Water Treatment, Cycle Chemistry, Boiler Operation and Related Problems/Failures on Steam Generator Systems > 30 bar

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Introduction of Referent
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1 Introduction
In many low and medium scale industrial plants steam generation is a reluctantly accepted part and always seen as a cost rising factor - until it fails! Only than one realised without steam no production and no product to sell. Large scale industrial and petrochemical plants know the importance of steam production, but it is still a side product. In power plants the steam is indirectly converted into electrical power and clearly seen as product for sale. Consequence: Steam production needs manifold more attention and support, if it is important for the production, that includes also operator’s training and development of ones knowledge.

2 Technical Definitions and Focus
This paper deals with steam generators of industrial plants (shell boiler & water-tube boiler) as well as with waste heat recovery boiler (HRSG) downstream of gas turbines of combined cycle power plants (CCPP) and waste heat boiler (WHB) in refineries and petrochemical plants. Due to the very different boiler types and operational conditions their requirements to the water treatment and feedwater (BFW) / boiler water (BW) quality is different and contains therefore manifold opportunities to make mistakes that may lead to problems or damages on boilers, turbines and production equipment. Experts are necessary to handle all these requirements in balance to prevent operational problems and failures - but well trained operators too!

2.1 Boiler Types
Shell boiler are mainly gas or oil fired three pass steam generators with one or two fire tubes and several smoke tubes - with BW around the tubes. Design dependent they are restricted to operation pressures up to about 30 bars and to a steam production up to around 30 t/h - rarely with economiser and super-heaters. They were delivered as a package on a frame and supply steam to small and medium scale plants, but are sometimes used as auxiliary boiler for start up in large-scale plants too. An overview exhibits Fig. 1.
**Water-tube boiler** are larger steam generators - with BW within the tubes - with natural or forced circulation for pressures up to 180 bars and a steam production in industrial plants up to approx. 300 t/h, in power plants up to 2000 t/h. They combusting gas, oil, coal, bio-mass etc. and are equipped with BFW pre-heater, economiser, super-heater and de-super-heater.

**Heat recovery boiler** (HRSG) downstream of gas turbines (CCPP) are mainly water-tube boiler with natural or forced circulation and up to 3 pressure ranges in one unit. All have pre-heater, economiser, super-heater and de-super-heater. Their gas inlet temperature is max. 650 °C. Boiler with horizontal orientated evaporator tubes mostly have forced circulation to get adequate flow within the tubes and should have sufficient water content (at least 15 wt-%) at the outlet of the evaporator tubes during every operational load. Flow sheets show Figs. 2 - 4.

**Fig. 2**

![Conventional Dual Shaft - Triple Pressure Reheat Unit](image)

**Fig. 3**  Single-Shaft Combined Cycle Triple-Pressure Reheat Steam Cycle (Siemens AG)
Waste heat boiler in refineries and petrochemical plants may be water-tube boiler or shell boiler. The latter are of particular design and mostly process gas coolers, with process gas within the tubes and boiler water around the tubes. The operational pressure is up to 140 bars, but their steam production regularly do not exceed 200 t/h. Sometimes more than one heat exchanger is connected to one steam drum and steam super-heating is often done in a separate unit.

Quench-boiler and trans linear exchanger (TLE) of e. g. ethylene, methanol or ammonia plants were heated with process gas of up to 900 °C and operating mainly as quench coolers, that means they must cool down the process gas as fast as possible to stop thermal crack or decomposition reactions. Therefore the heat transfer (kJ/m² ⋅ h) at gas inlet is extremely high. Shell type coolers must be commissioned with gap free tube/tube-sheet connections at least at the gas inlet (hot end) but it is recommended for the gas outlet too. Tube in tube type TLE must also be welded free of gaps.

Process steam generators or re-boiler with tube bundles heated by hot hydrocarbons, other products or HP-steam generate saturated steam up to a pressure of 30 bars. They are not heated by burners and therefore not facing problems due to overheating but mostly due to corrosion because of frequently low BFW quality.

Once through boiler are not covered in this paper because they were used primarily in huge electrical power plants at super-critical pressure >230 bar at steam temperatures up to 650 °C and not in industrial plants and medium scale power plants because this type of boiler needs imperative demineralised BFW.

