PROPER OPERATION OF CARBON BRAKES

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1. INTRODUCTION

Carbon brakes were introduced on Airbus aircraft in mid 80's in particular to take benefit of their advantages over steel brakes (higher braking efficiency and safety in a wide servicing range and consistent weight saving).

What appropriate procedures are required to operate carbon brakes? How can we improve carbon brake endurance? These recurring questions from many operators are due to several factors including:

- The high value of carbon brakes;
- Brake service life, obtained by some operators, were below what was expected;
- A large scatter ratio (equal to or higher than 2) in the carbon brake service life between operators, and this for any aircraft and brake type.

Therefore, brake manufacturers conducted tests and studies to understand why such differences exist. They determined the parameters that affect carbon service life and, some of them, have been providing dedicated (or not) recommendations to operate the brakes resulting, sometimes, in a higher service life.

As often explained, Airbus does not endorse some of these recommendations. However, our points of view about proper operation of carbon brakes have been continuously exchanged and agreements have been reached on some preferred carbon braking techniques.

The purpose of this article is to review the recommendations of brake manufacturers and of Airbus to highlight the agreements, disagreements and changes.

2. BRAKE MANUFACTURERS

For information, this table shows, the different brake manufacturers that provide carbon brakes on Airbus aircraft.

	A300B4 / A310 / A300-600	A319	A320	A321	A330 / A340
Messier-Bugatti	X	X	X	X (*)	X (*)
BF Goodrich		X	X	X (*)	X (*)
Aircraft Braking Systems (ABS)	X		X (**)	X	
Honeywell-ALS					X

(*) Joint venture Messier-Bugatti / BF Goodrich
(**) A321 wheels and brakes fitted on A320
Note: Honeywell-ALS (Aircraft Landing Systems), previously Bendix

Figure 1 - Carbon brake manufacturers on Airbus fleet

3. PARAMETERS AFFECTING BRAKE LIFE

Carbon wear is a very complex physical process. Furthermore, it should be noted that different types of carbon, sometimes having varying behaviors regarding wear, exist. This could even be applicable to different carbons proposed by the same brake manufacturer, as this is the case on Airbus fleet.

In the past few years, Airbus and brake manufacturers conducted laboratory testing and/or acquired some in-service brake life experience by working closely with the airlines. Based on this experience, two main factors affecting carbon wear performance have been identified and characterized: The number of brake applications and the carbon disk temperature.

3.1. Number of Brake Applications

The **number of brake applications,** combined with the total duration of brake application per leg, is definitely recognized as being **a major parameter governing heat pack service life.**
This is evidenced by the fact that airlines operating to/from congested airports, which favor multiple brake applications during taxi, generally show a 20% to 30% brake life decrease.

3.2. Carbon Disk Temperature

All brake manufacturers highlight the fact that **carbon wear is heavily affected by brake temperature**.

Figures 2 to 4 below show typical spectrums of the carbon wear rate versus disk temperature as provided by three brake manufacturers (Messier-Bugatti, Honeywell-ALS and BF Goodrich). Some reference temperatures are mentioned, and associated indicated temperatures in the cockpit are also mentioned. However, the relationship between the disk temperature and the temperature indicated in the cockpit to the crew is generally not linear, and also varies from one manufacturer to the other.

ABS agrees with the shape of these curves, although its data is slightly different.

