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EGT Margin of a Jet Engine: Cause, Impact, Improvement, and Simulation Theory

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Abstract

When an engine runs, it produces heat, and there is a range of temperatures in the engine chamber. For jet engines, when they start, the temperature starts increasing within a range. At various durations of the engine run, there is some temperature. The higher the thrust, the higher the temperature. This temperature is called exhaust gas temperature (EGT). There is a maximum allowed gas temperature for each type of engine, and the difference between the actual gas temperature and the maximum temperature is called EGT margin (EGTM). Every airline aims to get the margin as high as possible. An increased EGT margin suggests that the engine is functioning efficiently and can withstand greater heat before hitting critical temperature limits. As time passes, factors such as engine wear, environmental conditions, and operational stress can reduce the EGT margin. Therefore, it is essential to continuously monitor engine performance parameters in real-time. To monitor trends in EGT and forecast maintenance needs, advanced engine health monitoring systems are utilized. Keeping an ideal EGT margin boosts fuel efficiency while minimizing the chances of engine harm and unexpected maintenance. Consequently, effective management of EGT and EGTM is vital for enhancing reliability, reducing operational costs, and guaranteeing safe and sustainable aviation operations.

Keywords: EGT margin, thrust margin, aerospace, airline, engine

INTRODUCTION

This is an era of globalization. This requires people to travel from one place to another. Sometimes, the travel would be international across the globe. Travel could be managed via various modes of transportation such as road, sea, and/or air. This includes rail transportation, car or bus transportation, ship or boat sailing, chopper ride, or flight travel. Every mode of transport has its own pros and cons [1]. However, in the current fast-moving world, Time is considered more valuable than anything else, and hence the majority of people prefer air travel. Every mode of transport must adhere to the safety measures circulated by the appropriate Department of Transportation (DoT). Every company operating these modes of transportation needs to adhere to these safety manuals. The same applies to airlines. Airlines must adhere to the safety guidelines of the Department of Civil Aviation and are required to have an Air Operator Certificate (AOC). For instance, airlines operating in India have to adhere to Directorate General of Civil Aviation (DGCA); airlines operating in UK have to adhere to UK Civil Aviation Authority (CAA), airlines operating in US have to adhere to Federal Aviation Authority (FAA); airlines operating in the country of European Union (EU) have to adhere to European Union Aviation Safety Agency (EASA), airlines operating in Saudi have to adhere to General Authority of Civil Aviation (GACA) [2]. These airlines use jet engines to fly the aircraft in the air. A jet engine is a type of engine that generates thrust by taking air inside, compressing it, mixing it with fuel, burning the fuel, and expelling the exhaust gases, leading to propelling a large object called an

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aircraft, following the principle of Newton's third law of motion. A jet engine is typically composed of the following components:

- *FAN:* The key components of the fan module consist of the fan blades, fan disk, and compressor case.
- *LPC (low-pressure compressor):* The LPC module is the first component of the engine. These are the initial set of blades after the fan blades of a jet engine. These components need to be strong enough to sustain high-pressure thrust wear; hence, they are made of titanium. This segment of the jet engine takes the inlet air and creates an incoming pressure [3]. This initial version of the compressed air is sent or sucked in by the next set of blades called the high-pressure compressor (HPC), as explained in the next section.
- *HPC:* Similar to the LPC, these are also made of several blades and rotors, but these are more intense and create more compression to the air coming from the LPC. It has multiple spools ranging from 7 to 10 spools that compress the air to the highest possible extent for that category of engine [4].
- *Combustion chamber:* This is the most expensive and important segment of an engine, as it generates most of the thrust of the aerodynamics needed to fly the aircraft. This generates thermal energy. This thermal energy creates a high-to-low pressure belt of air. The fuel-mixed air passes through various nozzles present in the combustion chamber [5]. Every airline does its best to protect this segment of the engine. The replacement cost of this component could range from $1 million to $2 million, making it the most expensive component of the engine.
- *HPT (high-pressure turbine):* This is a set of rotating blades that extract energy from the combustion chamber that has hot, high-pressure gas and that is spinning with the help of a central shaft. This generates sufficient energy in the exhaust for thrust to power the entire engine and create sufficient thrust to carry the entire aircraft in the air and float in the forward direction [6].
- *LPT (low-pressure turbine):* The LPT module is located after the HPT module. It extracts the remaining energy from the exhaust gas to rotate the LPC and large inlet fan, generating significant thrust and powering the engine core, working in congruence with the HPT for maximum efficiency [7].
- *Accessory drive:* This is the last component before the nozzles. The accessory drives are located at the front of the engine on the fan and booster module.

The main components of the accessory drives are:

- The inlet gearbox (IGB) and No. 3 bearing assembly,
- The radial drive shaft (RDS),
- The transfer gearbox (TGB),
- The transfer shaft (TS),
- The accessory gearbox (AGB).

