Rolls-Royce

Derated Climb Performance In Large Civil Aircraft

Article **6**

Will James and Phill O'Dell
Rolls Royce

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This article is presented as part of the 2005 Boeing Performance and Flight Operations Engineering Conference, providing continuing support for safe and efficient flight operations.

1. Introduction

This paper reviews the subject of derated climb performance on modern transport aircraft. The 777-200 powered by the Rolls-Royce Trent 892 is used in illustrative examples but the basic principles and findings are similar to other engines and aircraft.

2. What Determines Climb Rating?

Aircraft are designed to meet performance targets at maximum takeoff weight (MTOW) including takeoff field length and climb time / distance to cruise altitude. At takeoff, engine failure has to be considered; engine failure on a four-engine aircraft results in 25% loss of thrust, but on a twin- engine aircraft 50% of thrust is lost. Typically the engines on twin-engine aircraft are sized to meet takeoff targets, but the engines of four-engine aircraft are sized to meet climb time/distance targets. As a result, twin-engine aircraft tend to have better climb performance than four-engine aircraft.

In either case operation at less than design MTOW will usually allow a reduction of both takeoff and climb thrust from maximum ratings. This is recognised by the industry as being beneficial to engine life (see section 6) and is why both takeoff and climb derate are available on large modern aircraft.

3. The Potential To Use Climb Derate

The following examples of 777-200/Trent 892 performance at MTOW and at 3000 nmi illustrates the potential for climb derate in typical operation:

At the MTOW of 656,000 lb, climb time at ISA + 10 °C to the optimum cruise altitude of 31,000 ft is 25 minutes; this is a very good time by industry standards (fig. 1).

At 3000 nmi, approximately 520,000 lb TOW, climb time is less at 20 minutes even though climbing to a higher optimum cruise altitude of 35,000 ft.

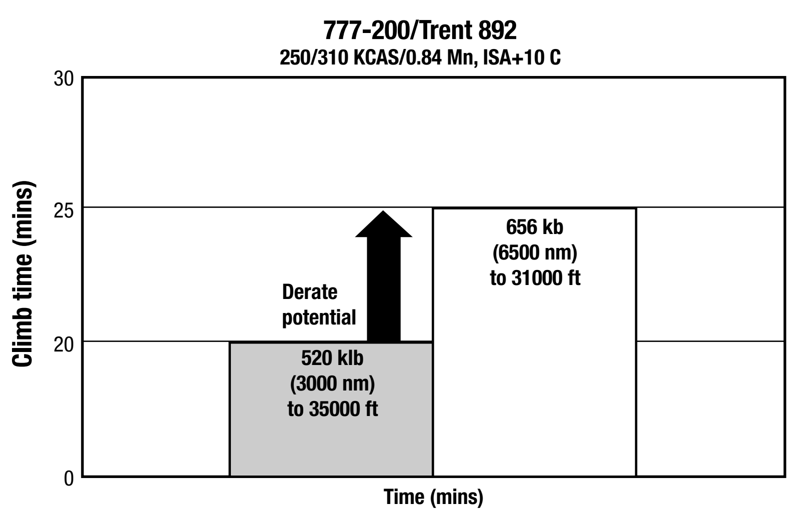

Figure 1. Climb time

Climb distance presents a similar story (fig. 2).

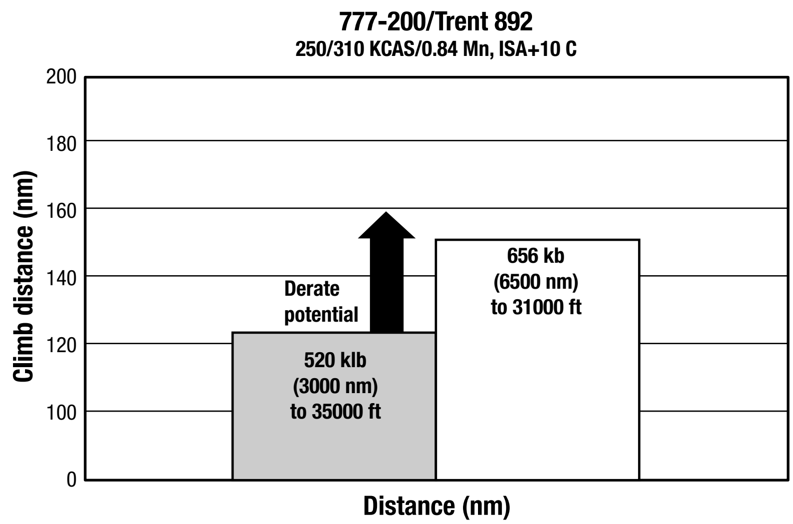

Figure 2. Climb distance

If climb time at MTOW is acceptable to the operator, then there is potential to derate in climb at lower takeoff weights and increase time to an acceptable level.

Rate of Climb (ROC) is also a consideration (fig. 3).