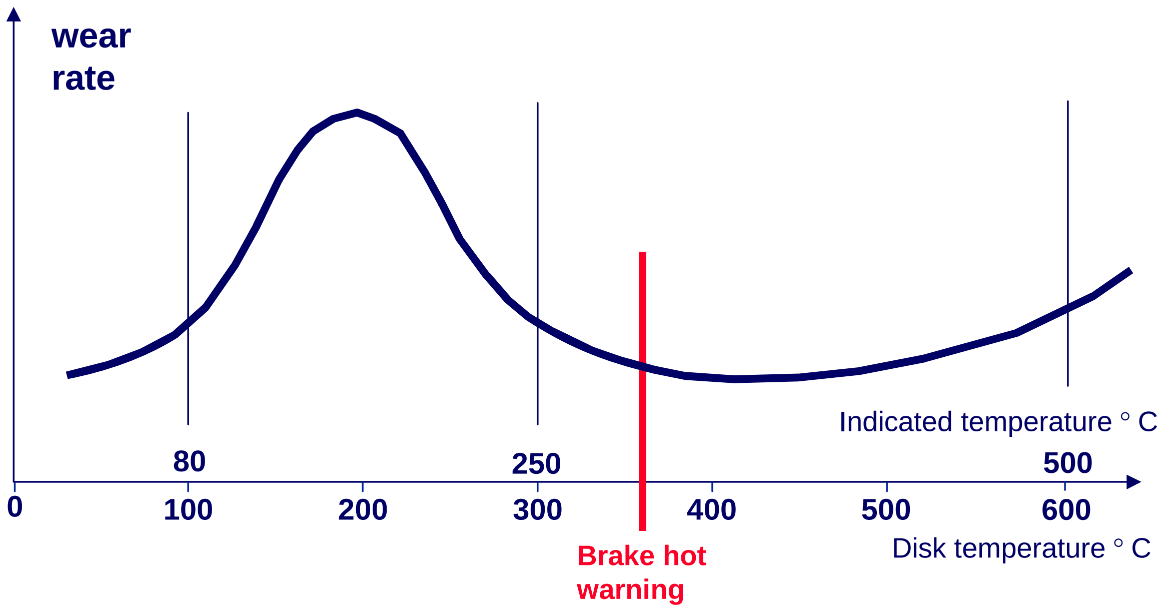

Figure 2 - Typical Spectrum of Carbon Wear vs. Brake Temperature according to MESSIER-BUGATTI

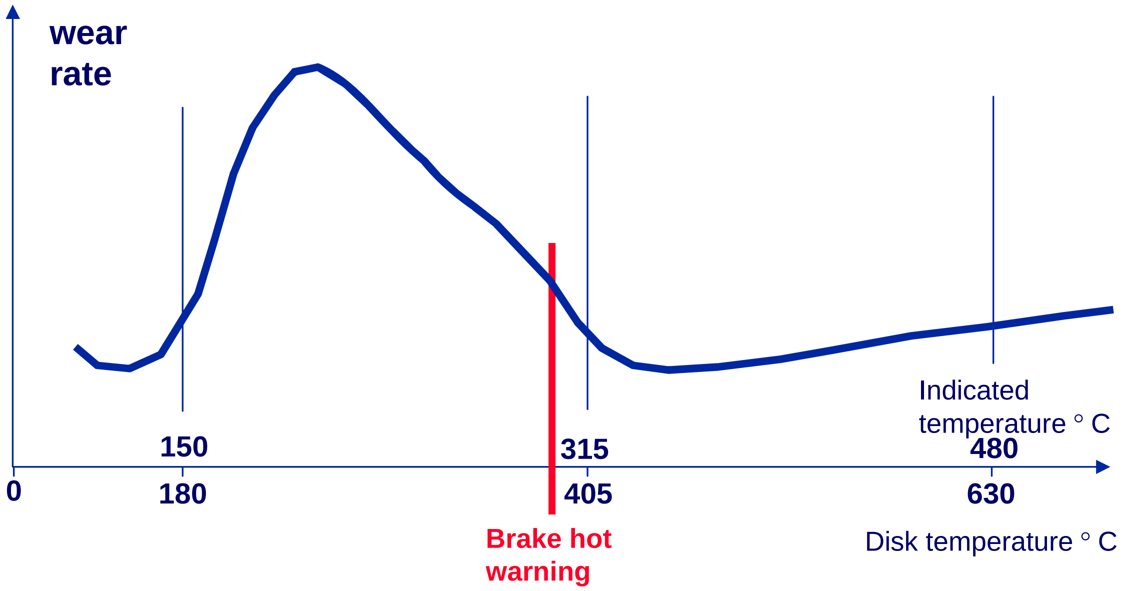

Figure 3 - Carbon Wear vs. Brake Temperature according to HONEYWELL-ALS (A330 / A340)

The wear spectrum from BF Goodrich in Figure 4 displays the combined results from dynamometer simulation (above 100°C) and theory (below 100°C). Due to the lubricating effect of atmospheric moisture adhering to the carbon particles, wear rates below 100°C are reduced. Above 100°C, wear rates are reduce as temperature increases.

