Using Steam Path Audits in a Performance Guarantee Program

Deborah H. Cioffi, P.E.

Encotech Engineering

Using Steam Path Audits in a Performance Guarantee Program

Deborah H. Cioffi, P.E., Technical Director, Encotech Engineering, P.C.

Steam turbine owners have a variety of upgrades from which to choose for improving turbine performance. New LP rotors, new stage and packing designs, coatings, and nozzle set backs are some examples, which often come with guarantees of heat rate or efficiency improvement from the vendor. Performance tests before and after the upgrade outage measure the improved performance but they do not differentiate between improved performance due to new parts and improved performance due to routine maintenance conducted during the outage such as grit blast cleaning, packing replacement, and nozzle weld repairs. Here, the author describes how a Steam Path Audit becomes an integral part of a Performance Guarantee Program to assure vendors remain accountable for the new part's performance and to assure that credit for routine maintenance remains with the owner. A numerical example demonstrates application of the method.

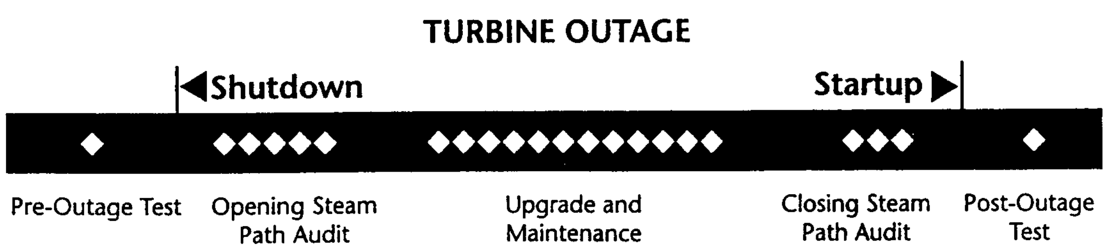
Introduction

When installing new parts, turbine owners take advantage during the outage to perform routine maintenance on the steam path to improve performance. A Steam Path Audit is an assessment of the condition of the stationary and rotating parts, which is conducted while the turbine is opened during a major overhaul. Maintenance and performance personnel use the results of a Steam Path Audit to prioritize maintenance action items during the overhaul. The Steam Path Audit fits appropriately in a Performance Guarantee Program for the new part because it quantifies the performance improvement resulting from routine maintenance and it does not interfere with the disassembly and reassembly of the turbine during the overhaul (see Figure 1).

The Steam Path Audit compliments a Performance Guarantee Program by quantifying, specifically, performance improvements resulting from both routine maintenance as well as improvements resulting from new parts. The methodology of using the Steam Path Audit in the Performance Improvement Program involves six steps.

1. **Pre-Outage Test.** A heat rate or enthalpy drop efficiency test before the overhaul establishes the condition of the unit before installation of the new part. The test results may indicate that, for example, the HP turbine efficiency is down 4%, but it does not indicate the cause of the poor performance.
2. **Opening Steam Path Audit.** Immediately upon opening the

Figure 1



Presented at the 1997 Performance Software User's Group Meeting sponsored by Scientech, Inc. and American Electric Power Corporation, June 23–27, 1997, Columbus, Ohio.

steam turbine an inspection of the steam path aids to quantify the damage and degradation found in each stage in terms of efficiency, power, and heat rate. For example, a Steam Path Audit will quantify solid particle erosion, rubbed packing seals, and foreign object damage in the HP casing that accounts for the measured 4% decrease in HP casing efficiency.