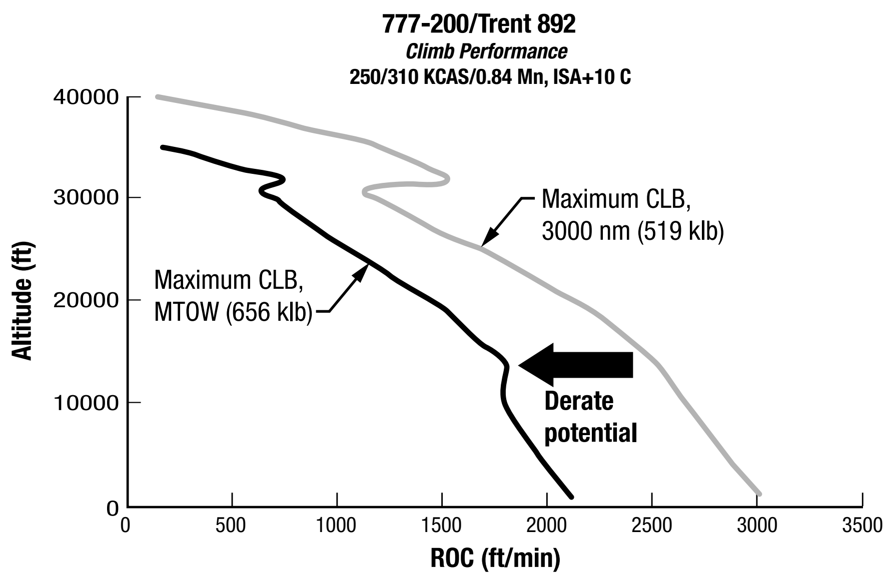

Figure 3. Rate of climb

If ROC at MTOW and max climb thrust is acceptable to the operator, then there is potential to derate in climb at lower takeoff weights, keeping ROC at an acceptable level – perhaps similar to that at MTOW.

Other aircraft will show similar trends, but the most potential for climb thrust reduction will be seen in long range aircraft when operated at shorter ranges. This is due to the large difference in TOW between long and short range operation.

4. Climb Derate Options

On the 777 and on many other airplanes, two levels of tapered climb derate are available but with a pre-configured choice of fast or slow tapers (fig. 4). The pre-configured choice is hard-wired but changeable by Service Bulletin.

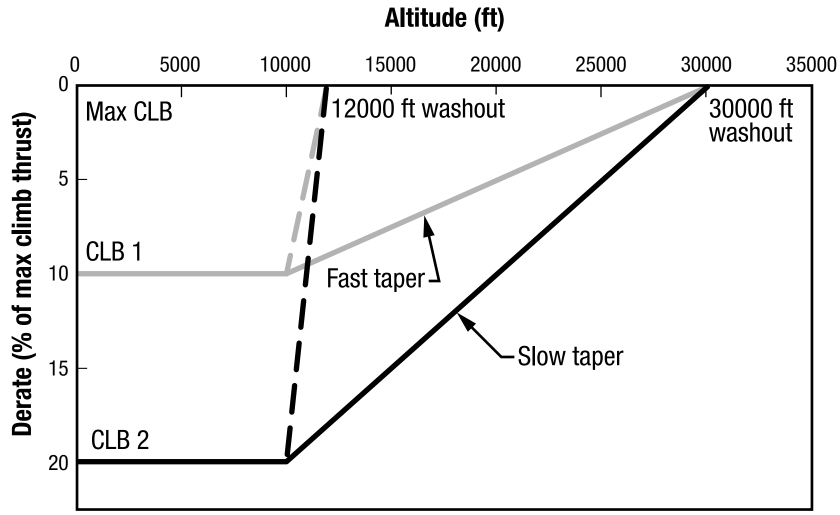

Figure 4. Climb derate tapers

Early climb derate options on other aircraft were typically fixed and manually selected, such that when ROC fell below an acceptable level, the next higher climb thrust would be selected. Later options are typically tapered and wash-out to maximum climb thrust at higher altitudes; in this way altitude capability is automatically protected.

5. Effect On Airplane Performance

In the case of the 777-200/Trent 892, the climb derates (fig. 4) give the following performance at 3000 nmi (Initial climb weight of 520,000 lb, climbing at 250/310 KCAS/0.84 Mn, ISA+10°C to 35,000 ft optimum cruise altitude). Climb time (fig. 5) increases by up to 3.5 minutes, but is still less than 25 minutes.

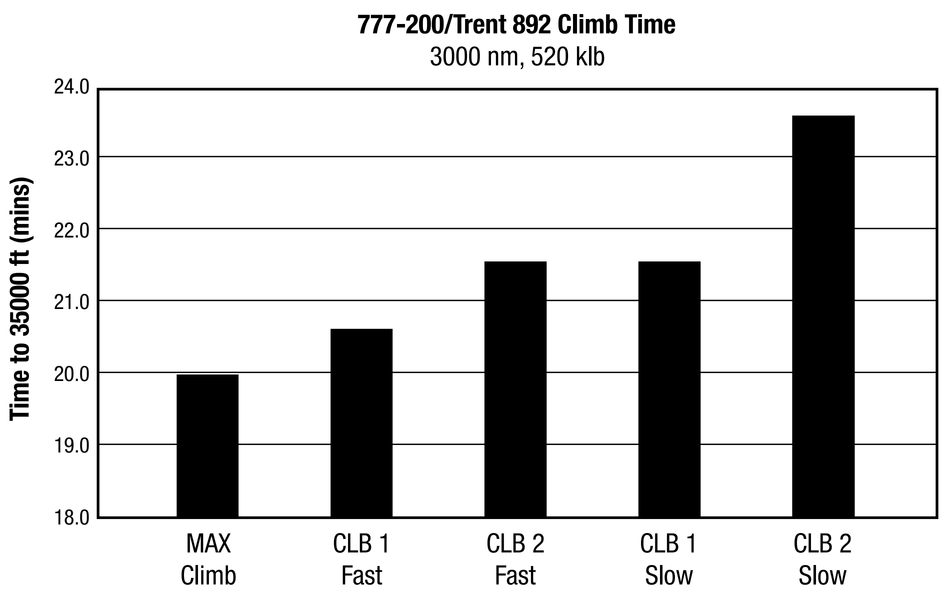

Figure 5. Climb time

Climb distance (fig. 6) increases by up to 21 nmi, but is still less than 150 nmi.

