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Investigation of Geothermally Sourced Combined Power and Freshwater Generation Systems

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Abstract

To address the concurrent water and energy shortage issues regions where geothermal sources are abundant, three geothermally sourced combined power and freshwater generation technologies are investigated. Two of them are based on traditional power generation systems, including a steam system (SS) and a single flash system (SFS). The other one is a proposed trilateral flash system (TFS). Instead of focusing solely on their power generation potentials as previous geothermal exploitations did, the condensation process which produces desalinized freshwater is particularly investigated. To obtain a comprehensive evaluation, system performance under various geothermal wellhead conditions have been considered and compared. Results indicate that, for a typical liquid-dominated well, SS has absolute power generating advantage over SFS and TFS under low wellhead pressure and high wellhead vapor quality conditions. However, the TFS shows more stable power-generating and freshwater-generating performance when the wellhead condition varies, especially when the vapor quality gets lower. Efficiency of the total-flow turbine of TFS determines its system power potential. A turbine efficiency of 50% enables TFS to obtain comparable specific power with traditional power systems. Moreover, fresh water generation is a distinct advantage of the TFS, qualifying it a promising choice in remote arid geothermal terrains for both power and freshwater generation.

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Keywords: Geothermal source; Combined power-freshwater generation; Trilateral flash system (TFS)

1. Introduction

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Geothermal energy, especially the more promising high-temperature (>200°C at 1 km depth) geothermal water in in arid to semi-arid regions are vastly under-utilized and represents an exciting means of addressing energy challenges, alleviating poverty, and promoting economic development [1]. Up to date, initiatives to address the concurrent water and power energy issues are largely being pursued separately in geothermal field. Traditionally, most of the high-temperature geothermal energy is exploited through power plant, while low-temperature geothermal energy can be optionally used for desalination and freshwater generation [2]. However, besides of generating power, the high-temperature geothermal flow can be further utilized for desalinized freshwater by condensing the steam after expansion. Based on this, a novel combined power and freshwater generation method is proposed.

Date and Akbarzadeh et al [3-5] has been researching on a combined power-water generation system since 2009. They started by proposing a system for simultaneous desalination and power generation based on trilateral flash cycle (TFC). Comparing to traditional power cycles, trilateral flash cycle can more effectively utilize most of the energy available in low/medium grade heat sources. Steam after expansion is condensed into freshwater and stored instead of being abandoned. By upgrading the expansion device from two-arm rotor to reaction turbines, the performance of the system has been improved significantly, demonstrating a good potential of the combined TFC and water generation concept [6].

By now, the concept of combined power and freshwater generation for addressing the twin-issue of energy and water scarcity is rather novel for geothermal applications. In this work, a typical high-temperature geothermal well is chosen from Aluto Langano geothermal field of Ethiopia. On the basis of practical wellhead condition analysis, three combined power and freshwater generation configurations have been proposed and compared. Performance investigated includes the power generation ability, system efficiency as well as freshwater generation capacity.

2. Heat Source Analysis

2.1. Geothermal well information

The Aluto Langano geothermal field is grouped as a high-temperature liquid-dominated geothermal field [7]. And discharge tests had been conducted before any energy utilization units were built there. Among the wells, the one numbered 'LA-8' is selected as the heat source well in this work. As concluded from the discharge tests, the geothermal well LA-8 is a two-phase, fluid-dominated one. Therefore, the wellhead temperatures (WHT) are saturated temperatures corresponding to wellhead pressures, showing as the blue line in Fig. 1.

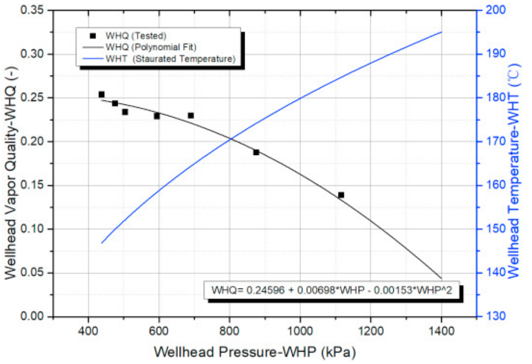

Fig. 1. Geothermal wellhead discharge test data

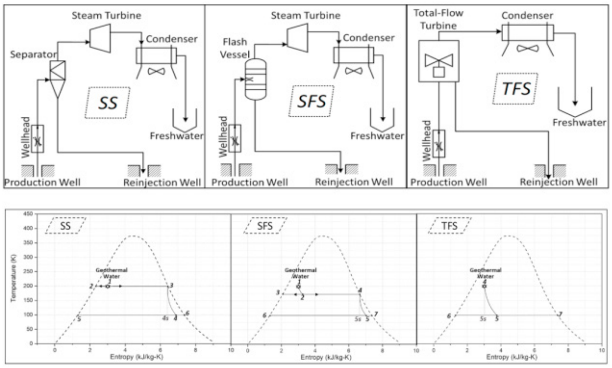

Fig. 2 Configurations and temperature-entropy diagrams of steam system (SS), single flash system (SFS) and trilateral flash system (TFS)

Applying the 'data and empirical' methodology, a polynomial curve is fitted to the test points of the well to correlate the well flow from the corresponding wellhead pressure to obtain the full well production characteristics. Based on the relationship, a correlation formula of wellhead vapor quality is developed as shown in Fig. 1. As the wellhead pressure increases from 436.7kPa to 1400.5kPa, wellhead quality decrease from 0.25 all along to 0.04.