3. **Upgrade and Maintenance.** During the overhaul, the new part is installed. After the results of the Steam Path Audit are presented, the maintenance crew sets out to conduct the most cost-effective routine repairs to the steam path. The cost-effectiveness, or benefit-to-cost ratio, of individual maintenance actions is calculated using the heat rate penalty assigned to the damage identified in the Steam Path Audit results and the corresponding repair costs. For example, first stage solid particle erosion increases heat rate by 80 BTU/kWh, the annual cost of a Btu/kWh is $3,000 and the cost of repairs is $60,000. The benefit-to-cost ratio of repairing the solid particle erosion damage is therefore 80 * 3,000 / 60,000 = 4, which is a very good return on investment in one year and would likely be high on the maintenance priority list.
4. **Closing Steam Path Audit.** After the new part is installed and the remaining maintenance has been performed, the Closing Steam Path Audit predicts the return-to-service condition of the unit. Like the Opening Steam Path Audit, the Closing Audit identifies stage-by-stage losses and quantifies the performance penalty associated with each. For example, after repairing the first stage solid particle erosion damage, the nozzle trailing edges were left at 40 mils rather than at their design thickness of 30 mils. Additionally, some grinding marks were left on the suction side of the nozzle exhaust. The Closing Steam Path Audit would quantify the trailing edge thickness and grinding losses as, say, 10 BTU/kWh. Therefore, the predicted performance improvement would be 70 BTU/kWh (80 from the Opening minus 10 from the Closing). The difference between the Opening results and the Closing results is the performance gain due to routine maintenance.
5. **Post-Outage Test.** Shortly after the unit is back on line, a post-outage heat rate or enthalpy drop efficiency test measures the actual return-to-service condition. The difference between the Pre- and Post-Outage tests is the performance improvement due to both the upgrade and the routine maintenance. Again, the test results do not differentiate between the two.
6. **Actual Performance of New Part.** The heat rate or efficiency improvement due to the new part is equal to the improvement due to all outage activity (as measured by the Pre- and Post-Outage tests) minus the improvement due to routine maintenance (as measured by the Opening and Closing Steam Path Audits). Mathematically, the change in heat rate is as follows:

(Pre-Outage – Post-Outage)Test – (Opening – Closing)Steam Path Audit = Heat Rate Improvement due to New Part

Stepping Through An Example

Procure New Part

Long before anything is mobilized to commence the overhaul, a contract is drawn up between owner and vendor for the new part. It is at this stage where use of a Steam Path Audit in the Performance Guarantee Program must be agreed upon. Today, Steam Path Audits are accepted as a reliable and accurate means for quantifying performance deterioration found during an inspection. In fact, at least two turbine manufacturers conduct their own Steam Path Audits using licensed software from Encotech.[1]

The contract between vendor and owner pinpoints the type of performance guarantee, the type of acceptance test and how the test results are to be used. One type of guarantee is an improvement in casing efficiency, another is an improvement in gross turbine heat rate. The guarantee may be an improvement over the original design conditions or the conditions measured just prior to the upgrade. In the former case, the ASME PTC6 acceptance test should be used as a basis for comparison rather than the guarantee heat balance since the heat balance contains manufacturer's margin whereas the ac-

[1] Steam Turbine Performance Evaluation (STPE) Copyright ©1994, all rights reserved throughout the world. Download a demo and request more information at www.encotech.com.

ceptance test measured actual performance. Where units have had upgrades installed during previous outages, the post-upgrade acceptance test results should be used as a basis for comparison since the upgrades render the original acceptance test obsolete. Theoretically, it is sound practice to use the acceptance test method. However, it is the author's experience that most acceptance tests are non-existent. In the unlikely event that an acceptance test was conducted, the people who conducted it are usually impossible to reach and the test is often clouded with skepticism and uncertainty.

In the latter case, where the guarantee is an improvement over the condition just prior to the upgrade, all parties can be involved in establishing the basis for comparison. The Pre-Outage Test measures the heat rate or casing efficiency before the upgrade and the Post-Outage Test measures the heat rate or casing efficiency after the upgrade. The difference between the two is the performance improvement due to the new part, right? Wrong. The difference is the performance improvement due to the new part *and* the other maintenance conducted during the outage. A turbine owner is not going to open up the unit without taking the opportunity to grit blast deposits, replace or sharpen packings, conduct minor weld repairs and to conduct other performance-enhancing maintenance. Therefore, in order to isolate the portion of the improvement resulting from the new part, the Opening and Closing Steam Path Audits are used to quantify the performance improvement caused by the routine maintenance. The performance improvement due to the new part then equals the improvement from the outage (as measured by the tests) minus the improvement from routine maintenance (as measured by the Steam Path Audits).

Another important consideration in writing the contract language is precisely when results will be calculated during the chronology of events, who will be involved in each step, and how will differences be resolved. Confusion and oversight in these areas often works to the vendor's advantage. To protect the interests of the owner, it is desirable to make contract language simple but specific. For example, the Pre-Outage Test results should be calculated and agreed upon immediately following the Pre-Outage Test and before the Opening Steam Path Audit. Test data should be reviewed and signed by both parties before leaving the site. The Opening Steam Path Audit results should be documented and agreed upon before leaving the site as well, even if arbitration is necessary. Likewise, the Closing Steam Path Audit and the Post-Outage Test should follow the same pattern: gather information, calculate results and agree before moving on to the next phase. Adherence to this procedure will reduce the likelihood of mysterious post-facto correction factors working their way into results to the clear benefit of one party.

