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Water Induction in Steam Turbines for Power Generation: Understanding and Preventing Water Damage

Technical Brief — *Steam Turbines—Generators and Auxiliary Systems*

Overview

Water induction refers to the damaging condition of water or vapor being introduced into a steam turbine during operation. Such events are not uncommon in both fossil and nuclear units and can have consequences ranging from minor seal rubs all the way to catastrophic failure of the turbine. The primary mechanisms of damage include thermal shock, overload to components, and rubbing wear caused by thermal distortion. This Technical Brief describes the nature of various types of water induction damage, identifies the common causes of water induction, and provides an overview of recommended practices for averting or minimizing water induction damage. Most water induction incidents can be prevented by appropriate design in conjunction with proper operation and maintenance procedures.

Introduction

Water induction continues to be a widespread problem in fossil combined-cycle and nuclear units, and the effect of each incident can be significant. In severe cases, water induction damage results in extended forced outages for refurbishment and replacement of major components. It is therefore important that plant engineers and operators be familiar with the various sources, consequences, and means of mitigating water induction. All types of steam generators are susceptible to water introduction—by superheater and reheater carryover from fossil-fired boilers, by parallel operations at different state points and loading in combined-cycle combustion turbine steam generators, and by lower-pressure saturated steam admission in nuclear steam generators. In addition, feedwater heater tube failure in all thermal cycles can result in an extraction backflow of condensate.

Water can be introduced into an operating steam turbine from external sources or condensation within the system. Examples of an external source are a leak in a feedwater heater that causes condensate or feedwater to back up into the turbine through the extraction line or liquid condensate carryover from the superheater/reheater. During startup or trip conditions, condensation can form in main and reheat steam lines and subsequently be introduced to the turbine unless properly drained. Condensate is formed during steam generator depressurization and cooling at shutdown, collecting in the superheater and reheater loops. Without sufficient heating to vaporize, the liquid condensate will accumulate or be carried over to the turbine during startup and loading. Once water is introduced to the turbine, some level of damage is inevitable to the steam path and might not be identified without turbine disassembly.

Nature of Damage

The primary mechanisms of water induction damage are as follows:

- Thermal shock caused by the action of cool liquid on the hot turbine
- Impact damage and component overload due to the high density of the fluid
- Rubbing damage from thermal distortion or excessive thrust load

In a water incident, the operator's immediate actions are crucial in minimizing turbine damage. Some power plant designs (such as once-through boiler configurations or units that require extended condensate/feedwater pressurization for system cleanup and cooldown) are more susceptible than others. Frequent cycling also leads to increased potential for water induction because approximately three-quarters of water induction cases occur during startups, shutdowns, trips, or load reduction or while on turning gear.

This report introduces the typical categories of water induction damage, identifies common sources of water induction, and illustrates the types of recommendations. American Society of Mechanical Engineers (ASME) Standards TDP-1 and TDP-2 provide a more complete list of design, operational, and maintenance practices for mitigating water induction damage.

Water induction generally results in geometric distortion of the affected turbine component. The following six categories of damage can result from water induction:

- ***Damaged buckets/blades.*** Buckets/blades can be warped or broken, primarily from impact. Water inducted from an extraction at the L-1 stage nearly always results in cracked tie-wires or covers or, in extreme cases, broken blades in the L-0 stage. Figures 1 and 2 show blades damaged by water induction incidents. In Figure 1, the force of water has bent or destroyed the blades.
- ***Thermal cracking.*** Thermal cracking of inner and outer casing and diaphragms can result from high thermal stresses or repeated thermal loads of lesser magnitude. Water in the steam seal system can cause cracks in the packing casings and packing regions of the rotor.
- ***Rub damage.*** Differential thermal expansion of turbine parts can occur with water induction; these changes can introduce various rotating-to-stationary component radial rubs at packings, seals, and deflectors.
- ***Thrust bearing failure.*** Thrust bearing failures can be caused by high axial thrust, fore or aft depending on the relative flow. Water carryover to the turbine can increase thrust by up to 10 times the normal level from impulse or phase change expansion.