Attention: New Combined Cycle Power Plants may be equipped with once though boiler!

2.2 Definition of Water Types

Softened water is domestic water or pre-treated water downstream of a softener using strong acidic cation exchanger in sodium form and sodium chloride (salt) as regenerant. A softener exchanges hardness (Ca- and Mg-ions) to sodium ions; see Fig. 5. The conductivity is similar
Fig. 5
Ion exchange with strong acidic cation resin in Na-status in a softener filter. Hardness (Ca + Mg compounds) is exchanged to sodium (Na) compounds. Regenerant: Salt (NaCl) solution.

to that of raw water, silica content is unchanged. During operation cycle the hardness is < 0.01 mmol/l = < 1 ppm CaCO₃.

Decarbonised water is treated water downstream a lime hydrate decarbonisation after filtration or decarbonised water downstream a weak acidic cation exchanger. Both waters must be softened if used as make-up water. The water is distinct lower in carbonate hardness and conductivity but silica is unchanged if ion exchanger is used. Hot lime decarbonisation may reduce silica for 10-30 %. Decarbonisation using weak acidic ion exchanger see Fig. 6.

Fig. 6
Decarbonisation with weak acidic cation exchanger in H-status exchanges only carbonate hardness to carbonic acid (H₂CO₃ = CO₂ and H₂O = water) with subsequent softening and degassifier (CO₂ stripping) to reduce CO₂ to < 10 mg/l.
Regenerant: Hydrochloric acid

Partly demineralised water is softened water from a reverse osmosis plant (permeate) or water from an ion exchanger plant consisting of cation and anion filter - without mixed bed filter. The water is free of hardness (< 0.01 mmol/l) and indicates at least a direct conductivity at 25 °C < 30 µS/cm (mostly < 10 µS/cm) and silica content < 0.2 mg/l (ppm) SiO₂.

Demineralised water is treated water downstream a demineralisation plant consisting at least of cation, anion and mixed bed filter with a direct conductivity at 25 °C < 0.2 µS/cm, silica content < 0.02 mg/l SiO₂ and TOC < 0.2 mg/l. The chemical actions can be seen on Fig. 7.

Make-up water is treated water used as substitute for the loss of condensate in the system.
**Fig. 7:** Demineralisation plant consisting of strong acidic cation exchanger (K H\(^+\)), weak basic anion exchanger (A\(_1\) OH\(^-\)), CO\(_2\) stripper, strong basic anion exchanger (A\(_2\) OH\(^-\)) and mixed bed filter (MB H\(^+\)/OH\(^-\)). Particularly designed for water with higher organic content.

Condensate return is clean condensate return from consumers or turbine condensers. It should not be mixed with make-up water prior thermal deaeration. Possible contamination with impurities from production or cooling water requires adequate online quality control and e.g. condensate treatment.

Boiler Feedwater (BFW) is the treated, conditioned and deaerated water fed to the steam generator. It is mostly a mixture of condensate return and make-up water. For pH adjustment and oxygen scavenging mostly "conditioning" chemicals are added.

Demineralised BFW shows during operation continuously an acid (cation) conductivity at 25°C < 0.2 µS/cm, a silica concentration < 0.02 mg/l SiO\(_2\) and is supposed to be free of caustics (NaOH/KOH < 0.01 mg/l Na + K). This high quality BFW is essentially for spray water de-super-heating and application of “All Volatile Treatment” AVT.

Boiler water (BW) is the water circulating within the boiler. It consists of concentrated BFW.

