**Proceedings of ASME Turbo Expo 2011**
**GT2011**
**June 6-10, 2011, Vancouver, British Columbia, Canada**

**GT2011-46708**

# GAS TURBINE INLET FILTRATION SYSTEM LIFE CYCLE COST ANALYSIS

**Melissa Wilcox**
Southwest Research Institute®
San Antonio, Texas, USA
Phone: 210-522-6046
Email: *mwilcox@swri.org*

**Klaus Brun**
Southwest Research Institute®
San Antonio, Texas, USA
Phone: 210-522-5449
Email: *kbrun@swri.org*

## ABSTRACT

Gas turbine inlet filtration systems play an important role in the operation and life of gas turbines. There are many factors that must be considered when selecting and installing a new filtration system or upgrading an existing system. The filter engineer must consider the efficiency of the filtration system, particles sizes to be filtered, the maintenance necessary over the life of the filtration system, acceptable pressure losses across the filtration system, required availability and reliability of the gas turbine, and how the filtration system affects this, washing schemes for the turbine, and the initial cost of any new filtration systems or upgrades. A life cycle cost analysis provides a fairly straightforward method to analyze the lifetime costs of inlet filtration systems, and it provides a method to directly compare different filter system options. This paper reviews the components of a gas turbine inlet filtration system life cycle cost analysis and discusses how each factor can be quantified as a lifetime cost. In addition, an example analysis, which is used to select a filtration system for a new gas turbine installation, is presented.

## 1. INTRODUCTION

Gas turbines ingest large amounts of air during operation. If the air entering the gas turbine is not adequately cleaned, the contaminants in the ambient can cause issues such as erosion, fouling, and corrosion to the gas turbine internals. This leads to performance degradation and/or premature failures of gas turbine components. A 22.37 MW Solar Turbine Titan 250 gas turbine has a reported exhaust flow of 245,660 kg/hr [1]. At this air flow rate, one ppm of particles in the ambient air is equivalent to 5.9 kg of particulates entering a gas turbine without filtration each day. Therefore, inlet filtration systems are placed upstream of the gas turbine inlet to clean the ambient air. The level of inlet filtration used depends on many factors such as the type and amount of contaminants present in the ambient air, weather patterns, the gas turbine air quality requirements, the gas turbine performance requirements, the operational scheme for the gas turbine, and the maintenance preference of the gas turbine operators.

Inlet filtration systems are sometimes selected without a full understanding of the contaminants that are present in the surrounding environment. The troublesome contaminants can be discovered during operation when performance degradation or failure occurs. Operators may also find that the performance degradation rate of the gas turbine due to inlet air quality or the occurrence of weather events (such as heavy rain) is unacceptable. Any of these situations may lead to the operators evaluating their inlet filtration system and deciding if upgrades or changes are warranted. A Life Cycle Cost (LCC) analysis provides a method to evaluate upgrades or changes to the inlet filtration system in a quantitative manner. The analysis quantifies various factors in terms of present day value in order to compare the lifetime costs of different system options. This paper reviews the basics of LCC analysis and discusses how it can be used to evaluate a gas turbine inlet filtration system. An example analysis is also provided.

## 2. LCC ANALYSIS BASICS

The LCC analysis is a tool that is used to calculate the overall lifetime costs of a system. The analysis is completed for a specific time period (usually correlated to the life of the filter system). One of the advantages of the LCC analysis is that it can indicate which factors or costs in the system have the greatest influence on the lifetime costs. Sometimes, new systems are purchased based primarily on initial cost, and later it is found that the maintenance or other recurring costs have a more significant impact on the lifetime costs. A LCC analysis can identify these influences up front.

The analysis is based on calculating the Net Present Value (NPV) of each cost during the life of the system and summing all the individual NPVs to calculate a lifetime NPV for the system. The costs included in the analysis are the purchase, installation, operation, maintenance, and disposal cost of the equipment. Items purchased for the system are easily quantifiable and included in the analysis. Other factors which can be quantified in terms of a monetary cost can also be included. For example, the effect of pressure loss across an inlet filtration system can be quantified in terms of revenue lost; this can be included as a reoccurring cost. The items which are quantified for an inlet filtration system LCC analysis are listed below.

