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A STATIC TEST FACILITY FOR THE STUDY OF DEPOSIT FOULING ON STEAM TURBINE BLADES

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ABSTRACT

For several decades it has been recognised that deposition on the surfaces of steam turbine blades during operation can result in significant loss in thermal performance and, in some cases, a large reduction in the steam swallowing capacity. One principal cause of deposit fouling on HP turbines is copper, although other elements, for example silicon, can also be problematic. Copper is initially corroded from condenser and feedheater tubes by the water which then contaminates the inner surfaces of the boiler as the water is evaporated. The steam from the boiler becomes contaminated with copper oxides as a result of the copper fouling inside the boiler. The solubility of copper compounds in steam is a strong function of pressure. As the steam expands through the turbine and pressure reduces, the copper oxides deposit out onto the blade surfaces, roughening them and resulting in loss of performance [1].

A test facility is being developed by Durham University to allow copper deposition under real steam conditions to be investigated in a laboratory environment. The facility consists of a non-flow 'box test' type arrangement. The initial experimental arrangement consisted of a single reactor vessel. Superheated steam at typical boiler conditions was created in the reactor vessel and held at these conditions for several 10's of hours. The reactor vessel also contains a copper sample and a sample of target blade material. During this first stage of the test, copper dissolves into the steam, contaminating it with copper metal and its oxides. In the second stage of the test the steam conditions are quickly reduced to lower pressure values that are representative of the latter stages of a typical HP turbine cylinder from a large fossil-fired unit. The reduced solubility of copper in steam at the lower pressure results in copper depositing out onto the sample of blade material. Conditions are held constant again for 10's of hours during this second stage of the test, to allow sufficient time for a reasonable amount of deposition to occur. The reactor vessel is then cooled and the sample of blade material removed for analysis.

Results from some initial testing using the single reactor vessel arrangement are described in this paper. The results demonstrate that it is possible to create a copper transport and deposition process under representative steam conditions using a test facility of this type.

It was found to be difficult to control, accurately, the single reactor vessel tests, particularly during the second phase when the steam conditions were reduced. A revised test set-up is proposed consisting of two reactor vessels, in order to improve the operability of the facility.

The ultimate aim of the work is to use this facility to investigate, systematically, deposition under different steam conditions and to produce a physically based model of the process. The facility will be validated by comparing test results with deposit samples taken from real turbines that experience copper fouling during operation.

INTRODUCTION

Copper deposition in steam turbines has been recognised as an issue affecting the performance of steam turbines from the 1950s, when high pressure units were introduced into the US. The issue of copper deposition was experienced at Ohio Power Company Philo 6 supercritical unit in 1958 and later on Cleveland Electric Avon Unit 8 in 1960 [2]. Copper deposition has since been reported in a number of stations across the globe, though the majority of data obtained thus far originates from US stations reporting the accumulation of deposits in operating turbine units.

Operators at stations experiencing deposition determined through chemical analysis of deposit samples that a number of materials were present. These include, but are not limited to, silicates (usually in the IP turbine), sodium and, for instance, calcium, chromium, iron, zinc and aluminum in addition to copper. The variety of chemicals present in the deposits indicates the breadth of chemical processes taking place in the water-steam cycle that result in deposition on turbine blades. Copper is consistently found as a deposit constituent and has received the most attention as a result.

The accumulation of deposits on blade surfaces roughens them, causing reductions in performance; it can also reduce output through blockage of the blade throat areas. This has led to increased research in this field and has driven the current program at Durham University. Understanding and controlling deposition processes is particularly important to the steam turbine retrofit industry, where projects are evaluated against guaranteed improvements in thermal performance of units. Deposits can lead to significant reductions in turbine performance after low operating hours and consequently the retrofitting company can be held liable for large liquidated damages due to performance shortfalls against guaranteed levels.

Improving the understanding of the deposition mechanism and subsequently predicting the process of deposition can assist in reducing the turbine retrofitter's exposure to penalties. For the utilities, the management of deposited materials can be improved if more is known about their formation, structure and other deposition patterns. The process for the introduction of copper into the water-steam cycle, transport through the boiler and eventual deposition in turbine blades is described in later sections.