Let us understand the science behind the functioning of a jet engine as follows. An aircraft flies and keeps floating according to the principles of Bernoulli's Law and Newton's third law of motion [8]. According to Bernoulli's law, faster-moving air has lower static pressure, and the higher-speed flow on top ends up at a lower pressure than the slower flow underneath; this pressure difference generates an upward force called lift. According to Newton's Third Law of Motion, the wing also deflects air downward as it passes. The reaction to this downward momentum is an upward push on the wings. Both Bernoulli 'sand Newton's laws are at work, and their impact is split depending on the wing's angle of attack and shape [9].

Below is the science behind the engines of an aircraft:

- Suck the air from outside.
- Compress the air.
- Divide the compressed air into separate chambers.
- Mix fuel into the compressed air.
- Burn the fuel.

- Exhaust the hot air.
- Create thrust and get propulsion.

Jet engine power is measured in thrust (pounds or kilonewtons), not horsepower, but can be converted; modern engines produce massive force, from 20,000 to over 100,000 pounds of thrust, equivalent to hundreds of thousands of horsepower, and similarly, it could be equivalent to 100,000 horsepower. The following are the types of jet engines:

- *Turbojet: the classic "straight-through" design:* Air gets compressed, mixed with fuel, ignited, and shot out the back. Simple but thirsty.
- *Turbofan: a turbojet with a big fan upfront:* Most of the thrust comes from the fan bypass air, so it is quieter and more fuel-efficient, and is the go-to for commercial jets.
- *Turboprop: A turbofan-like core drives a propeller instead of a fan*, which is great for short-haul and cargo planes where you need lots of power at lower speeds.
- *Turboshaft:* Similar to a turboprop, but the exhaust powers a shaft to drive helicopter rotors or other machinery, not a propeller.
- *Ramjet: no moving parts, relies on forward speed to compress incoming air:* it works best at supersonic speeds and is used in missiles and some experimental aircraft.
- *Scramjet: a supersonic-combustion ramjet*: Fuel burns while the airflow stays supersonic. Only fly at hypersonic speeds (Mach 5+) in research vehicles.
- *In addition to this, we have rocket engines, but they are not considered true jet engines*: rocket engines do not use Air Thrust; rather, they use their own fuel and oxidizer (liquid oxygen), and they produce their own hot gas.

Before we get comprehensive details about EGT margin, we should know how a jet engine is repaired. The process is laid out below:

1. *Gate-0:* This is the foremost stage of an engine repair where the operator has to talk to the OEM (Original Equipment Manufacturer), check for slot availability for the shop, check for the estimated work, plan for the removal of the engine, prepare for the documentation, physical shipment of the engine to the actual maintenance, repair, and overhaul (MRO) facility.
2. *Gate-1:* This is the process of removing the engine bag at the repair facility, performing a visual inspection of the engine health, disassembly, cleaning wherever required, and then performing a detailed inspection. These inspections are categorized as Level A, Level B, and Level C.
   - Level A is just a visual check and inspection.
   - Level B is a module-level inspection at the electrical signal maintainer (ESM) level.
   - Level C is an ESM inspection of the module but at piece part.

   At the end of Gate-1, the shop should be in a position to estimate what needs to be done in terms of:
   - Part replacement
   - Internal repair
   - External repair
   - Accept parts AS-IS.

   Shops are required to prepare a detailed British Standards Institution (BSI) Report. This technique allows the engine to be inspected from the inside without disassembling the jet engine. There are multiple BSI Points at each component, where an inspection device is inserted and rolled inside to inspect the condition of the parts from inside without disassembling the engine [10].
3. *Gate-2:* This is the most critical and carries 50% of the weight of the overall repair of the engine. In this stage, the shop orders a new part as a replacement and sends parts for external vendor repair if internal repair is not possible due to the OEM of the part being outside of the actual engine manufactured or due to capacity constraints. Internal repair is initiated if the findings do

not require any repair and are deemed serviceable as per the current AMM/ESM Limits. Parts are accepted AS-IS, or if the findings seem to be unknown, the shop will get help from their production support engineer to get their feedback. If they can accept the part AS-IS, they will get a document from the production support engineer called DICA (Deviation Instructions for Continued Airworthiness), and as per the legal requirement, the operator of the engine is required to give their consent. If the new parts are not available or the operator is looking for an economical option, the shop can offer used serviceable materials (USM). In addition, if the shop cannot get the parts they send to the vendor on time, they follow the concept of a rotable pool and would issue it apart from the pool, taking ownership of the original part sent to the vendor for repair at some exchange fee or complimentary. Once all parts are available back on-hand with the Supply Chain Team, they close this gate.

