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Quantifying the Economic Benefits of Using Erosion Protective Coatings in a Low-Pressure Compressor (Aero-Engine): A Case Study Evaluation

Jasem Alqallaf [1,2,*] and Joao A. Teixeira [1]

[1] School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield, Bedford MK43 0AL, UK; j.a.amaral.teixeira@cranfield.ac.uk
[2] Kuwait Army, Kuwait Ministry of Defense, Safat 13128, Kuwait
* Correspondence: j.alqallaf@cranfield.ac.uk

Abstract: Gas turbine engines (GTEs) frequently operate in desert environments where the main components are exposed to erosive media such as sand and dust. In these circumstances, a crucial problem, particularly with compressor blades, is solid particle erosion (SPE). Positioned in the front of the GTE, the compressors suffer most from SPE in terms of inflicting damage on compressor hardware such as blades, decreasing the GTE's working life and increasing fuel consumption, energy losses, and efficiency losses. Results obtained from Turbomatch, an in-house performance tool, showed that degraded compressors can experience increased turbine entry temperature (TET) and specific fuel consumption (SFC), which leads to a significant increase in the operating, maintenance and component replacement costs, in addition to fuel costs. Fitting erosion protective coatings (EPCs) is a conventional approach to reduce SPE of the compressor blades of aeroengines. Titanium nitride (TiN), applied via physical vapour deposition (PVD) techniques, is often used to extend the life of compressor blades in erosive conditions. This paper reports the outcomes of a cost benefit analysis (CBA) of whether applying an EPC to the booster blades of an aeroengine is economically beneficial. The case study takes into account the available coatings potential of the market, in addition to all of the available technical data in the public domain regarding the compressor of the research engine. To identify the economic consequences of employing an EPC over the blades of a compressor, a CBA study was carried out by investigating consequent benefits and costs. The results indicate that under certain conditions the application of an EPC can be profitable.

Keywords: compressor; coatings; cost benefits analysis; solid particle erosion; surface roughness

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1. Introduction

1.1. Background

In order to reduce the life cycle costs of gas turbine engines (GTEs), significant research is taking place into the trade-offs between measures seeking to enhance performance and strategies leading to a reduction in maintenance costs. An important cause of reduced GTE performance is compressor losses linked to the operation degradation phenomenon. The blades in modern GTE compressors operate in severe environments, characterised by factors including solid particle impacts, resonant vibrations, and high temperatures. [1]. In particular, solid particle erosion (SPE) entails the removal of surface material due to the different sizes of solid particles entrained into the GTE that impact on and damage, for example, the compressor blades. This is a characteristic and common problem since GTEs operate across the globe in sandy environments, with an inevitable interaction between sand particles and compressor blades [2]. The sand particles usually hit the blades at high velocity and, in sufficient quantities, even relatively minute particles can induce considerable SPE damage, reducing the fatigue resistance of the blade by generating a concentration of stress at the impact site [3,4]. SPE affects the first component of the

GTE, the low-pressure compressor (LPC), most severely. SPE-generated weakening of the blade surfaces reduces blade strength, which can adversely affect the structural integrity of the compressors. In addition, SPE has an impact on important variables of the cycle such as pressure ratio (PR), specific fuel consumption (SFC), non-dimensional mass flow (NDMF), turbine entry temperature (TET) and efficiency [5,6]. GTE performance is heavily dependent on LPC efficiency; thus, it is important to maintain the compressor at its best condition [5]. Consequently, much work has been undertaken to better understand the mechanisms by which SPE induces material loss [7–10], and to improve protective methods to enhance the lifetimes of components [11–14]. One effective technique to protect the components of the LPC from erosion is to use erosion protective coatings (EPCs) [15–17]. Tough surface coatings with high strength can significantly reduce the adverse effects of the solid particles ingested by the GTE and greatly enhance the service performance of the compressor [18].

1.2. Benefits of Utilising EPC Techniques

Alqallaf et al. [19] provided a wide-ranging review of research into the SPE phenomenon and available techniques for applying EPCs to compressor blades. A detailed explanation was provided of how SPE causes surface degradation and reduces overall GTE cycle efficiency. The authors concluded that EPCs can be very cost-effective to help increase GTE availability, performance and reliability. Appropriate coatings, suitably applied, will extend the active life of the material being protected and simultaneously reduce cost of maintenance. According to the authors, physical vapour deposition (PVD) methods can be applied to a wide range of material surfaces, to produce a smooth surface finish corresponding to roughness values (Ra) of the order of 0.19 μm [20]. Sputtering deposition, considered a state-of-the-art technique for PVD coating methods [19,21], has been shown to give excellent resistance to erosion when applied to the blades of compressors.