In our example, assume Megawatt Electric will procure a new last stage (stationary and rotating components) and the vendor guarantees that gross turbine heat rate (defined mathematically in the contract) will improve by 1% over the clean condition of the unit prior to the outage. The clean condition is calculated by subtracting the heat rate degradation measured during the Opening Steam Path Audit from the heat rate measured during the Pre-Outage Test. Both parties agree to conduct the ASME PTC6 1996 Abbreviated Heat Rate Test before and after the overhaul and that test uncertainty will not be used as a tolerance. An Opening and Closing Steam Path Audit will be conducted using Encotech's Steam Turbine Performance Evaluation computer program (STPE) (in this case let's assume the vendor will be using its licensed version), and results will be verified on site by the owner (who will be using its licensed version of STPE). The contract language states that all Steam Path Audit differences between parties will be resolved before leaving the site by a neutral third party familiar with the Steam Path Audit process (e.g., Encotech, K.C. Cotton, etc.)[2]

Conduct the Pre-Outage Test

Although volumes may be written on the application of the ASME PTC6 code to the Pre-Outage Test, that subject is beyond the scope of this paper. Rather, let's continue our discussion of Megawatt Electric, where they and the vendor participated equally in the Pre-Outage Test. Further, assume that a third party oversaw the process and verified correction curves and results, and the gross turbine heat rate was 9,200 BTU/kWh. Therefore, the guarantee from the vendor provid-

[2] In the case where the owner or the vendor does not have a license to use STPE, Encotech can conduct the Steam Path Audit on their behalf, but in this position, Encotech cannot act as arbitrator.

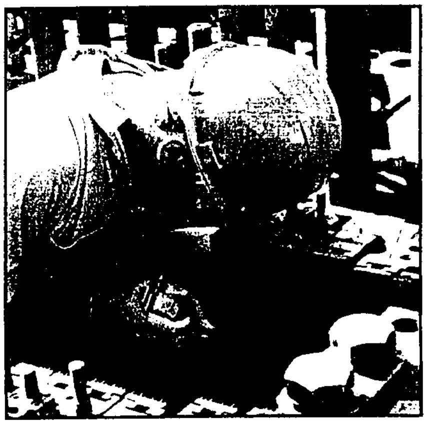


Figure 2

Figure 3

Figure 4

ing the last stage is to improve heat rate by 1% of the difference between 9,200 BTU/kWh and Opening Steam Path Audit losses.

Opening Steam Path Audit

Immediately after exposing the steam path during disassembly, Megawatt Electric conducted an Opening Steam Path Audit. The purpose of the Steam Path Audit is to quantify steam path deterioration on a stage-by-stage and casing-by-casing basis. One engineer typically takes between 3 and 6 days to collect the data, generate the loss reports, and present the preliminary results before leaving the site and before Megawatt Electric makes any repair decisions. The timing of the Steam Path Audit is concurrent with turbine disassembly, and does not interfere with the outage schedule. The cost to subcontract a steam path audit is typically $8,000 to $12,000, depending on the location of the plant and the number of rows of blading. The Audit Engineer measures losses in the following categories:

- Interstage Packings (Diaphragm Packings or Shaft Packings)
- Tip Spill Strips (Shroud Seals)
- End Packings (Shaft Packings, Dummy Packings, N-1, N-2, etc. Packings)
- Miscellaneous Leakages (Snout Ring, Bell Seal, Manhole Cover Gasket, Horizontal Joint, etc.)
- Solid Particle Erosion
- Deposits
- Mechanical Damage (Broken Blading, Foreign Object Damage, etc.)
- Surface Roughness (Deposits, Machining, etc.)
- Deposits Under Rotating Blade Covers (Deposits Under Shroud Bands)
- Trailing Edge Thickness (from previous weld repairs)
- Hand Calculations (anything that does not fit into the above categories)

Figures 2, 3, and 4 show an Audit Engineer taking Steam Path Audit measurements.

