadblocks" published by *Aviation Week & Space* in 2012, the following three principles are essential to fundamentally change a company culture and make the transition to a more positive and effective Just Culture:

Integrity. Consistency and predictability help build trust. If employees know that a safety policy/procedure applies to every person in the company, and that it will be enforced fairly, the consequence of violating this policy/procedure is then 100 percent predictable. The compliance to the safety policy/procedure will be improved, and consequently safety performance will be improved.

Commitment. Commitment-based safety is more proactive than compliance-based safety because employees willingly participate in the former. To encourage frontline employees (e.g., maintenance technicians) to be more actively involved, they need to be empowered and given more control. For example, they can participate in activities to improve work processes. When frontline employees feel that their voices are heard and valued by management, they will become more motivated and proactive.

Transparency. Establish a mechanism that allows employees to express their opinions without fear. If there is no such mechanism or it's impossible to have such a mechanism, find the root cause. Sometimes there is a mechanism established, but it doesn't function, such as an unused suggestion box or managers who collect employee feedback as a formality but don't actually listen to what employees have to say.

contributing to bad events are due to individual issues (e.g., complacency) while the remaining 80 to 90 percent are system issues, such as poor training, inadequate equipment and/or hangar facilities, misleading or incorrect maintenance task information, design issues, inadequate task handover process, task interruption, and time pressure. If 80 to 90 percent of actions leading to an unsafe event are caused by system issues, then discipline is not warranted in a majority of the events.

A Just Culture doesn't completely eliminate discipline; instead, it draws a clear line between acceptable and unacceptable behavior while specifying potential discipline for committing unacceptable behaviors. In general, a Just Culture should lead to an overall reduction in the use of discipline. Management must also ensure that the discipline is carried out consistently for any member of the company who commits unacceptable behaviors. These acceptable and unacceptable behaviors need to be made known to all employees through a clearly written, easily accessible policy and training.

For example, a company can specify that "it is unacceptable to purposefully skip an operational check at the end of a maintenance task." If a technician deliberately chooses to bypass the operational check disregarding the consequence, there will be some form of discipline. On the other hand, if a technician over-torques a bolt because the torque wrench is out of calibration, then he or she should *not* be disciplined. Also, companies should base discipline on the behavior and not on the outcome of an event caused by the behavior.

THE DRAWBACKS OF DISCIPLINE

According to studies cited by psychologists Carole Wade and Carol Tavris in their 2010 book *Psychology*, using discipline as a control method for behaviors has a number of limitations:

- Discipline is often administered inappropriately.
- People are so mad that they may make decisions based on emotion instead of facts. Discipline may be applied in haste without detailed, deliberate fact gathering.
- The person being disciplined often responds with anxiety, fear, or anger.
- The effects of discipline can be temporary and can depend on whether the person who carried out the discipline is present. People only learn "not to get caught."
- Discipline often provides little information. It may tell the person what not to do, but it doesn't usually tell the person what he or she should do.

From a psychological perspective, the effect of discipline is much less useful than the effect of reinforcement. Disciplining employees teaches them what not to do (or not to get caught) but doesn't teach them about expected behaviors. Because each employee can't be watched and monitored constantly, the ultimate goal is to have employees perform good, expected behaviors on their own. Discipline often causes employees to hide problems and mistakes.

For example, one organization formerly gave a monthly "no mistake" bonus that constituted an important portion of employees' monthly income: without this bonus, their daily living would be affected. As a result, all of the maintenance technicians in the company reached an unspoken agreement that nobody would disclose a mistake or problem in maintenance operations. When a part was damaged during

Key behaviors

A "Key Behaviors Initiative" is part of an airline's overall effort to reduce technician errors in airplane maintenance. Key behaviors are specific maintenance behaviors intended to minimize the frequency and impact of maintenance errors that could affect flight safety and reliability. One airline's program included the following key behaviors:

1. When performing critical systems or principal structures maintenance, review the current maintenance instructions before beginning a task.
2. Document all additional disassemblies not specified in the task instructions.
3. Document job status at the end of a shift or when moving to a new task.
4. Flag all disassemblies that might be inconspicuous to anyone closing the work area.
5. Confirm the integrity of each adjacent connection after installation of any line replaceable unit.
6. Complete all required checks and tests.
7. When closing a panel, conduct a brief visual scan for safety-related errors.

a remove-and-replace task, the technicians would not report it so they would not be disciplined — losing the "no mistake" bonus. They waited for the pilots to discover any problems during a revenue flight.