### 2.3 Definition of Chemical Operation Modes

**Solid alkaline treatment** is defined as the dosing of non-volatile, solid alkalising agents like tri-sodium or tri-potassium phosphate or caustic soda (sodium hydroxide) to adjust the correct pH in BW. These chemicals alkalising the liquid phase e.g. BW only and permits the use non-demineralised BFW containing dissolved solids. The alkalisation effect of these chemicals is excellent at room and boiler operation temperatures, see **Fig. 8**. To alkalise the steam and condensate additional volatile alkalising agents like ammonia or amines are recommended as far as products in direct contact with steam or condensate do not exclude their application. Please be informed that coordinated or congruent phosphate treatment (CPT) is not any more recommended because of several boiler failures. Last experience in the United States confirmed European long term experience to use tri-sodium or tri-potassium phosphate that leads mostly to a Na:PO\(_4\) ratio of 2.8 – 3.2 now called equilibrium phosphate treatment (EPT) for HP-boiler or phosphate treatment (PT) for boiler with lower pressure, see **Fig. 9**.
All volatile treatment (AVT) uses volatile alkalising agents exclusively and is permitted only if demineralised BFW is fed. AVT restricts the acid conductivity of the BW to < 5 µS/cm for boiler with max. heat transfer of 250 kW/m² and for heat transfer above to < 3 µS/cm. Due to the distribution rate (concentration in steam phase to concentration in water phase) of volatile chemicals, lower pressure liquids are frequently insufficient alkalised, see Fig. 10. All volatile chemicals show excellent alkalisation effect at room temperature (during lab analyse) but contrary to solid alkalising agents - massive reduced alkalisation effect at boiler operation temperatures, see Fig. 11 and 8.
3 Possible Problems on the Water Side of Steam Generators

3.1 Water Quality and Boiler Type

3.1.1 Selection of Water Treatment Plant

The type of make up water treatment depends on raw water quality (with its changes throughout the year!) and the requirements to the boiler feedwater and boiler water quality primarily requested of the boiler manufacturer (warranty related!). This paper presupposes raw water of Southeast Asian Countries, which is mostly relatively soft (total hardness 1-2 mmol/l = 2-4 meq/l = 100-200 ppm CaCO$_3$) and shows low total alkalinity (< 2 meq/l) but contains significant amounts of silica. By the use of river water the content of silt (very fine undissolved matter - mostly clay suspension) must be removed by adapted pre-treatment units (filtration, flocculation combined with filtration or membrane separation units like ultra filtration) to avoid trouble on the following treatment plant. Some clay particles are very fine and not easy visible (colloidal), may pass ion exchanger and cause trouble in the boiler itself because of their thermal decomposition and subsequent formation of scale with low heat transmission, particularly at spots with high heat transfer.

For any boiler (except vertical shell boiler with pressure < 10 bar) at least softening of the make-up water is necessary to avoid scale formation. For boiler with pressure up to 40 bars softened make up water in mixture with adequate amount of condensate return can be sufficient. As lower the amount of condensate return and as higher the raw water alkalinity and silica content, as higher is the blow down rate that leads to uneconomical boiler operation.

For intermediate pressure boiler and lower pressure boiler with less condensate return, decarbonisation or reverse osmosis is more economical for make-up water.
For boiler pressures up to 60 bars permeate of a reverse osmosis unit may be used if the condensate return (in good quality) is for sure > 90% of the BFW.

For boiler with pressure > 60 bar, demineralisation plants including mixed bed filter are recommended, particularly to eliminate silica, but consider silica is not indicated by conductivity measurement!

For boiler pressure above 80 bars and boiler with high heat transfer (e.g. process gas coolers) demineralised make up water and condensate is imperative.

Injection water for steam attemperation (de-super-heating) must be pure condensate or better demineralised BFW and may contain only volatile conditioning chemicals, like ammonia.

![Diagram of pH and Conductivity](image)

Modern demineralisation (demin) plants operate in counter flow regeneration mode, saving chemicals and achieve better demin water quality than plants with equal flow. They must be equipped with sensitive on-line conductivity meter, that are specifically temperature corrected to the reference temperature of 25 °C. Conductivity < 0.2 µS/cm requires different correction factors! Qualified conductivity measurement can replace pH measurement, see Fig. 12.

**Fig.12**
Correlation between pH and Conductivity of Hydrochloric Acid (HCl) and Sodium Hydroxide (NaOH) in pure Water at 25 °C.

At conductivity of 0.2 µS/cm the pH must be between 6.4 and 7.8

For recalibration of on-line quality control systems, parallel measurement with mobile equipment for conductivity and specific sampling for other analyser is important - not only electrical check!

**Condensate treatment** must be taken into consideration if contamination of condensate return is probably. Additional reliable quality control device is essentially to indicate dangerous contamination as fast as possible. In many cases measuring of - temperature corrected - direct and/or acid conductivity is sufficient. Oil and fat ingress may be indicated by turbidity meter. Condensate with high risky contamination should not taken back to the feedwater.