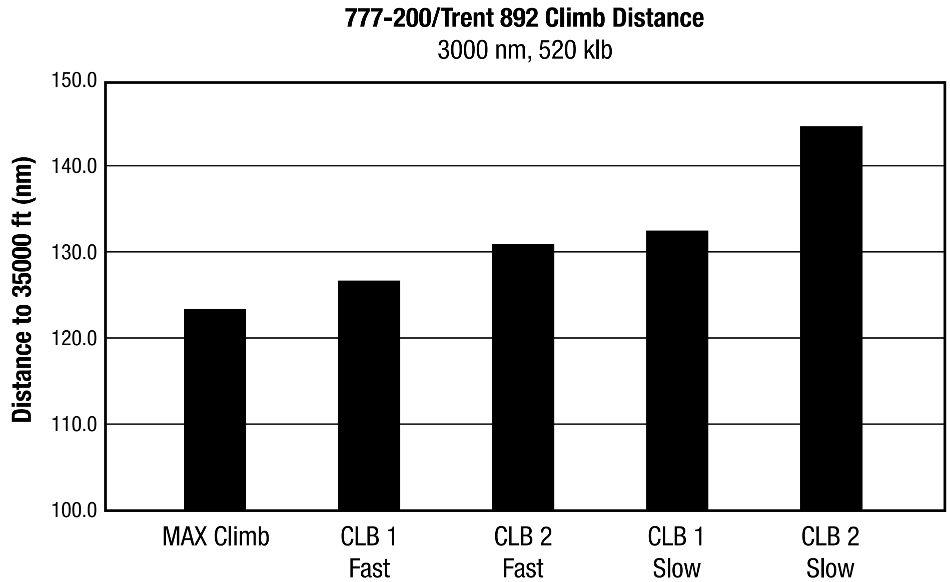

Figure 6. Climb distance

Climb Fuel (fig. 7) increases by over 800 lb.

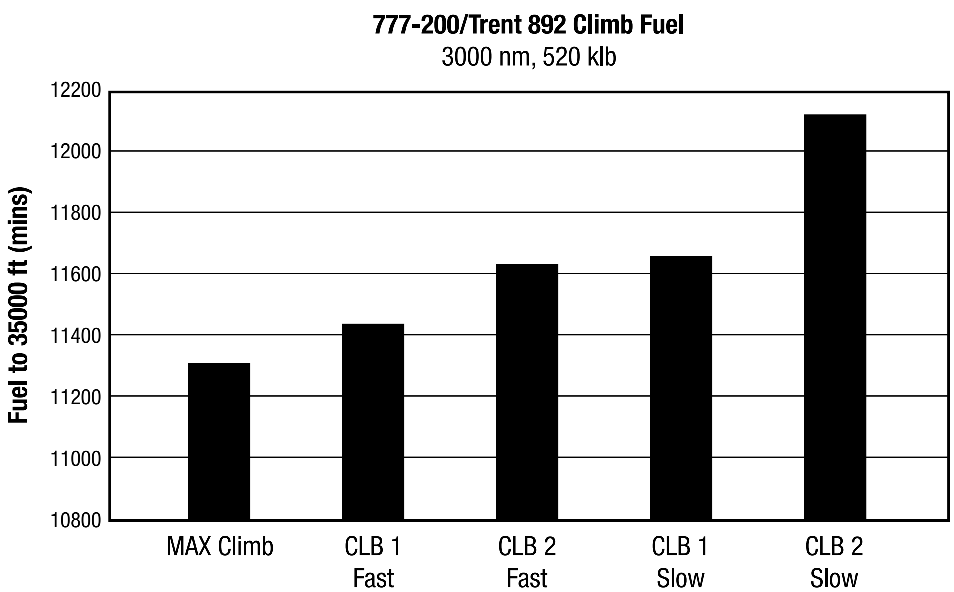

Figure 7. Climb fuel

There are operator perceptions that the climb time, distance, and in particular, fuel increases are too large to justify the use of derate during climb, and consequently climb derate has not been widely taken up.

However, these increases are only half the story:

Although climb time, distance and fuel have all increased with the use of climb derate, the cruise distance is less, so less cruise fuel is used (fig. 8). The overall mission trip time and fuel is the correct comparison (distance is fixed and the same).

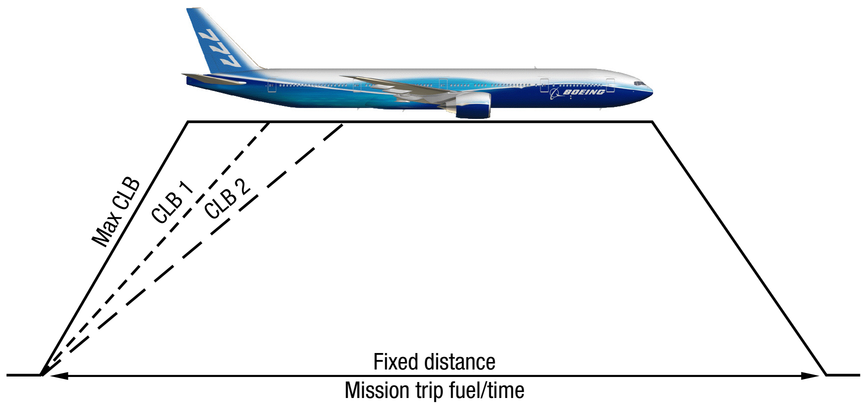

Figure 8. Less cruise distance

When this is accounted for the trip fuel and time differences are very small (fig. 9).