EVOLVEMENT OF SAFETY CULTURE IN THE UNITED STATES

Since the mid-1990s, aviation safety culture has evolved through three stages for airlines operating in the United States:

Stage 1. Companies adopted event investigation tools such as MEDA to systematically investigate maintenance-caused events. Previously, airlines tended to blame individual technicians for making errors. Airline management worried that they would lose the ability to discipline people if they committed to MEDA investigations. Gradually through systematic investigations using MEDA, airlines began looking into factors that contributed to the technicians' errors that caused the events. Organizations started to realize that in most cases the errors were due to system issues rather than individual factors like complacency. Disciplining technicians without fixing those system issues would do nothing to reduce the likelihood that the same error would occur in the future.

Stage 2. The FAA had the insight to realize that if they disciplined technicians through letters of investigation and certificate action, then technicians would not voluntarily report important safety-related information. The FAA encouraged airlines to establish an ASAP (see Advisory Circulars 120-66 and 120-66B), a joint program sponsored by the FAA, company management, and labor. An ASAP encourages employees to report safety issues (e.g., incorrectly performed maintenance, near misses, safety concerns, and hazards) at work. If a report is accepted by the Event Review Committee (composed of three members representing the FAA, airline management, and labor), regardless of the size of the event or its financial impact, the FAA promises no certificate enforcement action against the technician in exchange for information that otherwise may remain unknown.

Stage 3. Airlines promoted and implemented a Just Culture.

Note that the above stages are not sequential or mutually exclusive. They often overlap with one another and evolve together.

CREATING AN EFFECTIVE SAFETY CULTURE

An airline culture that heavily emphasizes punitive actions is not compatible with SMS because discipline deters people from voluntarily reporting safety events and concerns, makes them less forthcoming with information when they participate in event investigations, and alters their usual performance to model expected behavior when they are observed during normal operations.

To establish and maintain a good safety culture, management must consider taking the following specific actions:

- Tell employees what are acceptable behaviors and what are unacceptable behaviors. (See "Key behaviors" on this page.)

- Obtain commitment from the employees that they agree with and will comply with these key behaviors.
- Obtain commitment from management that they will not tell technicians to break any of the key behaviors.
- Ensure that leads and supervisors monitor frontline employees to make sure they comply with the company's safety policy (i.e., exhibit key behaviors and do not engage in unacceptable behaviors).
- If an employee doesn't perform key behaviors or commits unacceptable behavior, there must be consequences (e.g., coaching or a verbal warning). However, a gray area exists between unacceptable behavior and blameless unsafe acts, where the discipline has to be decided on a case-by-case basis.

Ultimately, the active involvement of executive management is essential for establishing and maintaining a good safety culture. Major safety improvements are possible only if they are driven down from the top. (See "Developing an effective safety culture" on page 15.) SMS emphasizes that the company chief executive officer, not the safety or quality director/manager, is the accountable manager for safety.

DEALING WITH INEFFECTIVE NORMS IN THE WORKPLACE

Ineffective norms (e.g., "everybody does it") should be considered a system problem, not an individual problem. Ineffective norms are the result of unacceptable behaviors going uncorrected and, therefore, being perceived as condoned.

Management also needs to act as a role model for key acceptable behaviors and face the same consequences as frontline employees if they violate them. Otherwise, employees will get the erroneous impression that requirements don't necessarily have to be followed. For example, if a company requires everybody to wear safety glasses and hearing protection in the hangar, then management needs to wear safety glasses and hearing protection in the hangar — and monitor and correct employees' use of this personal protective equipment. It's also critical to provide safety glasses and ear plugs in the hangar and line maintenance area so that technicians have easy access to them.