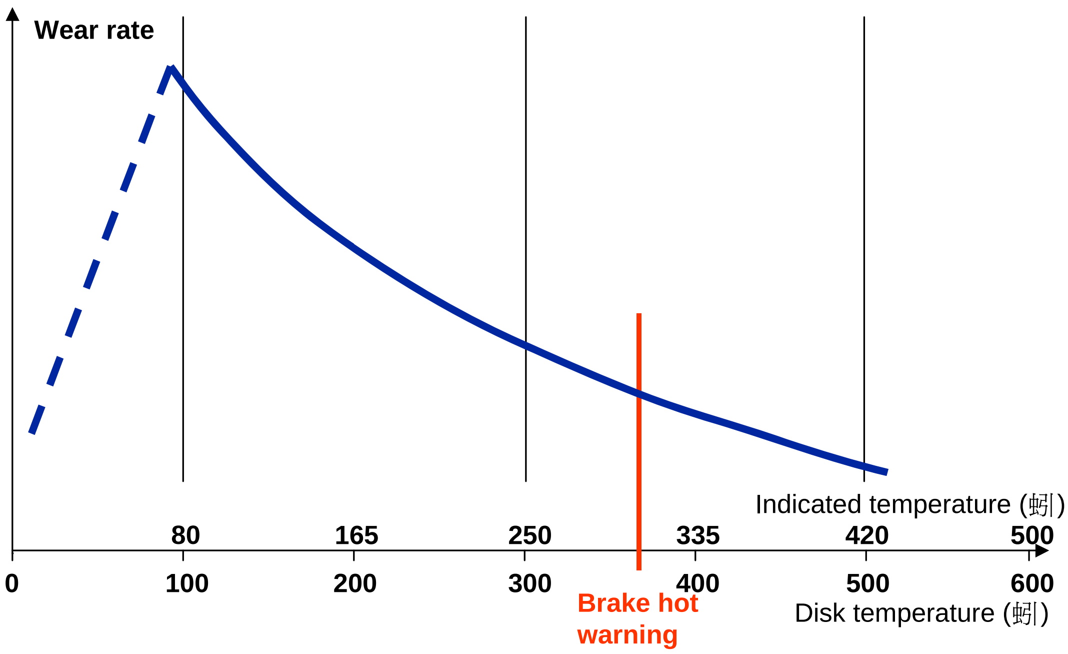

Figure 4 - Carbon Wear Rates vs. Temperature according to BF GOODRICH (SUPERCARB - A321 / A330 / A340)

Note: Airbus' opinion is that all this data published by brake manufacturers is not always directly applicable to practical life through quasi-mathematical procedures. Procedures and tools used by different brake manufacturers to build these curves are never exactly the same. Laboratory data may for instance easily use single disk to disk tests instead of complete brake assembly tests.

3.2.1. Energy

As shown in Figure 5, energy is theoretically not the primary parameter for carbon wear, whereas it is the most important one for steel brakes. Nevertheless, applying more energy on the brake will have a direct effect on wear due to the induced increase in brake temperature.

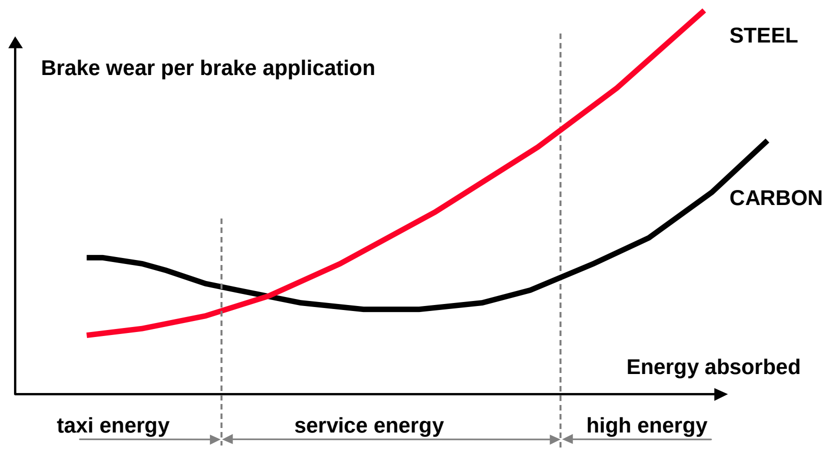

Figure 5 - Typical Spectrum of Brake Wear vs. Energy
(Case of single brake application from ambient temperature)

3.3. <u>Other Parameters</u>

Some other parameters of less importance may affect carbon brake life and are recalled below.