777-200/trent 892 Climb Derate Trip Differences Example

Climb Rating	Max CLB	CLB 1 Slow	CLB 2 Slow
Range, nm	3000	3000	3000
Initial Climb Weight, lb	519389	519389	519389
Optimum Cruise Altitude, ft	35000	35000	35000
250/310/0.84 Mn, ISA+10 C			
Time from 1500 ft to Optimum Cruise Altitude, min	19.9	21.5	23.5
Distance from 1500 ft to Optimum Cruise Altitude, nm	**123.5**	**132.8**	**144.7**
Fuel from 1500 ft to Optimum Cruise Altitude, lb	11312	11656	12127
Delta Cruise Distance	21.2	12.0	Base
Start Cruise Weight	508077	507733	
0.84 Mn, 35000 ft Nams	0.03164	0.03164	
Fuel for Delta Cruise	671	379	Base
Fuel for 144.7 nm	**11983**	**12035**	**12127**
Delta Trip Fuel, lb	Base	52	144
Delta Trip Fuel, USG	Base	7.8	21.5
Delta Trip Fuel Cost at $1.2/USG	**Base**	**$9**	**$26**
Time for Delta Cruise	2.6	1.5	Base
Time for 144.7 nm	**22.6**	**23.0**	**23.5**
Delta Trip Time (mins)	**Base**	**0.4**	**0.9**

Small trip differences

Figure 9. Small trip differences

At shorter ranges and lighter TOW's, optimum cruise altitude is higher but the differences in trip time and fuel remain small (fig. 10 and 11).

