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Steam Drum Design for Direct Steam Generation

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Abstract. For the direct steam generation in solar fields, the recirculation concept has been demonstrated in several installations. Water masses in the solar field vary during transient phases, such as passing clouds. The volume of the steam drum can serve as a buffer during such transients by taking in excess water and providing water storage. The saturated steam mass flow to the superheating section or the consumer can be maintained almost constant during short transients; therefore the steam drum plays a key role for constant steam supply. Its buffer effect depends on the right sizing of the steam drum for the prevailing situations. Due to missing experiences, steam drums have been sized under conservative assumptions and are thereby usually oversized. With this paper, experiences on the steam drum of the 5 MW_{el} TSE1 power plant are discussed for optimized future plant design. The results are also of relevance for process heat installations, in which saturated steam is produced by the solar field.

OPERATING EXPERIENCE OF THE TSE1 PLANT



FIGURE 1. TSE1 plant, Kanchanaburi, Thailand

The TSE 1 power plant (see Fig 1) was built in 2010/2011 by Thai Solar Energy (TSE), Thailand, for which Solarlite CSP Technology GmbH, Germany provided the solar field. TSE1 is being operated by TSE in the region of Kanchanaburi in Thailand. It is the first solar thermal power plant in Southeast Asia, having started operation in January 2012. The solar field has a nominal power of 19 MW_{thermal} driving a 5 MW_{el} turbine by superheated steam at 30 bar and 330 °C. Its layout is described in [1]. The TSE1 power plant is the first power plant with direct steam generation (DSG) and superheating in parabolic troughs. The present study is based on an extensive database of records of almost 500 sensors installed in the power plant (solar field and power block). The data has been provided by Solarlite with a time resolution of about 1 minute. A time span of 18 month has been investigated. A stable operation could be demonstrated [2] [3]. Evaluation of the operation data helped to learn about the parallel flow behavior in DSG. Superheating events in the evaporator could be observed and several factors were detected which might cause or prevent superheating, respectively. The implemented control strategies were evaluated. From the experiences with the TSE1 power plant conclusions could be drawn to improve the layout and control of future DSG plants. The content of this paper is the evaluation of the steam drum performance in TSE1 to support the future design process of this vital component in the context of DSG.

ANALYSIS OF STEAM DRUM DESIGN FROM EXPERIENCE

Design of the TSE1 Steam Drum

For direct steam generation plants the recirculation concept is known to have advantages in stability and control [4]. Part of the recirculation concept is a device to separate the two phase flow behind the evaporator field. In previous works compact separators for every loop have been investigated and showed a good performance at the DISS test facility at the plataforma solar de Almeria [5]. For the TSE1 solar thermal power plant in Thailand one steam drum was chosen for the whole collector field. An extensive amount of measurement data of the solar plant has been investigated with a particular focus on the steam drum size.

For the design of the drum, a dynamic simulation of the evaporation in the TSE1 evaporator field was provided by DLR [6] [7]. A constant pressure of 40 bar for the saturated water entering the solar field and a constant aperture normal irradiance (ANI, i.e. direct normal irradiance corrected by the cosine of the incidence angle) of 200 W/m² during startup were assumed. The resulting surplus of water in the evaporator during start-up has been calculated to be 54 % of the overall water volume in the absorber tubes and the header pipes being pushed from the solar field to the steam drum within 30 minutes at a mass flow of 16 kg/s entering the solar field. For greater mass flows, smaller water surplus was simulated.

Additional space in the steam drum needs to be foreseen to avoid that liquid water is carried with the steam into the steam outlet. Thus, the level should not rise beyond a maximum level, whilst a minimum level needs to be kept to avoid that steam reaches the recirculation pump.

The TSE1 steam drum was designed smaller in order to reduce investment cost. Excess water can be removed from the steam drum to other atmospheric tanks. Therefore, the installed steam drum has an overall volume of 74 % of the overall water volume of the solar field of which due to its control limits less than half is usable (= net volume), which correlates to 29 % of the overall water volume of the evaporator piping.