- ***Permanent warping or distortion.*** This can occur as a result of severe quenching. The damage type is typically caused by water contact on one side of the diaphragm or bowed rotors, when distortions introduced by heavy rubbing have stalled the turning gear. There can also be shell or inner/outer casing distortion.
- ***Secondary effects.*** These include axial rubbing after a thrust bearing failure or damage to bearings, foundations, and oil lines caused by turbine vibration accompanying heavy rubbing (see Figure 3).

Figure 1 – First several rows of a turbine damaged by water induction

Figure 2 – Closeup of the damage

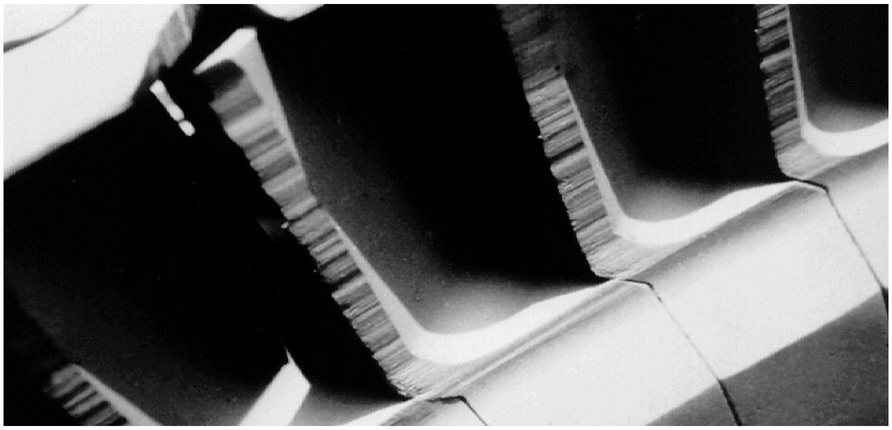

Figure 3 – The turbine rotor moved axially upstream, causing the rotating blades to rub against the stationary blades of this row (Edge-on view of the rotating blades with rub marks along the edge.)

Sources of Water Induction

Any connection to the turbine is a potential source of water induction. As illustrated by Figure 4, experience has shown that most water incidents are associated with extraction and main steam lines. These and other sources of water induction are summarized in the following, organized by flow order:

- ***Steam generator.*** Once-through flow units are more prone to create conditions for water induction because steam condenses in cold pipes during startup. However, high water levels in the steam drum can lead to water carryover in conventional boilers as well, and accumulation of condensed water in superheater pendant tubes is likely in the event that the boiler fire rate lags complete liquid vaporization.
- ***Steam attemperators.*** Spray water introduced ahead of the final superheater or reheater is a way to control steam temperature entering the turbine. Both overspraying during low load conditions and leaking spray control valves can result in water accumulation in pendant elements of superheaters and reheaters. Rapid increases in steam flow can cause water to be injected into the turbine. Depending on the reheater piping arrangement, water can also flow back to the turbine because of low steam velocity. Spray block valves should be verified closed during startup and shutdown to prevent leakage. Tail pipe temperature detection is essential to identified excessive spray or valve leakage.