In this program of research the philosophy is first to investigate the current understanding of copper deposition by reviewing open literature and data that has been made available to project team directly from industry. Secondly, the project aims to establish and validate a new laboratory test methodology for investigating the deposition process. The next stage will be to use this facility to investigate and develop a model of the deposition process. Finally, the information obtained on fundamental aspects of deposition processes and further testing will be used to develop methods and techniques to control and reduce the impact of deposit fouling on steam turbine blades.

The next section of this paper contains a literature review. This is followed by a description of the copper corrosion, transport and deposition process onto turbine blade surfaces in the water-steam cycle of affected plants. The test arrangement, methodology and results from first generation laboratory tests carried out within a single reactor vessel are then described. A proposal for an improved test arrangement using two reactor vessels is described in the next section. Finally, results from analysis carried out on deposition samples taken from in-service units are described and discussed. Ultimately, it is intended to use site information of the type described in the last section to validate the deposit samples created in the laboratory environment, once the two-box test arrangement has been fully developed and commissioned. This work is ongoing at the present time.

LITERATURE REVIEW

Much of the current understanding of copper deposition is based on site experience. Studies that focus on the impact of copper deposition on surface roughening of blades have shown significant reductions in cylinder efficiency (Figure 1), and on the reduction of steam swallowing capacity and hence unit output through constriction of the blade throats [3]

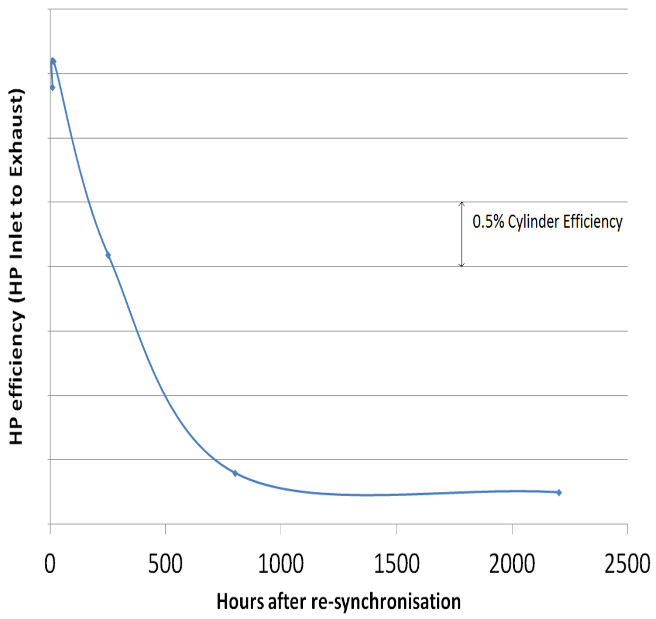


Figure 1: Generating station cylinder degradation resulting from deposits, courtesy of ALSTOM.

Figure 2 shows a photograph of a turbine blade that has experienced significant deposition on its surface. Copper was identified to be one of the main components present in the deposition layer. Deposits typically accumulate on turbine blades during the first few hundred operating hours, after which time the system stabilizes and no further increase in deposit thickness or degradation in unit efficiency occurs. This can be seen in Figure 1. In this example, cylinder efficiency drops by approximately 3.5% during the first 1000 hours of operation and then remains essentially constant after that point. Also the deposits accumulate on the fixed turbine blades to a greater extent than the moving blades. It is hypothesised that this might

be because the fixed blades offer more favourable static conditions that encourage crystal growth and nucleation of copper on the blades.
Several approaches for reducing the impact of deposits on unit performance have been proposed. These include decreasing the boiler pressure in order to reduce the solubility of copper in steam, for example at Lambton [3], regular chemical and mechanical cleaning of deposit affected turbines, [4] and introducing rigorous water chemistry monitoring and control [4]. This last point can be considered to be an important step towards water-steam cycle water chemistry optimization [5]-[6]. The variety of solutions attempted highlights the difficulty in developing a single industry standard solution for minimizing the effect of deposits. No such solution exists at present to deal with the formation of these deposits [4].

Some utilities have experienced increased copper deposition while attempting to deal with other operational issues. At Tarong 7, erosion of steel components led to the introduction of Oxygenated Treatment (OT) in a previously mixed metallurgy water-steam cycle. The term mixed metallurgy refers to the usage of materials such as copper alloys and steel in the water-steam cycle components. From this, surges of copper in the system occurred, potentially through secondary transport from copper reservoirs in the boiler. As was stated by Jonas et al. [4] a purely chemical solution is difficult to achieve and such a solution has not yet been developed and widely implemented in the industry.