A Steam Path Audit measures heat rate degradation from the new and clean condition (as determined from either the VWO heat balance or the acceptance test results). Let's say Megawatt Electric's Opening Steam Path Audit revealed a 300 BTU/kWh increase in heat rate over a design heat rate of 8,800 BTU/

Figure 5

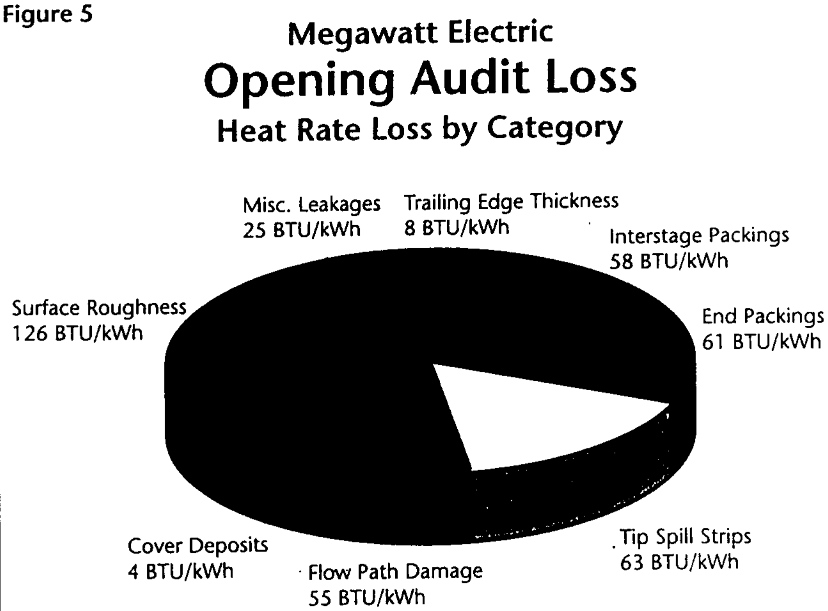


Table 1

Action Item	Heat Rate Benefit (BTU/kWh)	Heat Rate Benefit ($1,000)	Repair Cost ($1,000)	Benefit/Cost
Sharpen HP stg 6 interstage packing	3.1	9.3	0.3	31.0
Sharpen HP stg 4 interstage packing	2.8	8.4	0.3	28.0
Sharpen HP stg 5 interstage packing	2.6	7.8	0.3	25.0
Sharpen HP stg 2 interstage packing	2.5	7.5	0.3	25.0
Sharpen IP stg 3–6 tip spill strips	7.0	21.0	1.2	17.5
Replace 1st IP stg tip spill strip	13.0	39.0	4.0	9.8
Polish HP nozzles, exhaust side	13.0	39.0	4.0	9.8
Replace 2nd IP stg tip spill strip	9.0	27.0	4.0	6.8
Polish IP nozzles, exhaust side	8.0	24.0	4.0	6.0
Second reheat stage minor repairs	10.0	30.0	8.0	3.8
Replace top half snout rings	23.0	69.0	19.0	3.6
Sharpen 1st IP stg tip spill strip	0.3	0.9	0.3	3.0
Replace IP stg 3–6 tip spill strips	12.0	36.0	16.0	2.3
Sharpen 2nd IP stg tip spill strip	0.2	0.6	0.3	2.0
Replace stg 2 interstage packing	4.0	12.0	7.5	1.6
Replace stg 6 interstage packing	3.5	10.5	7.5	1.4
Polish LP nozzles, exhaust side	3.0	9.0	7.0	1.3
Replace stg 4 interstage packing	3.0	9.0	7.5	1.2
Replace stg 5 interstage packing	3.0	9.0	7.5	1.2
Second reheat stage major repairs	15.0	45.0	55.0	0.8
Replace bottom half snout rings	2.0	6.0	19.0	0.3
Total repair cost for B/C > 3.5			45.4	
Total repair cost for B/C < 3.5			127.6	

kWh. The resulting Steam Path Audit reports go on to itemize the losses as shown in Figure 5.

The clean pre-outage condition of the unit is the heat rate measured during the Pre-Outage Test minus the heat rate degradation identified during the Opening Steam Path Audit, or 9,200 – 300 = 8,900 BTU/kWh. A 1% heat rate improvement over the clean pre-outage condition is therefore 89 BTU/kWh.