3.3.1. Maintenance Practices

Brake life is, of course maximized by keeping them on the aircraft as long as possible. It is, therefore, recommended to apply all extension life concepts developed by brake manufacturers.
It is also recommended that **the brakes be used up, to flush wear pin**. However, **when the wear pin is flushed**, the heat pack is fully worn and **the brake must be replaced**.

Criteria for brake removal at the main base should also be developed. (For example: If the remaining wear pin length is found to be 3mm. If the average operator recording is 1600 LPOs, with a 65 mm heat pack wear length, the wear rate is determined to be 1600:65 = 24.6 landings per mm. Therefore, the remaining 3mm wear pin should allow 73 landings before the next visit to the maintenance base).

3.3.2. Area of Operation and Climatic Conditions

Some brake manufacturers (e.g. Messier-Bugatti) report that the wear rate decreases, as a function of the absolute humidity: Hot and humid climates favor carbon brake life.

4. PREFERRED CARBON BRAKING TECHNIQUES

All recommended braking techniques should aim at reducing the number of brake applications and optimizing the carbon brake temperature.

4.1. Reducing the Number of Brake Applications

Main parameters that drive the number of brake applications are:

- Airport layout and traffic volume: Long runways and taxiways, number of turns, congestion;
- Taxiing speed and engine flight idle settings;
- Aircraft weight;
- Use of the autobrake at landing.

To reduce the number of brake applications, the following points should be considered:

4.1.1. Do Not "Ride" the Brakes

The Airbus FCOM SOP stresses that for the taxi phase:

- The normal maximum taxi speed should be 30 knots in a straight line, and 10 knots for a sharp turn. As the ground speed is difficult to assess, monitor ground speed on the Navigation Display. Do not "ride" the brakes. As 30 knots are exceeded with idle thrust, apply the brakes smoothly and decelerate to 10 knots, release the brakes and allow the aircraft to accelerate again.

4.1.2. Single (two on A340) Engine Taxi

In addition to the fuel savings it provides in congested airports, this procedure may be considered to decrease the total engine thrust when the aircraft accelerates at flight idle (e.g. at low aircraft weights), thus avoiding immoderate use of brakes during taxi.
Nevertheless, the single (two for the A340) engine taxi procedure is not advisable for short taxi times, as engine warming and engine cooling times should be respected when using this procedure.

4.1.3. Alternate Left and Right Braking

This technique may be considered when slowly taxiing on normal surfaces.

4.1.4. Use of Autobrake at Landing

The design purpose of the autobrake system is to maintain a constant deceleration rate during landing roll, or to apply maximum braking as soon as throttles are reduced during a rejected takeoff.
This is achieved by modulating the brake pressure within a single brake application. Therefore, **use of the autobrake reduces to one the number of brake applications**, and thus provides an advantage regarding brake wear. Beyond, it is a means of brake temperature optimization (easy and accurate management within daily cycles), as we will see below.

4.2. Optimizing Brake Temperature

As seen in Figures 2 to 4, the typical spectrum of carbon wear versus carbon disk temperature shows an alternation of low wear and high wear areas, from low to high disk temperatures. Therefore, operational recommendations to increase carbon brake life should focus on keeping the carbon temperature outside the high wear areas.
Generally speaking, to increase carbon brake life, brakes should either be operated cold or hot but not at intermediate warm temperatures.

Pilots should be provided with easily-achievable instructions aimed at operating brakes, on an average basis, in optimum temperature ranges with regards to low carbon wear and operational constraints.

At this end, looking at Messier-Bugatti data given in Figure 2, the pilot should be instructed to taxi with indicated brake temperature below 80°C, or above 250°C. For Honeywell-ALS brakes, as shown in Figure 3, it's below 150°C or above 315°C. For BF Goodrich brakes, as per Figure 4, it's probably at ambient temperature (well below 80°C) or above, lets say, 250°C.

However, care should be taken that these instructions shall be dedicated to a given brake type used in given operating conditions; in other words to a given aircraft type at concerned operator.

Recommended temperatures for taxi should not be mismatched between different brake types. As evidenced in Figure 6, the relationship between carbon wear and approximate brake temperature indicated in the cockpit really differs with the brake type.