- Initial costs (filters, filtration system hardware, spare filters, instrumentation, installation and commissioning costs)
- Energy costs (pulse system for self-cleaning filters)
- Operating costs (labor, inspections)
- Maintenance costs (replacement of filters, repairs to system, labor, repainting of exposed or corroded housing)
- Gas turbine downtime costs (due to replacement of filters, offline washings, any abnormal shutdowns due to inlet air quality)
- Gas turbine effects costs (performance degradation due to fouling or increase pressure loss: decreased power output and increased heat rate)
- Decommissioning and disposal (disposal of filters)

The NPV of each cost is calculated using one of Equations 1 through 4. Equations 1 and 2 are the NPV for a cost occurring one time with Equation 2 including an escalation rate, *e*. The escalation factor accounts for changes in the value of the dollar or changes in the cost overtime. Equations 3 and 4 are used to calculate the NPV for a cost which is reoccurring, meaning that the same cost happens each year with Equation 4 including an escalation rate, *e*.

One Time Cost

$$NPV = A(1+i)^{-n} \tag{1}$$

$$NPV = A(1+(i-e))^{-n} \tag{2}$$

Recurring Cost

$$NPV = \frac{A}{i}\left(1-[1+i]^{-n}\right) \tag{3}$$

$$NPV = A\left(\frac{1+e}{1-e}\right)\left(1-\left[\frac{1+e}{1+i}\right]^{n}\right) \tag{4}$$

In Equations 1 through 4, the value *A*, is the cost that occurs. The discount factor is *i*, which is the value that brings the cost from the year it occurs back to present day terms. The discount factor is defined as the rate of return that is used to compare expenditures at different points in times. The year in which the cost occurs is *n*.

The NPV values are directly comparable between systems, if the lifetime costs have been accounted for in a consistent manner for each system. For equipment installation/ changes, the NPV values will be negative, unless revenue from production is included. A negative value (when not including profits/ revenues) is acceptable. In this case, the result of the analysis would indicate that the least expensive system to install, operate, and maintain is the one with the lowest negative value. For example, a system with an LCC of -$1000 would be chosen over a system with an LCC of -$5000. If the profit/ revenue is included in the analysis, the system chosen would be one with the highest positive value. If the profit/ revenue is included, but the analysis still produces a negative value, this is an indication that the overall cost of the system is higher than the expected profits/ revenue [2].

## 3. GAS TURBINE FILTER SYSTEM LCC ANALYSIS CONSIDERATIONS

Before beginning an LCC analysis on a gas turbine inlet filtration system, one should become familiar with the existing inlet filtration system. This includes understanding:

- The characteristics of the ambient air on-site (type of contaminants present, quantity of contaminants that must be filtered, and any localized sources or seasonal changes in the contaminants)
- The systems operational characteristics (pressure losses, filter change out rates, how often the gas turbine is operated)
- The operational and maintenance goals for the filter system
- The system’s current short comings (what is not being filtered that needs to be)
- Any past failures that have occurred on the gas turbine due to poor inlet air quality

These factors are important to correctly quantify the existing system’s performance for the LCC analysis. This will also help to clarify the upgrades or changes that need to be made to the existing system in order to achieve the desired inlet air quality for the gas turbine.

Once the existing system is well understood, an LCC analysis can be completed. There are several variables, which must be considered when completing an LCC analysis on a gas turbine inlet filtration system. The variables, which are discussed in detail in this paper, are initial costs, maintenance costs, cost of power loss and increase heat rate, pressure losses, gas turbine degradation, failure costs, and availability/ reliability. It should be noted that an LCC analysis of a gas turbine inlet filtration system is not limited to the costs outlined in this paper.

### Initial Cost

The initial cost is comprised of all costs that occur in the first year of the analysis’ time period. This includes cost such as:

- Purchase price of new system or new system components

- Cost of installing and commissioning equipment (material, labor, equipment rental)
- Spare filters purchased during first year
- Loss of production due to downtime for system component installation

The majority of the values for these costs can be obtained from vendor or contractor quotes. The loss of production only applies to existing system which is being upgraded. If the plant is being brought down for another reason, and the installation of the new filter system components does not affect normal production, then it is not necessary to include this cost.

## Maintenance Cost

The cost of the maintenance, done to the filter system throughout its life, should be included in the analysis. The primary maintenance cost is filter replacement. Estimates from past experience or from a filter vendor for filter change-out intervals can be used to determine in which years the filters will be replaced. It is important to use realistic values for filter change-out frequencies. If the filter vendor estimates that the filters should be replaced every six months, but based on typical maintenance practices, the filters will actually only be changed out one per year, this should be used instead of the six-month interval. The LCC analysis can also be used to evaluate the benefit of various filter change out schemes.

Other maintenance costs are inspection and repair of filter housings. This cost is important to include for locations that have carbon steel filter housings or are in a corrosive environment (coastal, marine, offshore, tropical). If the filter housings are allowed to degrade over time, then leak paths through the housing may be created. This negates the whole purpose of having the filter system. Carbon steel housings often require repainting or spot painting repair in order to remain in good operable condition.