Figure 2: Generating station deposit accumulation on turbine blades, courtesy of ALSTOM

Matthews and Daniels et al. [7]-[10]published work on copper deposition and present the issue in a broad manner describing it in high level terms. Jonas et al. [4] expand on that work, providing greater detail and understanding of the copper deposition process. For example, [4] gives additional background information on the issue of copper deposition and the report concludes with a set of recommendations to tackle the problem.

Investigations carried out by Pocock and Stewart [1] and Palmer et al. [10]-[12] provided a more scientific approach to the issue by systematically investigating the copper corrosion, transport and deposition mechanisms. This work demonstrated that copper and its oxides have appreciable solubility in steam. The research generated by Palmer et al. was aimed at evaluating the thermodynamics and solubility of copper and its oxides in both steam and water.

Much of the work undertaken to understand copper deposition is documented under “Program Copper” [5]-[6], [13]-[14] an EPRI funded project that aimed to progress the current understanding of copper corrosion, transport and deposition in the water-steam cycle of generating stations. These reports provide a valuable knowledge base for much of the current understanding of copper deposition. “Program Copper” issues recommendations that follow a full diagnosis of the copper deposition problem. These recommendations include immediate and long term actions to tackle the issue and include, for instance, chemical and mechanical cleaning, optimizing field chemistry and the removal of copper-bearing equipment from the water-steam cycle.

Additional investigations by EPRI studied the effects of turbine blade roughening [14]-[15] and deposition of materials in the water-steam cycle [16]. In the studies [14]-[15], the main conclusion drawn was the relationship made between surface finish of blades, deposit accumulation and cylinder efficiency. Turbine efficiency could be improved by good blade surface finish. In [16], the key parameters involved in deposition activities in the boiler and turbine are discussed.

DESCRIPTION OF THE COPPER DEPOSITION PROCESS

The process for copper corrosion, transport and deposition is described in this section. These processes are not well established with various processes and reaction routes proposed leading to different conclusions. What follows is based on the literature that has been reviewed in the previous section.

The copper transport process is initiated by copper-bearing equipment such as feedwater heaters or condensers in the water-steam cycle being corroded, eventually producing copper species that are transported into the water. These species are then transported into the boiler and superheater. As the solubility of the copper species is much less in steam than it is in water, much of the copper plates out onto the boiler surfaces, effectively forming large copper reservoirs [5]-[6]. Once present, the processes that result in the formation of copper deposits are extremely difficult and expensive to eradicate from the water-steam cycle. Simple replacement of copper bearing equipment does not wholly remove copper from the cycle once reservoirs have formed in the boiler/superheater. Further deposition will take place on equipment in the water-steam cycle, fed by copper that has originated for these reservoirs.

The copper species are carried over from the boiler into the steam exiting from the superheater via one of several routes. The first of these involves direct carry-over of boiler water liquid droplets into the saturated steam entering the boiler superheater from the steam drum. These droplets are then evaporated in the superheater, depositing the copper species onto the internal surfaces of the superheater. The copper species deposited in the superheater then find their way into the steam exiting from the superheater through a range of potential processes such as dissolution, evaporation and mechanical exfoliation. A second route is by vaporous carry-over. Here, copper species are carried over from the boiler water into the saturated steam leaving the steam drum by the simultaneous evaporation of the volatile copper species along with the steam. A third possible route is through direct injection of feedwater into the superheater through the attemperation sprays used to control the superheater temperature. In this case, any copper species within the feedwater are transported by dissolution or evaporation into the superheated steam [5]-[6].

The solubility of the copper species in steam is a very strong function of pressure. As the superheated steam expands through the turbine, the copper species present in the steam precipitate out onto the turbine surfaces, including the blades, as the pressure drops [1]. The deposits are typically found in the HP steam turbine cylinder. According to data obtained from EPRI, the majority of the deposit builds up on the final HP stages [2].

Copper deposits are often found on older stations that operate with mixed metallurgy equipment such as feedwater heaters and condensers. The combination of materials presents a dilemma in terms of managing the cycle chemistry, as different materials require different water chemistry. Often a compromise between optimum conditions for these materials may offer the best solution. Once deposit reservoirs have formed in the boiler through the processes previously described, it is essentially impossible to eradicate them from the system, even years after the parent copper containing cycle components have been replaced by non-copper containing alternatives. Remedial work such as chemical cleaning of the turbines to remove any copper deposition, generally only temporarily relieves the issue. An improved understanding of copper deposition and its control is needed to achieve sustained performance recovery on copper affected units.