Bousser at al. [15] carried out an experimental study to examine the mechanisms by which material was lost from hard coatings subject to low velocity impacts (60 m/s) of angular alumina particles of 70 μm size. All coatings were deposited using the sputtering deposition technique with three substrates: single crystal silicon, a titanium alloy (Ti6Al4V) and a stainless-steel alloy (AISI 410). An in-house sand-blast tester was used for the SPE tests. Experimental results showed that Titanium nitride (TiN), when used as a coating material, with 10 μm thickness offers good protection against SPE.

Khoddami et al. [22], experimentally and numerically, attempted to optimise EPC when employing the sputtering deposition technique to deposit a single coating layer of TiN on the surface to be protected. Once again, for the SPE tests an in-house sand-blast tester was used. Silica sand was used as the eroding material, with 100 μm diameter particles, impacting at a 30° angle and a speed of 15 m/s. The authors concluded that thicker layers TiN gave better protection against erosion than thin layers but noted that, for values of the thickness >8 μm, there was little or no further increase in the normalised Maximum Tensile Stress (MTS) on the surface. Thus, a coating thickness of 10 μm of TiN was chosen as reasonable to be sputtered onto the target material.

Bonu et al. [11] studied the resistance to erosion of multi-layered coatings of 9 μm thickness on substrates of titanium alloy and silicon subjected to the impacts of silica and alumina particles with average diameters of 50 μm with sharp edges, at speeds of between 30 and 90 m/s. The impact angles for the erosion tests were between 30° and 90°. The magnetron sputtering deposition deposited multiple ultra-thin coating layers of Ti/TiN and TiAl/TiAlN. SPE testing of coatings/substrates was conducted using a gas jet erosion tester. The average relative values of erosion rates for uncoated to Ti/TiN-coated substrates were in the material ratio of 74 for a particle speed of 30 m/s, and 13 for a particle speed of 60 m/s. When the coatings were TiAl/TiAlN, the respective ratios were 100 and 10.

Obviously, there are benefits to be gained from using erosion protective coatings on GTE compressors. EPC can be very cost-effective and can help improve GTE availability, performance and reliability. Other EPC benefits include (1) minimising erosion and wear,

(2) reducing blade surface roughness, (3) increasing GTE power output recovery (up to 1%) and (4) GTE efficiency ageing recovery (≈0.3%) [19].

To date, TiN erosion-resistant coating material is widely accepted as a means of reducing erosion of materials and is widely used as an EPC for compressor blades [23]. Now, the use of plain TiN as a blade coating material has largely been superseded by multi-layered Ti/TiN and TiAlN coatings due to their superior erosion protection. However, for the purposes of this case study we make use of TiN as the coating material given the availability of economic information applicable to this material. It has been shown that the sputtering deposition technique will give a hard, dense and defect-/void-free coating because of the high plasma density and ionisation rate used [24,25]. The selection of sputtering as the deposition technique considered for this study follows a similar argument, related to the access to costing information. However, for the sake of clarity, it will be stated that alternative deposition techniques are commercially available, including cathodic arc evaporation, which is known to offer better coating adhesion whilst requiring shorter deposition times.

1.3. Aim of the Study

This paper reports the results from a cost benefit analysis (CBA) carried out to investigate whether the application of EPCs to the blades of the LPC (booster) of a GTE (aeroengine) is economically beneficial. Three accepted indicators were used: (1) Net Present Value (NPV), (2) Benefits-Cost Ratio (BCR) and (3) Internal Rate of Return (IRR), to evaluate the economic sustainability of utilising EPC on LPC blades. The CBA study presented includes the initial calculations of the costs of the proposed project in terms of (1) EPC deposition and (2) maintenance costs. Then, the study continues by investigating the potential GTE life variations that can be associated with the EPC upgrades. The economic benefits related to the EPC installation can be listed as follows: (1) LPC longevity, (2) fuel consumption saving, (3) high-pressure turbine (HPT) life considerations and (4) GTE disposal savings.

CBA is an accepted means of mapping the dispersal of short- and longer-term costs and benefits of applying EPC to LPC blades. A CBA implies identifying and valuing every cost and benefit relevant to the given intervention in monetary terms, which enables the production of ranked comparisons. A CBA requires a detailed evaluation of the overall benefits (positive) and costs (negative), and reports these as a net cost or a net benefit [26]. The latter will lend support to implementing the use of EPCs. The EPC process is costly, so the ultimate decision of whether or not to coat will generally be determined by this consideration.

The research engine employed in this case study is an in-house model of an LPC compressor based on NASA's E3 engine [27–29]. The case study considers the available technical and performance data available for the LPC, and the data available concerning EPC deposition techniques, including relevant coating materials. Turbomatch, in-house performance software, was employed to evaluate the response of the research engine in terms of the changes in TET and fuel flow, to illustrate how the EPC affected recovery of GTE performance and cycle behaviour.

Previous studies in this area are not sufficiently comprehensive nor directly applicable in the application of EPCs to the compressor of a GTE [30]. Thus, we present a comprehensive economic evaluation of the use of EPC on the LPC of a GTE.