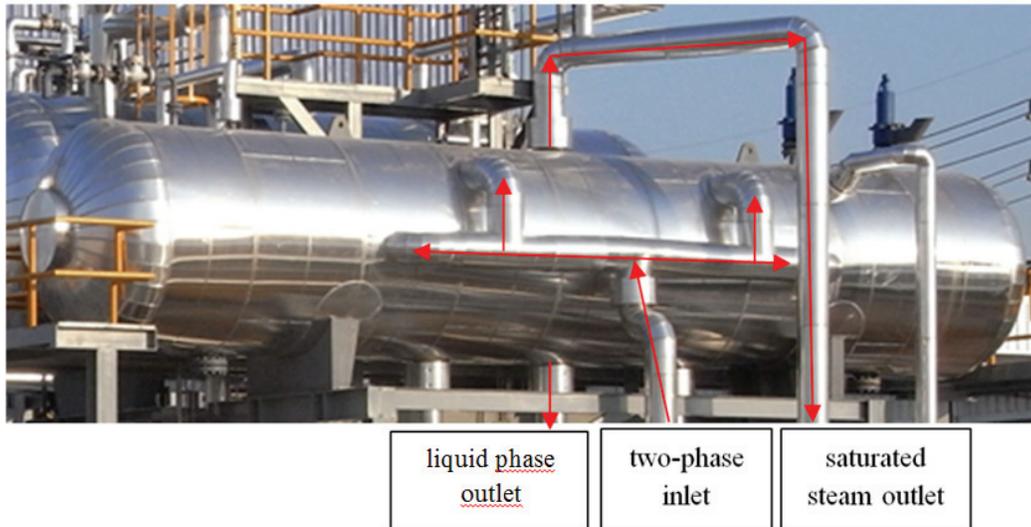


FIGURE 2. Steam drum at the TSE1 plant

Figure 2 illustrates the mass balance of the steam drum. A two-phase flow of water and steam enters the steam drum from the evaporator field. Inside the steam drum the liquid phase and the gas phase separate due to gravity. The saturated steam does not stay inside the drum but leaves towards the superheater field and moves on to the turbine. The liquid phase either stays inside the steam drum and raises the level or exits at the bottom from where it could either recirculate to the evaporator field again or be drained into one of the additional tanks.

Evaluation of Steam Drum Levels

To rate and improve steam drum design and control, the data of steam drum levels and mass flows at TSE1 have been evaluated. Different situations are considered in the following.

Evaluation of Steam Drum Levels during Constant Irradiance

During a day of constant irradiance, a constant steam drum level is expected. Analysis of the operational data of DNI and steam drum level shows that the steam drum level can be kept relatively stable during a day of nearly constant DNI (see Fig. 3). On the 14th of January 2013, constant irradiation as well as good control measures kept the steam drum level constantly at about 500 mm during operation. Only at start-up and after shut-down the steam drum level was below the lower boundaries. Even with a start-up from a level slightly above the low level, the high level would not have been reached.

However, there are many days during which the steam drum level varies strongly and even sometimes exceeds the level boundaries, although the irradiation is constant. These instabilities have several reasons but are all caused by incorrect operation. For example, on the 2nd of January 2013 (see Fig. 4) at about 11:30, the recirculation mass flow was increased from 12.5 kg/s to 15.3 kg/s without increasing the feed water mass flow at the same time. The extra amount of water was taken from the steam drum. Since the level of the steam drum was low already, the low limit was almost crossed.

The observed causes for the change in the steam drum level during constant irradiance are changes in the supply of feed water, changes in the number of focused mirrors and changes in the mass flow recirculating from steam drum to evaporator. Depending on the state of the steam drum and the gradient of the change due to these level changes, limits can be exceeded. An improved operation strategy thus shall consider the actual states of the steam drum and the related changes in the solar field.