## Cost of Gas Turbine Power Loss and Heat Rate Increase

The inlet filtration system has an effect on the power loss and heat rate increase during the gas turbine's life. Specifically, the pressure loss and the gas turbine degradation due to inlet air quality related to erosion and fouling will lead to a decrease in the gas turbine power output and increase in the heat rate. These two effects (pressure loss and gas turbine degradation) are usually two of the most significant costs in the LCC analysis. Therefore, it is important that the cost from power loss and heat rate increase due to these effects is estimated accurately.

The method used to calculate the cost of power loss and heat rate increase depends on the application of the gas turbine. For example, the cost in a power generation facility will be estimate differently from the cost in an LNG production facility. The power generation facility will be more concerned with lost electrical output (MWe), where the LNG facility will correlate its losses to reduced GJ output. The considerations for estimating the cost of power loss and heat rate increase for two different applications are discussed below: a power generation facility and a gas transmission station.

*Power Generation Facility*

This is perhaps the most straightforward facility to estimate the cost of power loss and heat rate increase. In a power generation facility, any degradation of the gas turbine is directly a loss in power output of the facility. The cost of the power loss and heat rate increase can be estimated using Equations 5 and 6.

$$C_{PL} = \Delta P * C_{kWh} * T \tag{5}$$

$$C_{HR} = \frac{1}{10^6} * \Delta HR * P * C_{NG} * T \tag{6}$$

In the first equation, $\Delta P$ is the average power reduction per year per engineering unit (EU) of the variable which leads to the degradation. The $\Delta P$ variable can also be replaced by $R_{PL}*P/2$, where $R_{PL}$ is the degradation rate, and $P$ is the initial power output of the gas turbine. The variable $C_{kWh}$ is the cost of the electricity per kWh. In both Equations 5 and 6, $T$ is the operating time of the gas turbine in hours per year.

The $\Delta HR$ in Equation 6 is the average change in heat rate per year per engineering units (EU) of the variable which leads to the degradation. As mentioned for the power, the $\Delta HR$ variable can also be replaced by $R_{HR}*HR/2$, where $R_{HR}$ is the heat rate increase rate and $HR$ is the initial heat rate of the gas turbine. The cost of fuel for the gas turbine is represented by $C_{NG}$. The estimation of the power loss and heat rate degradation rates will be discussed in later sections of this paper.

It is important to note that the equations provide above are for a facility where the gas turbine is required to output the full rated power. This is not necessarily true for all facilities. If the gas turbine is operating at part load, then the loss of power is not necessarily as critical. Therefore, the cost of power loss should be reduced for that type of analysis.

*Gas Transmission Station*

At a gas transmission station, the primary concern is the ability to transport a specified amount of gas. Revenue is made based on the amount of gas moved through the pipeline and the price the end customer pays for the gas. Therefore, for this type of facility, the cost of power loss and heat rate increases should be based on the reduction in gas flow through the compressor driven by the gas turbine.

To calculate the cost due to the power loss, a correlation is required between the flow through the compressor and power provided by the gas turbine. When the power of the gas turbine is decreased, one of three scenarios can occur: the pressure ratio will remain constant and the flow will decrease, the flow will remain constant and the pressure ratio will decrease, or both the flow and pressure ratio will decrease. Any one of these scenarios can occur based on the operating conditions of the pipeline, but one must be chosen to complete the LCC analysis.

The scenario where the pressure ratio remains constant and the flow decreases, is the worst case scenario, since it will have the highest decrease in flow through the pipeline station. If this scenario is used, then using a compressor map and the relation between power, flow, and head of the compressor, the change in flow can be estimated. Figure 1 shows an example of the calculation of change in flow for a 9% reduction in power in a gas turbine with all three of the scenarios mentioned above. The scenario that has the maximum flow reduction is, when the head (directly related to pressure ratio) is held constant, and the flow is decreased. The calculated flow reduction can then be used with Equation 7 to calculate the cost of the power reduction. It should be noted that the power change and flow reduction in Figure 1 are much higher than what would be expected due to inlet air quality. These measurements are exaggerated in order to show the difference between the three scenarios.