The application of EPC carries financial risks so it is valuable to have a projection of the likely economic consequences of that application as early as possible. Most published surveys of EPC technology have been concerned purely with the technical and scientific performance of the materials [31–33]. However, commercial decisions are invariably based on economic considerations, with differences in operating costs a major factor in deciding whether to adopt a new technology. Historically, rising fuel costs—which typically are 40% of the operating costs of an aircraft—have pushed operators to press for improved energy efficiency from older, less efficient aircraft [34]. Of course, it is to be hoped that the advancement in green technology will assist in reducing costs. Fuel is not the only

operational cost for GTEs, so it is essential to determine the likely total economic and commercial benefits and viability of applying EPCs. Establishing the economic benefit and commercial viability of the application of EPCs is not often seen in studies.

2. Methodology

Input data to, and assumptions for, the CBA case study, including those made in the Turbomatch performance tool, were based on the data and assumptions presented and discussed in this section. This was undertaken in order to identify the most feasible options for the application of EPCs to a LPC based on the current market available options.

2.1. Cost Benefit Analysis (CBA)

To evaluate the economic sustainability of using EPC on the blades of the LPC used in the case study, a CBA was used. This included data from: GTE manufacturers and users, companies providing EPCs, including the initial costs for a LPC system, maintenance costs, costs of blade replacement and the economic consequences of increasing longevity as a result of employing EPC. Some assumptions were derived from published papers concerning EPC research and practice. Obviously, this work will be revised with greater experience and when more and better data are made available due to research and development of EPC technologies related to aerospace applications.

CBA is a widely used instrument for the relative evaluation and appraisal of alternative solutions to problems with a commercial dimension [35]. CBA is a popular forecast and evaluation method to assist decision making on, e.g., proposed projects. Its purpose is to give an overall view of the (estimated) benefits and costs of alternative proposals, and to present the conclusions in monetary terms for direct comparison. CBA values, in money terms, the financial impacts over the lifetimes of alternative projects, discounted to a specific year. This enables the ranking of possible alternatives using the same monetary measure, commonly NPV. The fundamental stages of a CBA are [36]:

- Defining project choices to be evaluated.
- Deciding which costs and benefits are to be counted.
- Selecting suitable measures and measuring of relevant benefits and costs.
- Estimating outcomes of benefits and costs during an appropriate period of time.
- Converting all benefits and costs into a common currency.
- Calculating the NPV for each project options.
- Carrying out sensitivity analyses.
- Providing recommendations based on the NPV and sensitivity analyses.

Consequently, all benefits and costs of the proposed project need to be evaluated and results presented in three traditional forms: NPV, BCR and IRR, as follows [37]:

$$\text{NPV} = \sum_{t=0}^{n} \frac{(B_t - C_t)}{((1+i)^t)} \tag{1}$$

$$\text{BCR} = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t} / \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{2}$$

$$\text{IRR}: \sum_{t=0}^{n} \frac{B_t}{(1+r)^t} = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{3}$$

where B_t is the benefit gained and C_t is the cost incurred, both in year (t), i is the discount rate, t is the year of incurrence, n is the number of iterations (usually years) and r is the IRR.

According to Tangvitoontham and Chaiwat [37], for the project to be economically viable, NPV > 0 and the project benefits must outweigh the costs. NPV is the discounted monetary value of the expected net benefit during the period of the analysis [38].

The BCR is intended to avoid the drawback of the NPV criterion and it evaluates a project in terms of benefit per unit monetary cost. A development is worthy of investment only when the BCR is greater than 1 [37].

The IRR is the discount rate at which the NPV is just equal to zero, it is the highest interest rate that a project owner can economically pay. For a project to be worth investing in, the IRR needs to be more than the discount rate [37].

2.2. Turbomatch Performance Tool

GTE simulations are valuable for engine development because they evaluate the likely behaviour of the engine under varying operating requirements whilst still at the design stage, thus decreasing design and development costs. Here, the calculations representing the thermodynamic cycle were performed on Turbomatch, a 0-D software package designed and built at Cranfield University to provide for analyses of GTE behaviour using scaled maps of turbines, combustion chambers and compressors. Turbomatch depends on a number of subroutines, each of which simulates an aspect of the performance of the components of the GTE. The user assembles relevant modules, also known as "bricks", to create an engine model with the desired specification. Such a process permits a substantial level of flexibility when investigating alternative operational arrangements for GTEs. A comprehensive explanation of the Turbomatch tool is presented in [5]. A schematic representation of the complete research engine model is shown in Figure 1. Here, a Turbomatch model was built corresponding to accessible technical information on the E3 engine [27–29]. The effects of applying EPCs to the case study compressor were ascertained through the evaluation of the performance of the GTE in terms of TET and the fuel flow changes in the cycle for a nearly constant thrust.