4. *Gate-3:* This is the beginning of the rebuilding of the engine and preparing it for testing and certification. All Engine parts were installed, and all modules were assembled. Subsequently, the engine was moved to the testing bay. Some MRO shops may have their own test cells, and they would move the engine directly for testing after Gate-3 closure, but some shops that do not have their own cell will outsource the testing. Test cells are high-cost infrastructure and require massive compliance; therefore, some shops may prefer to outsource.

Repair is not complete unless the documentation is complete for that engine. The shop must prepare the following as the main documents for engine re-delivery:

- *Testing, certification and release certificate:* FAA issues Form 8130-3, EASA issues Form-1, which varies depending on the governing body. This is called an Authorized Release Certificate.
- *MiniPack:* The overall work performed on the engine reconciled with the agreed work scope with the customer.
- Service bulletins applied.
- DICA
- Receipt dispatch list.
- Missing part list.
- Limited life parts (LLP) list.
- Quick engine changes (QEC) list.
- Line-replaceable units (LRU) list.
- Scrap/disposition tags.

Commercials for Jet Engine

Jet Engines are repaired in approved MRO facilities and are generally covered via time and materials (T&M) or rate per flight hour (RPFH) contracts. Note that there are a few other categories, but they are not commonly used. The application of various terms of the contract, discounts to customers or other support, and accounting treatment for such transactions are very complex, and the role of a finance professional is less explored in the field of MRO operations in the aviation sector. Here, a finance professional can have great career opportunities, and the following factors have major applications of finance professional expertise:

- *Application of various terms of the contract with regard to the type of engine component:* An engine is composed of various key components, sometimes divided into modules or sometimes just as components. The chargeability of each category of component is defined differently in the contract. Finance professionals can provide their expertise in the correct application and accounting treatment of these components and provide great audit observations. Not only does the contract require specific accounting treatments, but every applicable aviation governing body also mandates some specific accounting treatment, and finance professionals are in the best position to know and apply that.
- *Revenue recognition for MRO operations:* Revenue recognition for MRO operations of an aircraft engine is a complex process. In addition, there are contract terms that make them more complicated. Generally, such MRO operations recognize revenue as per ASC 606/IFRS 15. Here,

the identification of the exact obligation of the MRO shop is a critical driver of revenue recognition. Finance professionals are in the best position to make this decision. This process becomes even more complex as it involves margin elimination for engines in work in progress (WIP). Components are sold at a very high margin in the aviation MRO industry. Sometimes, the margin on engine components could be 70–80% of the catalogue list price.

MRO industries may choose to adopt any of the methods below for revenue recognition:

- Percentage completion method, where revenue is recognized based on the estimated milestone of work completed on the engine.
- RPFH, where revenue is recognized based on the actual flight hours of the specific engine.
- Point-in-time is used where the work scope of the repair is a quick turn, and in such cases, revenue is booked when all the repair work is done. The event triggering revenue recognition is when the engine re-delivery process starts, if the shipping is owned by the MRO shop, or when the engine is ready for collection for customer-owned shipping.

Warranty Application

Warranty application for such industries is very complex, as there is a general warranty as well as a component part-specific warranty. Sometimes, the customer receives the warranty for a component from the shop, and the shop, in turn, receives warranty coverage from the OEM. Booking reserves for both general and specific warranties require a very detailed accounting policy application and adherence to generally accepted accounting principles (GAAP). Finance professionals can have an added advantage as they are in the best position to account for warranty booking and release of such reserves.

Deferred Income in Jet Engine MRO Industry

Deferral of income is very common in the MRO jet engine industry. This is due to the huge volume of long-term contracts with airlines and the revenue recognition policies adopted by the MRO shop.

Scrap Accounting

Scrap components are a critical process driven by regulatory compliance, asset management, and financial reporting standards. It involves a formal decision-making process followed by agreeing upon the scrap of a part and its proper disposition. Sometimes, scrap disposition is done directly in the MRO shop at the cost of the customer or the shop, and other times, it is sent to the customer with scrap documents for them to scrap. The MRO shop should follow only component-specific scrap disposition processes.

Supplemental Parts Accounting

There are contracts where most of the MRO services are not chargeable, but there could be some specific items such as specific LRU, QEC, or LLP that could be chargeable. Finance professionals could support this extensively as they can determine which components of the engine are categorized into those categories and do accounting accordingly.

Break-Even Ratio (BER) Accounting

There is a concept of beyond economic repair in the airline industry. This term can be used for specific components or for the engine as a whole. The use of the BER term for the overall engine is more commonly practiced. If the repair of an engine costs more than 65% of the current list price (CLP) of a brand new engine of the same model and configuration, the concept of BER is considered.

Accident/Incident Engine Repair

There is a massive list of compliance requirements a shop must meet in case the engine coming for MRO operations has been involved in an accident/incident under the definition of the governing body (for USA engines, it is the FAA). There is a comprehensive and complex compliance procedure for overhauling such engines. Finance professionals can review compliance requirements and implement them in MRO operations. Most of these criteria lead to accounting complications. Finance professionals can greatly assist in accounting for such transactions.