In many cases mechanical filtration in paper cartridge filters, activated carbon or coke filters is sufficient to remove undissolved corrosion products. In case of possible ingress of hardness, for low pressure boiler subsequent condensate softening may be enough, but for HP-boiler condensate polishing (consisting of cation and mixed bed filter) is necessary.

Consider condensate softener release sodium hydroxide if they were fed with alkaline condensate containing ammonia or amines!

Possible ingress of e.g. hydro carbons, food products, acids, free caustics, see water etc. requires particular on-line control device and adapted treatment equipment.

3.1.2 **Boiler Feedwater and Boiler Water Requirements**
The requirement to the boiler feedwater (BFW) and boiler water (BW) quality depend on different factors as they are primarily:

**BOILER PRESSURE:**
As higher the pressure and the heat transfer as better the quality of the BFW and BW must be, see the national or international standards and manufacturer requirements. Extracts of the requirements of the last draft (04.2003) of the European Guidelines prEN 12953-10 for shell boiler and prEN 12952-12 for water-tube boiler are shown in the Annex in Figs. 13/1-13/4 and Figs. 14/1-14/7.
All Guidelines focus basically on developing and maintaining a protective layer on steel, which is stable only at alkaline conditions, see Fig. 15 as well as on scale prevention.

![Fig.15 Magnetite solubility depending on pH and temperature.](image1)

For HP boiler silica is restricted due to its steam solubility to prevent silicate deposits in steam turbines. For LP boiler silica restrictions exist to prevent silica deposition on heated surfaces, because silica deposits reduce heat transmission extremely.

Please be informed that coordinated or congruent phosphate treatment (CPT), former recommended by ASME and EPRI is not any more recommended because of several boiler failures in the United States. Last experience in the U.S. confirmed European long term experience to use tri-sodium phosphate and a Na:PO₄ ratio of 2.8-3.2 now called equilibrium phosphate treatment (EPT) for HP-boiler or phosphate treatment (PT) for boiler with lower pressure, see Fig. 9.

**BOILER TYPE:**
The requirements to the BFW and BW quality (treatment and chemical dosing) basically focus on preventing scale formation and corrosion on the boiler system and utility units.

Common shell boiler requires at least BFW with total hardness < 0.02 meq/l = 0.01 mmol/l or < 1 ppm CaCO₃, alkaline pH at 25 °C of (8.8) 9 - 9.3 and oxygen content < 0.02 mg/l or excess of oxygen scavenger. If softened water with conductivity ≤ 30 µS/cm, partial demineralised and fully demineralised make up water without or with condensate is used as BFW, dosing of tri-sodium phosphate is urgently suggested to adjust and to keep the necessary pH in the BW. Caustic soda must not be used without phosphate to reduce the risk of caustic stress corro-
sion cracking (CSCC) at tube/tube sheet connections with heated gaps, which is standard design. AVT is not recommended for boiler with pressure < 25 bars.

Common water-tube boiler require at least the same minimum requirements than shell boiler but need by increasing pressure above 40 bars and higher heat transfer BFW with reduced content of dissolved solids. However for boiler with operational pressures above 60 bars de-mineralised BFW is highly and above 80 bars and/or locally high heat transfer is explicit recommended. As far as the boiler is commissioned without heated gaps or heated phase boundaries, caustic soda and tri-sodium phosphate may be used. AVT is possible at boiler pressure > 30 bars and suggested for boiler > 100 bars and/or high heat transfer.

Heat recovery boiler (HRSG) downstream of gas turbines require at least the same water quality than common water-tube boiler. For boiler units with more than one pressure step all volatile treatment (AVT) may cause problems in the economiser and in the LP steam system due to erosion corrosion if the tube material is common carbon steel. Dosing if non volatile alkali-sation agents or application of low alloyed steel, see Fig. 16 can solve that problem.