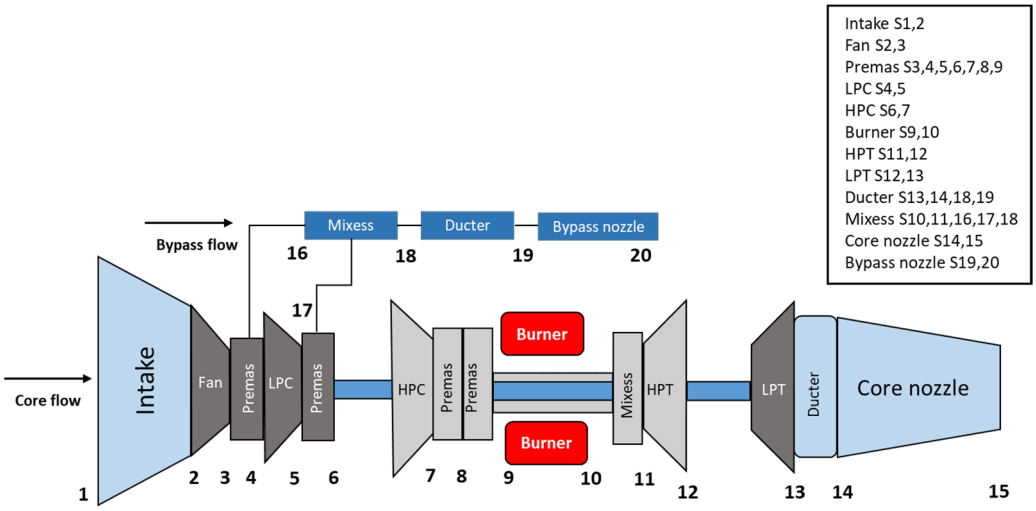


Figure 1. Research engine Turbomatch thermodynamic model showing numbered stations and component modules.

2.3. Case Study Details

As previously mentioned, the case study selected for this research is based on the first two stages of the LPC based on NASA's E3 engine [27–29]. The LPC comprises inlet guide vanes (IGV), second rotor (R2), second stator (S2), third rotor (R3) and third stator (S3), comprising a total of 458 blades. Comprehensive technical details of the research engine can be found in [5]. For the geometric details of the research engine showing the locations of the IGV and first two stages of the LPC, see Figure 2.

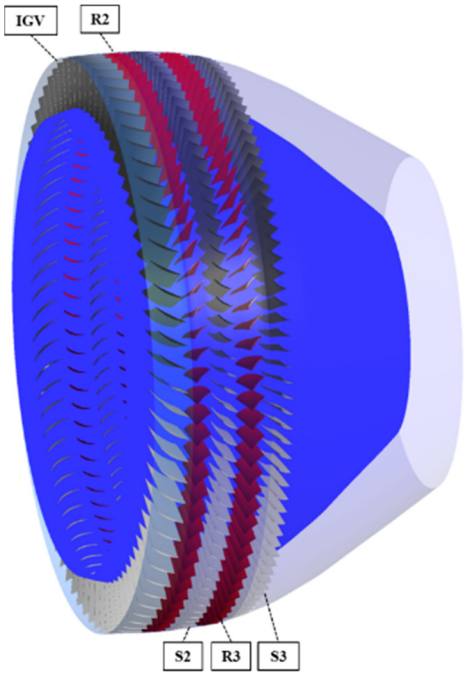


Figure 2. LPC geometry showing inlet guide vanes (IGV) and first two stages of the LPC.

Three scenarios regarding LPC degradation over the operational life of the research engine are investigated: uncoated LPC blades with the efficiency decrease of the compressor reaching 3% in the latter life of the engine; coated compressor blades presenting a reduction in the degradation of 25 and 50% by reference to the uncoated variant. These two scenarios are known as Case 1 and Case 2, respectively. The LPC performance deterioration with service hours is applied as an efficiency decrease whose asymptotic evolution follows the degradation observed in industrial GTEs [39], Figure 3. For the majority of civilian aircraft, compressor erosion does not represent a significant issue over extended periods of operation. However, where it does, service lives will be severely reduced, such as in the case of extensive exposure to airborne sand particles. The scenario we investigate is intermediate between these two situations in that the erosive degradation takes place over an extended period.