$$C_{PL} = 9.48x10^{-4} * \Delta Q * \rho * LHV * C_{NG} \qquad (7)$$

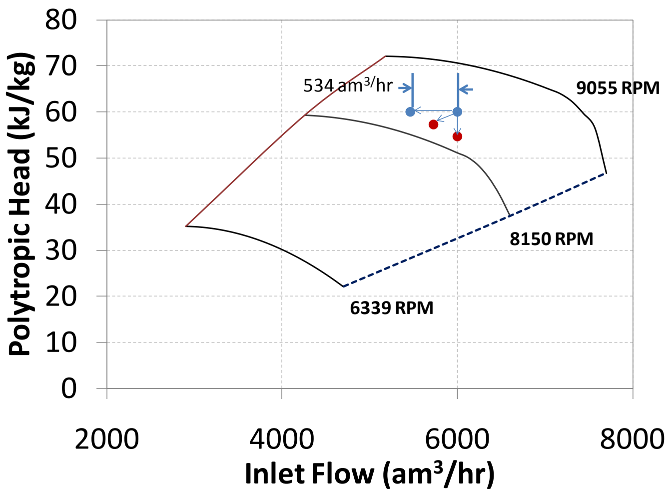


**FIGURE 1. REDUCTION IN COMPRESSOR THROUGHPUT DUE TO REDUCED GAS TURBINE POWER**

The variable $\Delta Q$ in Equation 7 is the average change in suction flow due to power loss per year. Also included in the equation are the density of the gas at the suction of the compressor, $\rho$, the low heating value of the gas, *LHV*, and the cost of the natural gas, $C_{NG}$. It should be noted that the price of the natural gas will depend on who is paying the bill: the shipper or the station owner.

Equation 6 can be used to calculate the cost due to the increase in the heat rate of the gas turbine for the gas transmission station.

*Other Applications*

If the gas turbine that is being analyzed does not fall into one of the two facilities discussed above, then the user must determine how the decrease in gas turbine power and increase in the gas turbine heat rate is related to a cost at the facility. Typically, the easiest approach is to relate the power reduction of the gas turbine to a reduction in an output which correlates to a revenue.

The cost due to heat rate can be correlated to the cost of fuel for the gas turbine, since as the heat rate increases, the fuel required to drive the gas turbine increases at a specific power level.

This step in the LCC analysis is important, since the cost due to pressure loss and the gas turbine degradation will directly depend on how these values are calculated.

## Pressure Loss

The performance of a gas turbine directly correlates to the pressure loss across the components on the inlet ducting. It is estimated that for every 250 Pa (1 in $H_2O$) the power output of the gas turbine is reduced by 0.5%, and the heat rate increases by 0.1% [3]. Every filter stage will add pressure loss to the inlet of the gas turbine. The actual pressure loss across the inlet can be measured during operation; however, the initial and recommended final pressure losses for each filter are reported in filter vendor literature.

When filters are newly installed, they have their minimum pressure loss. As the filter is loaded overtime, the pressure loss increases. The filter pressure loss change overtime is typically non-linear. An example is shown in Figure 2.

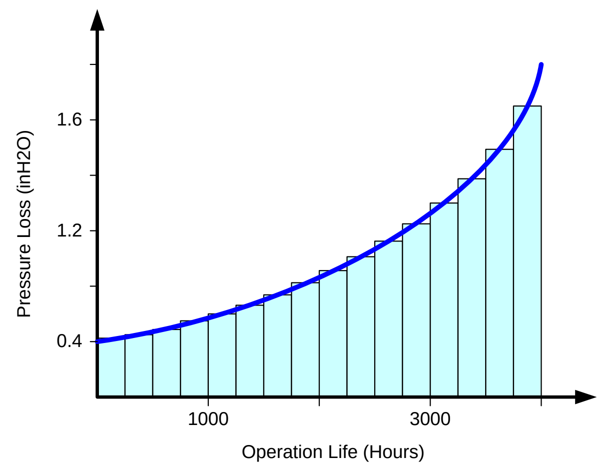


**FIGURE 2. FILTER PRESSURE LOSS CHANGE OVER TIME**

It is important to consider the pressure loss across the life of the filter. If only the initial pressure loss is considered, then the power losses and heat rate increase due to pressure loss calculate for the gas turbine will be underestimated.

Since the pressure loss across the inlet of the gas turbine due to the inlet filtration system has a negative impact on the performance of the gas turbine, it should be considered in the LCC analysis. The first step to estimate the cost of the pressure loss is to determine an average pressure loss per year for the analysis. In order to do this for each filter stage, the initial and final pressure loss across the filter and the frequency at which the filters are changed out need to be defined. From this, the average pressure loss per year can be calculated.

Figure 3 shows an example of the pressure loss across a two-stage filtration system over a ten-year period. This system has a mist eliminator, F6, and F9 filter. The contribution of each filter is graphed in Figure 3. In addition, the points in time when the filters are changed out occur when there is a sharp change in the pressure loss across the filter. The dashed line at the top of the graph shows the overall pressure loss for the filter system. Table 1 provides a summary of the filter system and the average pressure losses calculated for each year.