SINGLE VESSEL BOX TESTS

The initial test arrangement set up by Durham University to investigate copper deposition consisted of a single reactor vessel. This was an autoclave vessel designed to operate at high temperatures and pressures typical of those found in steam turbine boilers. The single reactor vessel test arrangement is shown in Figure 3. The apparatus consists of a 145cm^3 316 stainless steel pressure vessel containing copper metal samples (washers) and target stainless steel samples. These were mounted apart on a steel threaded rod inside the vessel, so that copper could only be transported onto the surfaces of the stainless steel targets via the steam inside the vessel. The vessel was closed by an M32 threaded cap and sealed by a Grafoil graphite gasket. The pressure inside the sealed reactor vessel was measured by a siphon pressure gauge arrangement.

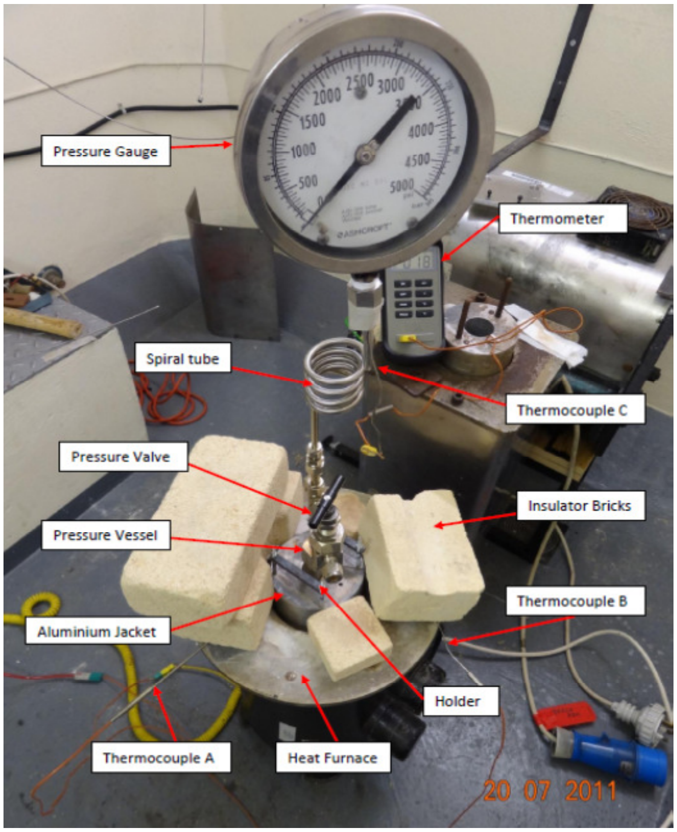


Figure 3: Single vessel box test arrangement from [17].

The reactor vessel was placed in a 1.2 kW furnace. The vessel was surrounded by an aluminium jacket in the furnace which effectively eliminated any air gap between the vessel and the furnace inner wall. Insulating bricks were placed over the exposed end of the vessel to reduce heat loss to the surroundings. The vessel temperature was measured by a wall-mounted K-type thermocouple positioned at the interface of the reactor vessel and its surrounding aluminium jacket. A schematic of the Durham single vessel box test arrangement is shown in Figure 4.