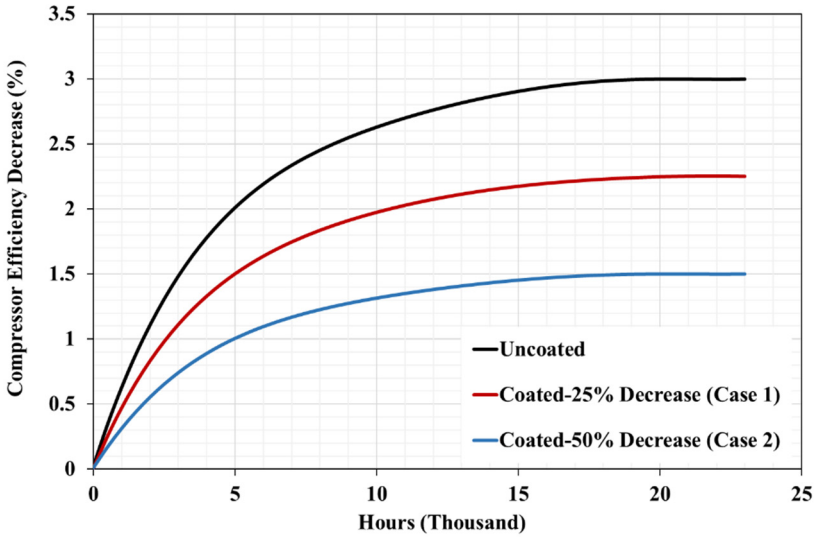


Figure 3. Performance deterioration with service hours.

2.4. Assumptions

The CBA was developed to evaluate the relevant life cycles of GTE without and with EPCs. Some of the assumptions made, and used to determine whether the EPC improved GTE performance, were based on data published in the literature referring to similar applications and tests. This means that this work will be revised as additional research and development data on the use of EPC within axial compressors becomes available. The acquisition cost of the GTE was assumed to be GBP 9,460,000 and the life expectancy for the engine was assumed to be 15 years [30]. The operational hours of the research engine were assumed to be 2000 h per annum. The CBA was based on the discounting method of benefits and costs, enabling alternatives to be assessed on an equivalent basis. The discount rate applied was 7% per annum [40]. The details of the case study compressor in terms of the technical data, including the economic parameters, are tabulated in Table 1.

Table 1. Low-pressure compressor (LPC) and the related economic parameters. Reprinted with permission from Refs. [27–30]. Copyright 2013 NASA Technical Report Server (NTRS).

Items	Unit	Value
Technical data		
No. IGV blades	-	76
No. second rotor blades (R2)	-	82
No. stator blades (S2)	-	102
No. third rotor blades (R3)	-	88
No. third stator blades (S3)	-	110
Mass flow rate (LPC) (100% speed-line)	kg/s	83.05
Pressure ratio (LPC) (for the first two stages)	-	1.33
Rotational speed for 100% speed-line	rpm	4215
Fuel flow (Maximum cruise)	kg/s	1.6
Engine operation hours	h per annum	2000
Economic life of engine Operation	years	15
Other data		
Discounting rate	%	7
Discounting period	years	15

3. Data Collection and Calculations

The beneficial economic effects of EPC systems are related mainly to GTE durability and maintaining the optimum conditions of operation. The benefits and costs relating to coating deposition, maintenance, fuel flow and TET were quantified as described below.

3.1. Calculated Costs

3.1.1. EPC Deposition Cost

In this study, the estimated costs of the EPC installation were determined according to the following specifications, with costs and relevant information obtained from commercial suppliers: (1) sputtering deposition, (2) coating thickness of 10 μm and (3) utilising TiN as the coating material for all 458 blades of the LPC. There were significant price differences between the EPC systems quoted. The optimum estimated cost was quoted by Plasma Quest Ltd. (PQL) (Hook, Hampshire, UK), which offered High Target Utilisation Sputtering (HiTUS), a proprietary technique with significant benefits when compared to conventional sputtering, providing thin film coating of excellent quality with good adhesion and high deposition rates [41]. The cost estimation provided by PQL is included in the NPV figure used and covers EPC and transportation costs.

3.1.2. Maintenance Cost

One major advantage of EPC is the extension to the working life of the LPC blades it provides. The maintenance requirements and associated costs of EPC will depend on

the GTE's operating environment, with longer engine removal times reducing the cost of maintenance. These savings are one of the benefits associated with investing in EPC.

The costs of GTE maintenance can be divided into two components, labour and materials. In 2017, the reported time spent on overhauling a GTE was between 3500 and 4000 h at GBP 60 to 75 per hour labour costs [42,43]. Baseline costs were GBP 60 per hour for an assumed 2000 h, with only engine maintenance costs included, since EPC only applies to the GTE and not the entire aircraft. However, EPC does require an annual maintenance check to confirm the coatings continue to meet design requirements during the operational lifetime of the GTE. The specific costs of this annual maintenance check were taken to be 10% per year of the total deposition cost.

3.1.3. Total Costs

The annual total cost, relative to the uncoated case, reflecting the items listed above, is GBP 123,966 for Case 1 and Case 2.

3.2. Measured Benefits

3.2.1. Low-Pressure Compressor (LPC) Longevity

The extended life of the LPC resulting from use of the EPCs promises attractive economic benefits from the cost savings obtained due to the increased LPC longevity. This results in a longer working life and fewer maintenance visits over the engine's life, which translates to a reduction in maintenance and component replacement costs. In this study, the saving due to the component replacement costs was GBP 41,000 per annum employing the methodology described in [42].