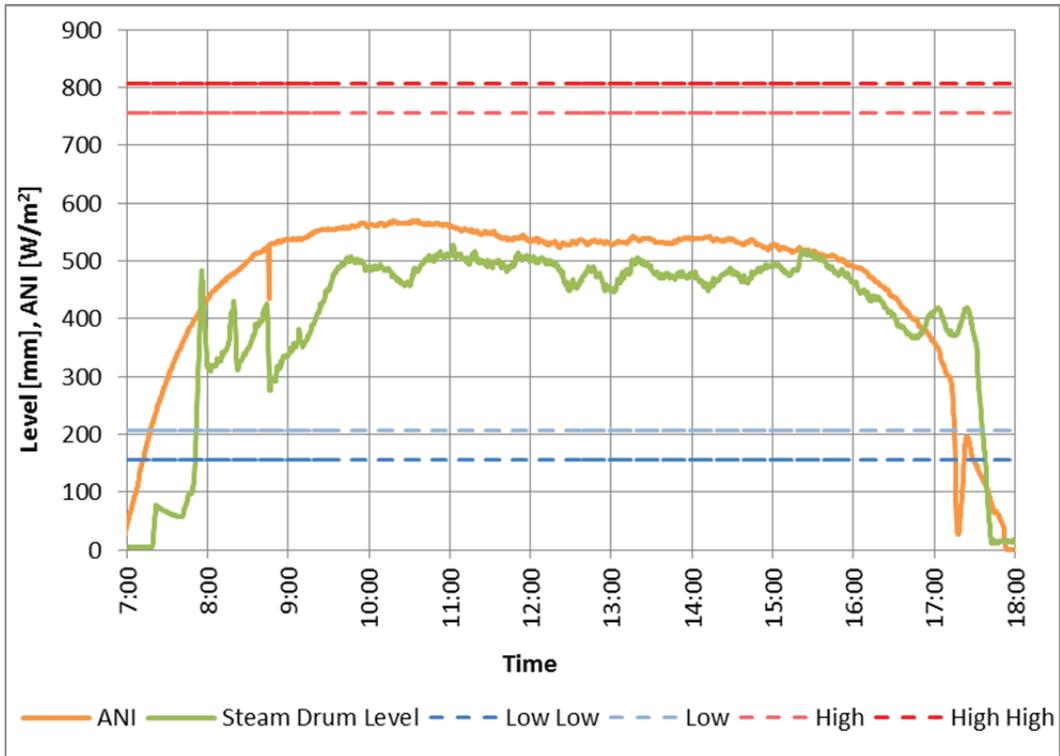


FIGURE 3.: Steam Drum Levels during constant operation, example of 14th of January 2013.

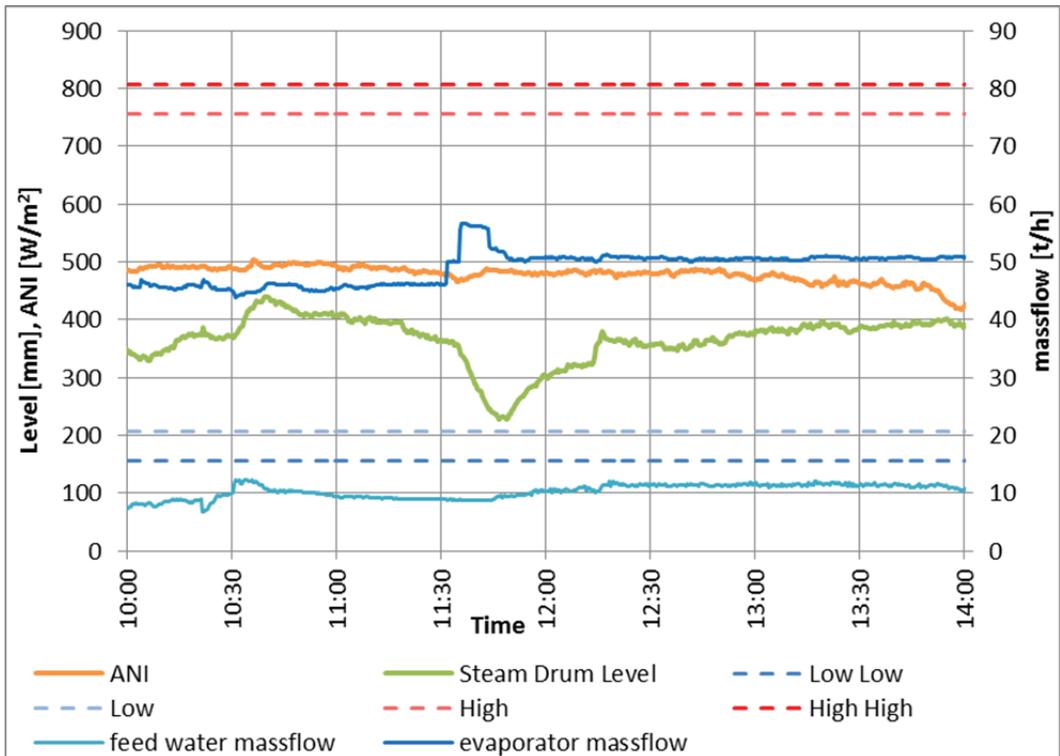


FIGURE 4. Steam drum level decreases due to increased recirculation during constant irradiance on the 2nd of January 2013