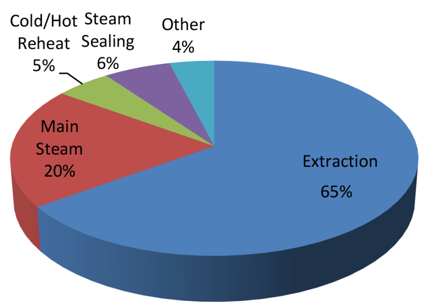

Figure 4 – Incidence of water induction events

- ***Motive steam systems.*** Motive steam lines include main steam, cold/hot reheat, and boiler feed pump turbine steam supply. Condensate could form during startup conditions, or water could be introduced from attemperators and feedwater heaters through extraction lines directly connected to the cold reheat piping. Process steam lines sometimes tie into the motive steam lines to divert flow to plant services or outside processes; these can also be a source of water. A properly designed and used drain system is crucial in all motive steam lines. Steam bypass systems should also be provided with the same level of protection as motive steam piping.
- ***Individual heat recovery steam generator (HRSG) restart following daily or peak reserve shutdown.*** Standby HRSG steam outlet thermodynamic state points vary significantly from in-service HRSGs, and significant moisture carryover has been identified during the startup cycle as the standby HRSG subcooled captured pendant steam is blended in the main steam to the turbine. Additional instrumentation and drains might be necessary to ensure that steam superheat is reached prior to securing bypass operations and turbine admission.
- ***Feedwater heaters and extraction systems.*** These are the most frequent sources of water induction. Water is present a short distance from the turbine, and equipment failure, operating errors, and system design weaknesses can all cause serious problems. Specifically, open feedwater heaters, leaking tubes in closed feedwater heaters, inadequate warmup procedures, and startup pressurization of heater shells provide a source of water. Failure or inadequacy of feedwater heater level controls and drains will allow this water to rise in extractions and enter the turbine.
- ***Condenser steam and water dumps.*** Improperly designed steam dumps that do not dissipate sufficient incoming steam energy can cause backflow of water from the condenser into the turbine exhaust.
- ***Steam seal system.*** Improper design or operation might lead to water in the steam seal system. This is a particular problem for high-pressure (HP) and intermediate-pressure (IP) sections that have high metal temperatures relative to the accidental leakage of water through steam glands. In addition, condensate return drain blockage has restricted moisture separation, resulting in carryover to the gland packing.

Design Recommendations

In accordance with ASME Standards TDP-1 and TDP-2, effective mitigation of water induction damage requires a design that can do the following:

- Detect water in the turbine or, preferably, external to the turbine before the water has caused damage
- Isolate the water by manual or, preferably, automatic means after detection
- Dispose of the water by manual or, preferably, automatic means after detection

In addition, the design should satisfy the criteria that no single failure of equipment, device, or signal or a loss of electrical power should result in water or cold steam entering the turbine.

Figure 5 illustrates a typical drain pot configuration with redundant level elements typically used in high-risk areas and is a good example of these principles. The power-operated drain valve should open automatically on high water level or high-high water level detected by the drain pot level elements (LEs) and should not be capable of remote manual control to the closed position anytime water is detected in the drain pot. A high-level alarm (LAH) and a high-high level alarm (LAHH) should be initiated in the control room for both events. The drain valves should be configured to fail-open on loss of power, air, or ICS processor communications as applicable. Standards TDP-1 and TDP-2 also provide guidelines for the drain pot diameters and configurations to minimize risk of blockage and malfunction.

Specific design recommendations for addressing the various sources of water covered in the previous section are detailed in TDP-1 and TDP-2. Some examples include:

- Have two independent means of automatically preventing water from entering the turbine from the extraction system (such as an automatic drain system and power-operated block valves).