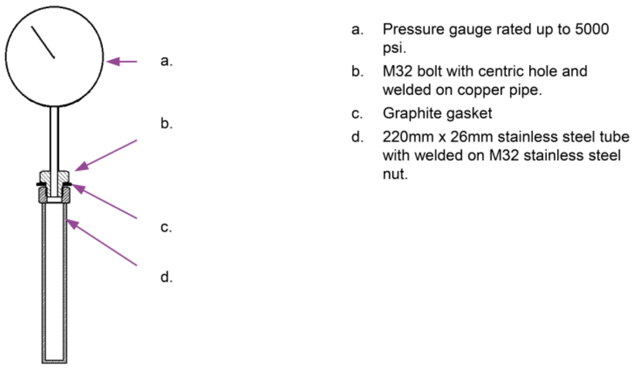


Figure 4: Schematic of the Durham single vessel box test

The vessel was prepared by cleaning its internals with soap, acetone and distilled water before each test. A predetermined quantity of water was placed into the vessel, together with the rod-mounted copper and stainless steel target samples. The vessel was then sealed and placed into the furnace. As the internal volume of the reactor vessel is known, steam properties can be used to calculate the amount of water required at the start of a test to achieve any desired steam pressure for a given vessel temperature. In the various tests that were carried out with this arrangement, sufficient water was used to create steam pressures inside the vessel of up to 200 bar(g) at a vessel temperature of 550^{o}C; these conditions are representative of superheated steam between sub-critical and super-critical boiler conditions. The conditions were held in the tests for typically a 24 hour period allowing time for transport of copper from the base samples into the steam. The temperature of the furnace was then reduced for the second phase of the test. The pressure of the steam drops as a result of the lower vessel temperature. These conditions, representative of steam conditions part-way through the steam turbine expansion, were then also held for a 24 period, triggering deposition of steam borne copper species onto the vessel internals and the stainless steel target washers.

Figure 5 shows target stainless steel washers from a test during which the steam was initially held at 200 bar(g) and 550^{o}C, before being reduced to 60 bar(g) for the second phase of the experiment.

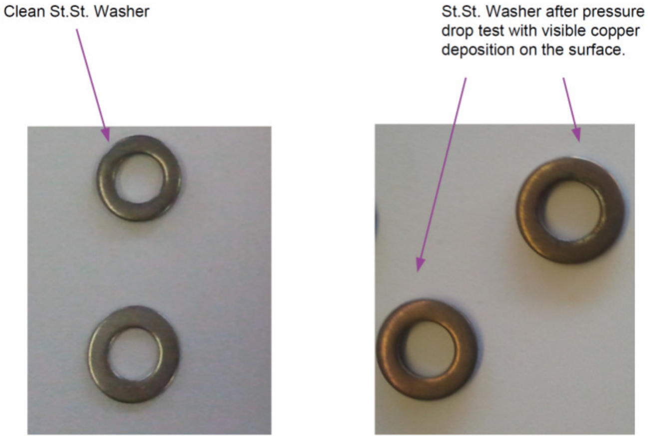


Figure 5: Before (left) and after (right) the single reactor vessel test, showing surface copper deposit on the stainless steel washer.

A visual inspection of the stainless steel washers before and after the test shown in Figure 4, confirms that copper has been successfully transported by the steam and deposited onto the target washers during the test.

Ion Beam Analysis (IBA) was used to investigate the surface deposits on the washers. The result from the test is shown in Figure 6. The result confirms the presence of copper (through a peak in this IBA channel) in the deposit layer together with iron, carbon and oxygen originating from the stainless steel and the test environment.

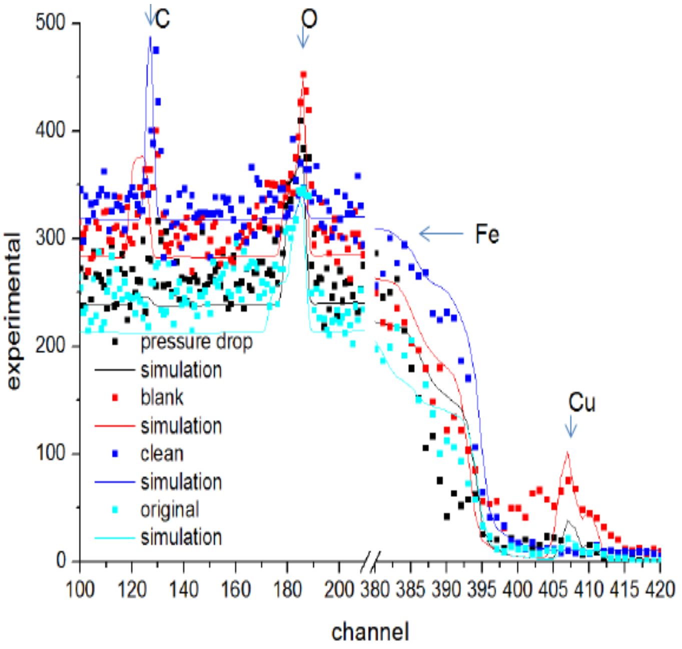


Figure 6: IBA test results from analysis of used stainless steel washers

The single vessel box test was successful in demonstrating that copper transport and deposition could be achieved in the laboratory environment in a 'static' steam test, avoiding the need for a significantly more complex steam 'flow' type experimental arrangement. For example, EPRI have carried out tests with HP and LP converging-diverging nozzles using bled steam from a power plant, where steam is introduced into a pipe and gradually expanded as the pipe area increases, resulting in the release of steam borne impurities onto a target material surface [15]. Box' type tests potentially offer a much simpler and lower cost alternative for achieving similar results.