Evaluation of Steam Drum Levels during fluctuating Irradiance

The highly fluctuating irradiation of the tropical climate of Thailand increases the difficulty of operating the steam drum within its boundaries. A varying irradiation leads to varying evaporation conditions along the loops and, therefore, a varying steam volume fraction in the absorber tubes and the header to the steam drum. Evaluation of the TSE1 data shows that, during highly fluctuating phases, the steam drum level is influenced by the profile of irradiance. Thereby, steam drum level limits are often exceeded. One day with high and strongly fluctuating irradiation was the 13th of July in 2012 (see Fig. 5). At about 13:45 o'clock the steam drum is at high level of about 700 mm. Clouds shade the evaporator and the ANI is reduced from 800 W/m² to 0 W/m². Within about 15 minutes, the steam drum level decreases to 0 mm (which does not mean that the drum is completely empty, but that the level is beneath the level sensor). When the ANI raises back to 800 W/m² after 14:00 h, the steam drum level overshoots its limits and reaches 870 mm within 9 minutes. This translates to a water volume of 45 % of the overall solar field shifted from the solar field back into the steam drum.

One of the functions of the steam drum is to buffer the fluctuation of irradiance. Its varying level shows that the buffer function works. The number of incidents, in which the limits are exceeded suggests, that for the climate and the way of operation of TSE1 this steam drum is undersized. Crossing the steam drum level limits could be prevented by a bigger steam drum volume, a higher recirculation rate or better control measures. One criterion for the design of the drum size is thus what kind of irradiance disturbances shall be buffered securely and what kind of disturbances and related 'off-design' operations can be accepted.

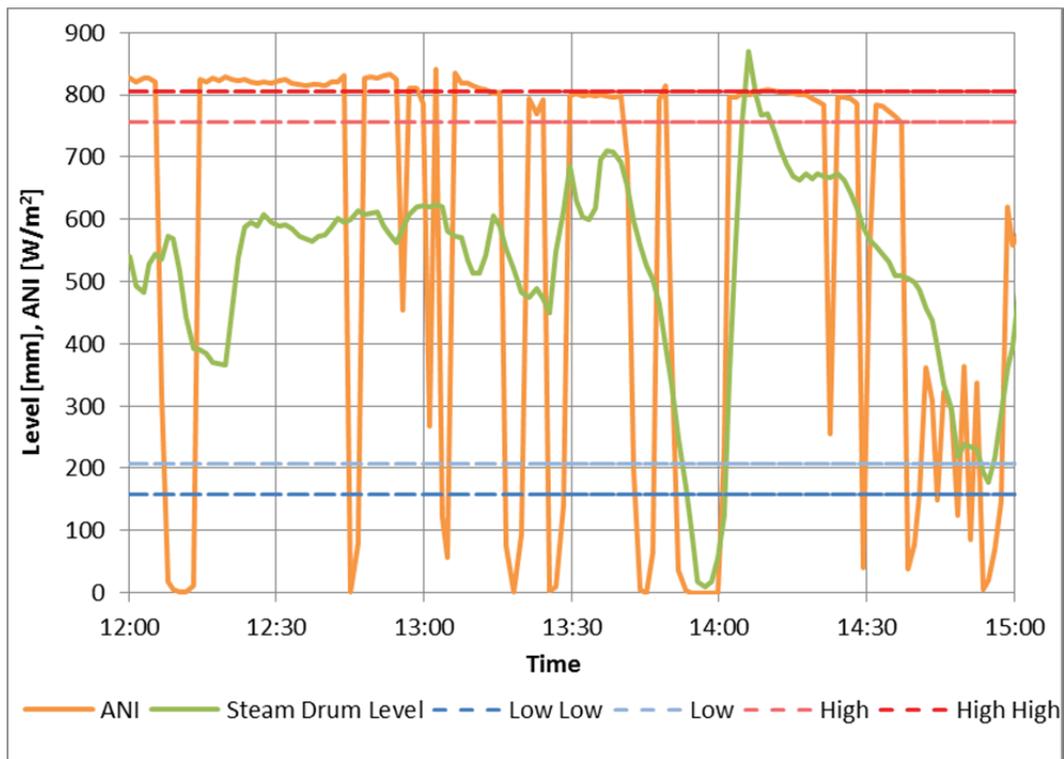


FIGURE 5. Steam drum level exceeds limits due to highly fluctuating irradiation on the 13th of July 2012