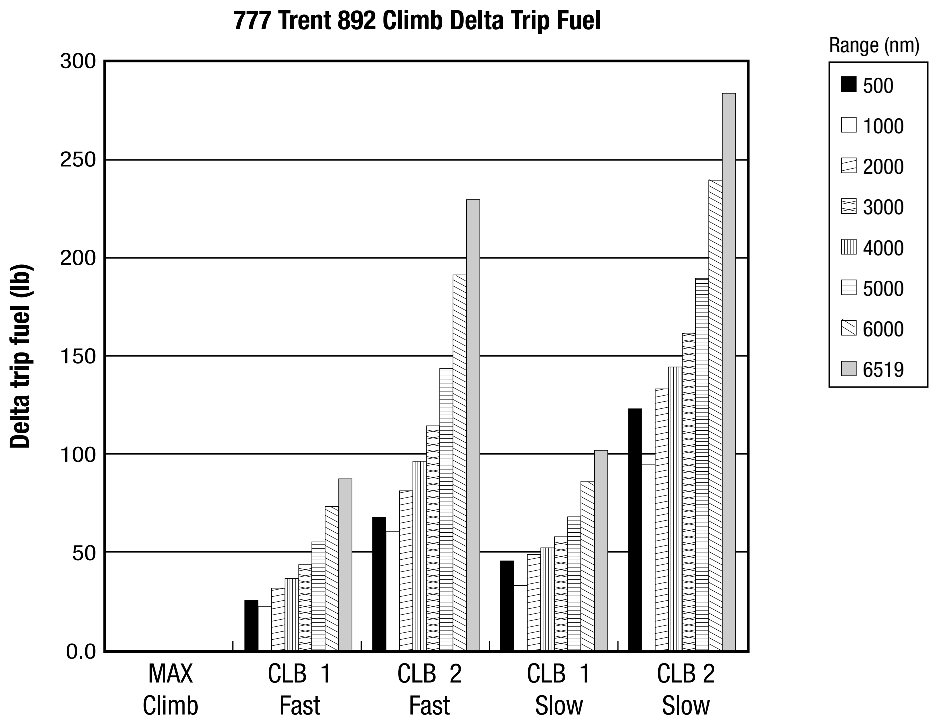

Figure 10. Delta trip fuel

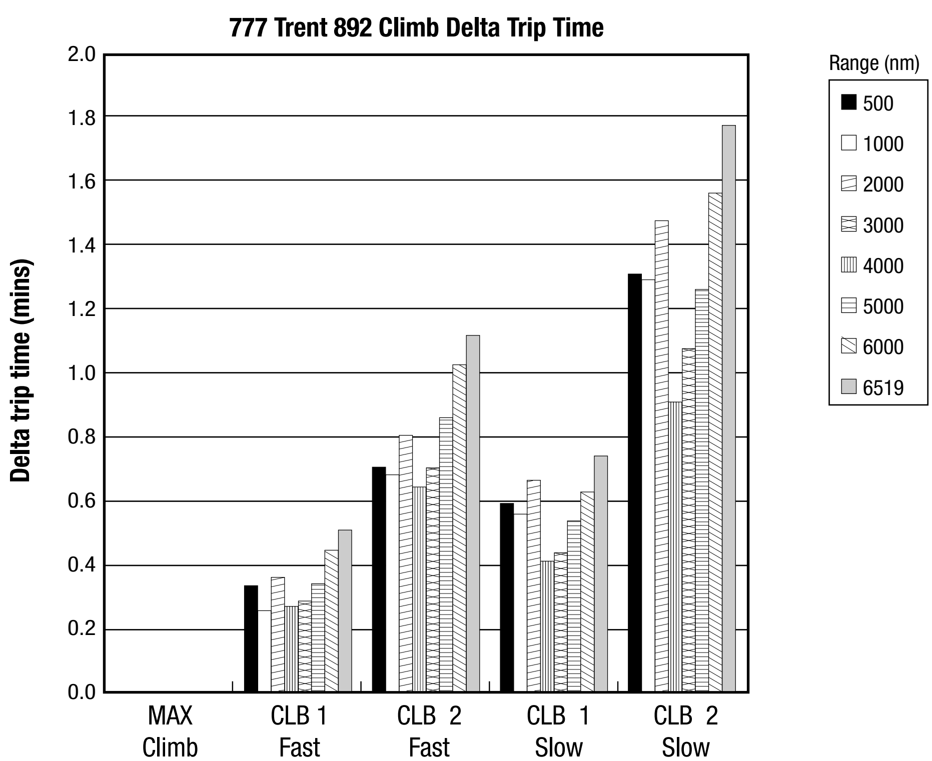

Figure 11. Delta trip time

Rate of Climb is only reduced at low altitudes for the 777 due to the tapered climb derate profiles previously shown (fig. 4), also high altitude capability is not affected by climb derate (fig. 12).

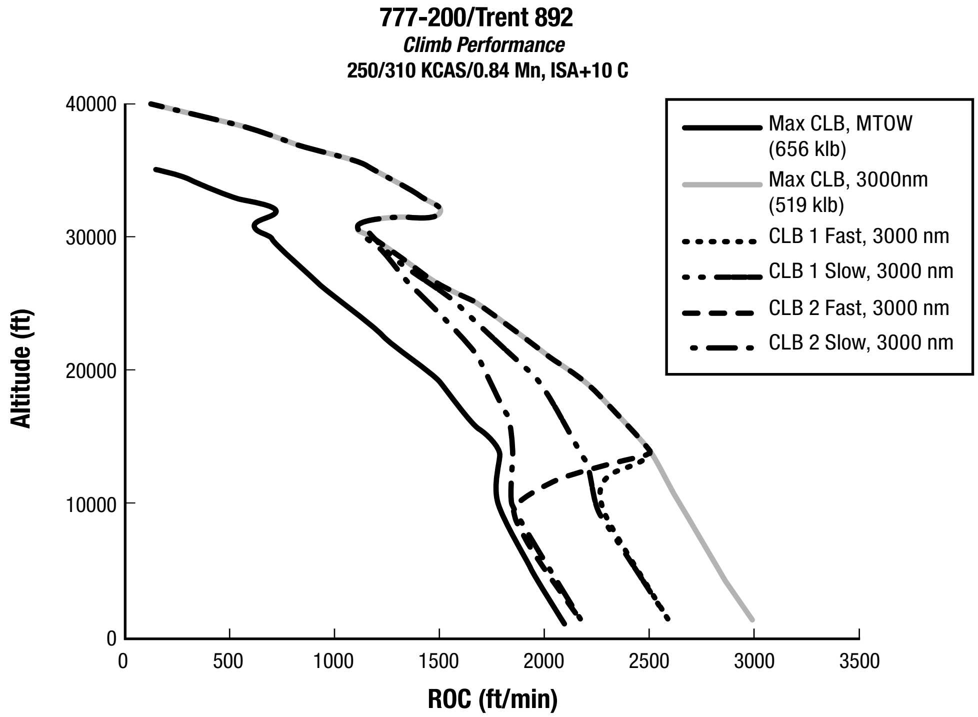

Figure 12. ROC

Below 10,000 ft, all climb derates at a weight for 3000 nmi, (519 Klb) offer better climb performance than Maximum climb rating at MTOW (656 Klb).

Also, above 30,000 ft, all climb derates provide the same ROC as Maximum climb rating.

6. Engine Benefits From Derate

Time between engine refurbishments and cost of refurbishment are directly related to how an engine is operated. The key drivers are stage length, cycles per year (the majority of component degradation is based on cycles rather than hours) and how hard the engine is used, i.e., shaft speeds and core temperatures during takeoff and climb phases plus adverse environmental factors. This is true for engines regardless of manufacturer.

The main benefit of reduced thrust to the engine is operation at reduced core temperatures. The highest core temperature measured in an engine is Turbine Gas Temperature (TGT) which is usually measured by thermocouples in the low pressure turbine nozzle guide vanes (fig. 13). (Hotter upstream temperatures cannot be measured as the thermocouples would melt).

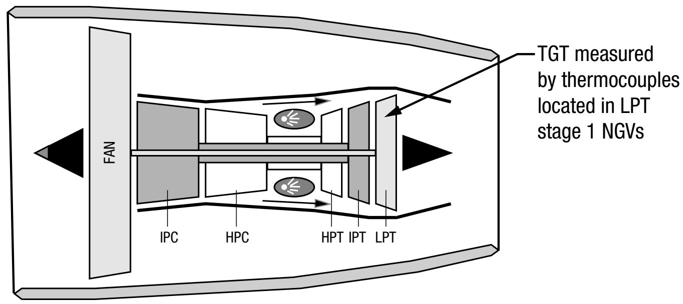

Figure 13. TGT measuring

TGT increases with Outside Air Temperature (OAT) until the maximum is reached at the 'Kink Point' (fig. 14). Engine thrust is usually 'Flat Rated' up to the kink point. At OAT's above the kink point, TGT usually remains constant and thrust reduces.

