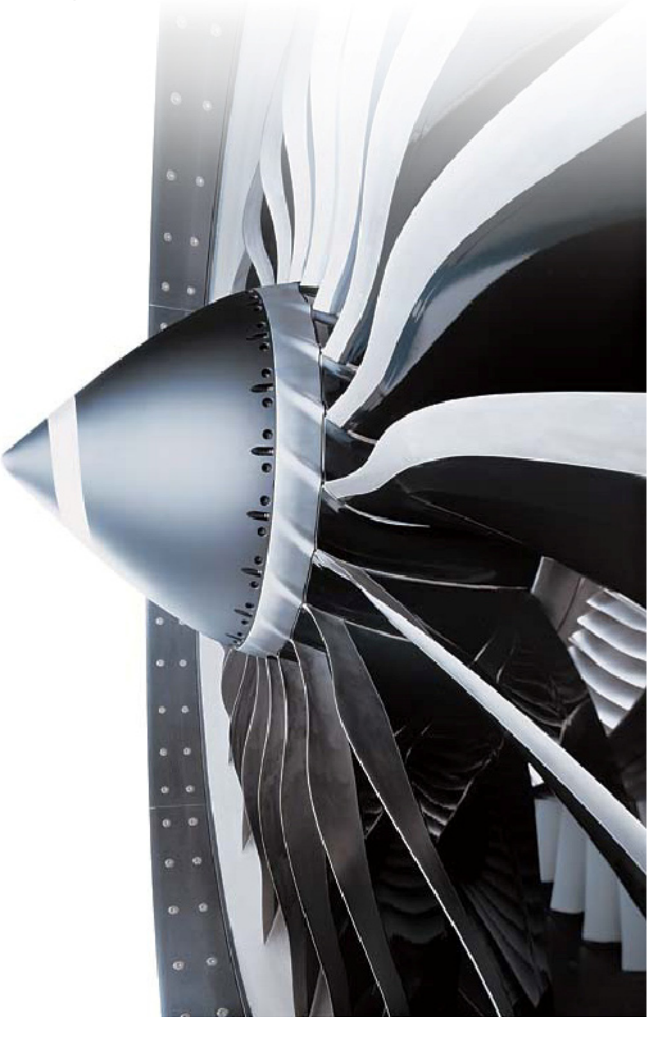
imagination at work

Article **8**

Economic Impact of Derated Climb on Large Commercial Engines

Rick Donaldson, Dan Fischer,
John Gough, Mike Rysz
GE



This article is presented as part of the 2007 Boeing Performance and Flight Operations Engineering Conference, providing continuing support for safe and efficient flight operations.

Introduction

Aircraft engines are sized and power managed to meet takeoff field length and climb rate requirements at the maximum takeoff gross weight (TOGW). When operating at reduced TOGW, reduced thrust (derate) may be used in both takeoff and climb to extend engine life and reduce maintenance cost. The benefit of takeoff derate is clear because takeoff is typically the most severe operating condition for flowpath components and its impact on mission time and fuel is minimal because of its short duration. Consequently, most operators make frequent and systematic use of takeoff derate.

The net impact of using climb derate is less obvious because it involves opposing influences whose magnitudes depend on the particular aircraft and engine in question. Use of climb derate increases the time and distance to climb to cruise altitude. This will generally result in a small increase in block fuel burn because a smaller fraction of the total range will be flown at the most efficient cruise altitude and power setting. It may however result in a small reduction in maintenance cost. The existence and magnitude of the maintenance cost reduction depend on the severity of climb operation relative to takeoff and the specific failure modes that drive engine life. Because four-engine aircraft typically require a higher fraction of takeoff thrust in climb than twin-engine aircraft do, climb operation is more likely to influence engine life on four-engine aircraft. However if the failure modes that drive the engine off wing are predominately related to low cycle fatigue, engine life will only be affected by takeoff thrust as long as it is not reduced below the climb rating. Other failure modes such as oxidation and corrosion are more likely to be influenced by climb thrust rating because they are dependent on time at temperature, but reducing climb thrust is not always beneficial because it increases time of exposure while it reduces temperature. In addition, reducing climb thrust may move material temperatures from the oxidation regime to the corrosion regime, which may be the more life limiting failure mode.

The purpose of this paper is to examine these conflicting influences in order to provide operators guidance as to the use and potential benefit of using climb derate.

Approach

In order to gain an understanding of the economic impact of climb derate several wide body aircraft were examined, including both twin-engine and four-engine configurations. Mission analyses were performed at maximum and derated climb thrust with maximum passenger loads at 3,000 nm ranges for long-range applications and 800 nm for short-range applications. The passenger loads and ranges were selected to produce TOGW's consistent with operation at takeoff thrust derate levels typically used in service.

Time, temperature and speed histories from the mission analyses were used to evaluate the effect of climb derate on the lives of the critical parts known to dominate the time on wing of each engine type examined. The mission fuel burn and life impacts derived from these analyses were then combined to assess the net operational cost impact as a function of climb derate.

Results

Of the configurations examined, the GEnx-1B54 powered 787-3 and GEnx-1B70 powered 787-9 provide the best illustrative examples. While both of these aircraft are twin-engine wide bodies, they require significantly different levels of takeoff thrust from the same engine model and consequently have very different climb severities relative to takeoff. They are also intended for very different purposes, the 787-3 being a short haul aircraft and the 787-9 being a long haul aircraft. These differences drive different responses to the use of climb derate, the study of which is useful in extrapolating the results to other aircraft.

The 787-3 and 787-9 results will be presented in some detail in the sections that follow. Some observations as to how the results from other aircraft differed from these examples will also be offered.

Mission Analysis and Fuel Burn

Like earlier Boeing aircraft, 787 pilots have two basic climb derate selections: CLB1 corresponding to a nominal 10% derate and CLB2 corresponding to a nominal 20% derate. The actual climb thrust reduction corresponding to the two derate levels is presented as a function of altitude in Figure 1. The nominal reduction is effective up to 10,000 ft, at which point it is faired out to zero. The default rate at which it fairs out is an option pre-selected by the airline. The fast taper (FT) option fairs out the nominal derate between 10,000 ft and 15,000 ft. The slow taper (ST) option fairs out the nominal derate between 10,000 ft and 30,000 ft. Unlike earlier models, the 787 will give the pilot additional flexibility in selecting both derate level and the altitude at which the derate fairs out to zero. As will be shown later, the derate level and fair-out altitude can significantly affect economic performance.