SUMMARY

About 80 to 90 percent of actions leading to safety events are caused by system issues. Focus on correcting system issues instead of blaming individuals. An effective safety culture is one that clearly states acceptable and unacceptable behaviors while specifying potential disciplinary actions for committing unacceptable behaviors. It encourages employees to maintain professional accountability and voluntarily disclose safety-related information, such as errors, safety concerns, and hazards. It focuses on understanding and addressing safety issues instead of blaming the technicians who were involved. In this self-reporting environment, safety concerns (e.g., hazards) tend to get resolved, which improves morale.

Boeing provides implementation support to customer airlines on a wide array of maintenance human factors safety processes and programs.

For more information, email MHF@boeing.com.

Alkali metal runway deicers clearly damage carbon brakes resulting in catalytic oxidation of the carbon.

Effects of Alkali Metal Runway Deicers on Carbon Brakes

Alkali metal (i.e., organic salt) runway deicers have caused catalytic oxidation of carbon brakes, resulting in mechanical damage to the brakes, and have the potential to degrade airplane stopping performance. Mitigating actions can reduce the severity of catalytic oxidation of carbon brakes but cannot eliminate the occurrence of catalytic oxidation of carbon brakes as long as cold weather airports continue to use alkali metal runway deicers.

By Michael Arriaga, Service Engineer

Two types of oxidation can occur on carbon brakes: thermal oxidation and catalytic oxidation. Thermal oxidation occurs as the temperature of the carbon material is increased and an oxidizer, such as oxygen, is present. Catalytic oxidation of carbon occurs when a catalyst, such as an alkali metal(s), is present. When a catalyst is present, the temperature at which thermal oxidation occurs is lowered. Airplanes equipped with carbon brakes are susceptible to catalytic oxidation caused by exposure to alkali metal runway deicers. These deicers are in common use at cold weather airports around the world mainly due to environmental legislation. Although airplane deicers applied to the wings and fuselage do contain very small amounts of alkali metals, airplane deicers are glycol-based and do not contribute to catalytic oxidation of carbon brakes. SAE Aerospace Recommended Practice (ARP) 5149 (*Training Program Guidelines for Deicing/Anti-Icing of Aircraft on Ground*) and ARP 4737 (*Aircraft Deicing/Anti-icing Methods*) provide guidance to airplane deicing crews not to spray the landing gear or wheels and brakes with airplane deicer fluid.

This article explains the history of catalytic oxidation of carbon brakes, the catalytic oxidation process caused by alkali metal runway deicers, the effects of runway deicers on carbon brakes, and how airlines and airports can minimize these effects.

THE HISTORY OF CATALYTIC OXIDATION OF CARBON BRAKES

Widespread use of carbon brakes on commercial airplanes began in the mid-1980s. Carbon brakes offer a significant weight savings compared to steel brakes, which translates into a lighter airplane and directly contributes to decreased fuel consumption and reductions in engine emissions.

Carbon brakes also offer other advantages over steel brakes, including improved brake performance, high temperature stability, better wear characteristics and longer life, and the ability to reuse worn carbon disks to make refurbished carbon disks that would otherwise end up being disposed of in a landfill. (For more information about the advantages of carbon brakes, see *AERO* third-quarter 2009.)

By the early 1990s, airlines began experiencing catalytic oxidation of carbon brakes at about the same time that airports began using alkali metal runway deicers. These alkali metal deicing formulations — containing primarily, but not limited to, potassium, sodium, and calcium — were introduced because of environmental concerns over the use of urea- and glycol-based runway deicers. When airports were using urea- and glycol-based runway deicers, there were no reports of catalytic oxidation of the carbon brakes. Environmentally friendly alkali metal runway deicers were introduced because they reduce the biological and chemical oxygen demand (removal of oxygen from the water) on water systems around airports, limiting the environmental impact to aquatic and plant life.

