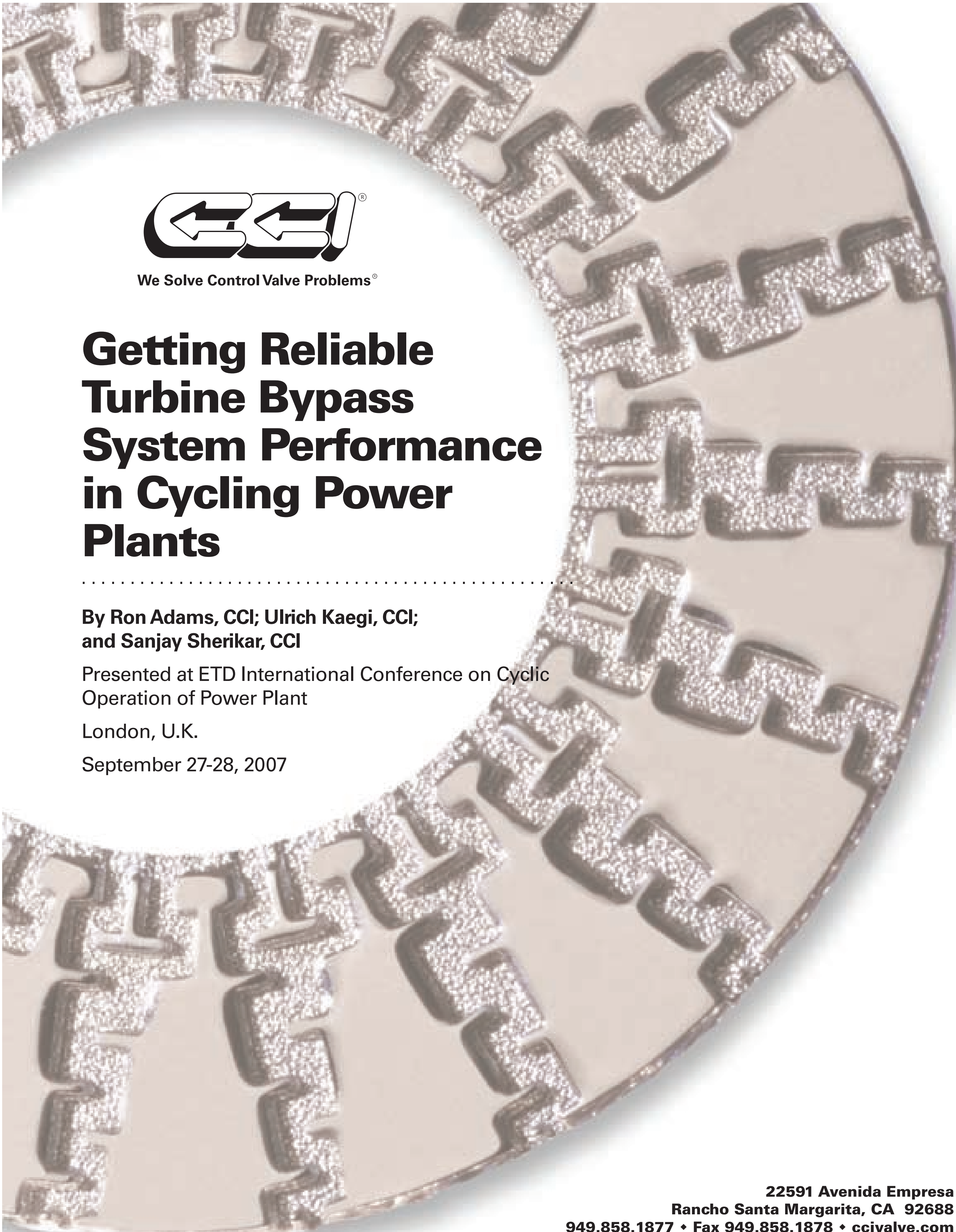

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Getting Reliable Turbine Bypass System Performance in Cycling Power Plants

By Ron Adams, CCI; Ulrich Kaegi, CCI; and Sanjay Sherikar, CCI

Presented at ETD International Conference on Cyclic Operation of Power Plant

London, U.K.