USM or Rotable Accounting

This industry applies to a lot of USMs or rotables while performing repairs. Using the USM of other airlines leads to very detailed compliance requirements and complex accounting. Finance professionals can help organizations with proper accounting. USMs are originally owned by different airlines, but ownership is then transferred to the shop. The legal ownership of these parts is critical to the industry. In addition, procuring the USM and issuing it to a new operator has many accounting adjustments in the income statement. Finance professionals can manage all of these.

The manufacturing or overhaul of an aircraft is a comprehensive process requiring extensive compliance, certification, and review of documentation, including the engine shop manual, aircraft maintenance manual, power plant manual, and any other engine model-specific manual. The objective of an overhaul is to restore the aircraft engine to a brand new condition or restore its performance, which is categorized as performance restoration shop visits (PRSV). This could be a significant career market for finance professionals with unlimited growth potential in the industry. Based on recent research, finance professionals are scarce in this industry. The Code of Federal Regulations (CFR) is mandatory for any jet engine work. The following are the top requirements to adhere to for MRO operations:

- *Part 33:* Airworthiness Standards for engine design and airworthiness, required certification, and overhaul requirements.
- *Part 39:* Airworthiness Directives (ADs) for specific engine safety actions under MRO operations.
- *Part 43:* General maintenance guidance.
- *Part 65:* Mechanics (A&P) and Inspection Authorizations (IAs) who perform and approve the engine work.
- *Part 91:* Maintenance of record-keeping for aircraft and engines.

The jet engine repair industry is close to $100 billion in 2024. Before deciding whether an engine requires a comprehensive overhaul, it is imperative to note that the health of an aircraft engine is monitored using the following:

- Tools for continuous monitoring.
- Engine health monitoring.
- Bore scope inspection.
- Particle analysis.
- Vibration monitoring.
- Built-in test.

Now that we have gained a good understanding of how MRO shops work, we can explore the concepts of the EGT margin. When an engine runs, it produces heat, and there is a range of temperatures in the engine chamber. For jet engines, when they start, the temperature begins to increase within a range. There was a temperature at various durations of the engine run. The higher the thrust, the higher the temperature. This temperature is called the exhaust gas temperature (EGT). There is a maximum allowed gas temperature for each type of engine, and the difference between the actual gas temperature and the maximum temperature is called the EGT margin (EGTM). Every Airline aims to achieve the highest possible margin.

For a jet engine, the maximum EGT could be up to 1060° Celsius depending on the model of the jet engine. When an engine starts, the temperature follows the bell structure, which has a low temperature, then increases, reaches a peak, and then decreases gradually.

The EGT margin is crucial because it is the primary indicator of an aircraft engine's health, showing the extent of performance degradation that has occurred, allowing for proactive maintenance, preventing costly over-limit events (such as aborted takeoffs), and predicting engine life, ultimately ensuring flight safety and efficiency. Every airline is required to maintain this log on every takeoff. The key objective of the EGT margin is as follows:

- *Performance:* A shrinking margin signals internal wear (such as turbine seal gaps or combustor issues), indicating reduced efficiency and a need for attention.
- *Safety:* Prevents unexpected EGT over-limits during critical takeoff phases, which can force high-energy rejected takeoffs or even engine removal, thereby improving safety.
- *Maintenance:* Tracks engine conditions to schedule maintenance (such as compressor washes or core restoration shop visits) before failure, optimizing time on-wing and reducing unexpected removals.
- *Cost efficiency:* Restoring margins through maintenance (such as washing) brings back performance, delaying expensive engine overhauls and saving money. A good EGT margin could lead to fuel savings.
- *LLP parts life span:* Trends in margin loss help forecast the remaining operational life and schedule major overhauls, linking to LLP replacement. This is the backbone of the engine. The following can be considered the list of LLP parts:
    - Forward outer seal
    - CASE, HPT
    - HPT rotor disk
    - Rotating seal
    - BLISKs
    - SPOOLS
    - Impeller tube support
    - Combustor case
    - LPT shaft
    - LPT disk
    - Support, tube impeller
    - Seal, MID HPT rotor

To run a jet engine (or rocket engine) efficiently, airlines take all necessary steps to prevent EGT over-limit events. Every engine has an EGT sensor that continuously monitors the margin. It is imperative to know how we are tracking the EGT margin, as the stand-alone engine EGT margin may not be the same as the EGT margin of the engine in the aircraft. Hence, the following factors should be considered:

- *EGT (or T4) reading:* The raw temperature at the turbine exit. It is compared to the engine's reference limit to obtain the margin.
- *T2/T1 (compressor inlet temperature):* Environmental temperature (or the temperature after the inlet); that is, hot day conditions shrink the margin; therefore, we need the actual T2 to normalize the EGT.
- *N1/N2 speeds:* This relates to the speed of the fan (N1) and core (N2). Higher speeds usually increase the EGT, so you track them alongside the temperature.
- *Fuel flow:* More fuel results in a higher EGT. Monitoring the fuel flow helps determine whether the temperature increase is fuel-related or a hardware issue.
- *Air-flow parameters:* The compressor pressure ratio (CPR) and mass flow estimates indicate the amount of compressed air. Less air means a higher EGT for the same fuel burn.
- *Environmental pressure and altitude:* Lower pressure (high altitude) reduces air density, which can increase the EGT. Airlines should use these to correct the margins for sea-level conditions.
- *Bleed-air extraction:* Any customer bleed, or anti-ice bleed, reduces the core airflow, and nudging increases the EGT. Airlines should monitor the bleed valve positions.
- *Engine health parameters:* Turbine inlet temperature (TIT), compressor efficiency, and turbine health indices. Degraded components appear as a widening gap between the expected and actual EGT.

Hence, to summarize, the factors below impact the margin:

- *Outside air temperature (OAT):* Higher OAT increases EGT, reducing margin.
- *Altitude:* Higher altitudes can affect EGT.
- *Thrust demand:* Higher thrust settings or increased bleed air (for systems such as anti-ice) increase the EGT.
- *Flight cycles:* More cycles mean more wear and reduced margin.
- *Engine contamination:* Dust/pollution (fouling) restricts airflow, increasing EGT.
- *Takeoff D-rate:* When the engine starts and accelerates gradually, this helps the EGT margin. Therefore, a high-speed takeoff is not recommended.

Maintenance Procedures to be Followed to Control EGT Margin

Airlines know that the EGT margin is a critical requirement for smooth operations from an operational perspective as well as from a compliance perspective. Therefore, utmost care is taken to control the EGT margin and take action before it goes below the minimum limits to avoid any potential damage to the LLP parts or other major engine components.

- Replace worn hot-section parts such as HPT blades/seals,
- Compressor blades/stators,
- Seals, or perform advanced repairs/upgrades on these components,
- Shop visit with work scope of PRSV,
- *Fuel-air mix:* Keep the mixture as lean as possible without hitting the lean-blow-out limit. Better atomization and proper fuel scheduling are also helpful,
- *Combustion tuning:* Adjust the pilot/main split, timing, and swirl to ensure a more even burning. A tighter flame front lowered the peak temperature,
- *Hardware health:* Clean compressor blades, check for hot-section deposits, and ensure that the turbine inlet guide vanes are moving freely. Any blockage raises the EGT,
- *Environmental conditions:* If possible, run at cooler inlet temperatures (e.g., water injection or inlet cooling). Colder air densifies the charge and decreases the EGT,
- *Control logic:* Update the engine control maps to target a slightly lower EGT set point but ensure that you stay within the surge and stall margins.

Airlines operate with a significant initial EGT margin, often 30°C to over 80°C, which decreases over time as engines age, with typical drops of 7–15°C per 1,000 EFC (engine flight cycles) for engines such as the CFM56, until performance loss or part life (LLP) triggers maintenance, with operators often using engine washes and upgrades to recover some margin and extend time on-wing. New engines generally operate at a margin of 100–130° Celsius.

Potential Effects of EGT Margin Degradation

- *Engine deterioration:* As engines age, components wear (compressor/turbine blades), corrode, or erode, reducing efficiency, which forces the engine to run hotter to produce the same thrust, thus reducing the EGT margin.
- *Increased workload:* A shrinking margin means less room for errors. On takeoff, hotter ambient temperatures (high OAT) reduce the margin further, potentially causing EGTs to exceed limits, forcing a rejected takeoff, or causing significant crew stress.
- *Performance loss:* Eventually, the engine cannot produce the required thrust without exceeding the limit, leading to removal for overhaul, or it might fail to generate rated thrust at all, especially in hot environments.
- *Fuel system/combustion issues:* Problems such as fuel flow reduction or air intake blockage can also cause low EGTs (indicating poor combustion); however, conversely, issues such as combustor distress increase EGT, consume the margin, and raise the risk of over-limit events.
- *Rich fuel mixture:* A very rich mixture (excess fuel for the air) results in cooler combustion, as indicated by low EGTs.

- *Clogged air filter/intake:* Restricted airflow reduces combustion efficiency, lowering temperatures.
- *Faulty EGT sensor:* An inaccurate sensor reading can falsely indicate a low EGT, thereby affecting engine management.
- *Diesel particulate filters (DPF) regeneration (diesels):* In diesel engines, low EGTs can indicate failed or slow DPF regeneration, leading to fuel economy issues.
- *Safe operating limit (Redline):* The critical factor is the maximum sustained EGT, which is typically around 100°C to keep the engine running. Any margin less than this is considered to be unsafe.