Airlines reported that carbon brakes were showing indications of oxidation (soft carbon) and structural deterioration of the carbon disks (i.e., chips, cracks, or complete disk failure). Chemical analysis of the contamination on the carbon brake disks by the brake manufacturers found high levels of the alkali metals potassium, sodium, and calcium (see fig. 1). Further investigation determined the source of these alkali metals was from airports' use of environmentally friendly runway deicers, since these alkali metals by themselves are not used during the manufacture of the carbon brakes or the airplane.

CATALYTIC OXIDATION OF CARBON

Catalytic oxidation of airplane carbon brakes is caused by contamination with a catalyst, in this case alkali metal(s). The rate of catalytic oxidation is a function of the time the carbon is exposed to the alkali metal catalysis while at an elevated temperature, which can be the normal operating temperature of the carbon brake. Over time, the catalytic oxidation of the carbon results in mechanical and structural degradation of the carbon disk material. Unfortunately, due to the many variables involved during normal takeoff and landing — weather conditions, airplane weight during takeoff and landing, airplane landing speed, thrust reverser usage, flap setting, autobrake setting, altitude of airport, outside air temperature, wind speed and direction at landing, after-landing instructions by air traffic control to vacate the runway, taxi distances, the worn condition (mass of the carbon heat-sink) of the carbon brakes, the amount and concentration of runway deicer on the runway and taxiway — it is not possible to predict the rate at which the carbon disks will catalytically oxidize.

DAMAGE TO CARBON BRAKES CAUSED BY ALKALI METAL RUNWAY DEICERS

Carbon brakes become contaminated by runway deicers during taxi, takeoff, and landing when runway deicers splash onto the carbon brakes (see fig. 2).

Once the carbon brakes are exposed to the alkali metal runway deicers, the alkali metal cannot be removed from the carbon disks. Subsequent exposure to these alkali metals on successive takeoff and landing cycles, combined with the braking action of the airplane, leads to the mechanical and structural degradation of the carbon disks.

Catalytic oxidation of the carbon does result in decreased service life (premature removal) of a carbon brake (see fig. 3). In rare instances, severely catalytically oxidized carbon brakes have caused a brake fire when a piston (or pistons) penetrates a severely catalytically oxidized carbon pressure plate (first rotor disk) and contacts the adjacent rotor disk, which is rotating at the same speed as the wheel. The rotational force of the rotor disc fractures the piston assembly, allowing hydraulic fluid to contact the carbon heat-sink, which is at an elevated temperature as a result of the kinetic energy absorbed by the brake during the landing stop (see fig. 4).

Figure 1: Scanning electron microscope analysis of carbon brake disk contamination

Laboratory analysis showed that carbon brakes were contaminated by sodium, potassium, and calcium, which caused the carbon to oxidize.