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■ **By Ron Adams,** CCI USA, **Ulrich Kaegi,** CCI Switzerland, **Sanjay Sherikar,** CCI USA, Presented at ETD International Conference on Cyclic Operation of Power Plant, London, U.K., September 27-28, 2007

Abstract

Recommendations to get reliable performance of turbine bypass systems are made. These are based on recent experiences in a number of cycling power stations. Results of an investigation into cracks in the pressure boundary downstream of turbine bypass systems in some power stations are described. Where failures occurred, these systems were behaving quite differently from the design intent or what the operators thought was going on at the turbine bypass system (TBS). The root causes were traced through analysis of failed components, reviews of plant layout and operation, analysis of DCS data, additional measurements at the site and finite element analysis. The primary contributors to such problems were the control algorithms, oversized spray-water valves, leaking spraywater lines, and thermal shocking of the system. Improper layout of the system is a contributor in some cases. All these, in varying degrees, contribute to the damage to the components and, over time, results in fatigue failures.

Introduction

Turbine bypass systems are a common feature in cycling power plants because of the flexibility that they offer in operation of the Unit [1-3]. These systems dissipate energy of the steam, which otherwise would have been used to produce electrical power, so that it can be dumped into the condenser safely. As a result, the process conditions experienced in this application tend to be severe. Each time the system is operated, the bypass components go through at least one significant stress cycle.

Until recently, most plants operated in base-load mode. Since the turbine bypass systems are typically required only during starts, shutdowns and trips, they experienced a rather limited number of stress cycles in their life. On the other hand, today a large number of steam power plants have to operate in cycling mode. The turbine bypass systems are used very frequently in such cases; it may occur several times a day. This causes the number of stress cycles to escalate very quickly. Even so, failures of these systems are not acceptable because they are a critical link in availability/ operability of the unit.

The combination of severe operating conditions and large number of such cycles does pose a challenge in getting these systems to perform reliably over the long-term [4, 5]. In recent years, a significant number of failures in the form of cracking in the downstream bypass pipes have been reported. Many of these have been in plants that experience heavy cycling duty. The reported failures have raised some difficult issues – does heavy cycling duty means that reliability, and availability, of the plant will be compromised? Or, should the bypass system limitations dictate the limits for plant operation?

Although these are fair questions in principle, it is desirable from a practical perspective that such questions not arise, i.e. turbine bypass systems do not become the performance-limiting component in operation of the plant. In other words, these systems have to perform reliably over long-term despite the severe operating conditions and large number of cycles. This can be achieved with the due diligence during the design phase of the system. The effort has to continue through its life-cycle with a systematic, and pro-active, monitoring and maintenance program. Prior experience provides useful guidance in this regard.

Field Experience

Turbine bypass systems are not new in power steam systems. With the correct sizing and selection at the design stage, and proper maintenance, such systems have performed reliably over many years. Despite the severity of the application, the early vintage systems incorporated simple, single-stage pressure drop valves; although the noise and vibration was high, they were able to survive the operation during start-ups, shutdowns and trips through a calibrated brute force approach. Over the years, these designs were made more robust; this includes introduction of multi-stage pressure drop technology to eliminate problems of excessive vibration and noise, wear and overall reliability.

Then why the sudden appearance of cracking issues relating to these systems? The answer can be found by examining how the nature of plant operation and, consequently, the demands on the turbine bypass systems, have changed over time. In the early systems and until recently, power stations operated largely in base-loaded mode. As a result, the frequency with which the turbine bypass systems are called upon to operate was rather limited. In the current environment, some power stations cycle frequently; this can result in the number of starts and stops in one year to significantly exceed that for base-loaded power stations by a factor of 10-100.

In practice, the starts/ stops are hard on the system from the stand-point of peak stresses and can cause a decrement in remaining life of critical components [6]. Critical components typically counted in such discussion include boiler tubes and turbines; however, turbine bypass systems are in the same league by virtue of sheer severity of the application. Field experience appears consistent with this logic. More cycling of the plants means that these systems are less forgiving to operation outside of the intended design envelope. From a different perspective, it is fair to say that it is necessary to attend to potential problems early, and eliminate them, in order to achieve high reliability of the turbine bypass systems in cycling plants.

There are many plants around the world that cycle frequently and have not experienced any significant problems. However, some of those that have experienced problems have also required major corrective actions to avoid repeated occurrences. All in all, a pro-active approach in this regard is necessary.