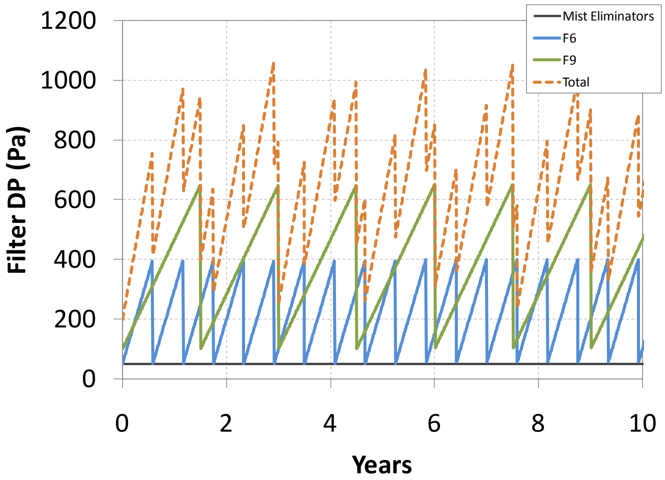


**FIGURE 3. PRESSURE LOSS OF FILTER SYSTEM OVER 10 YEAR PERIOD**

**TABLE 1. FILTER SYSTEM INFORMATION AND AVERAGE PRESSURE LOSS PER YEAR**

| Stage Description | Pressure Loss (Pa) | | Change out frequency (months) | |
|---|---|---|---|---|
| | Initial | Final | | |
| Mist Eliminators (ME) | 50 | 50 | n/a | |
| Stage 1 - F6 | 50 | 400 | 7 | |
| Stage 2 - F9 | 100 | 650 | 18 | |
| Year | Average Pressure Loss (Pa) | | | |
| | ME | F6 | F9 | Total |
| 1 | 50.0 | 202.5 | 283.3 | 535.8 |
| 2 | 50.0 | 217.5 | 371.9 | 639.4 |
| 3 | 50.0 | 234.2 | 463.6 | 747.8 |
| 4 | 50.0 | 224.6 | 284.9 | 559.4 |
| 5 | 50.0 | 209.2 | 371.9 | 631.1 |
| 6 | 50.0 | 228.7 | 468.2 | 746.9 |
| 7 | 50.0 | 248.3 | 284.9 | 583.2 |
| 8 | 50.0 | 206.7 | 376.5 | 633.2 |
| 9 | 50.0 | 224.0 | 466.7 | 740.6 |
| 10 | 50.0 | 240.0 | 284.9 | 574.9 |

Once the average pressure loss across the filtration system is found for each year in the study, the cost of the pressure loss is calculated. This cost includes both a gas turbine power loss and a heat rate increase. Equations 8 and 9 use the relationship between pressure loss, power loss, and heat rate stated at the beginning of this section. These equations provide the power loss and heat rate increase to calculate the cost. In both equations, DP is the average pressure loss across the filter system.

$$\Delta P = 2x10^{-5} * DP * P \quad (8)$$

$$\Delta HR = 4x10^{-6} * DP * HR \quad (9)$$

Once the power loss and heat rate increase are found, the equations and relationships discussed in the *"Cost of Gas Turbine Power Loss and Heat Rate Increase"* section can be used to determine the cost of the pressure loss for each year of the study. After this is completed, the costs will be brought back to present value using either Equation 1 or 2.

### Gas Turbine Degradation

Overtime, the gas turbine will experience degradation due to inlet air quality. Contaminants in the air can cause erosion, fouling, and corrosion. The rate of degradation will depend on the contaminants present in the air and the level of filtration present at the inlet of the gas turbine. The primary degradation mechanism due to inlet air quality is compressor fouling (which is considered here). Degradation directly affects the output of the gas turbine; therefore, the cost of the degradation needs to be included in the LCC analysis.

To include the degradation in the analysis, a degradation rate of the gas turbine due to inlet air quality needs to be determined. This is the most challenging part of including this cost. The rate can be determined empirically from past operating data (if the gas turbine is already in service and operational data is available) or based on values calculated from degradations models for gas turbines as reported in literature. The first method is preferred, but often, both methods will be used in an LCC analysis.

There are several thorough references available, which discuss the degradation mechanisms and degradation rates for gas turbines that can be used to estimate a degradation rate for the LCC analysis. A few select references are described below.

- Meher-Homji and Bromley present a thorough discussion of compressor fouling and washing reviewing various models and experimental data of the gas turbine degradation rates [4].
- Syverud et al. discuss the deterioration of the axial compressor from fouling due to the ingestion of saltwater [5].
- Kurz and Brun review the degradation mechanisms and discuss a gas turbine model to determine the effects of these mechanisms on the gas turbine performance [6].
- Meher-Homji et al. present a detailed review of fouling and analyze the fouling effects on 92 different gas turbines [7].
- Zaba investigates the effects of deposits on the blade and present a theoretical model with comparison with experimental data [8].