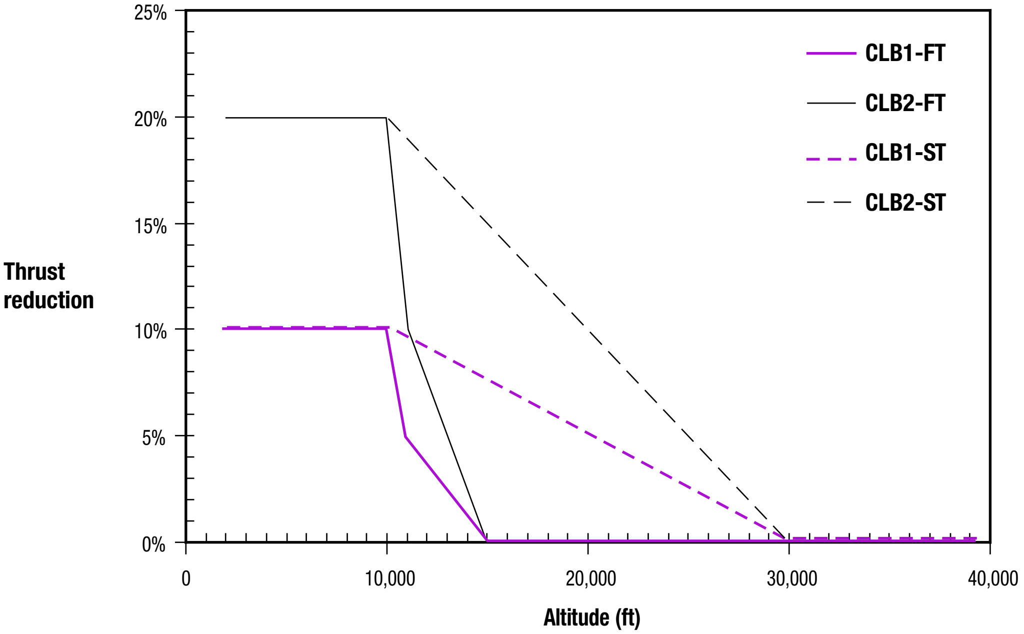


Figure 1. Climb thrust derate options

Reducing climb thrust through the use of derate reduces climb rate and hence increases the time required to reach cruise altitude, as shown in Figure 2. At the reduced TOGW's studied, these time increases are relatively small, none being greater than 2.5 minutes. Moreover, climb time is well under the 30-minute air traffic control maximum in all cases.

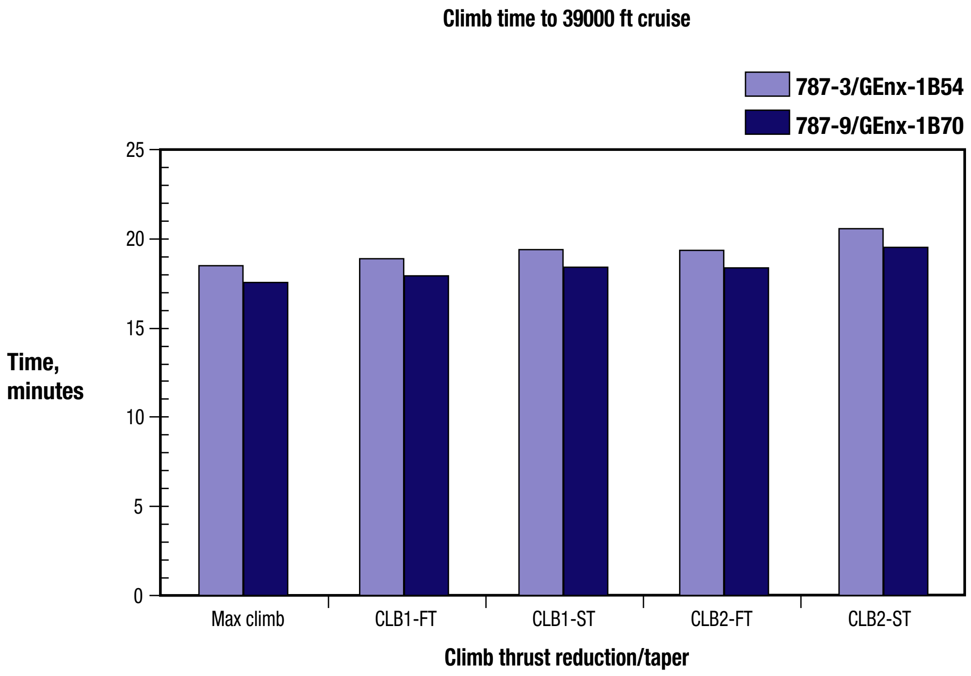


Figure 2. Impact of climb derate on time to cruise altitude

Similarly, use of climb derate increases the distance to climb by a small amount. As shown in Figure 3, the maximum increase is 13 nm and cruise altitude is reached well before the 200 nm air traffic control limit. Increased time and distance to cruise altitude should therefore not be an impediment to the use of climb derate.

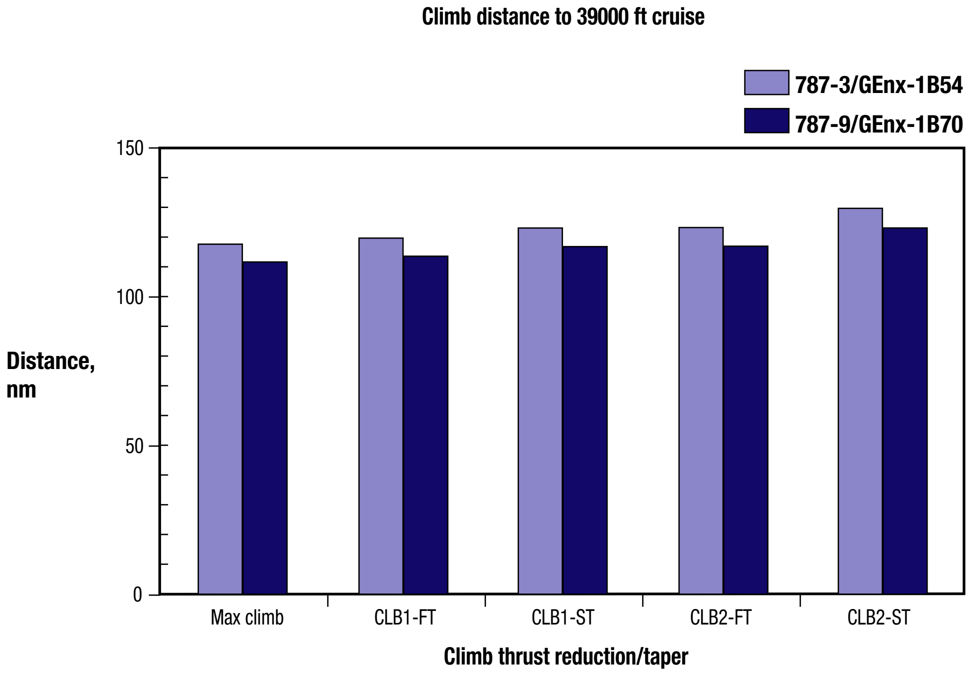


Figure 3. Impact of climb derate on distance to cruise altitude

As shown in Figure 4, increased distance to cruise altitude does result in a small block fuel burn increase because as more range is traveled in climb, less range is traveled at the more efficient cruise altitude and power setting.