Outage Maintenance

The Performance and Maintenance Engineers at Megawatt Electric used the results from the Opening Steam Path Audit to guide their maintenance decisions. They calculated the benefit-to-cost ratio for each possible maintenance action item then ranked them. Their financial planners established a minimum benefit-to-cost ratio of 3.5. The maintenance personnel at Megawatt Electric then replaced the top half snout rings, conducted minor weld repairs on the second reheat stage (despite OEM recommendations to do a major weld repair), sharpened rather than replaced 4 of the 7 stages of interstage packing in the HP because the benefit-to-cost ratio of each item exceeded 3.5. They also grit blasted with 220 aluminum oxide grit and replaced the conventional high pressure shaft packing with retractable packing. In this example, conducting the maintenance that had a benefit-to-cost ratio greater than 3.5 and not conducting maintenance with a lower benefit-to-cost ratio saved Megawatt Electric $82,200 (see Table 1).

Closing Steam Path Audit

The purpose of a Closing Steam Path Audit is twofold: 1) to estimate the-return-to-service condition of the unit and 2) to serve as a quality control check on maintenance conducted during the outage. It is the author's experience that sharpening packing teeth often falls by the way-side during the hectic schedule of a major turbine overhaul. However, the benefit-to-cost ratio of doing such work often exceeds 10 and the effort to do so is minimal. Other maintenance oversights, such as grinding marks left on weld repairs and deposits left under rotating blade covers, represent performance gains after minimal effort.

Megawatt Electric's closing Steam Path Audit identified 10 BTU/kWh in "last-minute" maintenance. Once Megawatt Electric personnel conducted the maintenance the plant saved an additional $30,000 the first year. After these repairs, the closing Steam Path Audit predicted a return to service heat rate of 8,875 BTU/kWh, or a 225 BTU/kWh improvement. These results were presented on site to maintenance and performance engineers and managers at Megawatt Electric by the Audit Engineer, 3 days after arriving on site.

Post-Outage Test

Like the Pre-Outage Test, the Post-Outage Test was conducted according to ASME PTC6 1996 standards with all parties involved in the testing process. Megawatt Electric's Post-Outage Test resulted in a gross turbine heat rate of 8,880 BTU/kWh, a 320 BTU/kWh improvement over the Pre-Outage Test.

Calculated Results

The guarantee heat rate improvement is 89 BTU/kWh after routine maintenance is considered. Megawatt Electric's outage resulted in a 320 BTU/kWh (9,200 - 8,880) heat rate improvement as measured by the Pre- and Post-Outage Tests. The routine maintenance resulted in a 225 BTU/kWh (9,200 – 8,875) heat rate improvement as measured by the Opening and Closing Steam Path Audits. The heat rate improvement due to the new last stage is 320 BTU/kWh – 225 BTU/kWh = 95 BTU/kWh. Therefore, the new last stage met and, in fact, exceeded its guarantee by 6 BTU/kWh.

Results and Discussion

Megawatt Electric's Performance Guarantee Program resulted in all parties being satisfied. However, what if the tested heat rate improvement were only 312 BTU/kWh instead of 320 BTU/kWh? The heat rate improvement due to the new last stage would then be 312 – 225 = 87 BTU/kWh. The result would then be the new last stage missed guarantee by just 2 BTU/kWh.

This difficult position indicates a problem with a) the new last stage, b) the testing, or c) the Steam Path Audit. The key to dealing with this situation is anticipation and planning during the contractual stage of the Performance Guarantee Program.

Performance testing problems can be minimized by getting both parties involved and a mutually acceptable third party to oversee the testing. Both parties should then agree to allow the third party to arbitrate any differences on site while all parties are still present.

Invariably, measurement uncertainty will be a subject of debate. When this occurs, the focus should be on those measurements that have the greatest impact on test results. Here, heat balance software can aid in this phase of the Performance Guarantee Program.

Like the testing, the Steam Path Audit should involve all parties as much as possible and a mutually acceptable third party should arbitrate differences in results immediately after completing the Steam Path Audits and before leaving the site.

Conclusion

A Steam Path Audit is an integral part of a Performance Guarantee Program when a turbine owner is procuring guaranteed new parts. A Performance Guarantee Program results in high quality performance testing, high heat rate recovery during outages, cooperation between parties, and verifiable results.

Summary

Steam Path Audits quantify performance improvement due to routine maintenance so the vendor can not take credit for performance improvements measured in the guarantee test. A numerical example of replacing the last stage demonstrated the use of the Steam Path Audit by using the following formula:

Delta Heat Rate (Test) – Delta Heat Rate (Steam Path Audit) = Delta Heat Rate (New Part).