When problems with turbine bypass have surfaced in cycling plants, pipe cracking downstream of the steam bypass valves among them is a serious issue. This has been the case at some sites. These failures have typically been at the steam valve-downstream pipe connection or at the desuperheater-downstream pipe connection. Root cause of these failures has been established through systematic studies. The key findings from to date are described in the following sections.

Determination of Root Cause

As in most practical situations, it would not be surprising that: (a) modes of failures at different sites may be different, and, (b) there may be one or two primary contributors while other contributors may only have a marginal effect, if at all. In that spirit, the efforts to determine the root causes can be divided in the following broad categories:

- Fabrication defects;
- Operation and controls;
- System layout issues;
- Component design (valve, desuperheaters etc); and,
- Other contributors (damage during commissioning).

Fabrication defects

This was the first issue to come to light as a result of investigations that were typically done by the operating plants themselves (who then followed up with corrective actions). The most common problem was defective welding. This was traced through metallurgical analysis of samples in the crack areas.

Occurrence of such failures is not a surprise considering that the materials in this part of the system these days are high-alloy steels such as P22 and P91. Working with the latter, in particular, has been a sore issue in steam plants. Often, change of materials, such as P91 valve body connected to a P22 pipe downstream, adds complications. Such failures are preventable through good welding practices.

Another issue relating to fabrication was a mismatch between pipe sections at the weld joint resulting from out-of-roundness; this was seen in the desuperheater to downstream pipe connection. Such mismatch results in local stress concentration in the presence of mechanical or thermal loads. However, as described in later sections, the contribution to the overall stresses of this effect alone was rather limited for the cases analyzed.

Operation and Controls

This was found to be the biggest and most common contributor in the cases of failures studied to date. It is also a difficult issue because it covers many different aspects, namely: number of cycles, control logic, interlocks for spraywater, temperature sensor spraywater valve size and characteristic etc.

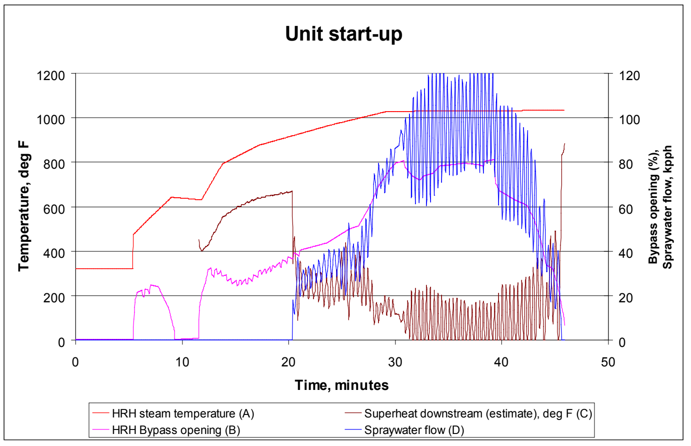

Figure 1: Unstable operation of turbine bypass system; data shown is for a hot reheat (HRH) bypass during a start-up.

The estimated effect of such transients on component life was also evaluated and is covered separately in Section IV.

Poor control of pressure upstream of the turbine bypass valves also contributes to instability of all the control elements downstream. An example of this is illustrated in Figure 3 by the DCS data for a plant during a trip condition.

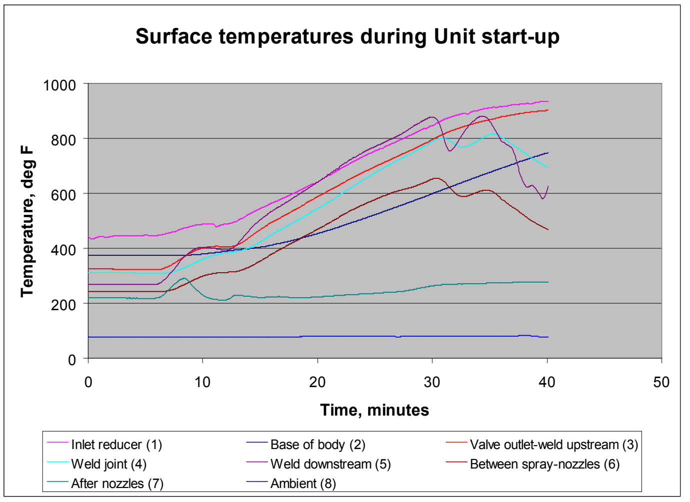

Figure 2: Metal outside surface temperatures during a start-up transient, as in Figure 1, in a turbine bypass system; thermal shock is evident in the trends for locations 4-6.