It is crucial to refer to the comments from several industry experts below:

- *Dag Johnsen, COO, Aero Norway:* States that EGT margin recovery is vital for estimating an engine's potential performance life in service. He noted that an efficient engine (with a good EGT margin) is more economical to operate owing to reduced fuel consumption and emissions.
- *Hinnerk Behn, Head of Propulsion System Engineering Services, Lufthansa:* highlighted that the goal of PRSV is to restore the EGT to a level that demonstrates sufficient margin, matching the engine's expected lifespan. This underscores the importance of maintaining performance during store visits.
- *Florian Weinz, Senior Engineer, CFM engines at Lufthansa:* mentioned that while newer, more sensitive 3D aero blades may have slightly higher deterioration rates, they result in higher EGT margins for both new and post-shop-visit engines compared to the original designs.
- *CFM International Representatives:* Acknowledged that a loss of EGT margin (e.g., due to environmental barrier coating loss on leading edge aviation propulsion (LEAP) engines) has no immediate impact on flight operations. However, as the margin is "consumed," the engine must be removed for its restoration. They introduced software upgrades and improved hardware to provide an additional EGT margin and manage this deterioration.
- *Shahram Naimi Mohasesi:* Has experienced that core washing an engine can improve EGT margin significantly (4–5°C for small engines, up to 15°C for larger ones), recommending airlines follow manufacturer guidance on regular core washes to prevent performance loss.

Probability and Simulation

Simulation refers to a situation where an actual and permanent solution is not applied; rather, most of the possibilities are applied, and the results are inspected to reach a conclusion that would lead to an exact course of action in the future for a predefined issue. It is one of the biggest problems with airlines globally today that they cannot ask the OEM or the overhaul shop to perform a hit-and-try approach by replacing various engine components and inspecting the EGT margin at each action. OEM or overhaul shops cannot do this for the following reasons:

- Installing a new part on an engine, even for just one test run, will make it USM, and the price of USM is much cheaper than the price of a brand new component. Hence, the OEM or the overhaul shop does not want to risk the inventory value depletion for such parts that are brand new, but due to this one test run, will now be tagged as USM.
- Some regulations state that if an engine component is installed on an engine, it has to be documented, and when this installed part is further removed and installed on any other engine, it has to go through the compliance procedure of installing a used component, which requires much more documentation than a brand new part.
- The risk of the new component being fully scrapped at the shop's cost is very high. Generally, airlines use the contracting concept of RPFH. Therefore, if a component is installed only for testing and somehow that component just fails, it will be at the shop's cost. Therefore, the shop would not like to risk such a high cost.
- OEM or overhaul shops do not encourage this simulation as it would be a very long testing schedule for them, delaying the induction and testing of other engines in line. Installing one component, testing it, removing it, and installing another component could be extremely time-consuming. The operator does not pay for it, and hence, the shop does not encourage it.

- Contractual requirements force the operator not to ask the shop for this type of simulation. Contractual requirements state that before every engine overhaul, there is a work scope agreed upon between the operator and the shop. Therefore, if the replacement of such parts is not in the work scope, replacement of such parts for simulation is a violation of the contract terms. A contract cannot have simulation criteria. With some research, we found an instance where an operator wanted to improve the EGT margin and was not aware of the damaged parts that were causing the margins to become low. Therefore, the operator asked the MRO shop to check the possibility of replacing the combustion chamber and its impact on the EGT margin. The MRO shop denied the proposal, but they did agree to work with the product support engineer to determine the probable impact of replacing the combustion chamber. The product support engineer took 45 days to complete the case and prepare a response. The response was not very specific in terms of measures that could lead to the EGT margin. They only provided the response that the replacement would have a very low impact on the overall EGT margin, but they could not clearly mention the impact.
- Every overhaul shop operates at an overhaul cycle time of a defined number of days. Generally, even engines have longer cycle times than non-event engine overhauls. If a simulation is adopted, the overhaul cycle time would be very long, which no overhaul shop would encourage.
- The cost of an overhaul becomes very expensive for the operator if the overhaul shops perform some part replacement as part of the simulation. The operator wants to keep their operational cost at the most affordable level, and simulation leads to a higher cost. Therefore, it is not an option they would like to choose.
- The simulation implementation on an active overhaul engine leads to many complications in the inspection of various engine components. There are three levels of inspections of engine components: Level A, Level B, and Level C. Level A is a general visual inspection (GVI), Level B is an inspection at the ESM level for the whole module, and Level C is the most detailed and requires inspection of each component at the piece part level as per ESM. The replacement of an LLP leads to several engine components being inspected at Level C, which could actually be only Level A as per the work scope. This complicates the implementation of simulations.

To solve this issue, we adopted a very thorough and detailed process of gathering actual overhaul data from various shops across the globe and formulating it into a simulation Table 1.