If both empirical data and models in the literature are used to determine degradations rates, then any degradation rates obtained empirically should also be calculated with the models and these values compared. The models can be adjusted based on the operational data.

Once an average degradation rate is determined for each year of the analysis, the costs for the LCC analysis can be calculated as described in the *"Cost of Gas Turbine Power Loss and Heat Rate Increase"* section.

The gas turbine degradation cost will often be the highest contributor to the life cycle cost of an inlet filtration system. Because of this, the degradation is an important value to determine correctly. It is good to complete a sensitivity analysis on the degradation rate of a gas turbine for the LCC analysis in order to determine if varying the degradation rate slightly will influence the conclusions of the study.

Figure 4 shows an example of a sensitivity study on the degradation rate. The total NPV of the existing system is shown as a constant across the graph, and the total NPV of the proposed system is varied with the degradation rate. The total NPV of the proposed system increases with degradation. The proposed system shows a cost benefit when the degradation rate is less than 1.3%.

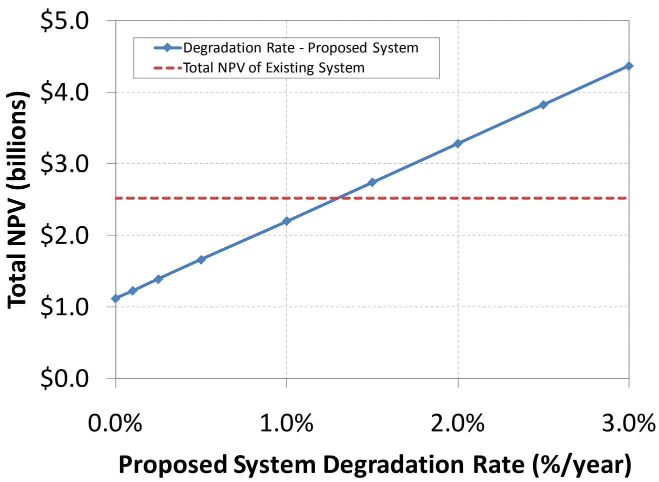


**FIGURE 4. SENSITIVITY STUDY OF DEGRADATION RATE FOR LCC ANALYSIS**

During operation, one method to renew the gas turbine performance after fouling has occurred is through compressor washing. Since this has a positive impact on the performance of the gas turbine, it will also reduce the cost of performance degradation of the gas turbine in the LCC analysis. However, if the gas turbine is shut down solely for the cleaning of the compressor, then the downtime costs should also be included. If compressor washing is performed on the gas turbine, then its effects need to be included in the analysis.

### Failure or Events Costs

If erosion, fouling, and corrosion are not controlled with proper inlet filtration, then failures can occur in the gas turbine. Operators will often only take a serious look at upgrading the filtration after a failure has occurred which can be directly linked to the inlet air quality. Failure events are nearly impossible to predict during the design phase, but if a gas turbine has already been in service, the operational experience can indicate if a failure is likely to occur or not.

If failures due to inlet air quality have been experienced or are anticipated to occur, then these need to be included in the LCC analysis. Costs that should be included are material costs, labor, cost of downtime, and any other services necessary for the repair. These costs should be included in the year that the failure is anticipated to occur.

Events can also occur related to inlet air quality that has an impact on the gas turbine operation. For example, an early morning fog can cause the inlet pressure loss to increase significantly or cause an accelerated fouling of the compressor, which can lead to shutdown of the gas turbine [4]. These types of events negatively impact the operation of the production facility where the gas turbine is being used and should be included in the analysis.

### Availability/ Reliability

The availability and reliability of the gas turbine influence the pressure loss costs and gas turbine degradations costs. Both terms provide an estimate of how often the gas turbine will operate during a given year. The availability is related to planned operational hours, and the reliability is related to the ability of the system to operate a specified number of hours. If the gas turbine operates every hour of the year, then it can be said to have an availability/ reliability of 100%. However, the majority of gas turbines do not operate 100% of the year.

When calculating the pressure loss or gas turbine degradation costs, the availability and reliability should be included when estimating the number of hours the gas turbine will actually operate.

### Summary

In summary, there were several costs discussed that should be included in an LCC analysis. The bulleted list below summarizes those costs. The value of each of these costs should be calculated. Then the cost should be brought back to present value using the NPV calculations (Equations 1 through 4). Lastly, all the individual NPVs should then be summed together to determine a total NPV for the system.