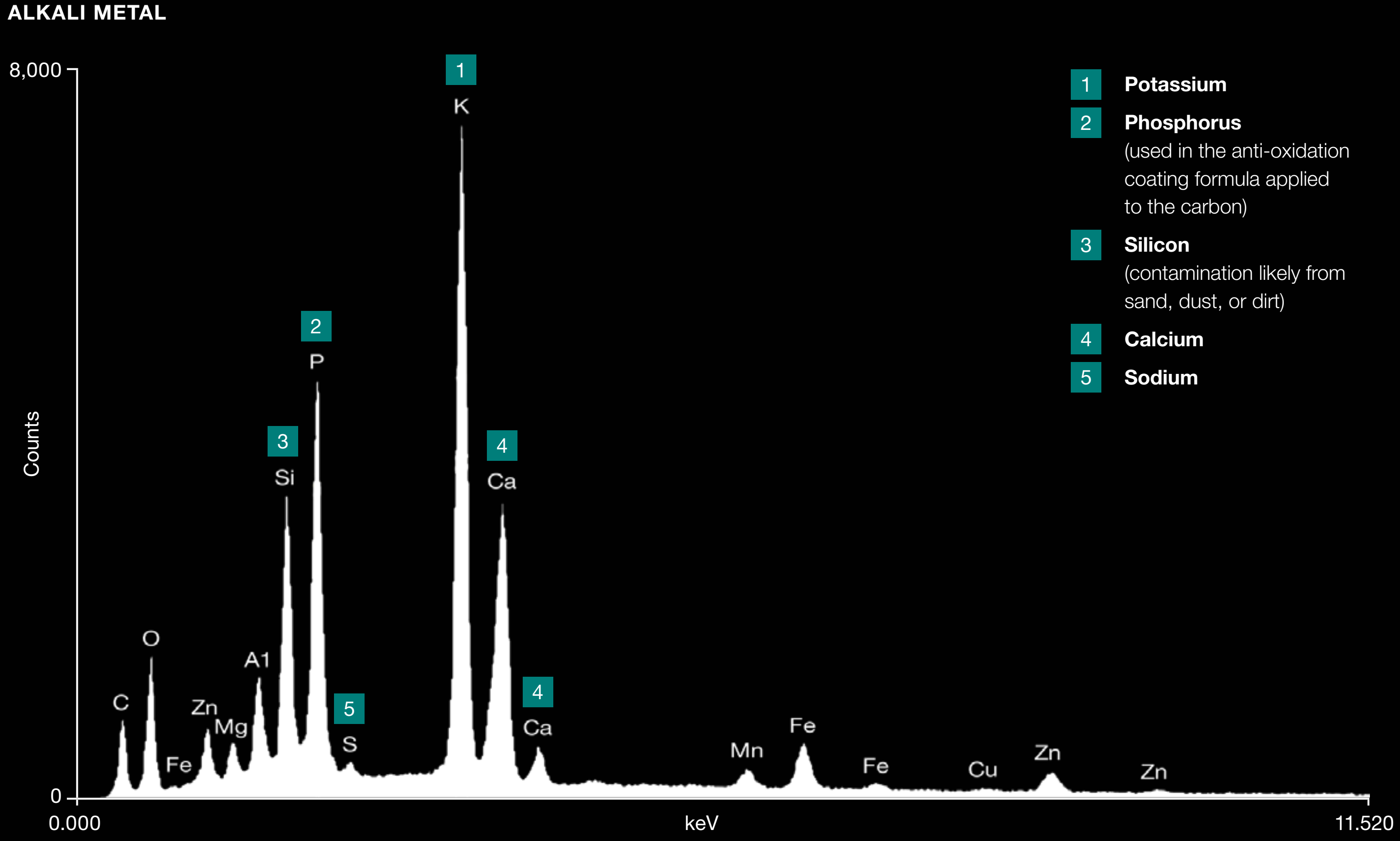


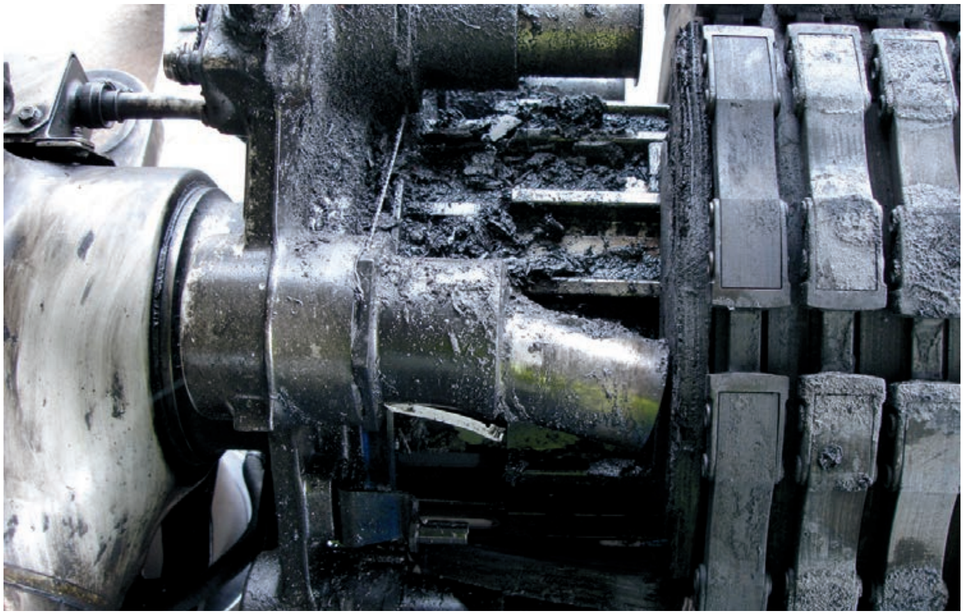
Figure 2: Carbon brake contamination by runway deicers