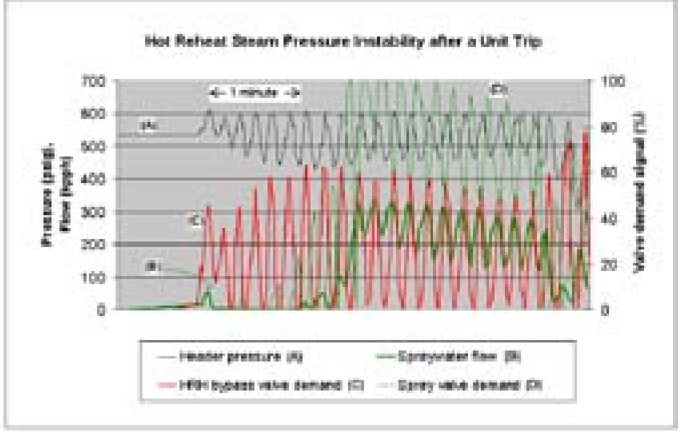

Figure 3: Instability resulting from oscillations in hot reheat steam (HRH) pressure

System Layout

There is a great deal of variability in layouts of turbine bypass system in different plants. It reflects different philosophies of their respective designers; the designers, in turn, depend on suppliers of the turbine bypass systems in varying degrees.

It was observed in some cases of failures that the system layout was far from desirable. One specific deficiency in this regard was the placing of the steam control valve far from the main steam line, without any pre-warming of the system. In such configurations, the steam control valve cools over time while the plant is in operation (since these valves are normally closed); when they are opened, during a shut down or Unit trip, high temperature steam rushes through the bypass system resulting in thermal shock to every element in its way.

Excessive distances from the main steam line to the steam pressure-reducing valve (PRV) are not desirable from other perspectives as well. It leads to accumulation of condensate during start-ups and erosion of the components downstream because of liquid impingement.

Component Design

Turbine bypass systems on the whole consist of the following elements: steam pressure reducing valve, desuperheater and spraywater valves; it is complemented by a temperature sensor downstream of the desuperheater and control logic that generates signals to the valves (steam and water), which are the final control elements.

A review of the control valve design indicated no apparent deficiency that could explain the cracking. This is not surprising because the industry as a whole, both the steam plant system designers and the valve industry, is conservative when it comes to valve design. Valve design, especially the pressure boundary requirements, is strictly governed by codes such as ANSI B16.34, ASME Section III, Pressure Equipment Directive (PED) and EN 12516.

Other Contributors

It is suspected that other factors, such as damage during the commissioning stage, poor condensate drainage or events during operation at a later stage, are likely to have contributed to reduced component life. Events such as water hammer in some cases were severe enough to leave their mark in the form of damage to the piping supports. However, these other contributors were not considered as primary cause of failure in the cases that were studied.

Finite Element Analysis

Finite element analysis (FEA) of critical areas was done to assess the impact of thermal shocks observed in the monitoring of turbine bypass systems. This analysis was carried out for two sets of operating condition:

bypass operation in which spraywater did not impinge on the pipe wall; and,

bypass operation in which spraywater impinged directly on the pipe wall.

The first condition is what is desirable, and is the design intent, in practice and serves here to establish a reference. In this case, the temperature transient results primarily from heating up the metal by the hot steam after the steam valve opens. The temperature distribution for the valve-desuperheater connection of Figure 4, and the corresponding stress distribution, is shown in Figures 5 and 6.