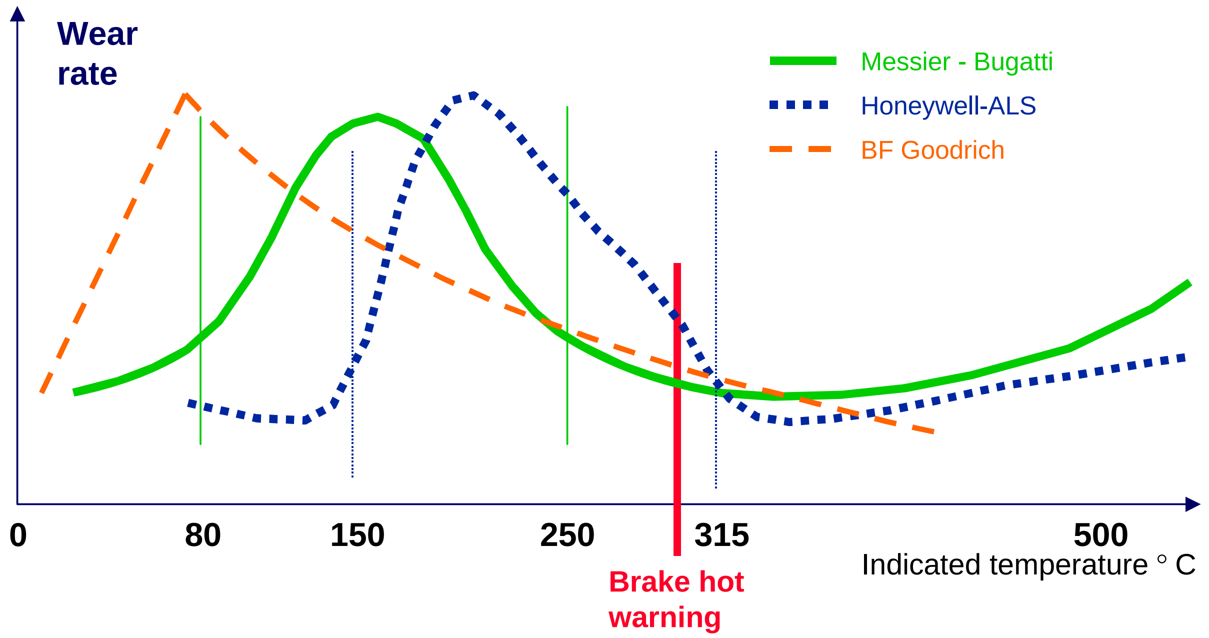

Figure 6 - Carbon Wear vs. Indicated Brake Temperature
Messier-Bugatti, Honeywell-ALS and BF Goodrich

Theoretically, temperatures applicable to one brake type are not necessarily applicable to others. In the above figure, for example, we can see that, while taxiing with an indicated brake temperature around 80°C seems adequate for both Messier-Bugatti and Honeywell-ALS brakes; it corresponds to the worst condition for BF Goodrich brakes.

4.2.1. Brake Temperature Management during Taxi

From the curves presented above, and as far as carbon brake life is concerned, the taxi brake temperature should be on either side of the peak of the appropriate wear curve.

The following figure shows a brake temperature profile, achieved on a series of short legs with given conditions (high landing energy, no brake fans). It shows both disk and indicated brake temperatures.

- The taxi in temperature is naturally on the right-hand part of the wear curve peak (at least for most of the brake types), due to heat build-up during landing. Therefore, it is advisable not to cool down the brakes after landing, as it would be impossible to go on the left part of the wear curve without operating in the high wear area.