When deicers are present on taxiways and runways, alkali metal runway deicers splash onto the carbon brakes.

Figure 3: Carbon stator-disk-drive lug damage

The damaged stator-disk-drive lugs on this carbon heat-sink are an example of the type of damage alkali metal runway deicers can cause to carbon brakes. The top photo shows a new carbon heat-sink. The middle photo reveals significant damage with most of the stator-disk-drive lugs missing. The bottom image shows a complete loss of all stator-disk-drive lugs.

Figure 4: Catalytically oxidized carbon pressure plate disk failure resulting in a brake fire after landing



REGULATORY AND INDUSTRY RESPONSE TO CATALYTIC OXIDATION OF CARBON BRAKES

As the extent of catalytic oxidation of carbon brakes has become widely known, the following bulletins and reports have been published.

- Transportation Research Board of the National Academies, Airport Cooperative Research Program Synthesis 6 (*Impact of Airport Pavement Deicing Products on Aircraft and Airfield Infrastructure)*, 2008.
- U.S. Federal Aviation Administration (FAA) Special Airworthiness Information Bulletin NM-08-27R1, December 31, 2008.
- European Aviation Safety Agency (EASA) Safety Information Bulletin 2008-19R2, April 23, 2013.
    - Both FAA and EASA bulletins recommend that when an airline removes a wheel and tire assembly from the landing gear axle, a detailed inspection of the periphery of the carbon heat-sink be performed per the aircraft maintenance manual (AMM) for indications of catalytic oxidation of the carbon disks.
- SAE G-12RDF Catalytic Oxidation of Carbon Brakes Working Group's yearly, *Aerospace Industry Report*.
- SAE A-5A Wheels, Brakes and Skid Control Committee developed and published AIR5567 (*Test Method for Catalytic Carbon Brake Disk Oxidation*), May 2009.
- SAE A-5A Wheels, Brakes and Skid Control Committee developed and published AIR5490 (*Carbon Brake Contamination*), May 2012.
- Aerospace Material Specification (AMS) 1431 *(Compound, Solid Runway and Taxiway Deicing/Anti-Icing)* Revision C published September 2010 to add AIR5567.
- AMS1435 Fluid *(Generic, Deicing/ Anti-Icing Runways and Taxiways)* Revision B published September 2010 to add AIR5567.

WHAT AIRLINE OPERATORS CAN DO

To help operators of airplanes equipped with carbon brakes comply with FAA Special Airworthiness Information Bulletin NM-08-27R1 and EASA Safety Information Bulletin 2008-19R2, Boeing added information to the Main Gear Wheel Brakes – Inspection/Check section of the AMM to help airline maintenance personnel identify catalytically oxidized carbon brakes when the wheel and tire assembly are removed from the main landing gear axle. These inspections and checks include examining the carbon pressure plate disk for piston impressions or chipped or cracked carbon disks, verifying that the stator disk alignment grooves have not migrated, and, if the rotor disks have rotor clips, assuring the attachment fasteners are not loose.