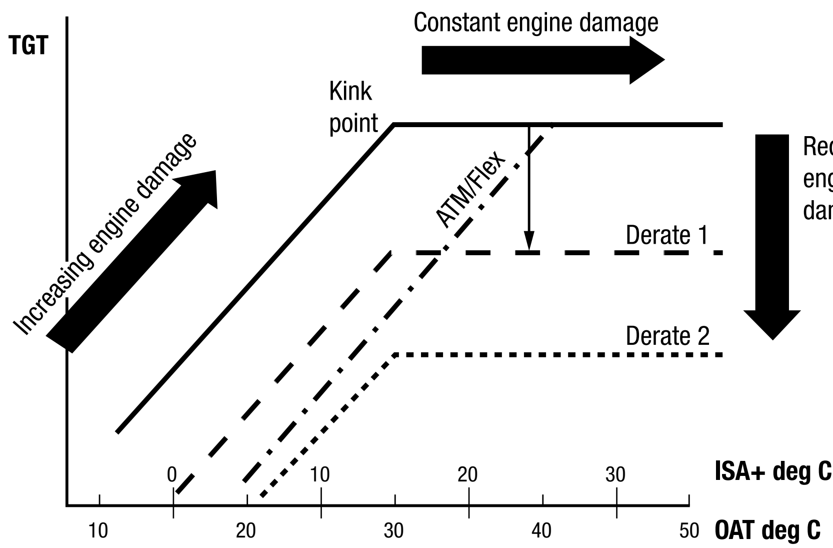

Figure 14. TGT variation

Engine damage or life is related to TGT and Figure 14 illustrates the effects of reduced thrust at takeoff by Derate and Assumed Temperature Method (ATM). The illustration is also applicable to climb (except ATM/Flex is not available in climb) as both takeoff and climb contribute to engine damage.

High Pressure Turbine Blades (HPTB's) achieve some of the highest temperatures in an engine and consequently are typically damaged by oxidation/burning and erosion (fig. 15). (Note however, that HPTB's are only one of a number of causes of high life engine removals for refurbishment).

Figure15. High Pressure Turbine Blades (HPTB)

<u>Reduced TGT's will therefore reduce engine damage and extend engine life.</u>

7. The Importance Of Climb Derate

The importance of climb derate compared to takeoff derate is illustrated by a comparison of takeoff and climb TGT's (fig. 16)

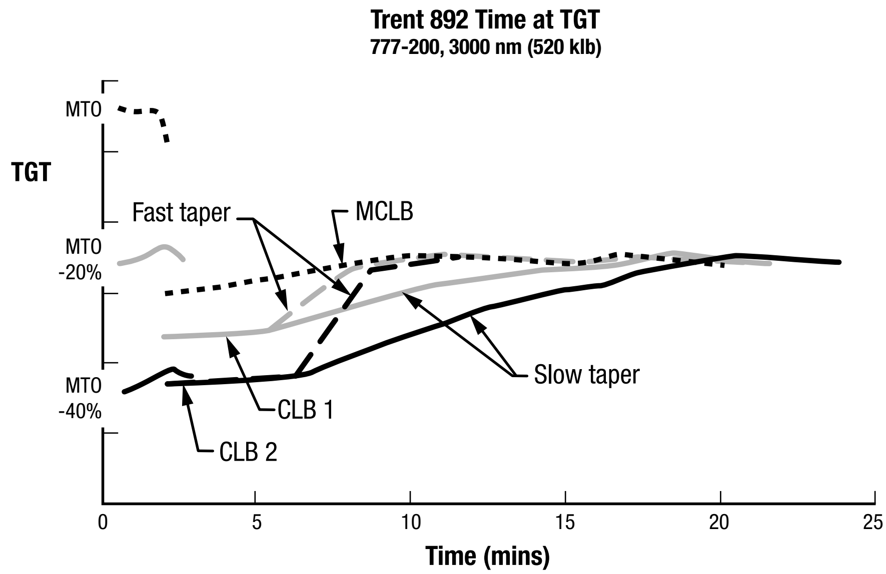

Figure16. Time at TGT

Although the TGT at Max Takeoff (MTO) rating is highest, operation at 20% takeoff derate is not uncommon. In this instance Max Climb rating gives comparable TGT's, but climb lasts approximately 8 times longer than takeoff. The use of climb derate is significant for this reason.

Figure 16 also shows that slow tapers offer lower TGT's than fast tapers. In order to assess the relative merits of these options Rolls-Royce calculates time-weighted average climb derates (TWCD) - an integration of derate and time up through the climb.

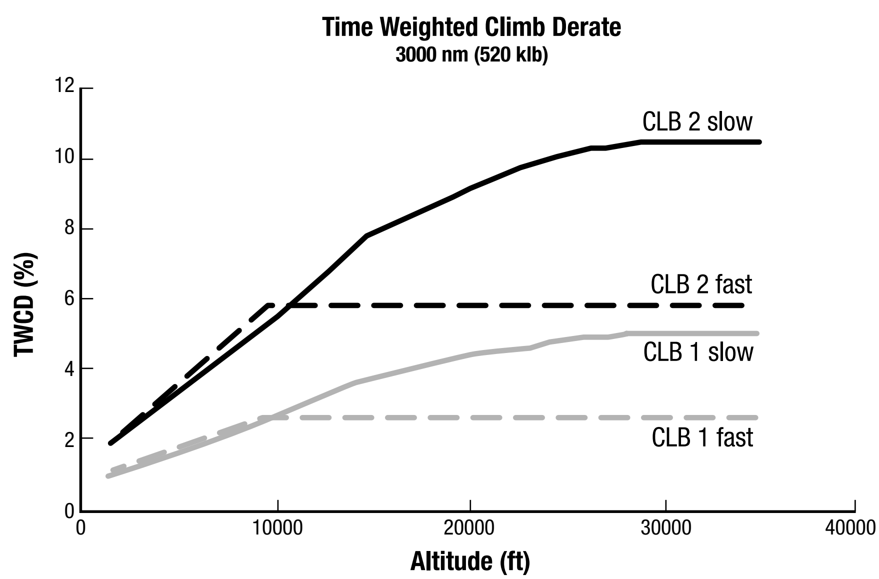

Figure17. Time weighted climb derate

Figure 17 shows an example of the integration to get a time weighted climb derate. Note that Fast tapers show no increase above 12,000 ft and slow show none above 30,000 ft. This reflects the tapers shown in Figure 4.