3.2.2. Fuel Consumption (FC) Saving

The savings in FC linked to the use of EPCs on the blades of the LPC are due to the reduction in losses occurring as a result of SPE. These economic benefits can be significant. Use of EPC can produce a 2.5% reduction in specific fuel consumption (SFC) for a GTE relative to the non-coated case [44]. The FC of the GTE was found using Turbomatch, which showed that EPCs can reduce the FC by as much as 0.19% for Case 1 and 0.33% for Case 2, relative to the non-coated case for the maximum LPC degradation investigated. The three degradation scenarios were investigated in terms of additional fuel costs incurred over the lifetime of the engine for the prescribed 2000 h yearly utilisation. The evolution of the annual penalty for each of the three cases is plotted in Figure 4, where both the yearly cost variation and its average for the life of the engine are included for the uncoated compressor and its two coated versions. The fuel cost penalties associated with degradation are sizable. For a fully degraded uncoated LPC, the additional yearly fuel cost is GBP 51.4 thousand at current JP8 fuel market costs. In this study, the additional yearly fuel consumption costs were estimated for the Case 1 and Case 2 coated scenarios to be GBP 38,000 and 28,200, respectively.

3.2.3. HPT Life Considerations

Variations in combustion patterns driven by the need to counteract the performance drop associated with LPC degradation, induced by SPE, through a rise in TET, change the distribution of radial temperature at the inlet to the turbine, with local elevated temperatures, greater leakages and clearances, decreases in flow-area, and increased distortions. All of these factors will decrease the remaining life of the turbine and reduce efficiency [45]. Especially worrying is the possibility that the turbines could be distorted due to prolonged functioning at too high temperatures and fluctuating high stresses. TET is linked to the working life of turbines [46].

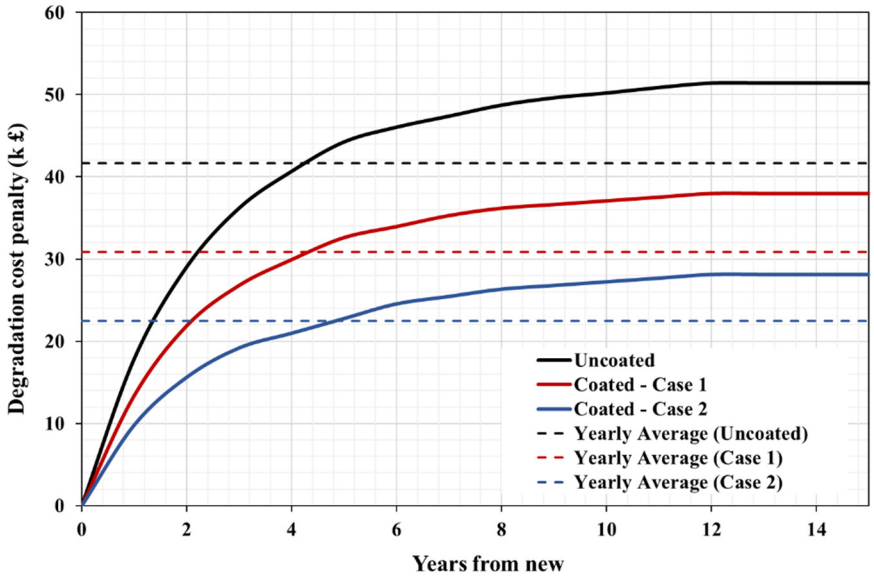


Figure 4. Fuel penalty degradation (yearly variation and average over the life of the engine).

The increase in TET with the degradation of the compressor was computed in Turbomatch for the uncoated scenario together with the two EPC cases that are being investigated. The results of the calculations portray an asymptotic increase, year on year, of TET by reference to the design value, for each of the three cases examined as is shown in Figure 5. As can be observed, the fitting of EPCs promotes the reduction in the yearly TET increases, thereby contributing directly to an extension of the useful life of the turbine, with direct implications on the economics of the GTE operation, as will be seen next.

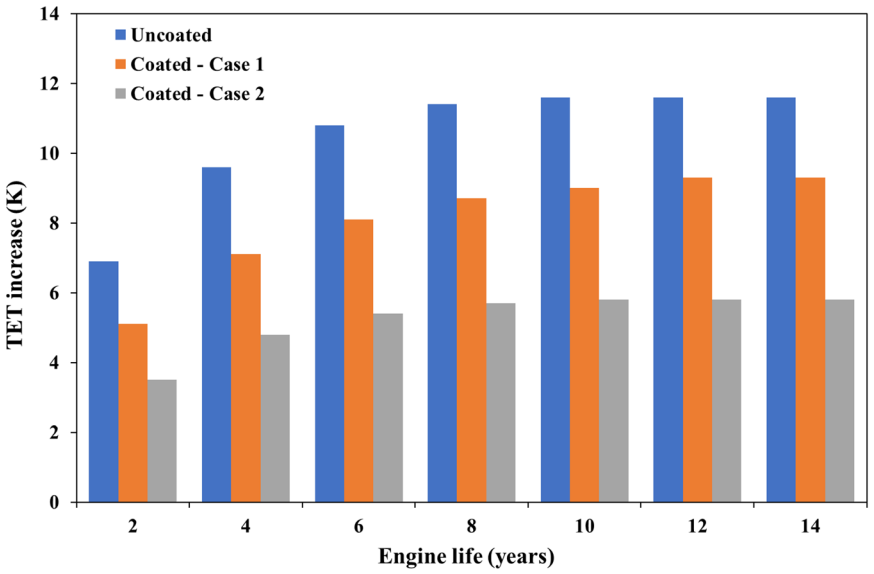


Figure 5. TET variation with time for uncoated and two LPC-coated scenarios.