- Initial Costs: Purchase price, installation and commissioning costs (include in first year)
- Maintenance Costs: Filter replacement and disposal, maintenance of auxiliary systems (recurring cost, include in year it occurs)
- Pressure Loss: Decrease in available power and increase in heat rate due to pressure loss across filtration system (yearly recurring cost)
- Gas Turbine Degradation: Decrease in available power and increase in heat rate due to gas turbine degradation related to inlet air quality (yearly recurring cost)
    - Compressor Washing: improves gas turbine degradation rate (yearly recurring cost)
- Failures or Events: Cost of gas turbine failure or event due to inlet air quality (occur in year failure or event happens)
- Availability/ Reliability: Include in calculation of costs due to pressure loss and gas turbine degradation.

## 4. LCC ANALYSIS EXAMPLE

An example of a simplified LCC analysis is presented here to help the reader understand the step-by-step process in determining and comparing NPVs of multiple inlet filtration systems. This example is a comparison of two systems for a new gas turbine installation. The gas turbine to be installed is a 25MW gas turbine with a heat rate of 9,952 Btu/kWh, which is driving a generator to produce electricity and generate steam for a small industrial plant. Any electricity that is not generated by the gas turbine must be purchased at a price of $0.0707/kWh [9]. Considerations for the filters effect on thermal losses to the steam generation are not included in this example analysis. The gas turbine is used in a rural environment, which has low dust levels but experiences several periods of heavy rain each year. The environment can also be considered industrial due to the plant's emissions. Two inlet filtration systems are proposed. Table 2 shows the details of each system.

**TABLE 2. SUMMARY OF TWO FILTER SYSTEMS FOR LCC ANALYSIS**

| Parameter | System 1 | System 2 |
|---|---|---|
| Stage 1 Description | Weather Hoods | Mist Eliminators |
| No. Filters | n/a | n/a |
| Initial DP (Pa) | 10 | 50 |
| Final DP (Pa) | 10 | 50 |
| Replace. Freq. (mon.) | n/a | n/a |
| Cost/ Filter ($) | n/a | n/a |
| Stage 2 Description | F9 Cartridge Filters | F6 Filters |
| No. Filters | 170 | 150 |
| Initial DP (Pa) | 100 | 50 |
| Final DP (Pa) | 450 | 400 |
| Replace. Freq. (mon.) | 8 | 7 |
| Cost/ Filter ($) | $300 | $130 |
| Stage 3 Description | n/a | F9Ffilters |
| No. Filters | n/a | 150 |
| Initial DP (Pa) | n/a | 100 |
| Final DP (Pa) | n/a | 650 |
| Replace. Freq. (mon.) | n/a | 18 |
| Cost/ Filter ($) | n/a | $180 |

The study was completed for a 15-year period with a discount rate of 10%. The cost of gas to operate the turbine was set at $4.22/MMBtu [10]. The gas turbine has an availability/ reliability of 95%.

The initial costs of System 1 and System 2 are $1 million and $1.5 million, respectively, which include the cost for the complete filter system. The power degradation rate of System 1 was estimated to be 1.7%. This rate is high, because there is no good water removal capability on this system. Therefore, the soluble particles captured on the filters can be unloaded into the turbine, if the filters get wet during a rain event, which leads to compressor fouling. The power degradation rate of System 2 was estimated to be 0.7%. This system has good water removal capabilities, so the degradation is reduced. No failures are anticipated related to inlet air quality.

Table 3 summarizes the results of the analysis. The NPV for the first system is approximately $5.3 million. The majority of this cost comes from the gas turbine degradation (approximately 57%). In System 2, the total NPV is $4.7 million with the cost evenly distributed between the initial cost, pressure losses, and the gas turbine degradation. System 2 has a $0.6 million cost advantage over the first system.

**TABLE 3. SUMMARY OF LCC ANALYSIS RESULTS**

| | NPV | |
|---|---|---|
| | System 1 | System 2 |
| Initial Cost | $1,000,000 | $1,500,000 |
| Filter Replacement | $566,815 | $375,283 |
| DP Losses | $707,527 | $1,606,690 |
| GT Degradation | $3,051,276 | $1,251,642 |
| Failures | $0 | $0 |
| Total NPV | $5,325,618 | $4,733,614 |
| Variance from Sys 1 | $0 | $592,004 |

Figure 5 graphically compares the various costs from the LCC analysis. The graph shows that the highest contributor to the total NPV is the gas turbine degradation for System 1. The highest contributor to the cost in System 2 is the pressure losses. The initial cost of System 1 is dwarfed by the cost due to degradation. The filter replacement cost has the least influence on the total NPV. Based on the LCC analysis, the second system shows the greatest cost advantage over the life of the filtration system.