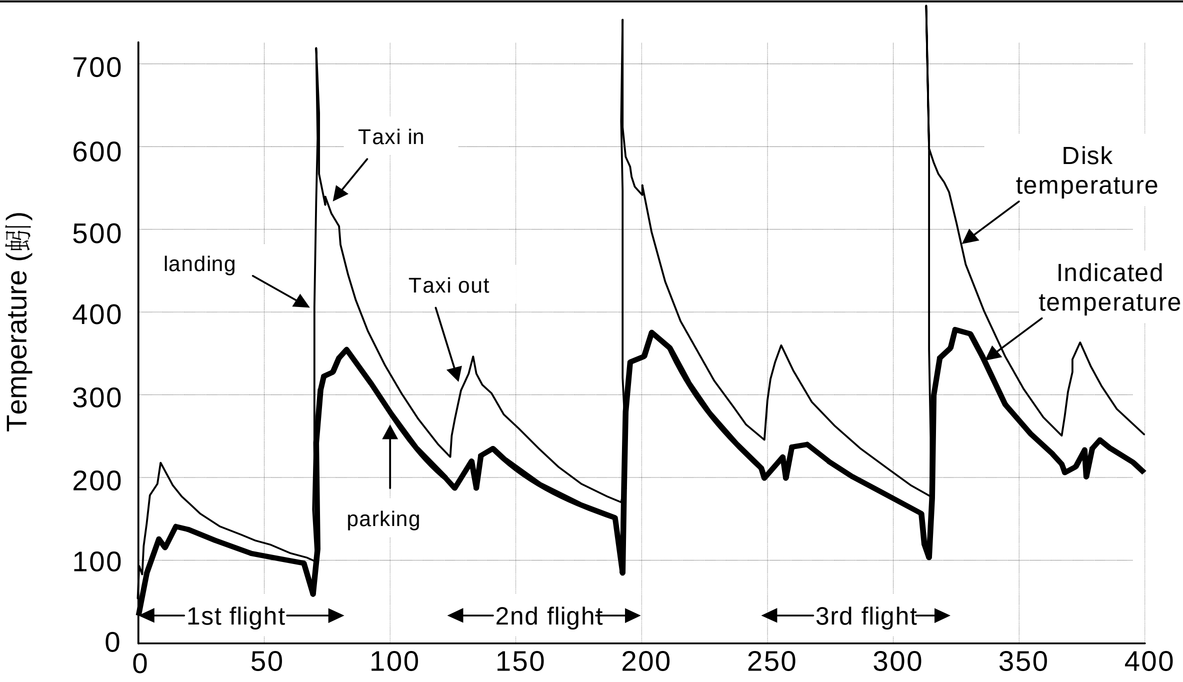

Figure 7 - Example of brake temperature profile achieved over given route data
(Aircraft not equipped with brake cooling fans)

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- For taxi out, Figure 7 illustrates a scenario where the turnaround time is such that, the brake temperature is not sufficiently cooled down to perform the taxi out with brake temperature in the "left-hand part" of the curves given in Figure 6. Therefore, as far as carbon brake wear is concerned, it might be advisable to keep the taxi out temperature in the "right-hand part" of the curve. This is what certain brake manufacturers (e.g. BF Goodrich and ABS) promote. It should be noted that their curves, although having the same shape, are shifted to the left, compared to those of Messier-Bugatti and Honeywell-ALS (see Figure 6). That is why:
  - BF Goodrich, according to data given in Figure 4 and 6, "believe that based on typical operating scenarios, it is usually more practical to reduce wear rates by generally operating with warm or hot taxi stops than to taxi out below 100°C".
  - ABS "suggest the optimum BTMU (indicated) temperature for taxi out is 150°C".

  It is obvious that, for Messier-Bugatti and Honeywell-ALS, according to Figure 6, an indicated temperature of around 200°C (achieved during taxi out, as evidenced by Figure 7), is far from being optimum for brake saving. That is why they both promote keeping the brake cool for taxi out:
  - Messier-Bugatti: "below 80°C".
  - Honeywell-ALS: "below 150°C".

However, the brake temperature management is not very easy. The best solution for that is **to use the brake cooling fans**, if available.

Note: Difficulty to manage brake temperature is increased by the fact that a non-negligible brake temperature difference may exist between the wheels in normal operation. Therefore some wheels may have their brake temperature on one side of the peak of the wear curve, and some on the other side (with possibly some just on the peak).
Brake temperature limitations requiring maintenance actions are mentioned in the FCOM. An extract of a typical example is illustrated here:
- The temperature difference between the 2 brakes on the same gear is greater than 150°C, and the temperature of either one of the brakes is higher than or equal to 600°C, or
- The temperature difference between the 2 brakes on the same gear is greater than 150°C, and the temperature of one brake is lower than or equal to 60°C, or
- The difference between the LH and RH brakes' average temperature is higher than or equal to 200°C.

4.2.2. Brake Cooling Fans

The brake cooling fans are proposed to improve heat dissipation and brake cooling. By reducing the cool down time, they prevent a takeoff delay on short turnarounds.
Indeed, Airbus Industrie designs aircraft to have the brake fans necessary for short turnarounds. This prevents oversizing the brakes and, thus, limits the transport of unnecessary extra weight. In addition, brake cooling fans are a helpful tool for managing brake temperature and thus improving brake life.