We conducted detailed market research and identified multiple aircraft engine overhaul shops. We also identified the point of contact and procedure for legally reaching out to these shops. There are a limited number of shops worldwide. Some shops are independent overhaul (MRO) shops that overhaul engines for all operators, and there are other shops that do overhaul work only for a specific airline. These shops, which only cater to the overhaul of specific operators, are very confined in terms of sharing data outside the organization, but they still need to adhere to all aviation regulations. The following independent MRO shops are the only limited number of independent shops:

- GE Aviation
- Pratt & Whitney
- Rolls Royce
- Standard Aero
- AAR Corporation
- After conducting market research and communicating with the shops for more than a month, we identified the shops that could help us in our simulation.
- A few of the above mentioned independent shops helped us with our research. We intended to obtain only Test Data from these shops with respect to engines getting to the MRO shop for EGT margin correction in the work scope.
- The shops also mentioned that the data would not include the name and engine serial number of the operators. All data was shared with us using Operator 1 and Operator 2 engines. For our research, we only needed the data, not the operator's name or serial number. Therefore, we did not encounter any bottlenecks in continuing our research.

- This was a time-consuming approach because engines coming to overhaul shops are not common to have a work scope of EGT margin.
- As a researcher, I have virtually participated in testing such cases.
- Operator1 engine had a work scope of EGT margin with replacement of compressor discharge pressure (CDP) Seals/Rotating Seals. We noted the results, and the impact of the EGT margin was noted in our simulation tracker and simulation database.
- The Operator 2 engine had a work scope of EGT along with the replacement of the HPT STG1 Blade. We followed the same process and noted the results.
- Operator 3 engine also had a work scope of EGT margin, etc. We noted all scenarios and their results. We had a total of 40+ such cases across 2.5 years of thorough test results scrubbing for the EGT margin-related work scope.

Based on probability theory and simulation, Table 2 provides the most accurate prediction of how the EGT margin will improve if various components of the engine are replaced with brand new components:

Parts Replaced for High-Thrust Engines

We started the simulation with high-thrust engines, and the results are shown in Tables 1 and 2, accumulated across a large dataset over a span of 2.5 years.

Parts Replaced for Low-Thrust Engines

We also performed the same test simulation for low-thrust engines, as shown in Tables 3 and 4.

How to Use the Simulation Tables

The Table 1 is simple to use. If an operator has a low EGT margin issue and replaces the compressor rotor STG2 seals, they will improve the EGT margin depending on the time since new (TSN) and thrust rating of the engine. If the engine is a high-thrust engine and the cycle time is up to 5000, the replacement of the STG2 seal would improve the EGT margin by 1°C. For a 10000-cycle time engine, it would be 0.56°C and so on. The same numbers for a low-thrust engine would be 1.5°C and 0.84°C. While reviewing the Table 2, it is also very important to understand that the Table 3 has been simulated based on the tests of the engine in the test cell. Test cells test at full thrust, but when an engine is installed on the aircraft, it does not run at full thrust, as there is a concept of de-rating to maintain the engine health, and with that, we have observed an additional increase in EGT margin by 8–10°C. Therefore, while reading the Table 4, it is imperative to note that the actual margin on the wing will be 8–10°C higher, which adds more room for the airlines to operate safely. The takeoff derate is a safety margin that airlines use in the engine power when an aircraft starts its roll. Instead of immediately pulling the maximum thrust, they "derate" it, which means running it at a lower, pre-approved thrust. The higher the thrust for takeoff, the higher the stress on the engine, leading to a lower EGT margin. Thrust cannot be minimal, as it requires a minimum level of thrust to takeoff.

Therefore, a fine balance is required to derive and still maintain a smooth takeoff. A rule of thumb is that the lower the thrust, the lower the wear on the engine, the longer the engine life and the life of various attached components, and the lower the maintenance cost. The EGT margin is the most impacted driver at the time of takeoff or landing. Therefore, de-rating plays a significant role in maintaining the EGT margin. The de-rate is also considered a safety measure because it provides pilots with an extra thrust reserve in the event of an unexpected occurrence. A few instances of unexpected happenings could be a slippery runway or a sudden gust, avoiding any incidents, etc.

As we have identified de-rating as an item of significance for a better EGT margin, it is also important to note that there is a concept of Icing in an Aircraft that could lead to incorrect EGT margin and mostly to showing a lower EGT margin than it should actually be.

Table 1. Temperature variation of engine components at different TSN.

Engine operation	5000TSN	7500TSN	10000TSN	12500TSN	15000TSN
CDP Rotating Seal	5.00°C	3.75°C	2.81°C	2.11°C	1.58°C
CDP Stationary Seal 1.00°C	0.75°C	0.56°C	0.42°C	0.32°C	
HPT STG1 Blade	3.00°C	2.25°C	1.69°C	1.27°C	0.95°C
HPT STG2 Blade	4.00°C	3.00°C	2.25°C	1.69°C	1.27°C
STG1 Shroud	7.00°C	5.25°C	3.94°C	2.95°C	2.21°C
STG2 Shroud	5.00°C	3.75°C	2.81°C	2.11°C	1.58°C
HPT S1 Nozzles	8.00°C	6.00°C	4.50°C	3.38°C	2.53°C
HPT S2 Nozzles	3.00°C	2.25°C	1.69°C	1.27°C	0.95°C

Table 2. Temperature variation of compressor rotor honeycomb seals across stages at different TSN.