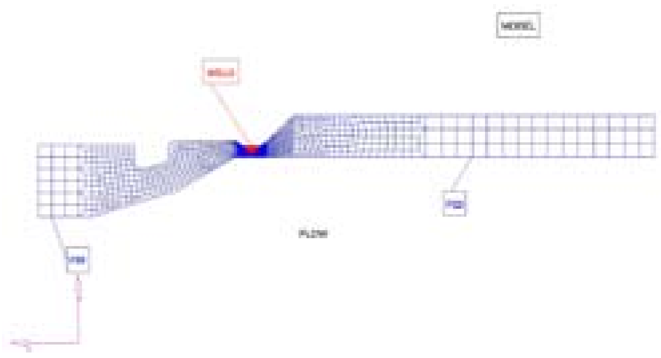

Figure 4a: Mesh for the section modeled

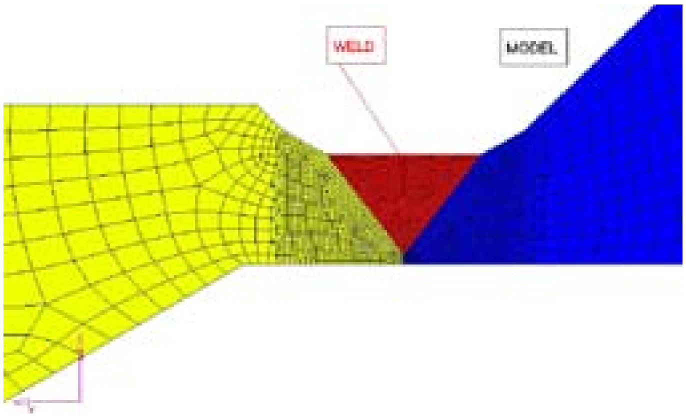

Figure 4b – Detail of the mesh at the weld joint

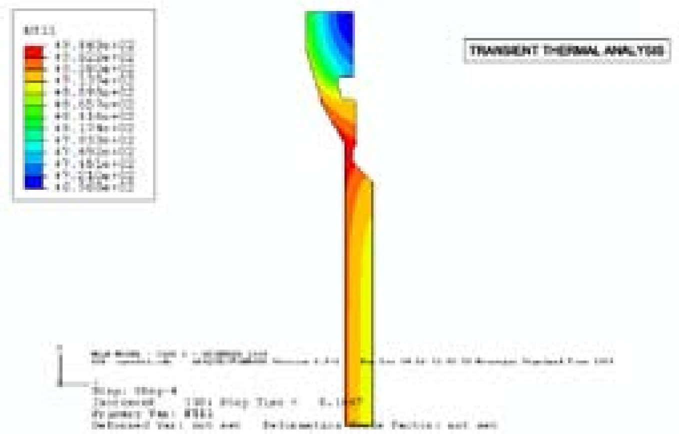

Figure 5: Peak Temperature is 986 F.

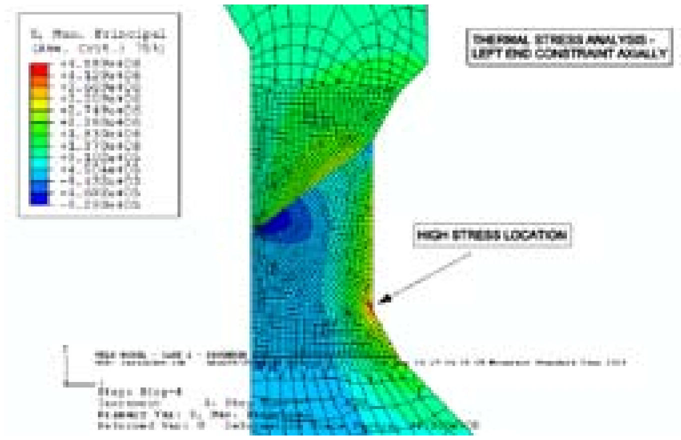

Figure 6: Peak Stress is 4.589E6 lb/ft2 or 31868 psi.

The same configuration was analyzed for the second condition representing abnormal conditions in real life resulting from poor control of the system in general, and poor control of spraywater flow in particular. In this case, the transient consists both of heating up of the metal by the steam and occasional quenching of the metal (on the inner diameter) when spraywater impinges directly on to the surface. The specific conditions for the transient during such abnormal operation are shown in Figure 7; they are based on field measurements. The periods of and over-spray under-spray were estimated so as to correspond to the temperatures on the outside of the pipe illustrated in Figure 2.