4.2.3. Hot Brakes: Setting the Limits

We have seen that taxiing with hot brakes could be advantageous in terms of carbon brake life. However, the following limits should be considered:

- **Taxi out**
  For safety reasons, Airbus does not promote any procedure that would systematically and intentionally increase brake temperature before takeoff. It is reminded that the certified maximum brake energy might not be sustained, in case of rejected takeoff with hot brakes. (For more information, see the 10th Performance and Operations Conference in San Francisco 1998 - High brake temperature issues).
  However, if the aircraft is not fitted with brake fans, the succession of short legs and short turnaround times (as described in the Figure 7 scenario), might lead to taxing out the aircraft with hot brakes. This is acceptable, as long as the BRAKE HOT warning does not come on prior to takeoff. In any cases, taxi out should not be started with BRAKE HOT warning illuminated.

- **Landing and Taxi in**
  In-service experience has shown a rapid degradation of some brakes because of carbon oxidation. Some disk ruptures, due to oxidation, have also been reported.

  Two types of oxidation may affect carbon:

  - **Catalytic Oxidation:** Mainly due to runway and aircraft de/anti-icing fluids, and other cleaning agents.
  - **Thermal Oxidation:** That is accelerated at high temperature. Therefore, if the brakes absorb too much heat, carbon oxidation will be increased. All manufacturers mention that for a normal utilization, brakes should not be repeatedly operated above 500°C. Furthermore, after heavy braking, use of the brake fans could increase oxidation of the brake surface hot spots, if the brakes are not thermally-equalized.

- **Parking**
  If brake temperatures are maintained at higher temperature levels for an extended time, temperatures of the critical surrounding structures, such as the brake housing, wheel rim, and axle, may reach unacceptable levels. In order to lessen this drawback, parking brake application should be avoided with high brake temperatures.

However, bear in mind that attaining the BRAKE HOT warning after landing is not an abnormal condition. Except in cases of brake binding, which are well documented (e.g. in the FCOM), the warning should be interpreted only as a suggestion to monitor the temperature. On future Airbus models, after intensive discussions with customers, the BRAKE HOT warning will be inhibited down to ECAM phase 1 (5 minutes after engine shut down). The use of BRAKE FANS after landing is, and will remain, dictated by SOP.

4.3. Airbus Recommendations

Keeping in mind what has been previously written, it is difficult to provide accurate and detailed recommendations for operation of carbon brakes that would cope with safety and economy, and be applicable to all customers and all brake types.
All brake manufacturers also highlight that brake saving recommendations should be customized for each operator, as the airline environment, the network, and the fact that aircraft may or may not be fitted with brake fans, greatly influence the way brakes should be operated.

The following are general Airbus recommendations for the proper operation of carbon brakes. They list all the systems involved in brake operation:

4.3.1. Autobrake at Landing

- MAX is not recommended and should not be used.
- When landing on a short or evenly contaminated runway, or when operating in low visibility weather conditions, the use of LOW or MED autobrake is recommended (With intermittent dry and contaminated patches, directional deviations problems may be encountered).
- In the other cases, selection of autobrake is left at captain's discretion.
  Use of autobrake brings a lot of advantages, such as reduction of pilot actions, smoother and optimized deceleration. When appropriate, it may be used to reduce the number of brake applications to one, and to increase brake temperature to a more adequate value for taxi in. Moreover, it may give constant brake functioning conditions for landing and taxi in.
  Selection of autobrake has also to be considered more particularly when significant need of brake application is foreseen. It is recommended to select the mode coping with the available distance up to the intended runway exit.
  If manual braking is used, modulate the brake pressure (avoid multiple applications).
  In order to prevent carbon thermal oxidation problems, landing techniques leading to repetitive excessive brake temperatures (about 500°C) should be avoided.

4.3.2. Engine Thrust Reversers

For safety reasons, Airbus recommends the systematic selection of full reverse thrust, **immediately after the main landing gear touches down**, mainly because its maximum efficiency is obtained at high speed.
If not selected at the beginning of the landing roll, the selection of full reverse thrust later on (if necessary) may not bring the expected help.
If airport regulations restrict the use of reversers, select and maintain reverse idle until taxi speed is reached.
In case of engine failure, use of the remaining reverser(s) is recommended. (On the A340, in case of Engine 1 or 4 failure, an interlock prevents the use of the remaining outer reverser).
If directional control problems are encountered, reduce thrust to reverse idle, until directional control is satisfactory.
After reverse thrust is initiated, a full stop landing must be made (no touch-and-go).