In addition, Boeing has released service letters regarding the corrosion caused by alkali metal runway deicers on various airplane parts located mainly in the wheel well where exposure to runway deicers can occur, including carbon brakes (767-SL-32-106, *Effects of Alkali Metal [Organic Salt] Runway Deicer on Carbon Brakes*), hydraulic tubes (737-SL-29-092, *Recommended Action to Resolve Corrosion of Hydraulic Tubes in the Wheel Wells Caused by Exposure to Potassium-Containing Runway Deicing Fluids*), cadmium-plated components (737-SL-27-184, *Flight Controls in Main Wheel Well — Changes to the Finish of Cadmium Plated Components*), and electrical connectors (737-SL-20-053, *Electrical Connector Corrosion in Unpressurized Areas*).

Because exterior airplane cleaners can also contain small amounts of alkali metal, airlines are encouraged to use wheel covers when washing their airplanes.

DEVELOPING A LASTING SOLUTION

Eliminating or reducing the effects of catalytic oxidation on carbon brakes, and other airplane components, requires an industry-wide effort. For example, airlines, airports, and interested parties can work together to discuss the selection of an AMS1431 and/or AMS1435 runway deicer that has the lowest AIR5567 mean normalized carbon weight loss percentage. The lower the carbon

Proper flight operations (e.g., touchdown speeds, landing points, using available runway) will help reduce the amount of kinetic energy absorbed by carbon brakes during landing, lowering the brake temperatures and reducing the rate of oxidation.

weight loss percentage, the less catalytic oxidation of the carbon that will occur.

Additionally, to help alleviate the problem:

- Carbon-brake manufacturers should continue to develop new and improved anti-oxidation coatings for application to the carbon disks.
- Airframe manufacturers should continue to work with brake manufacturers, airlines, airports, and regulatory agencies to raise awareness of catalytic oxidation of carbon brakes caused by alkali metal deicers.
- Airlines can improve brake inspection techniques to find and remove catalytically oxidized carbon brakes from airplanes before they result in a flight delay or cancellation and damage to the airplane, such as when carbon disks fracture and depart the brake. Carbon disk pieces departing from the brake results in foreign object debris, which could affect other airplanes moving through the runway, taxiway, or ramp areas.
- Airlines that service the same cold weather airport that are experiencing catalytically oxidized carbon brakes can collectively approach the airport's airfield maintenance department and discuss the type of runway deicer the airport is using that can be contributing to catalytic oxidation of carbon brakes. The optimum deicer for use at cold weather airports is the deicer with the lowest mean normalized carbon weight loss percentage per AIR5567 testing.
- Airlines should be cognizant of the type of runway deicer being used by the airport so that they can take appropriate maintenance and planning actions.
- Airlines can also contact airline trade organizations, such as Airlines for America (formerly Air Transport Association) and the International Air Transport Association, to request their assistance.
- Additionally, proper flight operations (e.g., touchdown speeds, landing points, using available runway) will help reduce the amount of kinetic energy absorbed by carbon brakes during landing, lowering the brake temperatures and reducing the rate of oxidation.
- Airports should utilize mechanical snow removal methods, such as broom trucks and snowplows, as much as possible to reduce the amount of runway deicer used. Airports should apply runway deicers per the runway deicer manufacturers' recommended application rates. Over-application results in higher levels of alkali metal exposure to carbon brakes.
- Airports can also use the best available technology to measure effluent levels to comply with environmental legislation. Total organic carbon (TOC) measurement, in place of biological oxygen demand (BOD5) and chemical oxygen demand (COD) measurement, is a reliable, inexpensive, and real-time method that can be correlated to COD. If airports are unable to use TOC measurement in place of BOD5 and COD, a containment system can be built to capture and treat effluent before it is discharged to a public water treatment system or water bodies around the airport.
- Aviation regulatory agencies such as the FAA, EASA, and Transport Canada can engage environmental regulatory agencies to discuss changes to environmental legislation to maintain and improve aviation safety.

SUMMARY

Alkali metal runway deicers are clearly associated with damage to carbon brakes resulting in catalytic oxidation of the carbon. Airlines can work with airports to use runway deicers that are less harmful to carbon brakes, and aviation and environmental regulatory agencies can engage in discussion to change environmental legislation to maintain and improve aviation safety.

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