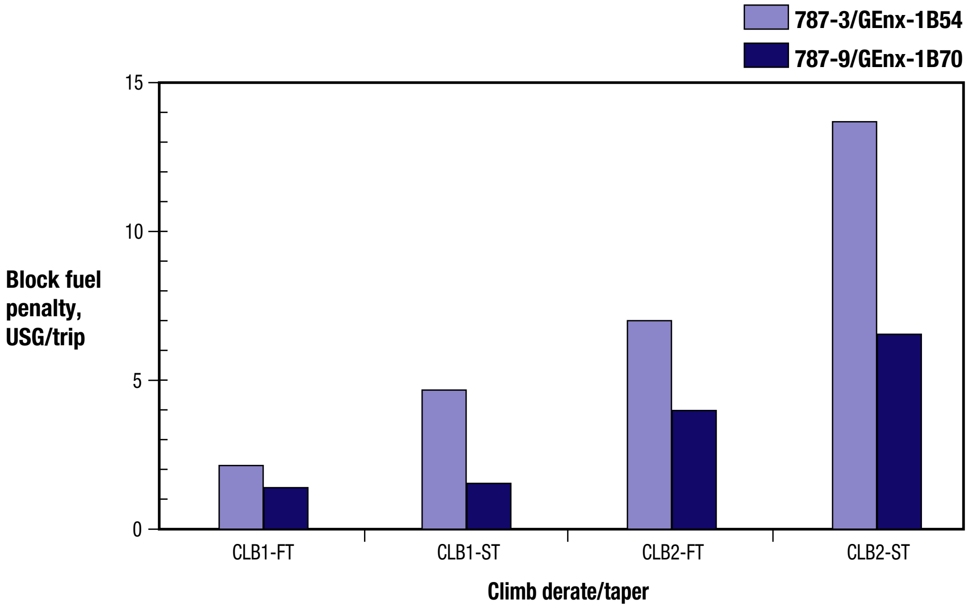


Figure 4. Block fuel burn penalty for climb derate

In terms of cost, this penalty can be as much as $1 per EFH for the 787-9 and $7 per EFH for the 787-3, as shown in Figure 5. The penalty per EFH is larger for the 787-3 because the shorter range magnifies the impact of climb, i.e. there are more climb segments flown per EFH. In both applications this penalty will tend to offset potential maintenance cost benefits, which will be examined next.

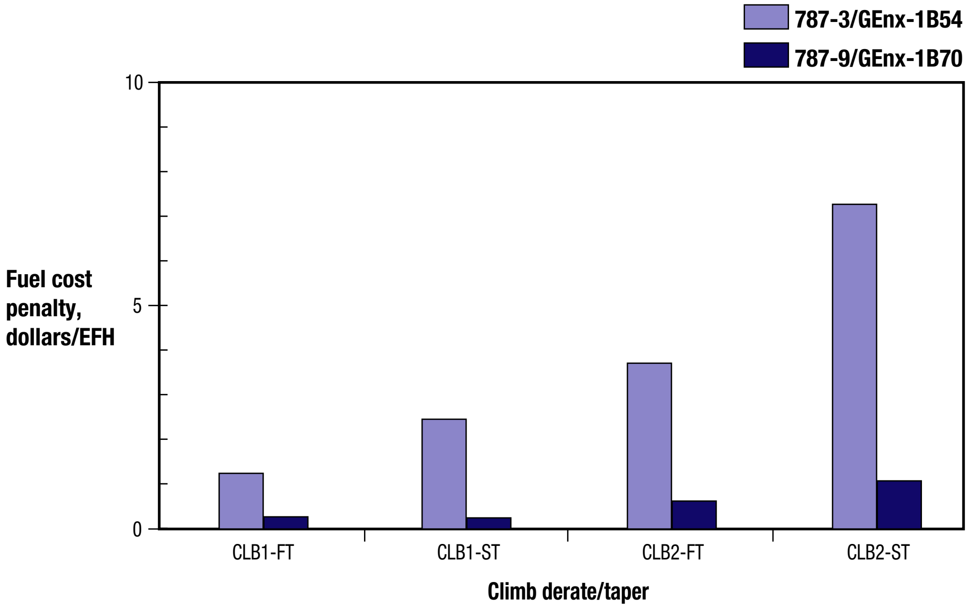


Figure 5. Fuel cost penalty for reduced thrust climb

Climb vs Takeoff Severity

The part life consumed during any portion of the flight is determined by the temperature and stress the part experiences. For some failure modes, such as oxidation, time of exposure is also a factor. The individual part temperatures and stresses are closely related to two key gas path temperatures: high-pressure compressor (HPC) discharge temperature and high-pressure turbine (HPT) inlet temperature. The impact of takeoff and climb derate on HPC discharge temperature is presented in Figure 6 for the GEnx-1B54 and Figure 7 for the GEnx-1B70. Similar trends in HPT inlet temperature are presented in Figure 8 and Figure 9. From these figures it is readily apparent that maximum climb temperatures become more severe than takeoff temperatures once takeoff thrust is reduced by approximately 7% for the GEnx-1B54 and 17% for the GEnx-1B70. The separation between maximum takeoff and maximum climb severity is larger for the GEnx-1B70 because it is near the top end of GEnx takeoff thrust ratings.