![Fig. 16](image.png)

Corrosion rate (g/m²·d) versus flow rate (m/s) of some different steel material at p = 40 bar, t = 180 °C, pH at 25 °C = 7
Oxygen ≤ 0.05 mg/l

St. 37.2 = Carbon Steel
15 Mo 3 = C steel with 0.3 % Mo
13 CrMo44 = C steel + 1%Cr + 0.4%Mo
10 CrMo9 10 = C steel + 2½ Cr + 1% Mo

Low alloyed steel with increasing chromium (Cr) and molybdenum (Mo) content makes materials more resistant against erosion corrosion (FAC).

Waste heat boiler in refineries and petrochemical plants with design of common water-tube boiler may be operated under same conditions than common water-tube boiler.

Process gas cooler, quench-boiler and trans linear exchanger (TLE) must be fed with de-mineralised BFW only. AVT is suggested for boiler > 100 bars operational pressure and/or evaporator with heat transfer > 250 kW/m² - but consider the requirement of continuously de-mineralised BFW and restricted acid conductivity in the BW.

The use of the solid alkalisation agents tri-sodium or tri-potassium phosphate in very little amounts (2 - 5 mg/l PO₄ for boiler with pressure < 120 bar(g) and 1.5 - 3 mg/l PO₄ ≥ 120 bars) is imperative recommended if the BFW quality corresponds not always - but mostly - to that of de-mineralised BFW.

Process steam generators (not heated by burners) need at least a BFW and BW quality corresponding to that of shell boiler or low-pressure water-tube boiler. Chemical dosing depends on the requirements to the steam quality, a possible carry over of BW must be taken into consideration. In case of more or less contaminated process condensate as BFW, solid alkalisising
chemicals together with volatile agents reduces corrosion problems.

TYPE OF STEAM ATTEMPERATION

There were two ways for steam attemperation in boilers,
– spray water injection, which is most common in new boilers and
– cooling of SH steam in coils below the water level within the steam drum and temperature
controlled mixture of SH and cooled steam to the desired temperature level.

Additional steam attemperation by spray water injection is required if a turbine by-pass is in
operation or HP-steam must be reduced in pressure and temperature.

The injected spray water must be free of undissolved and dissolved solids and must be treated
by volatile agents only. Presence of non-volatile chemicals may cause deposit formation,
blockage, over-heating or caustic stress corrosion cracking of super-heater coils if their con-
centration exceeds the steam solubility of these chemicals.

Silica and free caustics are highly soluble in HP-steam but show low solubility in LP-steam,
which may result in precipitation of silica in turbines and of free caustics in LP-steam lines of
back pressure turbines. The latter may result in caustic stress corrosion cracking particularly at
weld seams as far as the LP-steam is for more than 30 °C super-heated. This leads not to
problems at saturated steam conditions!

Please remember chapter 3.1.1 and the possible content of caustic soda in the condensate
downstream a condensate softener!

STEAM QUALITY

Boiler manufacturer requires specific (warranty related!) quality for BFW and BW but must
guaranty also steam purity, which is mostly expressed as boiler water content in steam. Some
manufacturer guaranty a BW content of < 0.5 % in steam, which is only acceptable if the boiler
is designed to produce saturated steam for indirect heating purpose. For boiler with
super-heater and turbine operation the BW content in steam must be < 0.1 % better < 0.05
which is achievable with correctly designed steam drums and optimised drum internals incl.
qualified water/ steam separation equipment.

Steam quality requirements of turbine manufacturer, particularly regarding acid conductivity at
25 °C < 0.2 µS/cm, contain uncertainties concerning warranty cases, because traces of car-
carbon dioxide affect the conductivity (0.1 mg/l CO₂ increase conductivity for 0.1 µS/cm!) but not
turbine deposits.

Correct steam purity measurement of saturated steam requires adequate sampling device with
probes according to international standards - a nozzle connected to a steam line is not suffi-
cient and leads definitely to wrong results because saturated steam pipes have always a liquid
film at the inner surfaces.

Representative results for super-heated steam require particular equipment - measurement is
more difficult than that for saturated steam, therefore use saturated steam and for steam de-
superheating demineralised BFW.

Steam purity measurement without influence of volatile chemicals like carbon dioxide, ammo-
nia, amines and organic acids is possible using on-line sodium monitor. As far as the BW con-
tains about 2 mg/l = 2,000 µg/l Na, qualified Na-monitors can indicate for sure 1 and 2 µg/l Na,
which allows indication of 0.1 % BW droplet carry-over.