Two issues need to be addressed before static tests in reactor vessels can be fully accepted as viable alternatives to nozzle flow tests for deposition studies. These are:

1. The speed of the transition between high pressure and low pressure test states and the controllability of the low pressure test state experienced in the single vessel tests described above both need to be improved upon to obtain more accurate test results.

2. The form and structure of the deposit samples created in static reactor tests need to be validated against deposit samples taken from turbines in operating power plants that are affected by deposition, to confirm that the test results are consistent with the deposition that occurs in real machines.

Progress on further work aimed at addressing both of these issues is described in the next two sections.

IMPROVED BOX TEST ARRANGEMENT

The single vessel box test offers a robust and simple approach towards carrying out a copper deposition test with the conditions inside controlled by amount of water added and heat applied. However, the thermal inertia of the pressure vessel and furnace system results in a transition time of several hours to move from the initial high pressure 'boiler' steam conditions to the lower pressure 'turbine' conditions part way through a test. A second drawback was found to be the difficulty of controlling the lower pressure steam conditions in the second half of the test to an acceptable accuracy, due to the long time period needed to achieve stable conditions. A two reactor vessel box test arrangement has been proposed in order to address both of the short comings identified with the original single vessel setup. A schematic diagram of the two-vessel test arrangement is shown in figure 7. The proposed two-vessel box test will offer better control of the test conditions than the single vessel box test described earlier. Reactor vessels I and II (Figure 7) are placed in separate furnaces. Vessel I, which contains copper and water samples is heated so that steam is formed at representative 'boiler'conditions. The steam conditions are held stable in Vessel 1 for 10's of hours allowing copper to transport into the steam. Vessel II is then preheated and Valve 1 is opened. Vessel II contains the sample of blade material. Opening Valve 1 allows the steam from Vessel I to flow into Vessel II, resulting in a rapid transition for 'boiler' to lower pressure 'turbine' steam conditions to be achieved. The 'turbine' representative conditions in Vessel II are held constant for several 10's of hours allowing sufficient time for significant copper deposition to occur within the vessel and onto the surfaces of the sample of blade material. When the test is complete the furnaces are turned off and allowed to cool before the test sample is removed.

The test rig has been built and is currently undergoing commissioning tests (see Figure 8). Larger pressure reactor vessels have been designed than that used in the single vessel test (2 x 1.35l compared to 0.145l for the single vessel tests). The greater reactor vessel volumes will result in increased rates of copper transport by the steam and reduce the additional volume effect of piping and other associated equipment.

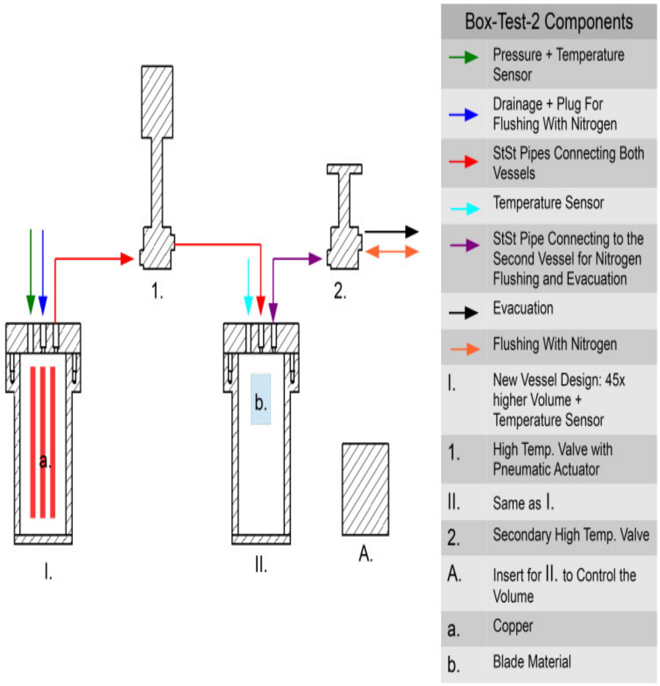


Figure 7: Schematic Diagram of the Two Reactor Vessel Box Test Arrangement.