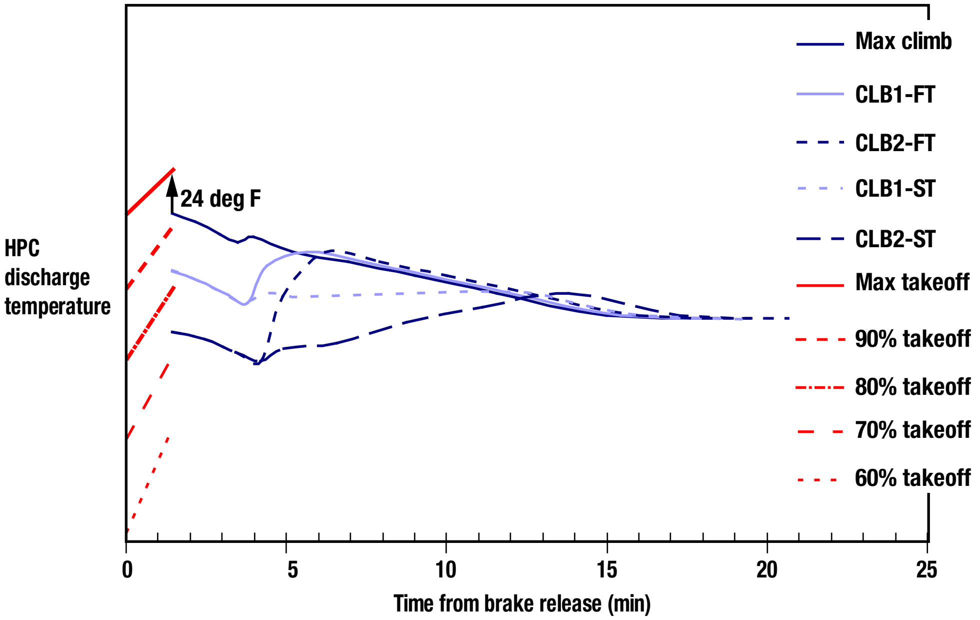


Figure 6. 787-3 / GEnx-1B54 HPC discharge temperature severity

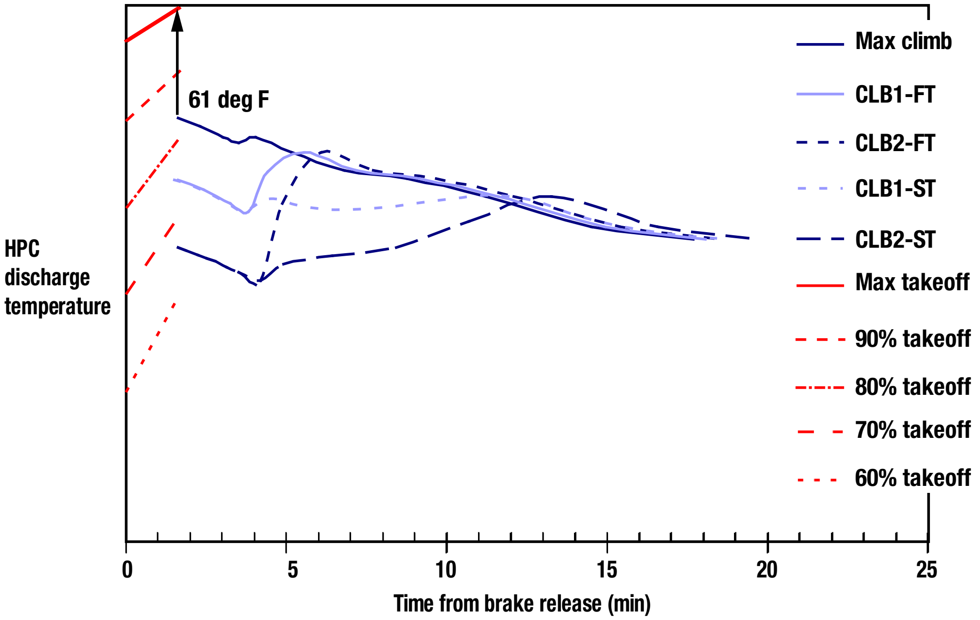


Figure 7. 787-9 / GEnx-1B70 HPC discharge temperature severity

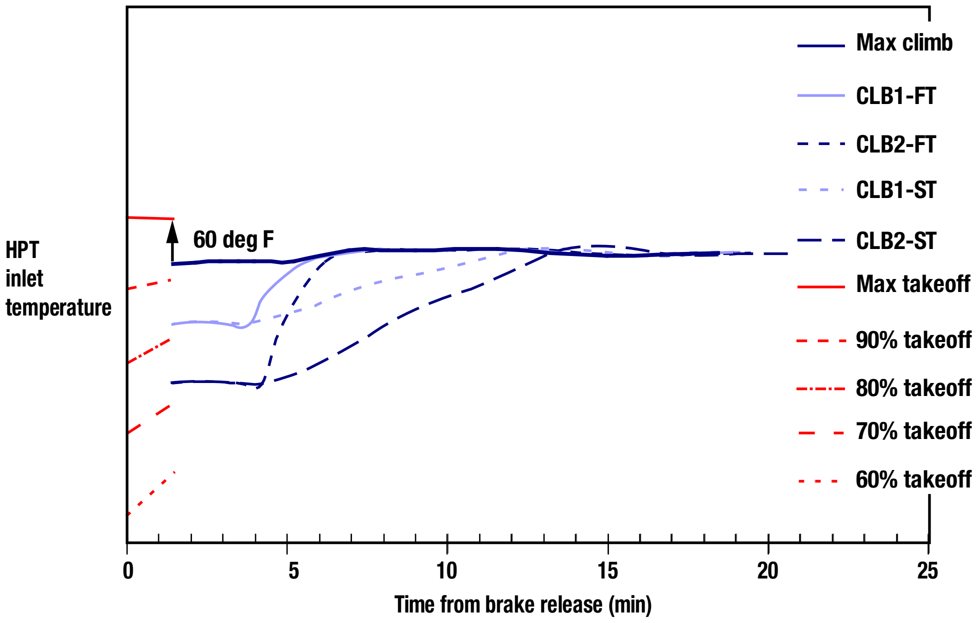


Figure 8. 787-3 / GEnx-1B54 HPT inlet temperature severity

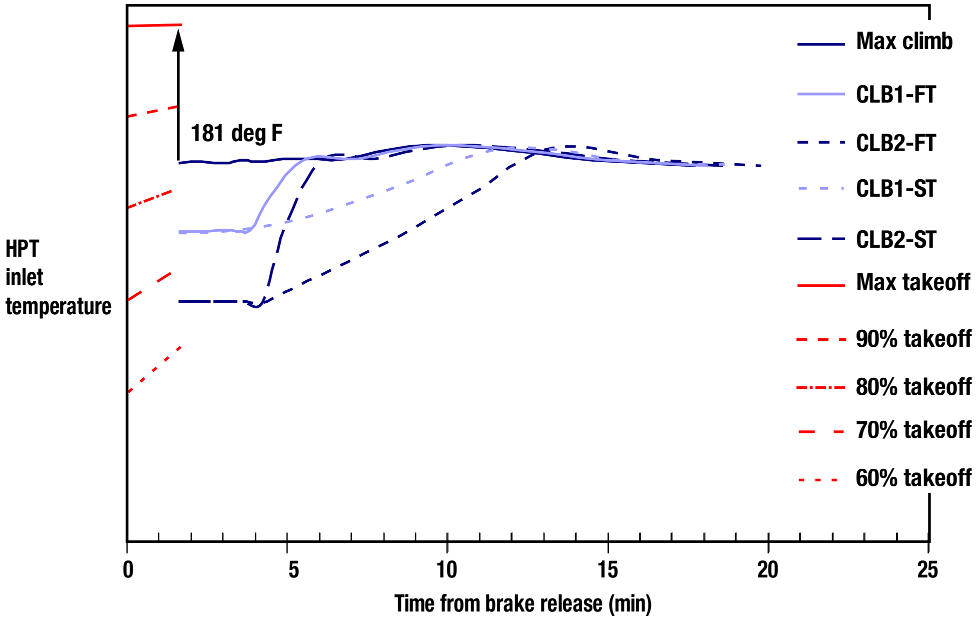


Figure 9. 787-9 / GEnx-1B70 HPT inlet temperature severity

It should also be noted that although the temperature severity is significantly greater at maximum takeoff, the time of exposure is much greater in climb. Failure modes such as oxidation, corrosion and creep rupture will therefore be heavily dependent on climb severity and climb time.

Engine Life Impact

In order to assess engine life impact, the specific engine removal drivers for each engine model were evaluated to identify the critical parts and failure modes that determine time on wing. These critical parts and failure modes were further examined to identify the subset that is sensitive to takeoff and climb thrust levels. Life analyses were then conducted on this subset at various levels of takeoff and climb thrust to quantify each individual part life impact.

In the case of the GEnx, two critical failure modes were analyzed: combustor corrosion and high-pressure turbine (HPT) stage 1 blade oxidation. Combustor corrosion results are presented in Figure 10 for the GEnx-1B54 and Figure 11 for the GEnx-1B70. Because corrosion increases with exposure time in the corrosion temperature regime, reducing climb thrust actually reduces corrosion life slightly. This effect is more pronounced on the GEnx-1B70 because the high temperatures associated with the increased thrust rating ensure that the combustor operates well into the corrosion regime. The cooler GEnx-1B54 actually exhibits an improvement in corrosion life between 10% and 20% climb thrust reduction owing to parts of the climb segment moving to a less severe portion of the corrosion regime. For both ratings, the fast taper produces somewhat better life because it reduces time to climb and hence reduces the time in the corrosion regime.