Although the increases in TET are modest in absolute terms, they nevertheless have a major impact on the working life of a high-pressure turbine (HPT). For the purposes of this study, we adopt a simple turbine life model according to [47] whereby, for every 20 K rise in the operational TET, by reference to the design point (DP) value, the creep life of the HPT reduces by half. The economic implications of the cumulative impact of the reduction in the useful life of the HPT associated with the TET variation described in Figure 5 is examined next. The solid lines plotted in Figure 6 correspond to the operational cost of

the HPT based on the predicted turbine life as a function of the running temperatures and initial acquisition cost (GBP 672,750) [42].

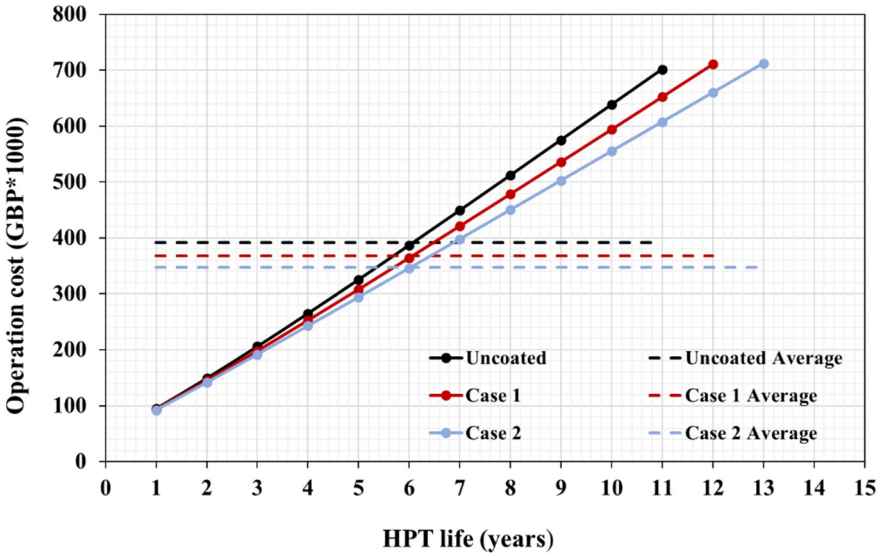


Figure 6. HPT operational cost, useful life and representative average.

The analysis of Figure 6 shows that the provision of EPCs is associated with an extension of the useful life from 11 years for the uncoated scenario to 12 or 13 years according to the particular level of erosion protection. For the purposes of this study, the yearly depreciation is represented by a single value, which, for the uncoated and coated Case 1 and Case 2, is GBP 391,281, 367,711 and 347,504, respectively. Therefore, the average saving by deploying EPCs is, over the life time of the HPT, GBP 23,570 and 43,776 for Case 1 and Case 2, respectively.

3.2.4. GTE Disposal Savings

Literature surveys show that the residual value of a GTE including the costs of disposal, comprising removal of associated structures, transport and recycling, is around 10% of the purchase price, although this may vary depending upon regional rates [48]. Based on the estimation of the GTE acquisition cost employed in this study, the estimated economic benefit associated with disposal of an engine is assumed to represent GBP 63,000 per annum.

3.2.5. Total Benefits

The total annual benefits due the operation of the GTE fitted with EPCs are, by reference to the uncoated case, GBP 135,900 for Case 1 and GBP 165,364 for Case 2.

4. Results and Discussion

An operator's decision to invest in EPCs would, typically, be based on a positive CBA that met economic expectations. Here we quantify and analyse the economic benefits of applying EPC to the LPC of the research engine. This included determining the associated cost penalties and saving advantages. The major costs and benefits of an EPC upgrade are given in Section 3. The impact of the EPC upgrade on the aeroengine with regard to TET and fuel costs are presented in this section.

4.1. CBA Evaluation

The CBA results show that EPC systems can be economically sustainable. Analysis of the indicators described below enables the assessment of the economic benefits. The project evaluation is presented in the form of (1) NPV; (2) BCR; and (3) IRR as follows, Table 2:

Table 2. CBA parameters.