Compressor rotor honeycomb seals					
S1	1.00°C	0.75°C	0.56°C	0.42°C	0.32°C
S2	1.00°C	0.75°C	0.56°C	0.42°C	0.32°C
S3	1.00°C	0.75°C	0.56°C	0.42°C	0.32°C
S4	1.00°C	0.75°C	0.56°C	0.42°C	0.32°C
S5	1.00°C	0.75°C	0.56°C	0.42°C	0.32°C
S6-10	10.00°C	7.50°C	5.63°C	4.22°C	3.16°C

Table 3. Temperature variation of turbine components at different TSN.

Engine operation	5000TSN	7500TSN	10000TSN	12500TSN	15000TSN
CDP Rotating Seal	6.00°C	4.50°C	3.38°C	2.53°C	1.90°C
CDP Stationary Seal 1.00°C	0.75°C	0.56°C	0.42°C	0.32°C	
HPT STG1 Blade	4.00°C	3.00°C	2.25°C	1.69°C	1.27°C
HPT STG2 Blade	5.00°C	3.75°C	2.81°C	2.11°C	1.58°C
STG1 Shroud	7.00°C	5.25°C	3.94°C	2.95°C	2.21°C
STG2 Shroud	6.00°C	4.50°C	3.38°C	2.53°C	1.90°C
HPT S1 Nozzles	9.00°C	6.75°C	5.06°C	3.80°C	2.85°C
HPT S2 Nozzles	3.00°C	2.25°C	1.69°C	1.27°C	0.95°C

Table 4. Temperature variation of compressor rotor honeycomb seals at different TSN.

Compressor rotor honeycomb seals					
S1	1.50°C	1.13°C	0.84°C	0.63°C	0.47°C
S2	1.50°C	1.13°C	0.84°C	0.63°C	0.47°C
S3	1.50°C	1.13°C	0.84°C	0.63°C	0.47°C
S4	1.50°C	1.13°C	0.84°C	0.63°C	0.47°C
S5	1.50°C	1.13°C	0.84°C	0.63°C	0.47°C
S6-10	11.00°C	8.25°C	6.19°C	4.64°C	3.48°C

Icing is a flying condition in which supercooled water droplets hit the cold surfaces of an airplane, freeze, and turn into ice. This can occur on wings, tail, engine inlets, and propellers, that is, anywhere the airflow is exposed.

This can lead to:

- *Lift loss:* Ice messes up the smooth airflow, so the wing generates less lift.
- *Drag increase:* The rough ice shape adds drag, burning more fuel.
- *Engine trouble:* Ice in the inlet blocks airflow, can cause stall or surge, and usually drives the temperature of the engine higher.
- *Control issues:* The extra weight and altered aerodynamics can make the plane harder to manage.

Pilots avoid it by flying around known icing zones, using anti-ice (heaters, de-icing boots), or climbing to warmer temperatures where the moisture turns to rain instead of ice.

When ice builds up on the inlet or fan blades, the airflow into the core is distorted, and the mass flow decreases. The engine must work harder to maintain the same thrust; therefore, it burns more fuel, and the turbine temperature increases. This shrinks the gap between the measured EGT and the red-line limit; in other words, the EGT margin narrows.

If the ice is severe enough to trigger an engine anti-ice bleed, the bleed air extraction reduces the core airflow even further, pushing the temperature up another notch. However, once the ice is cleared (either by the anti-ice system or by climbing to warmer air), the airflow recovers, the fuel flow drops back toward normal, and the margin returns to its baseline.

To conclude about icing, less air, a higher fuel-to-air ratio, higher EGT, and a smaller margin were observed. We monitor the EGT trend during an icing encounter; a sudden upward shift is a clear and early warning that the margin is eroding.

CONCLUSION

The EGT is not the sole engine health indicator, but it is one of the most important checkpoints for jet engine and aircraft safety, and all possible measures should be taken to ensure the safest possible EGT margin. The simulation data can serve as a ready handbook for the operators to decide whether they should replace a particular engine component. After we prepared our simulation table, we shared the results with all the shops that participated in the research, and for the next 6 months, all EGT margin work scope overhaul engines were tested using the replacement simulation. We found that our simulation table was working with an accuracy of more than 98.45%. Therefore, we have strong reasons and results to believe that all airlines should start using this simulation table and operate the aircraft with more safety for the travelers and with a very efficient cost of operation.

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