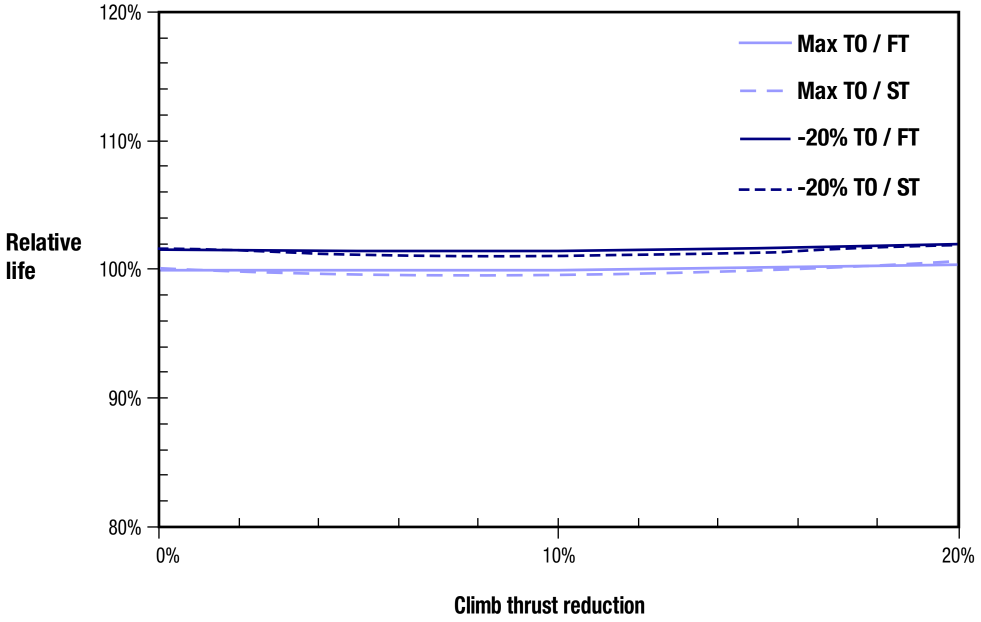


Figure 10. 787-3 / GEnx-1B54 combustor corrosion life

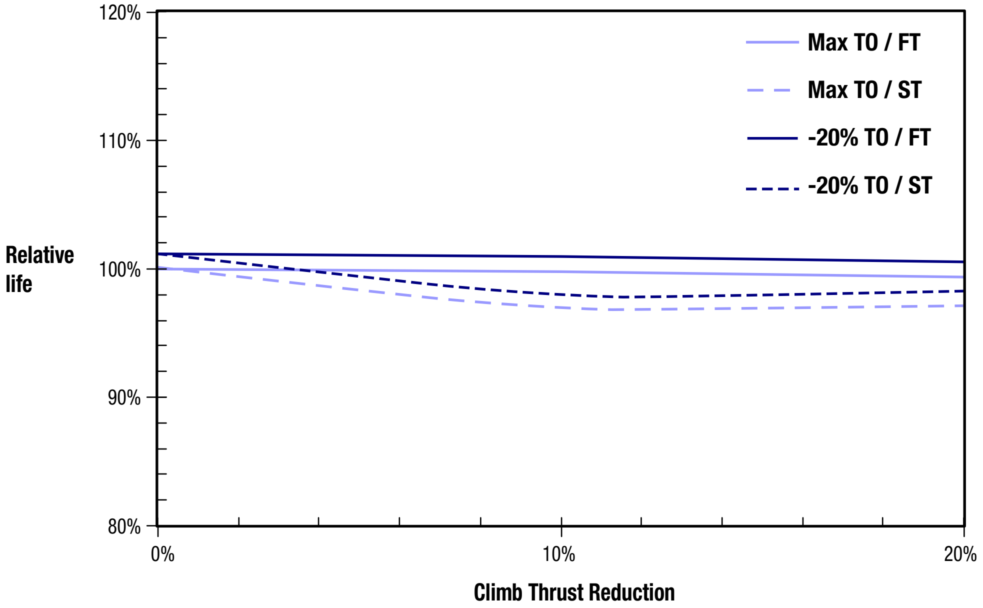


Figure 11. 787-9 / GEnx-1B70 combustor corrosion life

HPT stage 1 blade oxidation life analysis results are presented in Figure 12 for the GEnx-1B54 and Figure 13 for the GEnx-1B70. Like corrosion, oxidation damage increases with increasing temperature and time of exposure. However temperature is by far the dominant factor so that HPT stage 1 blade oxidation life improves significantly with climb thrust reduction despite the increased time to climb. Despite the increased time to climb, slow taper produces the most improvement because it reduces temperatures over the entire climb segment.

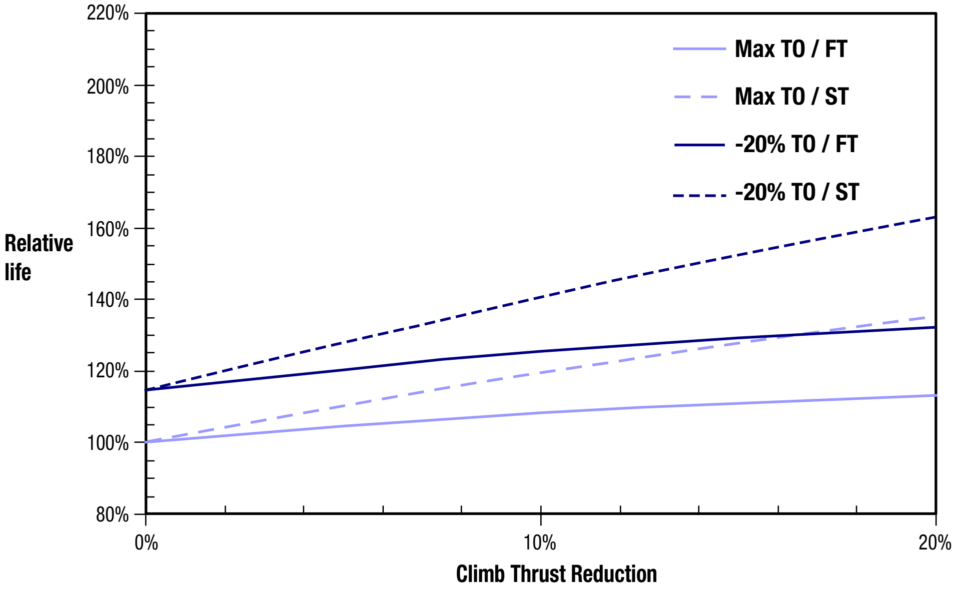


Figure 12. 787-3 / GEnx-1B54 HPT Stage 1 blade oxidation life

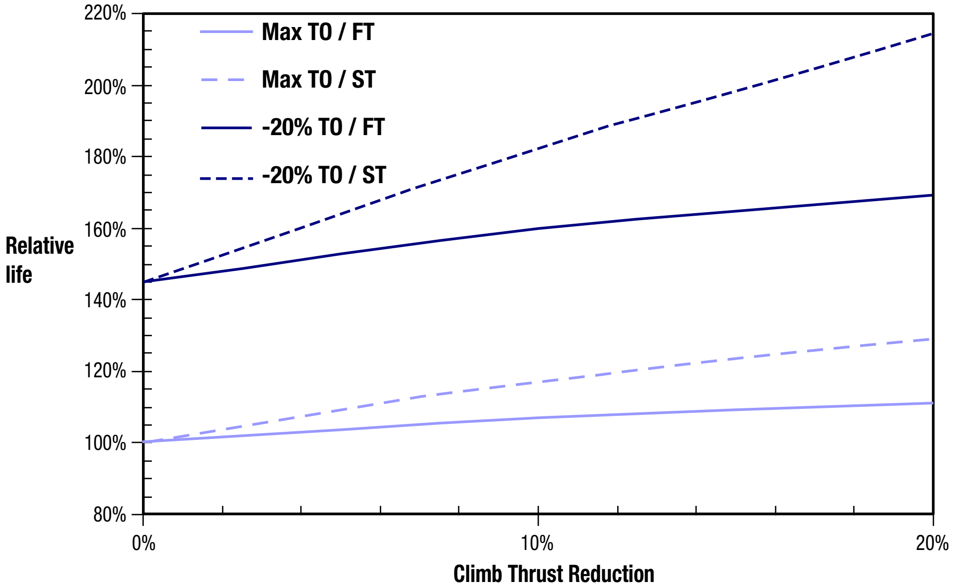


Figure 13. 787-9 / GEnx-1B70 HPT Stage 1 blade oxidation life

The results of these individual part failure mode analyses were then combined to determine the net sensitivity of part life to takeoff and climb thrust reduction. In this combination process, the most limiting failure mode (i.e. the one in which the part has the lowest life) will dominate the part life sensitivity, but other failure modes that are insensitive to thrust reduction will tend to reduce the overall sensitivity.

Finally, the results of the individual part life sensitivities were combined to assess the overall engine life impact. Because engine life is determined by multiple parts, some of which are insensitive to takeoff and climb thrust levels, overall engine life tends to be less sensitive to climb thrust variation than the individual critical parts discussed in the preceding paragraphs. The resulting engine time on wing sensitivity is presented in Figure 14 for the GEnx-1B54 and Figure 15 for the GEnx-1B70.