Dosing of volatile chemicals may be excluded if the steam must be pure e.g. for direct contact
with food products or pharmacy products.

3.2 Failures Caused by Design
Demand and production of always cheaper boiler and of boilers with particular design leads to an increasing risk for failures due to design and commissioning. Typical design problems are deficiencies in the natural circulation of BW in water-tube boilers, which may lead to both overheating due to lack in cooling of evaporator tubes and steam/water separation particularly in heated riser tubes with low slope (< 3-4 degree). The latter result to severe damage if the upper half of the tube - with its steam phase - is in touch with flowing hot flue gas. In that case the lower half of the tube with liquid phase shows no damage, but the upper half reveals thick layers of black magnetite, see Figs. 17. This excessive oxidation reaction takes place > 570 °C wall temperature and may cause hydrogen damage and brittle ruptures of tubes due to the following simplified reaction:

$$3 \text{Fe} + 4 \text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + 4 \text{H} \rightarrow 2 \text{H}_2$$

Figs. 17  Evaporator tube with insufficient water flow and low slope which leads to the separation of water (lower tube half) and steam (upper tube half), excessive oxidation on steam side (left, upper part) and brittle fracture due to hydrogen embrittlement (right, upper part).

Heavily varying steam production, pressure fluctuations and not proper working level control systems may lead to a fluctuating drum water level and affects the steam quality because of increased "droplet" carry over.

It may also result in temperature fluctuations in headers and evaporator tubes and to thermo-mechanical stresses of the steel and to damages of the protective magnetite layer, because of the different thermal expansion rate of steel and magnetite, see Fig. 18.

Fig. 18

Further-on circulation disturbance may occur, if down-comer tubes were significantly heated which leads to undefined flow directions and possible stagnant flow depending of the heat input. The BW in that
down-comer does not know shall it go down or up if the heat input increases and steam production rises.
Riser tubes with uncertain flow and high heat transfer may suffer of steam blanketing because a steam film reduces the heat transfer extremely and material overheating occurs.

Other weak parts of water-tube boilers are header/tube connections designed and commissioned with a gap or even with narrow crevices as far these connections were heated. Within heated gaps/crevices dissolved solids may concentrate and e.g. in case of concentrations of caustic soda to ≥ 4 wt-% in presence of high tensile stress (e.g. residual stress from welding) caustic stress corrosion cracking may occur. Process gas coolers may face the comparable problem - particularly at the gas inlet side (hot end) - if their tube/tube sheet connections are not free of gaps or appear welding voids with gap-like appearance.

Recently LP-boiler of CCPP plants were affected by erosion corrosion at tube bends on the outlet of evaporator tubes as AVT conditions were applied and normal carbon steel instead of low-alloyed steel (e.g. 2 ¼ % chromium and ½ % molybdenum) is installed. Because of the distribution coefficient of ammonia and some amines at pressure < 15 bars their concentration in the liquid phase is much lower than in the steam phase and leads to a too low pH at operation condition, see Figs. 10+11. Steam/water mixtures out-coming from LP evaporator tubes with relatively high velocity may remove localised the protective layer on steel faster as it can be newly built up and causes erosion corrosion or flow assisted corrosion (FAC). The mentioned low-alloyed steel develops protective layers of magnetite faster than carbon steel but requests more attention for welding. Similar problems may occur at economisers if locally the velocity of the BFW is too high (consider local turbulence zones!).

3.3 Failures Caused by Operation

Failures due to disoperation are manifold and many of them well known. Not well realised are e.g. the following failure possibilities:
• Too low feedwater temperature, particularly in waste heat boiler and process gas cooler but in highly loaded shell boilers too, as well as too high BFW temperature.
• Too fast start up of boilers from hot stand-by, particularly shell boiler.
• Operation at pressure significantly below design pressure and
• Heavily fluctuating steam production and fast pressure drop.