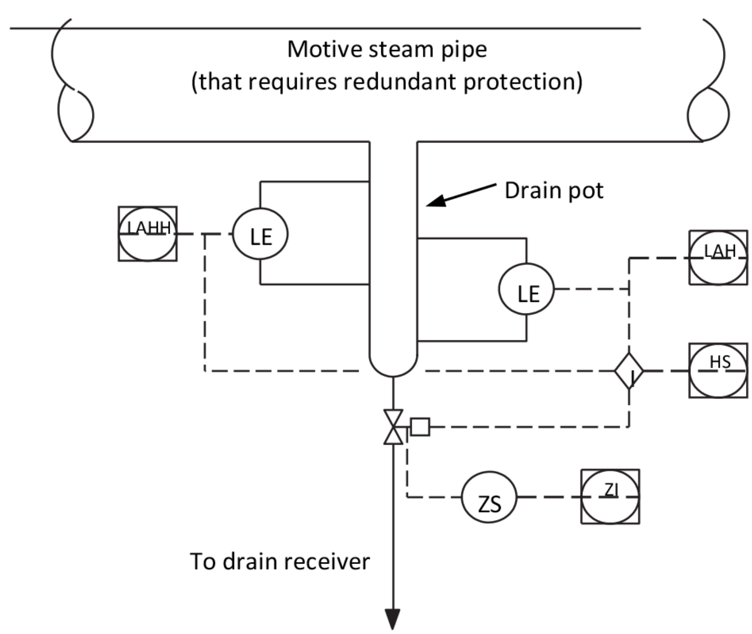

Figure 5 – Typical drain system with redundant level elements

- Install drains at each low point in the motive steam piping, in the extraction lines, downstream of steam seal desuperheaters, and on either side of non-return valves. Drain pots like the one shown in Figure 5 are recommended in high-risk areas (such as cold reheat lines and motive steam lines with less than 100°F [38°C] superheat).
- Install non-return valves on extraction lines, auxiliary drive turbine throttle steam pipe connected to the motive steam piping, and cold reheat system. (Power-operated non-return valves are preferred over swing check valves to ensure quick closure and that water induction does not cause the valve mechanism to fail from thermal distortion.)
- Install a power-operated block valve upstream of the attemperator spray control valve to prevent leaking and provide a second line of defense against a malfunction.
- Pipes associated with the steam seal systems should be pitched toward the source of the steam or, if not, must be drained.
- Pipe connections for source steam for steam seal and boiler feed pump turbine systems should be located on vertical legs or from the top of a horizontal run of piping.
- Placement and configuration of high-energy steam dumps should be such as to avoid velocity vectors toward the steam turbine and achieve maximum possible steam dispersion.
- Two power-operated block valves should be provided to isolate the motive steam or extraction steam line from the process steam line.

Operating Recommendations

Water induction events are a potential risk with transient operation of turbine, which can include operation at low load. During major load swings, startups, and shutdowns, the plant operator should be aware of certain indicators when water could enter or has entered the steam turbine.

ASME Standards TDP-1 and TDP-2 also provide operating procedures aimed at avoiding the introduction of water into the turbine as well as to minimize the damage in the event of water induction. Some of these suggestions are restated in the next section, followed by a list of indicators to help recognize the early warning signs of water induction.

Avoiding Water Induction

Some of the suggested procedures for avoiding water induction incidents are listed below. This is not an exhaustive list, but it illustrates the type of procedures that should be formulated and tailored to each specific unit:

- Prior to starting the unit, the condenser should be in operation and ready to accept drainage.
- Drain valves should be opened (and remain open) during steam turbine shutdown and steam turbine trip.
- Where the boiler startup cycle pressurizes feedwater heaters, the block valves between the turbine and the pressurized feedwater heaters should be interlocked closed during the startup cycle to prevent any backflow from the heaters into the turbine. This is in addition to any possible check-valve action.
- After a trip, operator intervention should be required to reset and reopen the attemperator block valves. Both the turbine and main fuel trip should be reset, and the attemperator spray control valve should be closed before the block valve is permitted to be opened to avoid wire drawing damage to the block valve.
- Turbine system drains should be verified open during startup and following a turbine trip. Drains should remain open until wet steam conditions have been corrected with sufficient flow and steam conditions.
- When the turbine is hot and it is necessary to transfer to any auxiliary source of gland seal steam, the operator should ensure that the piping is prewarmed, steam supplied to the gland is superheated, and the temperature is within manufacturer's limits.

The following are some general plant and turbine indications that might lead to a water induction event:

- Position of drain valves—knowledge of the position of heater drain valves at specific load points can be used to detect when a heater is leaking, even if levels are normal.
- Unstable steam generator operation—rapid changes in pressure, temperature, drum level, firing rate, and feedwater flow could indicate a potential for water induction.
- Low steam generator outlet conditions—concern is with condensation of water in the steam leads that could then be pushed into the turbine with a flow increase.
- High attemperation flow or any attemperation during periods of low turbine flow—potential for a large volume of water collecting at a low point that could be blown back into the turbine.
- Water-detection thermocouples—a high temperature differential between the upper and lower half turbine inner casings is usually an indication that a water induction event has occurred.
- Thrust bearing wear detector trip—excessive axial thrust on the turbine due to water coming through steam leads can cause wiping or thrust bearing.
- Turbine supervisory (TSI)—high eccentricity and unusual differential expansion are all potential indicators of a water induction event. Rotor bow can be a consequence of a water induction event, and the rotor will require inspection and additional attention to remedy. High bearing vibration can be indicated due to a rotor bow or rubbing resulting from casing distortion/quenching.

Identifying Water Induction

Even with precautions such as those previously listed, water induction sometimes occurs. For example, overreliance on automatic features has resulted in turbine water induction incidences.