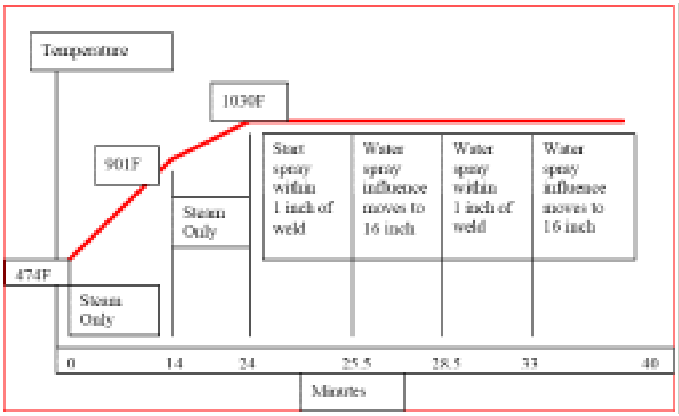

Figure 7. Graphical representation of transients in the steam valve outlet-desuperheater section of a hot reheat (HRH) bypass system. Even after the steam valve is opened, the spraywater flow does not come on until at 24 minutes. This is followed by two cycles, each cycle comprising a period of over-spray followed by a period of under-spray, as a result of poor control.

The temperature distribution, and the corresponding stress distribution, when the system is subjected to thermal shock are shown in Figures 8 and 9. This scenario is the most frequent cause for spraying to the hot walls. The lack of interlock between steam and water valve results in the spraywater opening before there is steam flow or remains open even after the steam valve is already closed. Over-spraying due to a cycling spraywater control is another common reason for spraying to the hot wall.

Overall, two important results were derived from this analysis. First, it correctly predicted the location of initiation of the crack. The second important result is that it gave an estimate of the reduction in component life because of thermal shocks as in Figures 2 and 7. The estimated number of cycles to failure for the reference case of operation as intended based on the computed peak stress values was estimated to be about 100,000 cycle per this analysis; this dropped to nearly 1000 cycles for the case of transients as in Figure 6.

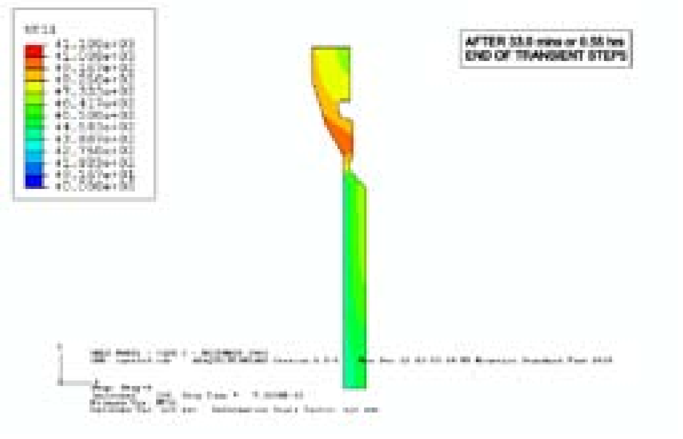

Figure 8: Temperature distribution when principal stress peaks at the weld joint on the OD

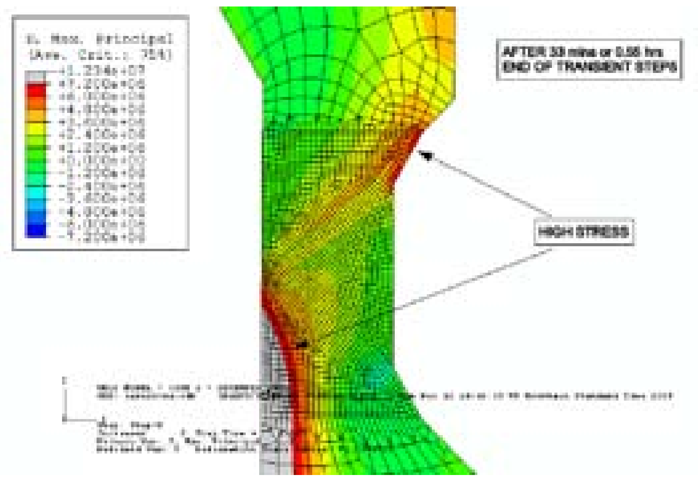

Figure 9: Peak Stress is 47,020 psi on the OD

The influence of water temperature on stresses is illustrated in Figure 10, which is based on extreme three-dimensional thermal gradients resulting from spraywater impinging directly on hot metal sections downstream of spray injection. Boundary conditions for these analyses were hypothesized based on qualitative observations. The peak stress is directly proportional to steam/water temperature difference, which is the driving "force". Extrapolation of these curves to zero temperature difference results in a zero stress as expected. Although failures of this type have not been reported to date, the magnitude of the calculated stresses underscores the importance of keeping spraywater away from hot metal sections.