Boiler feedwater temperatures significantly below the design temperature may lead to BW temperatures considerably below its boiling temperature (corresponding to the pressure in the steam drum) in the down-comer and at evaporator tube or heat exchanger inlet. The geodetic pressure difference between drum water level and evaporator inlet level worsens this problem. The mentioned facts lead to reduced cooling of the lower part of the heated surface because at this areas the BW must be heated first to its boiling temperature before it starts nucleate boiling. Heating of hot water – without steam production – extracts much lesser energy from the heated surface than production of steam, see following example:

Level difference drum/down-comer outlet: 20 m $= 2$ bar(a)
BW temperature at down-comer outlet: 15 °C below steam drum temperature
Boiler drum pressure: 38 bar(a) $= 247.3$ °C; Enthalpy $= 1072.7$ kJ/kg
Pressure at down-comer outlet: 40 bar(a) $= 250.3$ °C; Enthalpy $= 1087.4$ kJ/kg
Temperature at down-comer outlet: 247.3 °C − 15 °C = 232.3 °C $= E = 1000$ kJ/kg
Enthalpy difference to boiling conditions: 1087.4 kJ/kg − 1000 kJ/kg $= 87$ kJ/kg

The example shows clearly that 1 kg BW extracts maximal 87 kJ from a heated surface if it becomes only heated to boiling conditions, but evaporation of 1 kg BW is able to extract around 1,728 kJ, that means 20 times more! As greater the temperature difference as larger is
the necessary heating surface to approach the boiling conditions and as worse is the cooling effect there. Therefore the inlet side of heated surfaces of water-tube boiler is usually covered by refractory material – but sell boiler and e.g. process gas cooler does not have this possibility. It must be considered that nucleate boiling shows a much better cooling effect than heating of liquid water only and why bypassing of BFW pre-heaters is not only a loss of efficiency – it may also initiate damage due to overheating at the inlet of intensively heated surfaces like in process gas cooler.

Boiler feedwater with temperatures above or similar to the drum temperature may lead to circulation problems on water-tube boiler due to possible evaporation effects at the inlet orifice of evaporator tubes and /or to FAC at economiser outlet. In water-tube boiler the down coming circulating water must be distributed from headers to several inlet orifices of the riser tubes and must stay there in liquid form to supply the optimal mass flow to the tubes. If at these critical area evaporation occurs due to turbulent current, the volume flow may be the same but the mass flow will be reduced significantly. This may result also, if down-comer become heated and are feeding BW at boiling conditions to the riser tube orifices. Reduced mass flow leads to reduced cooling of heated tubes. This phenomenon do not exist on shell boiler or process gas cooler.

Boiling conditions and steam formation near the outlet of economisers may cause FAC at the eco-outlet because the economiser is designed to carry liquid phase only. Steam produced increases the volume and medium velocity.

*Boiler in hot stand-by* appears usually operational temperature and pressure but do not have normal BW circulation. Due to the existing temperature a specified temperature gradient for start up is not necessary to prevent significant temperature differences on components with bigger wall thickness. If the start up of boilers, particularly of shell boiler, is too fast the BW circulation may not follow the requirements and overheating may occur.

*Operation at pressure* significantly below design pressure of boilers leads to an increased specific steam volume and to steam space overload in the steam drum or steam space in a shell. Exceeding the regularly designed steam space load (active steam space in the drum or shell [m³] divide by the steam volume produced [m³/h] = m³/m³h) results in bad steam quality and increased physical (droplet) carry-over.

*Heavily varying steam production* and/or fast pressure drop in steam boilers may cause
– Fluctuating water level in the steam generator,
– Mechanical carry-over and poor steam quality respectively as well as
– Circulation disturbance in water-tube boiler.

Particularly fast load peaks in combination with pressure drop may cause severe boiler failures due to overheating of riser tubes and super-heaters (deposit formation). Significant pressure drop is mostly the result of rapid steam taking and leads first to an elevated boiler water level due to intensive steam production and volume expansion of the steam bubbles produced in the water phase, like rapid opening of a soda water bottle. At this time the BW circulation is seriously disturbed because riser and down-comer tubes are production tubes! The entire effect causes severe carry-over of boiler water and stops feeding of BFW because of high water level. Short time after this event the BW level drops below normal water level and the maximal amount of BFW is fed into the boiler. Rapid feeding of BFW may reduce pressure and temperature again may lead to the effects discussed above. In case of too rapid steam taking of consumers, it is urgent necessary to reduce the stem flow by throttling the steam outlet valve!

**Annexes:** Figs.13/1- 4 + 14/1-7