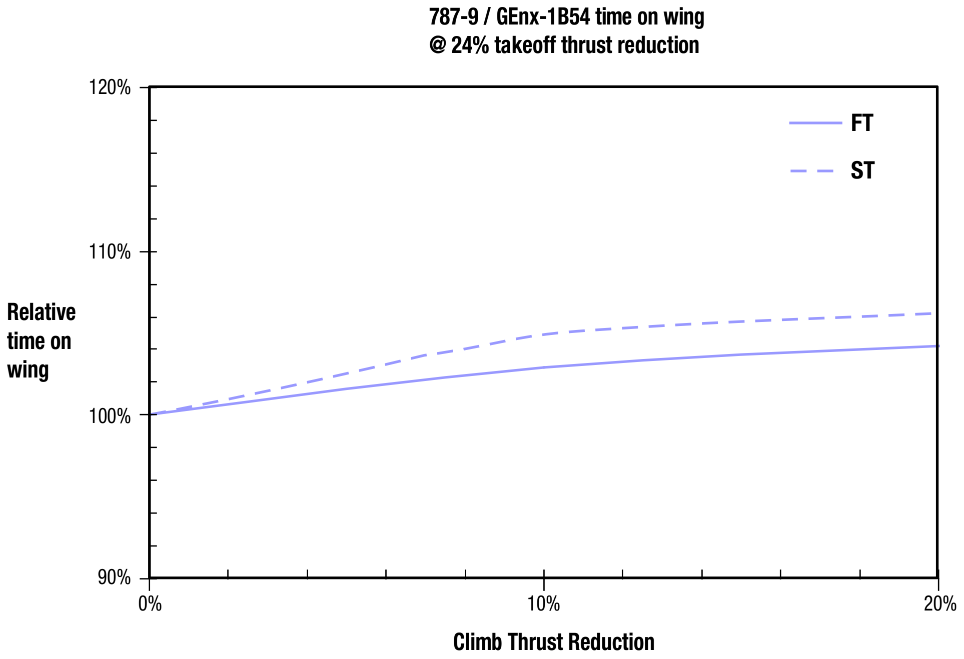


Figure 14. 787-3 / GEnx-1B54 time on Wing

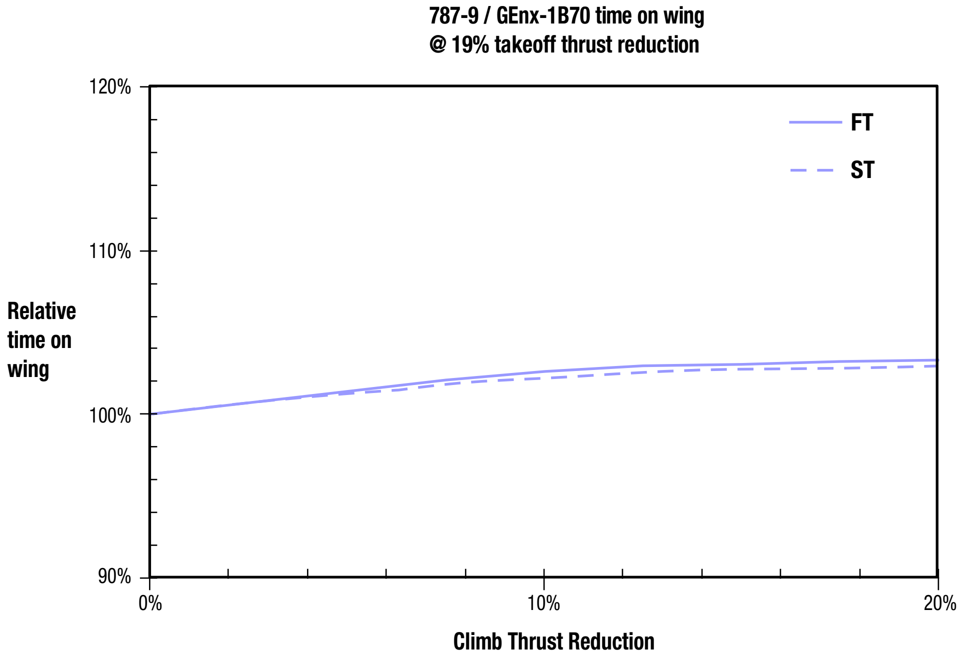


Figure 15. 787-9 / GEnx-1B70 time on wing

These results illustrate the interactions between various failure modes when individual part lives are rolled up to produce a time on wing. Note that the slow taper produces superior engine time on wing for the GEnx-1B54, indicating that the HPT stage 1 blade life is the dominant effect. In the case of the GEnx-1B70, the negative impact of slow taper on combustor corrosion is somewhat stronger and as a result time on wing is slightly less than with the fast taper. These interactions between failure modes drive differences among various engine models' maintenance cost sensitivity to climb thrust reduction.

The overall engine life sensitivities for each engine model were then applied to the base maintenance costs to obtain maintenance cost per hour contributions to the overall operating cost sensitivity.

Operating Cost Impact

The net operating cost impact of using reduced climb thrust was evaluated by adding the fuel burn and maintenance cost sensitivities described in the preceding sections. The results are presented as a function of climb thrust reduction at typical reduced takeoff thrust levels in Figure 16 for the 787-3 and Figure 17 for the 787-9. For both the 787-3 and 787-9, the fuel burn penalty associated with reduced climb thrust opposes the maintenance cost benefit such that the net operating cost is reduced somewhat between 0 and 10% climb thrust reduction. Beyond 10% climb thrust reduction the maintenance cost benefit levels off and the fuel burn penalty becomes steeper, resulting in a net operating cost increase.