Over the range of operating ranges and weight, time weighted climb derate is approximately constant (fig. 18).

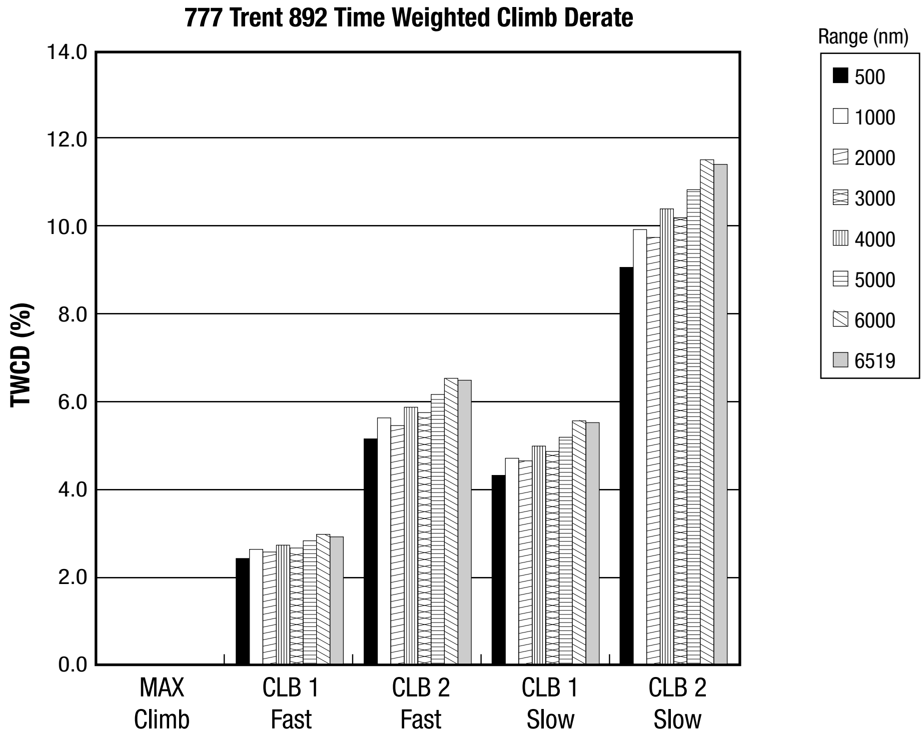

Figure18. Variation of TWCD

In fact, TWCD can be approximated as follows:

CLB1 Fast	2.7%
CLB2 Fast	5.9%
CLB1 Slow	5.0%
CLB2 Slow	10.4%

8. The Operator Benefits Of Climb Derate

As a rule of thumb, if the average time weighted climb derate achieved in operation is 5%, then Rolls-Royce estimates that this will typically result in 3% more time-on-wing to full refurbishment compared to using maximum climb thrust all the time (although other factors such as takeoff derate, stage length, harshness of operation, etc., also have an effect).

Three percent more time on wing to full refurbishment is equivalent to 3% reduction in Direct Maintenance Cost (DMC) per engine flying hour, so climb derate can offer some significant savings if used consistently.

As previously shown in section 2, the block fuel increase is very small; in the CLB 1 Slow example in Figure 9 the value was $9 per trip. Assuming 700 trips per year the cost of the increased fuel is $6,300 per aircraft per year, but the DMC savings due to 5% achieved climb derate could typically be 10 times this per aircraft per year.

9. How Is Climb Derate Implemented - Operational Perspective

There are several well-understood engine-rating levels for the Boeing 777:

- Maximum Takeoff (TO)
- Go-Around (GA)
- Maximum continuous thrust (CON)
- Maximum climb thrust (CLB)
- Maximum cruise thrust (CRZ)

In addition, derated takeoff and climb ratings are available:

- Fixed level derated takeoff (TO 1 or 2)
- Assumed temperature reduced thrust takeoff (D-TO)
- Fixed takeoff derate combined with assumed temperature reduced thrust (D-TO 1 or D-TO 2)
- Derated climb (CLB 1 or CLB 2)

This paper only considers climb derate. On the B777 there are two levels of climb derate available, CLB 1 and CLB 2. The climb rating is automatically selected depending on the level of takeoff thrust selected. Climb ratings can also be manually selected from the THRUST LIM page of the Flight Management Computer (FMC) (fig. 19).

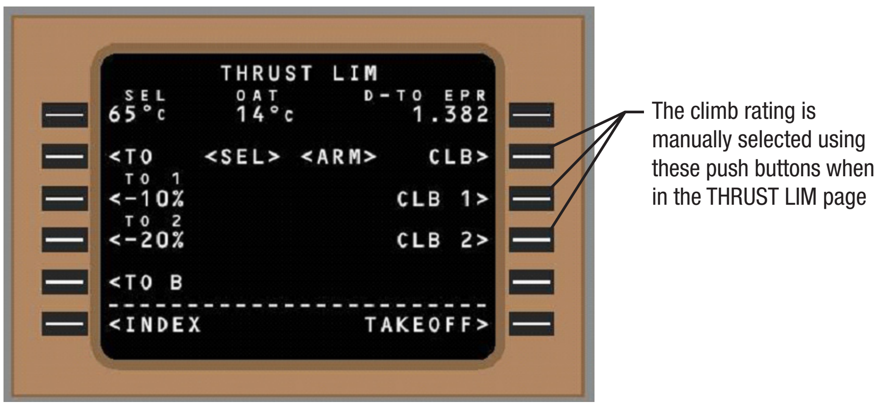

Figure 19. The FMC THRUST LIM page as part of the pre-flight sequence

The THRUST LIM page is displayed as part of the pre-flight sequence, and can also be accessed from the INIT/REF page of the FMC (for example, for changing climb rating during climb).