4.3.3. Brake Fans (if installed)

- **Taxi out**

If an arc is displayed on the ECAM WHEEL page, above the brake temperature (indicating a brake temperature > 100°C), select brake fans ON. This will ensure:

- Max energy rejected takeoff will be sustained.
- The brake temperature for taxi will be in the appropriate areas, regarding brake wear, as recommended by Messier-Bugatti and Honeywell-ALS.

- **Before takeoff**

If the brake fans are running, check that brake temperature is below 150°C (except ABS - see general remarks below). If temperature is above 150°C, delay takeoff until 150°C is reached with fans running, then switch them OFF.

- **Taxi in**

The Airbus recommendations mentioned below have been amended to reflect the advantages (claimed by all brakes manufacturers) provided by taxing with hot brakes, while also taking care of possible oxidation problems.
Brake fans selection should be delayed for a minimum of about 5 minutes or at the gate (whichever occurs first), to allow for thermal equalization and stabilization and thus avoid oxidation of brake surface hot spots.
However, when turnaround times are short, or brake temperatures are likely to exceed 500°C, use the brake fans (forget oxidation).

It should be emphasized that, the arc displayed on the ECAM WHEEL page, suggesting the selection of brake fans at taxi out, should be ignored for taxi in. Also, although displayed on the ECAM, the display of the BRAKE HOT warning after landing should not lead to the immediate selection of brake fans as long as 500°C is not likely to be reached (wait 5 minutes or gate arrival).

- **Parking**

Select the fans OFF, if no arc is displayed on the ECAM WHEEL page (temperature <100°C). If turnaround is short, keep the fans running down to temperatures close to ambient.

- **General remarks about brake cooling fans operation**

- Except for brakes manufactured by ABS (Aircraft Braking System), the temperature indicated in the cockpit when the brake fans are running is significantly lower than the temperature indicated when the brake fans are OFF. This is because the brake fans are ventilating the brake temperature sensor that is not located inside the material itself. Therefore, as soon as the brake fans are running, the indicated brake temperature decreases almost instantaneously (except ABS). Similarly, it will take several minutes for the indicated temperature to rise, and to match the actual brake temperature, when brake fans are switched OFF.
  For all brake types (except ABS), when the fans are running, the difference ranges typically from approximately 50°C at 100°C actual brake temperature up to about 150°C at 300°C actual brake temperature. As a consequence, if the BRAKE HOT warning is activated just before takeoff, the ECAM will request the selection of the brake fans, if installed, and the delay of the takeoff. When fans are selected, the warning will disappear instantaneously, but the takeoff must be delayed until the indicated temperature consistently decreases below 150°C (for a warning set at 300°C). Then, the brake fans should be switched OFF for takeoff. This is well documented in the FCOM.
- All of the indicated brake temperatures (mentioned in the above Figures 2 to 7) do not consider brake fans. Therefore, pilots should take into account the above-mentioned temperature shift, induced by brake fans operation, if targeting a brake temperature recommended for taxi.
- Brake fans should not be used during takeoff and landing roll to avoid foreign object damage to the fans and the brakes at high speed.
- If not already selected OFF, brake fans are automatically switched OFF when landing gear is retracted.
- If the BRAKE HOT warning appears after landing gear retraction, the landing gear should be extended, if performance permits, to allow cooling in flight as requested by ECAM and published procedures. However this should not happen, if FCOM-published Standard Operating Procedures are adhered to. On A300 and A310 aircraft, brakes fans may be switched ON as they have proven to increase cooling efficiency in flight. On other Airbus types, the cooling efficiency of the fans in flight is marginal, and next FWC version will no longer require selection of brake fans in flight.

4.3.4. Parking Brake

The parking brake should be released at the gate after chocks are in place when temperatures are above 300°C with fans OFF (150°C fans ON). Above 500°C with fans OFF (350°C fans ON), parking brake application should be avoided to prevent brake damage, unless operationally necessary.

5. CONCLUSION

Airbus recommendations always focus on safety first. However, whenever possible, the economic aspect is also addressed.
Over the past few years, we have discussed with brake manufacturers in order to provide recommendations to properly operate carbon brakes. Everyone agrees that, as far as brake life is concerned, the recommendations should be customized, so as to take into account the specificities of each customer's operation. We have also seen that brake manufacturers do not necessarily have all the same view and recommendations, probably because carbons are different.

Airbus has reviewed and amended certain procedures to, as much as possible, take into account in-service experience and brake manufacturers' information.