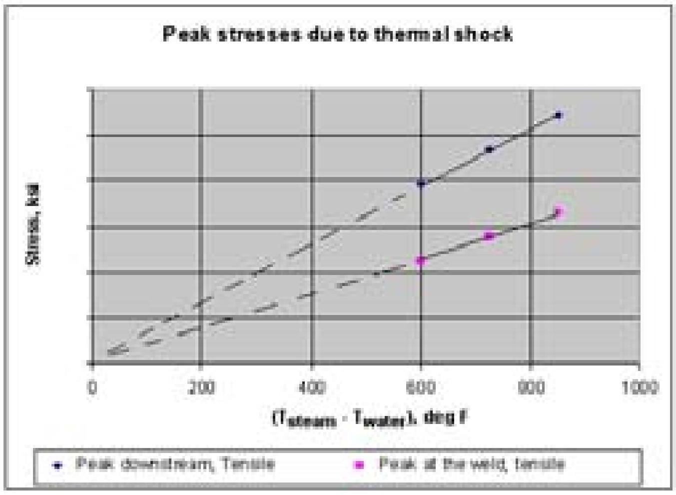

Figure 10: Peak stress versus steam/ water temperature difference.

FEA was also used in the estimation of increase in peak stress due to the following:

- hick section to thin section joints when compared to thin section-thin section joint,
- misalignment in welding piping, and,
- circumferential temperature gradients.

These were found to raise stresses marginally when compared to the effect of impingement of spraywater on hot metal as described earlier, so that their overall impact on the number of cycles to failure was insignificant.

Discussion - Recommendations for Reliable Performance

It is clear that a conscious effort is needed to get reliable turbine bypass performance in practice. The demands of the overall plant must be met, i.e. turbine bypass system should not be the limiting factor in plant operation. The valves, and the system as a whole, may be forgiving to severe operating conditions such as thermal transients to a certain degree. However, there will be technology- and physics-based limitations. There is a lot more than can be done in the form of better practices that will ensure reliable operation of turbine bypass systems. Analysis of pipe cracking failures in cycling plants leads to the following recommendations to ensure reliable turbine bypass system performance.

System Design and Layout

This is first place to influence the design of turbine bypass systems. Thermal shocking of the turbine bypass should be avoided to the extent that it is possible through proper system layout. There are many considerations in the optimal placement of the turbine bypass system with respect to the main steam line. For example, if long distances are dictated by the plant layout, then careful engineering of pre-warming and drainage of the connection pipes and the valves is critical for reliable operation. Material changes between components should be avoided; for example, if the upstream pipe is P22, then the valve body and the connecting pipe downstream should preferably be the same material. The downstream temperature sensor should be optimally located to get reliable a reliable temperature signal while avoiding unacceptable long time delays in response. Spraywater lines should be provided with strainers and isolation valves. Details in the layout of the spraywater line, such as location of the spraywater valves with respect to the injection points and strainer, can be extremely important. In addition, flow-meters are highly recommended in the spraywater lines for reliable feedback of proper operation. Sufficient distance downstream of spraywater injection is required before changes in pipe material to ensure that the steam temperature will have dropped to the desirable value; similarly, adequate straight distance after the desuperheater is required to avoid erosion damage at the pipe bends. Both these require detailed desuperheater calculations, which have only been recently developed.

Component Design and Selection

The critical components in turbine bypass systems, from the standpoint of experiencing severe conditions, are the steam pressure reducing valve, spraywater valve and desuperheater. All these are highly engineered equipment.

The steam pressure reducing valve as well as the spraywater control valves should be specified as severe service valves. Position feedback is recommended on both these sets of valves. Valves with multi-stage trim are recommended for high pressure drop services to avoid excessive vibration and noise. References [7, 8] provide comprehensive guidance on good specifications [7, 8], which are a key to selecting the right equipment for the job. The desuperheater selection process is similar. Quantitative criteria for droplet size and spray coverage in the desuperheater should be specified to ensure that the spraywater does not impinge on the pipe walls [9].