When a derated or assumed temperature takeoff is entered, the FMC automatically selects a climb rating. For a takeoff thrust reduction of less than 10%, maximum climb is selected. For a thrust reduction of between 10% and 20%, CLB 1 is selected. For a takeoff thrust reduction of greater than 20%, CLB 2 is automatically selected. The pilot can manually override the climb rating once the takeoff thrust limits have been entered in the FMC.

10. Operational Effect of Derated Climb

It should be noted that Rolls-Royce measures Turbine Gas Temperature (TGT), however cockpits display Exhaust Gas Temperature (EGT) which is Boeing's preferred nomenclature for TGT.

Derated climb was introduced to save the engine life by reducing EGT and hence DMC costs and time between overhauls. The use of this rating results in a slight reduction in Rate of Climb (ROC) and climb gradient with the consequence of an increased distance and time to achieve cruise level. A small increase in fuel consumption is also seen. Cruise distance will be slightly shorter and so cruise fuel is slightly reduced, as explained in section 5.

It is also noted that the use of derated climb has no effect on ROC above 30,000 ft as maximum climb thrust has been restored at this altitude and above.

The combination of reduced thrust takeoff (either by assumed temperature or derate) and climb derate has considerable effect in reducing EGT, which contributes significantly to reducing DMC costs and increases the time between shop visits.

As with all transitions from one rating to another, engine control is smooth and progressive when switching between climb ratings.

11. Operational Use of Derated Climb

For the reasons described earlier it is clear that the maximum available climb derate should be used wherever possible. Departure planning should reflect the use of 'just enough' power to complete the climb phases rather than simply accepting the perceived operational benefits of utilising the available excess power. Factors that might affect or modify the choice of climb rating include:

- Overall climb performance (both instantaneous and averaged)
- Mandatory height constraints during a standard instrument departure (sid) profile
- The effect of the selected rating on the ground track of the aircraft during slat/ flap retraction for noise sensitive routing
- Encountering icing conditions or turbulence
- ATC restrictions (achievement of FL XXX by ...)

In order to maximise the use of climb derate and provide the greatest benefit, Rolls-Royce recommends that operational constraints and the minimum acceptable climb rate are considered for each route to determine the maximum acceptable level of derate.

Whenever SID constraints, ATC factors and/or climatic condition permit, CLB 2 should be used for the entire climb segment. If factors preclude the use of CLB 2, use of CLB 1 should be the next option, then CLB. Once any such constraint has been passed, the maximum acceptable level of derate should be selected (or reselected).

Much discussion has taken place regarding the minimum acceptable rate of climb at which a lower level of derate should be selected. Operators are commonly using as low as 500 ft/min. If CLB 1 or CLB 2 has to be deselected in order to maintain an ROC of 500 ft/min, or to meet any imposed constraint, **there is no reason why derate cannot be reselected**, frequently if necessary and when appropriate, before the washout altitude to gain maximum benefit. Varying the climb rating in flight has no adverse effect on engine life, so should be performed as required.

When constraints are imposed, negotiation may enable flexibility and therefore the use of derate. Equally, slowing down to increase the ROC may well enable derate usage to be further maximised; the phrase "NEGOTIATE, DECELERATE, DERATE" has proven useful to operators.

It would seem appropriate to consider routes when deciding procedurally which climb derate setting to enter before takeoff. It may well be that CLB 2 is applicable on all flight, but clearly the airline is best placed to answer this.

It is therefore recommended that:

- On all sectors CLB 2 should be considered.
- If SID close-in constraints preclude the use of CLB 2, then CLB 1 should be considered.
- If SID close-in constraints preclude the use of CLB 1, then CLB should be selected.
- When SID close-in constraints have been achieved by the use of CLB 1 or CLB, consider employing CLB 2 for the remainder of the climb phase.
- At any stage, if ATC height constraints cannot be met at the existing level of derate, assisted by a speed reduction towards best angle of climb speed, select a lesser level of derate via the THRUST LIM page of the FMC.
- If ATC height restrictions, which had necessitated a reduction in the selected level of derate, are re-negotiated or removed, re-select CLB 2 as soon as possible.

At any time during the climb phase, whilst using CLB 1 or CLB, if no ATC constraints preclude, consideration should be given to selecting the next level of derate up to CLB 2.

12. Conclusion

For a small increase in block fuel and flight time the use of derated climb will result in a considerable saving on DMC costs and increase in time between overhauls.

By using a procedure that allows flexible use of climb derate based upon operational constraints, the savings will be maximised. The actual DMC cost savings are specific to an individual airline's route structure, average ambient temperature and other significant factors. Rolls-Royce willingly engages with individual airlines to discuss specific details of their operation. Overall a major net saving will be seen.

Many 777 operators have taken the 'Fast Taper' option, however Rolls-Royce recommends that the 'Slow Tapers' option should be incorporated to enable enhanced benefits. To maximise benefits, CLB 2 should be used in preference to CLB 1 whenever possible.