Evaluation of Steam Drum Levels during Start-Up and Shut-Down Procedures

In the morning, the evaporator is filled with water and the focusing of collectors starts the evaporation. Within a period of about 15 minutes, the increasing volume of steam in the absorbers replaces most of the water volume and pushes it into the steam drum. Therefore, the raise of steam drum level in general is expected to be the highest for start-ups. Until solar noon, the DNI might keep increasing, but the steam quality changes only slightly and, therefore, a further increase in steam drum level is subdued.

Evaluation of the data shows that design and operation of the plant are adjusted to the high water volume flow during start-up. Figure 3 shows a saw-shaped profile in the steam drum level during start-up of the 14th of January 2013. First, the level increases rapidly, but then a periodic decrease prevents the steam drum to exceed its upper limits. This is when water from the steam drum is released to the drain tank. The reduced steam drum size and therefore costs are traded off against the loss of warmed up water and therefore energy. The exact amount of water shifted to the drain tank cannot be determined due to the lack of measurement in the drain path. After focusing the evaporator field a volume of 23 % of the overall solar field water volume was shifted towards the steam drum within the first 16 minutes. Not counting the water shifted to other tanks, the volume shifted from the evaporator to the steam drum sums up to 48 % in the first two hours.

There are other days when the DNI increased even stronger and the upper steam drum level limit was exceeded. Fast automatic control measures can prevent the steam drum level from overshooting. One option is to increase the recirculation mass flow, such that a bigger share of the water volume is located inside the piping and the evaporator.

When the plant is shut down in the evening, the evaporation stops and the decreasing volume of steam in the absorbers draws water from the steam drum back into the evaporator. Therefore, the steam drum level decreases rapidly. On the 14th of January 2013, for example (see Fig. 3), 21 % of the overall solar field water volume were moved from the steam drum to the solar field within 18 minutes. Feed water control has to provide sufficient water to fill the evaporator field for the night.

Evaluation of TSE1 Steam Drum Design

For the TSE1 solar power plant, a transient simulation pre-study by DLR recommended a volume of 54 % of the overall water volume of the evaporator piping as the net design volume for the steam drum in order to buffer all relevant water masses during start-up. The evaluated data indicates that this volume is realistic. The steam drum of the TSE1 plant was designed smaller than calculated (net volume 29 % of overall solar field water volume), in order to reduce costs, but the option to shift volume to additional atmospheric tanks was implemented instead. In Figure 6, some examples of volume changes within a short period are shown for days with highly fluctuating DNI a major steam drum level goes beyond its usable volume of 29 % of the overall solar field water volume, since the operation team did not take action to shift the volume into the extra tanks. Furthermore, control measures of shut-down and start-up failed on a few days, such that the actual shifted water volumes could be determined (blue bars in Fig. 6). The measured volumes for start-up and shut-down did not exceed the design volume. The steam drum size of 29 % of overall solar field water volume is undersized compared to optimum for the high ANI gradients of Kanchanaburi with the way of operation of the TSE1. Additional automatic control strategies may keep the steam drum level within its limits.