The key requirement beyond performance is robustness, given the severe service that these systems experience. Unfortunately, this attribute does not lend itself to specification as such. The engineering support that the valve manufacturer can give is often an indication of their capability in this regard.

Commissioning

Good practices must be followed in the installation of all components. Manufacturers' recommendations must be sought in the installation of valves and desuperheaters as they may have special requirements; in addition, the use of materials like P22 and P91 demands special attention. All critical welds should be inspected to ensure that there are no significant defects.

Commissioning is also a difficult time for nearly all the critical components in the plant in terms of abnormal process conditions and transients. To the extent that it is possible, all severe events that may impact component life should be documented; this will facilitate estimation of remaining component life, if required, before a plant is handed over for commercial operation. Data on the transients and thermal shocks that the bypass system has seen should be reviewed and documented at this time.

This is also a good time to compare the actual plant operating conditions with the design intent. Spraywater valves are often oversized due to overly conservative specification of available pressure drop, which leads to insufficient rangeability and poor characteristics for controls purposes overall. If required, oversized valves can be "corrected" through trim upgrades.

From a maintenance perspective, all components should be inspected for their integrity and operability. Even simple problems caused by foreign material such as blockage in the valve trim, or sticking of the spray nozzles in open position and dripping water on to hot pipe, can contribute to accumulation of damage leading to failures.

Engaging the equipment supplier in such reviews at this stage is highly recommended. Any actions, if necessary at this stage, can then be taken to avoid failures at a later stage. It also sets the stage for preventative maintenance programs to ensure long-term reliable operation.

Operation and Controls

Setting up of good controls strategy begins in the system design stage and fine-tuning of the same in the commissioning stage.

Spraywater control for a dump to condenser desuperheater is a demanding task if the temperature downstream of the desuperheater (in the dump tube) is near saturation. This requires long evaporation lengths, special design of the temperature measuring points, and control loops with parameter variation vs. load and feed-forward support. Careful tuning of these loops for absolute stability over the whole load range is mandatory.

Correct algorithms should be selected depending on the application. An enthalpy-based feed-forward control method based with saturated or slightly wet conditions in the dump tube can be much more forgiving than temperature control loops. However, saturated conditions in the dump tube require a straight pipe run from the desuperheater to the dump device because of the water droplet content. This is the usual arrangement for the LP-bypass to condenser in coal-fired power plants but much less frequently seen in Combined Cycle power plants. HRH bypass to condenser application typically requires such a feed-forward algorithm that seeks to achieve a pre-determined enthalpy of the steam and spraywater mixture, prior to dumping to condenser, even if there is a small degree of superheat. On the other hand, a conventional PID control is generally adequate for HP bypass to cold reheat.

Interlocks are required to prevent induction of spraywater into the pipe when the steam valve is closed.

The loop for controlling pressure upstream of the bypass valves should be tuned well to prevent any instability of the steam pressure reducing valve.

Conclusions

Turbine bypass systems are exposed to severe operating conditions. Long-term reliable performance of these systems requires due diligence in all areas relating to them - system layout, commissioning, good performance of both control valve and desuperheater, and a thorough follow-up after the plant is placed in service. There are many critical details to attending to, which requires technical expertise and experience.

Good control valves and desuperheater specifications are necessary to ensure that the selected components are capable of standing up to the severe operating conditions in service.

Setting up the control of turbine bypass systems correctly is an important step in ensuring that spraywater flow does not inadvertently impinge directly on hot metal in the pressure boundary of the turbine bypass system. Shocking the system thermally results in high local stresses and strains, and, over a fairly short time, can lead to premature cracking in the material due to fatigue.

Systematic, and pro-active, maintenance programs are necessary to keep turbine bypass systems in good operating condition.

Acknowledgement

Finite element analysis reported in this paper was guided by Herbert L. Miller, P.E., CCI, and the computations were carried out by Dr. Sanjeev Kulkarni, formerly with KB Engineering and currently with Exponent Incorporated. Authors gratefully acknowledge their contributions.

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