Figure 8: Two Reactor Vessel Test Assembly before Commissioning (furnaces not shown and with substitute hand operated isolation valve between vessels in place of pneumatic control valve to be used in tests).

ANALYSIS OF DEPOSIT SAMPLES FROM IN-SERVICE MACHINES

The industrial partner ALSTOM made available a number of deposit samples taken from copper affected machines for the purposes of providing benchmarking data against which deposit samples created in the static vessel laboratory tests can be validated. The ultimate aim is to compare the site results with the test results to confirm that the structure and composition of the deposit created in the tests is representative of deposition in real machines. Once validated, the test rig will be used to investigate the effect of surface finish, surface treatments and steam chemistry on the copper deposition process, in order to identify techniques for controlling it and reducing its impact on turbine performance.

The first samples to be analysed for this program were obtained from the deposits on HP and IP steam turbine blades at two stations. X-Ray fluorescence (XRF) spectroscopy was used to analyse the samples. This technique allows elemental analysis of the samples to be carried out.

Figure 9 shows a typical XRF result for one of the samples. The samples were collected from the turbines by rubbing emery paper over the deposits on the surfaces of the blades. Two sets of data are shown in the spectra, the solid line is the background reading for the emery paper alone, seen to be high in silicon . The dashed line shows the readings obtained from the deposit sample embedded within the surface of the emery paper. This indicates the presence of appreciable quantities of elements including aluminium, calcium, potassium, iron, sulfur and copper in the sample shown. Apart from the presence of iron and copper in the deposit sample, the remaining elements are anomalies in the water steam cycle and could be due to contamination of the water steam cycle. Copper is present in the water-steam cycle through the mechanisms outlined earlier in this paper.

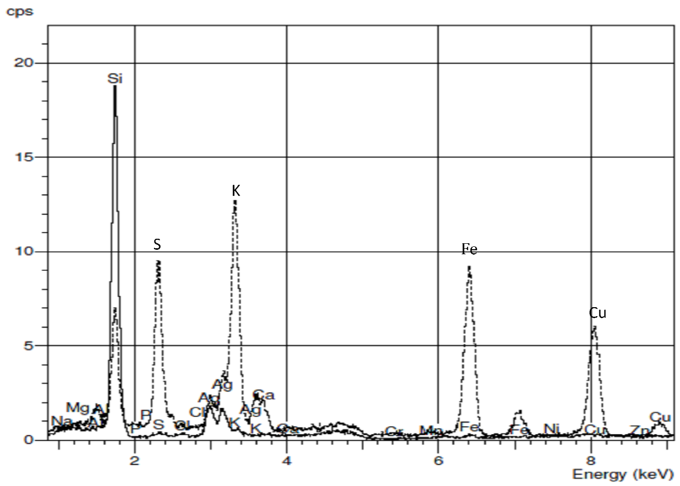


Figure 9: XRF Spectra Showing Presence of Copper in a Typical HP Turbine Blade Sample.

Figure 10 shows results for copper content from XRF analysis of a number of deposit samples taken from different locations in the HP and IP turbines of one of the units studied. The nomenclature used in the label on the horizontal axis in the figure identifies HP or IP stage number and whether the sample was taken from the diaphragm fixed (D – the unit has impulse turbines) or rotor moving (M) blade. The results show that the largest amounts of copper appear in the deposits in the latter half of the HP expansion. There is relatively little copper in the samples taken from the early HP stages and from the IP turbine.

The results shown in figure 10 are consistent with the results of others, for example the EPRI data shown in figure 11. Here, too, the majority of the copper contamination is found in the deposits taken from the latter stages in the HP expansion. The EPRI results are for a super-critical unit with a boiler pressure of 289 bar whereas the data shown in figure 10 is for a sub-critical unit with a boiler pressure of 160 bar. The figures confirm that copper fouling can affect both sub- and super-critical units. The difference in operating pressures possibly explains why evidence of significant copper deposition is found earlier in the HP expansion in the results in figure 10 than in figure 11. Both sets of site results indicate that the solubility of copper in the steam does not appear to change significantly as the pressure initially drops from boiler conditions. It is not until some way along the HP expansion that the solubility changes sufficiently for appreciable amounts of copper to be deposited onto the steam-washed surfaces of the turbine . It is intended that this type of observation will be investigated and better understood, using the test facility described in this paper once it has been commissioned and validated.