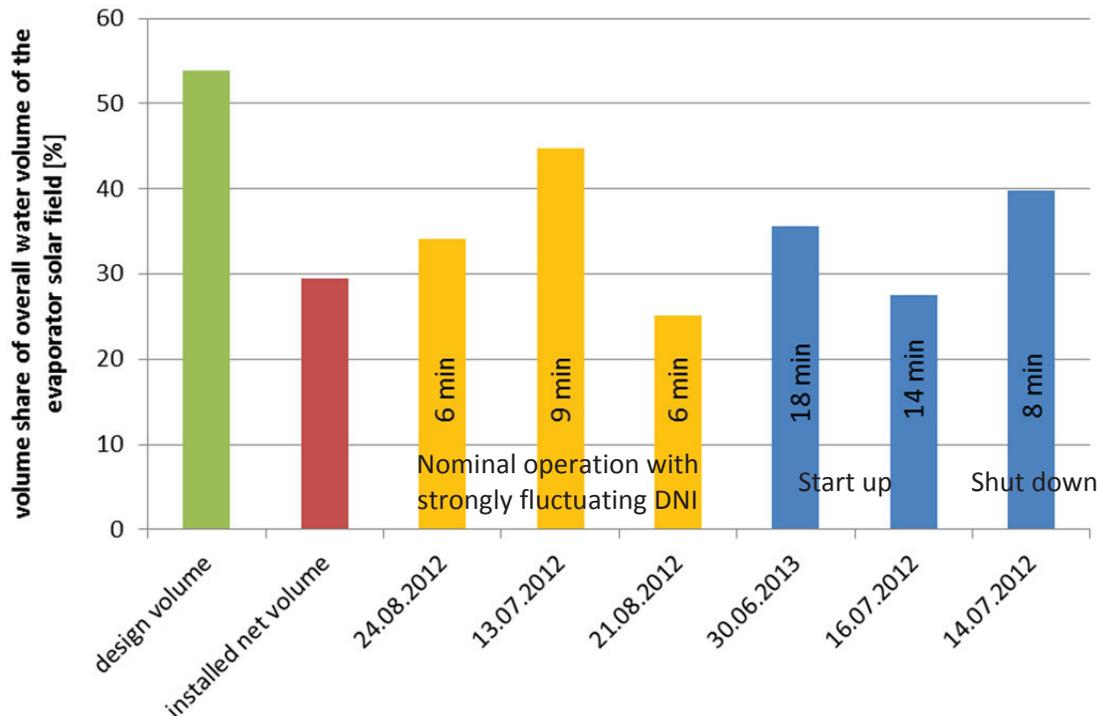


FIGURE 6. Comparison between simulated, installed usable and on exemplary dates needed steam drum volume

To prevent the steam drum of the TSE1 plant from exceeding its upper limits means preventing liquid water from entering the super heater field. To prevent the level to not fall below the lower limits means preventing steam from entering the recirculation pump. Additional control strategies should be implemented to prevent both. The control of the recirculation mass flow should consider the steam drum level. A set level value should be determined regarding the operating stage. For example, the steam drum level should be low before start-up and high before shut-down. In addition, the control of draining the steam drum to other tanks needs to be automated and to depend on the steam drum level and its gradient.

Conclusions for Future Steam Drum Design

The analyzed data suggests that the TSE1 steam drum design of 54 % of the overall solar field water volume is sufficiently large to cope with all appearing situations. However, this volume share cannot simply be extrapolated to future plants. It depends on the steam parameters (such as pressure, design steam quality etc.), feed water temperature as well as various dynamic interactions. A rough estimation for the steam drum volume can be achieved by a steady-state analysis of the volume difference of the water-filled solar field compared to the volume at nominal operating conditions. The experience from the TSE1 plant shows that two situations lead to high water shifting from the evaporator field to the steam drum. One is the start-up, which takes place regularly under defined conditions, and the other one is operation at highly fluctuating DNI conditions. A transient simulation of the evaporator field in dependence on the evaporator mass flow can predict the amount of water shifted during start-up reliably and easily. The change in the steam drum level during operation is highly dependent on the amount and fluctuating of DNI and on the control strategy. Detailed transient simulations can be used to analyze those situations in more detail and develop corresponding control strategies. The start-up simulations can already provide a good estimate for a conservative sizing, when considering TSE1 design. At locations with very stable irradiance, the steam drum size can be reduced, if an additional vessel can take the amount of water required for start-up. The same water could be released to the field during shut-down. In locations with highly fluctuating DNI, such as Kanchanaburi, large amounts of water need to be shifted during the day as well and the steam drum should be larger. Nevertheless, the better the control strategy is, the smaller the steam drum can be designed. For some locations and operations

strategies, it might be required to increase drum size compared to the steady-state analysis. In consequence, an optimized drum design is only achievable by transient simulation analyses for the particular requirements of the solar field.

OUTLOOK

One result from the evaluation is that improved control measures could help the TSE1 steam drum not to exceed its limits. One reason for the level to drop below or rise above its limits is a slow feedwater control.

A possible option to accelerate the level control is a direct link of feed water to the steam drum. However, one of the challenges of this option would be the high temperature gradient at the steam drum's feed water inlet, which would induce thermal stress and water/steam disturbances. Furthermore, the steam drum storage capacity would decrease and higher temperature variation of the drum would appear. It is not clear, if this option is reasonable, but it may be analyzed for possible future improvements.

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