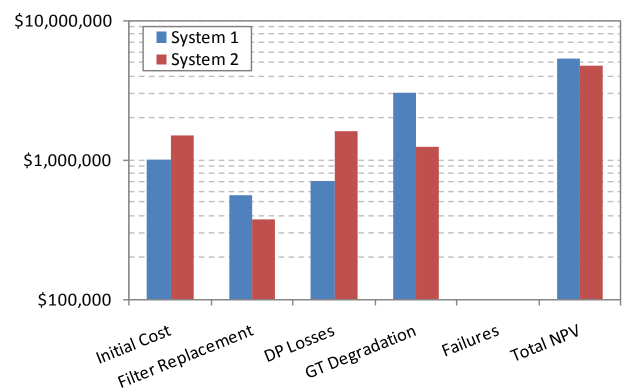


**FIGURE 5. GRAPHICAL SUMMARY OF LCC ANALYSIS RESULTS**

## 5. SUMMARY

The LCC analysis provides a convenient means to compare various gas turbine inlet filtration systems options quantitatively. The important parameters to consider in an analysis are the initial cost, maintenance costs, gas turbine performance effects due to pressure loss across the inlet filtration system, gas turbine degradation, and failure costs. This paper summarized an approach to completing an LCC analysis on gas turbine inlet filtration systems.

## 6. NOMENCLATURE

| | | |
|---|---|---|
| $e$ | = | *Escalation Factor (%)* |
| $i$ | = | *Discount Rate (%)* |
| $n$ | = | *Year Cost Occurs (years)* |
| $A$ | = | *Value of Cost in Year it Occurs ($)* |
| $C_{HR}$ | = | *Cost of Heat Rate Increase ($/year)* |
| $C_{kWh}$ | = | *Cost of Electricity ($/kWh)* |
| $C_{NG}$ | = | *Cost of Natural Gas ($/MMBtu)* |
| $C_{PL}$ | = | *Cost of Power Loss ($/year)* |
| $DP$ | = | *Pressure Loss across Filter System (Pa)* |
| EU | = | *Engineering Units* |
| $\Delta HR$ | = | *Change in Heat Rate (Btu/kWh-EU)* |
| $HR$ | = | *Heat Rate of Gas Turbine (Btu/kWh)* |
| LCC | = | *Life Cycle Cost* |
| $LHV$ | = | *Low Heating Value of Gas (MJ/kg)* |
| LNG | = | *Liquefied Natural Gas* |
| $NPV$ | = | *Net Present Value ($)* |
| $\Delta P$ | = | *Change in Power (kW/EU)* |
| $P$ | = | *Initial Power of Gas Turbine (kW)* |
| $\Delta Q$ | = | *Change in Flow (am3/hr)* |
| $R_{HR}$ | = | *Heat Rate Increase Rate of Gas Turbine (%)* |
| $R_{PL}$ | = | *Power Degradation Rate of Gas Turbine (%)* |
| $T$ | = | *Operating Time (hr/year)* |
| $\rho$ | = | *Density of Gas at Suction (kg/m3)* |

## 7. REFERENCES


[1] 2009, "Titan 250 Gas Turbine Compressor Set Datasheet," Solar Turbines, A Caterpillar Company.

[2] 2001, "Pump Life Cycle Costs: A Guide to LCC Analysis for Pumping Systems," Europump and Hydraulic Institute, First Edition.

[3] 2009, "Gas Turbine World 2009 GTW Handbook," Volume 27, pg 64.

[4] Meher-Homji, C., and Bromley, A., 2004, "Gas Turbine Axial Compressor Fouling and Washing," Proceedings of the Thirty-Third Turbomachinery Symposium.

[5] Syverud, E., Brekke, O., and Bakken, L., 2007, "Axial Compressor Deterioration Caused by Saltwater Ingestion," Journal of Turbomachinery, vol. 129, pp. 119-126.

[6] Kurz, R., and Brun, K., 2001, "Degradation in Gas Turbine Systems," Journal of Engineering for Gas Turbines and Power, vol. 123, pp. 70-77.

[7] Meher-Homji, C,. Chaker, M., and Bromley, A., 2009, "The Fouling of Axial Flow Compressors – Causes, Effects, Susceptibility, and Sensitivity," GT2009-53239, Proceedings of ASME TurboExpo: Power for Land, Sea, and Air, Orlando, FL, USA.

[8] Zaba, T., 1980, "Losses in Gas Turbines Due to Deposits on the Blading", Brown Boveri Review, 12-80, pp. 715-722.

[9] 2010, "Total Electric Power Industry Summary Statistics," U.S. Energy Information Administration.

[10] 2010, "Natural Gas Weekly Update-Overview (For the Week Ending Wednesday, December 15, 2010)," U.S. Energy Information Administration.