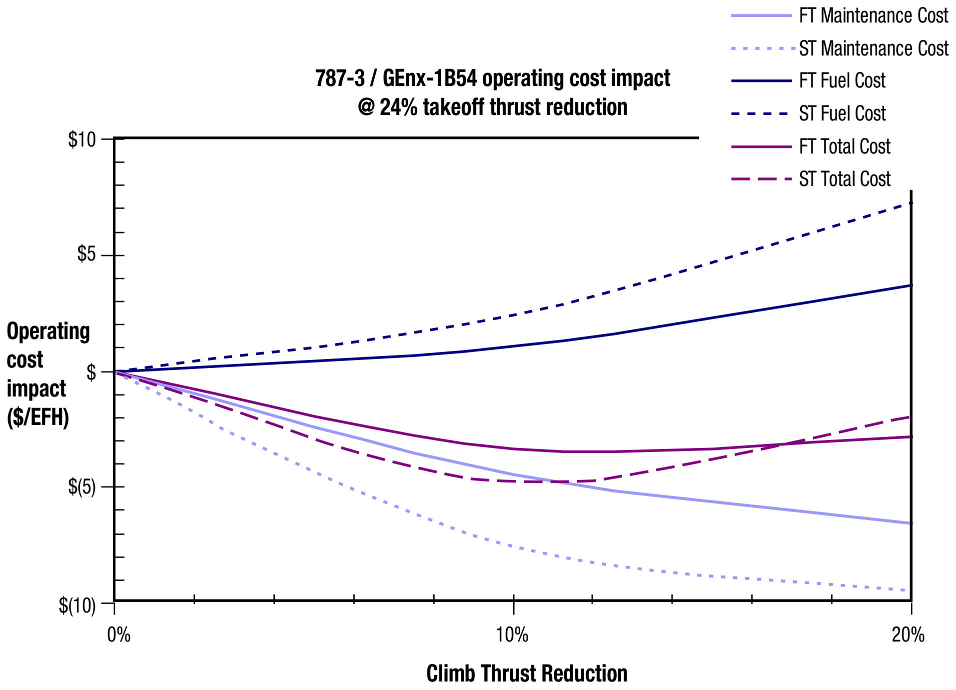


Figure 16. 787-3 / GEnx-1B54 Operating Cost Impact

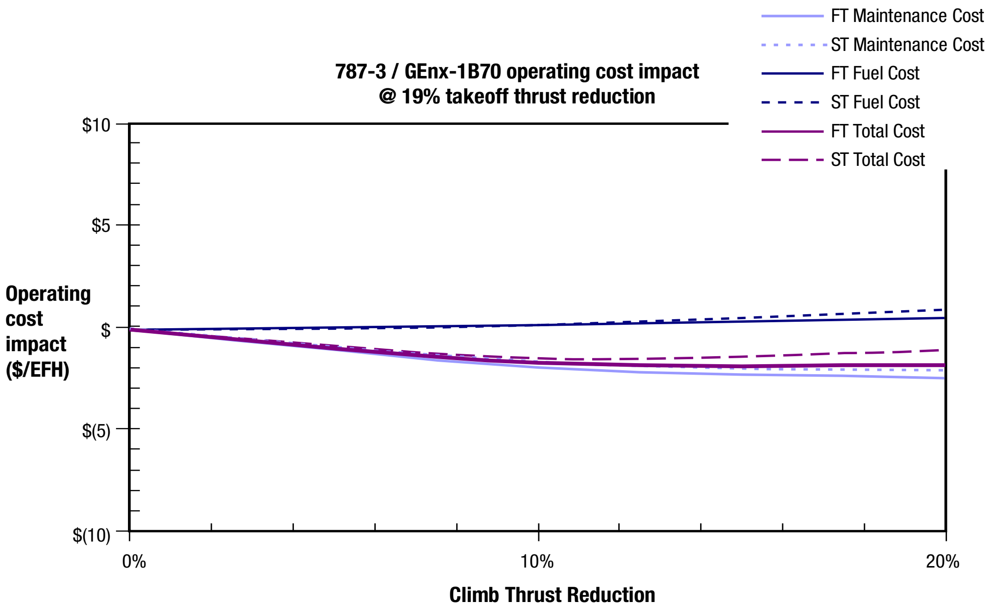


Figure 17. 787-9 / GEnx-1B70 Operating Cost Impact

While the general trends are similar for both 787 models, the magnitude of the potential benefit is somewhat different. The power management schedules for the 787-9 model are typical of twin-engine aircraft in that takeoff temperatures are much higher than climb temperatures. As a result, the net benefit of reduced thrust climb is small, $1.80 per EFH with fast taper and $1.40 with slow taper. Because the GEnx-1B54 is significantly derated from the maximum capability, there is a much smaller difference between takeoff and climb temperatures. Consequently, the net benefit of reduced thrust climb is larger, $3.40 per EFH with fast taper and $4.70 per EFH with slow taper.

It should be noted that the results presented above assume a typical level of takeoff thrust reduction, 24% for the GEnx-1B54 and 19% for the GEnx-1B70. When higher levels of takeoff thrust are used, the maintenance cost benefit of reduced thrust climb will be less because a smaller portion of the engine life is consumed in climb. When higher levels of takeoff thrust are required due to high TOGW, the maximum climb rate will be lower and the fuel burn penalty for reduced thrust will be higher. These two effects combine to make reduced thrust climb increasingly less attractive.

Similarity to Other Aircraft

Despite the differences in engines, ratings and engine life drivers, the other aircraft studied showed remarkably similar results: in most cases, use of 5% to 10% climb thrust reduction produces a small net economic benefit on flights where significant reduced thrust takeoff (15% to 20% or greater) is used. The magnitude of the maintenance cost benefit tends to be greater for low takeoff thrust ratings and for four-engine aircraft because climb consumes a relatively larger portion of the engine life. The magnitude of the opposing fuel burn penalty tends to increase as the time to climb at maximum rated climb increases. Hence as the inherent climb rate of the aircraft decreases, the likelihood of realizing a net benefit from the use of reduced thrust climb decreases.

Conclusions & Recommendations

This paper is a result of GE/CFM customer inquiries into fuel and maintenance cost savings and other industry papers recently published on this subject. Based on the results presented as well as similar results for other GE-powered aircraft, small reductions in climb thrust can produce small reductions in net operating cost due to a favorable trade between maintenance cost and fuel cost. For short haul aircraft requiring lower thrust ratings, the best fuel savings profile would be using as much reduced takeoff thrust as possible followed by the application of normal climb power. This can yield a fuel savings of between \$3-\$7 dollars per flight hour over a similar profile that uses derated climb. Consideration must be given to the increase in engine operating cost as described previously. For long range aircraft there is no significant fuel burn or maintenance cost saving in using normal climb over a derated climb. Maintenance cost savings tend to reach a maximum somewhere between 5% and 10% climb thrust reduction, after which the increase in fuel burn dominates the trend and the two end up offsetting each other. This result is applicable to flights on which TOGW is low enough to permit typical levels of takeoff thrust reduction in the 15% to 20% range. When higher levels of takeoff thrust are required, the optimum climb thrust will be higher and the potential benefit of climb thrust reduction will diminish and eventually disappear.

Consequently, it is recommended that use of reduced thrust climb be restricted to flights where significant reduced thrust takeoff, 15% or greater, is used for maximum savings on short haul aircraft. For long-range aircraft there is no significant impact on fuel or maintenance cost savings, regardless of the amount of reduced thrust climb.

In those cases where reduced thrust climb is used, the climb thrust reduction should not exceed 10%. Furthermore, climb thrust should not be reduced to the extent that climb time will exceed 25 minutes, as this is likely to produce an unacceptable increase in fuel cost. Many flight management systems automatically select a level of derate for climb dependent on the level of derate used for takeoff. Any change to procedures, per the aforementioned recommendations, should be coordinated between the airline flight operations departments and the aircraft manufacturer.