	NPV (GBP)	BCR	IRR (%)
Case 1	107,225	1.09	3
Case 2	377,100	1.34	11

For Case 1, the criteria indicate that EPC is worth investing in since it meets the two criteria set: NPV > 0 and BCR > 1. However, the value of the IRR is 3%, which is lower than the prescribed discount rate (7%). As a result, the fitting of an EPC that yields minor improvements by reference to the uncoated LPC, such as presented in Case 1, is not profitable and should not be pursued further. Conversely for Case 2, which yields a more substantial performance improvement, the criteria indicate that the EPC is worth investing in as it meets the three conditions set: NPV > 0, the IRR is 11%, which is greater than the discount rate, and the BCR > 1. These parameters demonstrate that deploying EPC would be economically beneficial with the monetary gains exceeding the corresponding costs.

4.2. Engine Life

The extended engine life due to the use of EPCs can generate attractive economic benefits as it can provide significant savings for every aircraft flight that takes place in an erosive environment. The savings are due to the decrease in engine maintenance costs as an EPC upgrade increases GTE efficiency. Longer life means increased time between engine removals with a consequent reduction in engine maintenance cost and longer periods of operation.

A compressor whose performance has been downgraded has a detrimental effect on many of the GTE's operating parameters. These include delivering a higher TET for the same pressure ratio (PR) or a lower PR if the TET is maintained constant, or disturbances in the secondary cooling airflow for the turbine. Maintaining the TET constant with a reduced PR will reduce power output. However, under certain conditions, such as take-off, the GTE must produce a given amount of power, or in industrial plants where a constant power supply is required, the compressor must deliver the same PR as for the design point. A less efficient engine due to SPE means consuming additional fuel in the combustor and increasing the TET. Again, as stated above, the additional thermal stresses will result in earlier turbine failure. Additionally, increasing fuel consumption of the combustor may increase the primary zone temperature to a degree that damages the liner via radiant heat transfer. Such an effect can also cause uneven radial and circumferential temperature distributions in the gas flow entering the turbine.

There will be a knock-on effect on the optimum turbine pressure expansion ratio. The additional SFC can change the fuel residence time, which can lead to a change in the correct location at which the fuel is burned on entering the turbine section. This can eventually lead to a blockage of turbine cooling holes, which inject cooling secondary air, causing uneven cooling and higher blade temperatures. Additionally, the exhaust nozzles experience the formation of soot, reducing the pressure recovery of the nozzle, thereby reducing the available pressure (thrust) from which to extract useful work.

5. Conclusions

This paper evaluated the potential economic benefits associated with the use of EPCs in a GTE, with respect to operational cost reduction/savings and revenue improvements occasioned by the EPC upgrade. This investigation provides a comprehensive economic analysis of the EPC system. The outcomes, both quantitative and qualitative, of this study are:

- The economic effects of EPCs on engine performance and resulting recovery were calculated with reference to the data currently available in the literature.
- The CBA method was proven to be a useful tool, providing information on EPC effectiveness and whether introducing EPCs would be financially beneficial.
- The results project an annual economic cost of GBP 123,966 for both EPC cases and economic benefits of GBP 135,900 and 165,364 for Case 1 and Case 2, respectively.

- For Case 1, the NPV and BCR parameters match or exceed economic viability requirements, but the IRR (3%) is below the discount rate acceptance threshold (7%), which is indicative of a financially unfeasible solution.
- The provision of an EPC with characteristics described by Case 2 entails a successful combination of NPV, BCR and IRR (11%), resulting in a positive return of the investment.
- These predictions show that installing EPCs will be operationally and economically beneficial subject to the technical performance of the particular method employed. The obtained results show that the investment in EPC systems delivered on its promise of reducing the operational expenses in terms of decreased engine maintenance cost and overall operating cost.
- It can be seen that compressor degradation can have a noticeable effect on the performance parameters of the GTE in terms of TET and fuel flow. It is estimated that even minor increases in TET and SFC can lead to a significant increase in maintenance requirements/intervals and decrease the engine's expected working life.

The potential benefits and attractiveness of EPC presented here could be useful in guiding decision makers on the appropriate investment when targeting improvements. CBA has been used in this study; however, a risk analysis should also be performed prior to any final investment decision.

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Nomenclature

BCR	Benefits-cost ratio
CBA	Cost benefit analysis
DP	Design point
EPC	Erosion protective coating
FC	Fuel flow
GTE	Gas turbine engine
HiTUS	High Target Utilisation Sputtering
HPT	High pressure turbine
IGV	Inlet guide vanes
IRR	Internal rate of return
K	Kelvin
LPC	Low-pressure compressor
MTS	Maximum tensile stress
NPV	Net present value
PVD	Physical vapour deposition
PR	Pressure ratio
R2	Second rotor
R3	Third rotor
SFC	Specific fuel consumption (g/kN.s)
S2	Second stator
S3	Third stator
TET	Turbine entry temperature (K)
TiN	Titanium nitride

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Alqallaf, Jasem; Teixeira, Joao Amaral

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