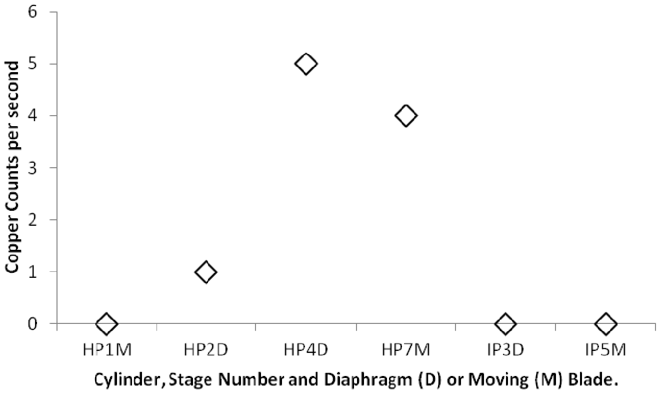
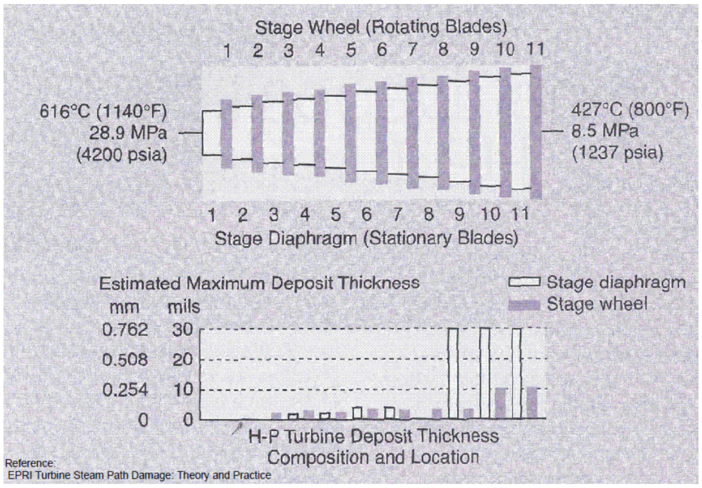


Figure 10: Presence of Copper Deposits at Various Locations along the Turbine Expansion for One of the Units for Which Data was Available.



Reference:
EPRI Turbine Steam Path Damage: Theory and Practice

Figure 11: Copper Accumulation in a HP Steam Path (taken from [6]).

CONCLUSIONS

Copper deposition in steam turbines can result in large reductions in generating output at affected generating stations. The issue is of particular interest both to station owners and turbine retrofit suppliers, the latter guaranteeing their products based on thermal performance improvements. The solubility of copper in steam is a strong function of pressure. Affected units have large amounts of copper in their boilers, which contaminates the superheated steam. As pressure drops in the expansion through the turbine, the copper precipitates from the steam and deposits on the turbine surfaces. Only limited studies exist in the open literature on the mechanisms behind the copper deposition process and on developments to control and reduce its impact.

A static reactor vessel test arrangement has been proposed as a relatively simple and low cost method for experimental investigation of copper deposition. Preliminary results from tests using a single vessel has shown that it is possible to transport copper from parent material and deposit it onto the surfaces of stainless steel targets, by controlling its solubility in steam in this type of experiment. A more advanced test arrangement using two reactor vessels has been described. This has been designed to allow more accurate control of the experiment. The improved facility is currently undergoing commissioning. Once this is complete the test methodology will be validated by comparing the structure and composition of deposits taken from operating turbines with the results from the static vessel tests. The analysis of some deposit samples from turbines has been described in the paper. Some general conclusions have been drawn concerning the locations in the turbine expansion where copper deposition is most likely to occur in affected units.

Once the facility has been commissioned and validated against site data it will be used to investigate the deposition process and to develop methods to control it.

NOMENCLATURE

AVT(R) – All Volatile Treatment, Reducing
HP – High Pressure
IBA: Ion Beam Analysis
IP – Intermediate Pressure
LP – Low Pressure
XRF: X-Ray Fluorescence

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