Many water induction events go undetected at the time of occurrence and are only subsequently diagnosed when the turbine is opened for maintenance. Yet if prompt and decisive action is taken at the first warning of water induction, damage can be minimized. The following are indicators of water induction:

- High-level alarms or indications from water induction detection systems.
- Fast coastdown times. Seal rubs, a common result of water induction, can cause

coastdown times to change. A marked change, such as from a typical level of 45 minutes to less than 30 minutes, is a sign of a potential problem.

- Squealing sounds caused by seal rubs.
- Sharp drops in metal temperatures in locations being cooled by encroaching water.
- Hammering or shaking of steam lines.
- Out-of-range indications from turbine supervisory instrumentation. Signs include (i) sudden onset of excessive vibration, (ii) sudden onset of differential thermal expansion of rotating to stationary parts, (iii) casing expansion, (iv) eccentricity, (v) rotor position, and (vi) thrust bearing temperature increase. Note that if these indications occur, depending on their severity, the operator might need to take immediate action.
- Thrust bearing alarm or trip for high temperatures, large movements of shaft, presence of babbit, or iron in oil.
- Change in bearing vibration caused by rubbing.
- Decrease in stage efficiency can be a sign of increased rubbing or warped blade profiles that result with water induction.
- Change in MW output or flow capability reflecting damage and blade area changes.
- Rotor rotation restricted or turning gear drive failure during operations or engagement following turbine trip.

Immediate Actions to Minimize Damage

Once water induction is detected, immediate operator action is required to prevent serious turbine damage. Operators should be trained specifically for each unit. The following are general recommendations for fossil or nuclear units:

- If water enters the turbine while operating at rated speed or while carrying load, do not trip the unit if the vibration and differential expansion are satisfactory and there are no other signs of distress. This can minimize local thermal distortion by maintaining the heating action of the steam. Find and isolate the water source immediately.
- If water enters the turbine while operating below rated speed, shut down immediately because rotor bowing caused by water induction might be aggravated. Isolate the water source.
- Once the unit is placed on turning gear because of possible water induction, never attempt to restart until (i) shaft eccentricity is within normal limits, (ii) the various turbine shell temperature differences are within manufacturers' allowable limits, and (iii) the source of the water has been identified and corrected. Restart should not be attempted in a period less than that recommended by the manufacturer.
- If the rotor is bowed or the shell distorted so that the turning gear cannot turn the rotor, periodic attempts (once per hour) should be tried to get the unit on turning gear. A crane or admission of steam to the turbine should not be used to attempt to free a locked rotor.

Maintenance and Monitoring Recommendations

ASME Standards TDP-1 and TDP-2 suggest monthly, three-month, and outage inspection schedules for the various water induction prevention systems. In addition, the monitoring techniques that can be used to detect conditions that have subsequently been associated with water damage to steam turbines include the following:

- Acoustic/ultrasonic detection of feedwater heater tube leaks
- Fast-acting thermocouples for detection of water in steam lines
- Acoustic monitoring of valves
- Electrical-resistance-based water-level elements in steam lines
- Thermography cameras for detection of clogged drain lines

Conclusion

Water induction is a longstanding issue that continues to result in severe and costly damage to steam turbines. Therefore, it is important that power plants be designed, operated, and maintained with preventive measures in mind. This report introduces the problem as well as some of the standing recommendations to help equipment manufacturers and operators reduce the risk of turbine damage by water induction. The reader is referred to the specific ASME standards that address prevention of water induction in fossil and nuclear units, respectively. Note that these are still only guidelines, and each specific installation must be designed and maintained according to its specific conditions.

Turbine Damage Resources

The Electric Power Research Institute (EPRI) published *Turbine Steam Path Damage: Theory and Practice*, a comprehensive, two-volume report with information on many turbine damage mechanisms, ranging from water induction to corrosion fatigue. This information will improve plant engineers' understanding of the potential for turbine damage, condition assessment, and mitigation options. Also available are a more concise field guide illustrated with dozens of color photos and a poster version of this information. For more information or to obtain a copy of these resources, contact James Wieters at jwieters@epri.com.

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For More Information

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