3. System Configurations and Modelling

3.1. System Description

The three proposed geothermally sourced combined power and freshwater generation systems are configured and shown in Fig. 2, including a steam system (SS), a single flash system (SFS) and a novel trilateral flash system (TFS). Corresponding temperature-entropy diagrams of the three systems are also shown in Fig. 2.

As shown in the figures, the first two traditional power system are mostly similar to each other, except that a separator is applied in SS while a flash vessel is adopted in SFS. The flash vessel is a 2-in-1 device that accomplishes both flow flashing and liquid/steam separating processes.

For the novel trilateral flash system, geothermal water from wellhead is introduced to the total-flow turbine directly. Less processes and components are needed in this system. Brine water and steam after expansion are separated in a specially designed turbine shell, with steam goes up through the condenser for freshwater while the brine water flow back to reinjection well by gravity.

Comparing with previous geothermal energy usage, instead of directly reinjecting the condensed water to geothermal reservoirs, or discharging it to the environment in the form of co-produced brine and/or uncondensed steam, the desalinized freshwater during condensation is wholly recycled in the proposed three systems.

3.2. Modelling Assumptions

Assumptions are needed before the system modelling:

1. A separation process is modelled as an isobaric process with constant pressure;
2. Any change in the kinetic or potential energy of the fluid is neglect as it undergoes a flashing process or an expansion process through the turbine;
3. Heat loss from the turbines are neglected.

3.3. Steam System (SS) Modelling

The key process for a steam system is the expansion in turbine, i.e. from point 3 to 4 as shown in Fig. 2. It should be noted that moisture occurs during the expansion process would reduce turbine efficiency. According to the Baumann rule [8], a 1% average moisture causes roughly a 1% drop in turbine efficiency. Although the inlet flow is saturated vapor, the steam turbine operates mostly in the wet region, degradation in performance caused by moisture should be taken into account. Adopting the Baumann rule, the turbine efficiency η_t is given by:

$$\eta_t = \eta_{td} * (x_3 + x_4)/2 \tag{1}$$

η_{td} is the dry turbine efficiency which is conservatively assumed to be constant at 85%; x_3 (=1) and x_4 denote the vapor qualities of inlet and outlet flows of the steam turbine.

To get the thermodynamic state of point 4, which is in return determined by turbine efficiency as shown in Fig. 2, fluid properties at state 4s - the ideal turbine outlet state would be used:

$$\eta_t = (h_3 - h_4)/(h_3 - h_{4s}) \tag{2}$$

h_{4s} is enthalpy of state 4, which is easily calculated from the known pressure and entropy values (s_{4s}= s_3).

$$h_{4s} = h_5 + (h_6 - h_5) * [(s_{4s} - s_5)/(s_6 - s_5)] \tag{3}$$

Adopting the Baumann rule, enthalpy of the turbine outlet state 4 can be obtained:

$$h_4 = \frac{h_3 - (\eta_{td}\ /2) * (h_3 - h_{4s}) * (1 - h_5/(h_6 - h_5))}{1 + (\eta_{td}\ /2) * (h_3 - h_{4s}) * (h_6 - h_5)} \tag{4}$$

Then the vapor quality x_4 is obtained from the condensing pressure and entropy value h_4.

Therefore, power produced by the turbine per unit mass of steam flowing through it is given by:

$$w_t = h_3 - h_4 \tag{5}$$

3.4. Single Flash System (SFS) Modelling

Comparing with steam system, the single flash system has a flashing process occurs at constant enthalpy before the liquid/steam separation and steam expansion processes, as shown in Fig. 2.

For a traditional SFS designed for a saturated liquid heat source, there’s a ‘rule of thumb’ about the optimal temperature of state 2 which determines the separation temperature as well as the inlet flow state of turbine [6]. However, calculations show that the rule is no longer applicable with two-phase heat source, as in this work. System performance of SFS is thus modelled by decreasing the temperature of state 2 from wellhead temperature to condensing temperature by a small temperature step of 0.1 ℃, and the optimal separation temperature and system performance is therefore accurately obtained.

Besides, modelling of the liquid/steam separation process, the steam expansion process and condensation is the same as those of a steam system.

3.5. Trilateral Flash System (TFS) Modelling

Modelling of the novel trilateral flash system is quite simple since only two processes are included and an average turbine efficiency is pre-set as constant. Detailed equations of each process in each system are listed in Table 1. It should be noted that, all the subscripts of parameters in this table are corresponding to those in Fig. 2.

Table 1 Modelling Summary

SYSTEM	PROCESS	MODELLING	PARAMETERS & NOTES
SS	Separation	$x_1 = WHQ$	Wellhead quality-WHQ
	Steam expansion	$w_t = x_1 * (h_3 - h_4)$	Specific power-w_t [kW/(kg/s)]
	Condensation	$q_c = x_1 * x_4 * (h_6 - h_5)$	Specific condensing heat-q_c [kW/(kg/s)]
	Freshwater generation	$x_{fw} = x_1$	Freshwater to heat source ratio[(kg/s)/(kg/s)]
	Energy utilization	$\eta_{SS} = w_t / E_{GW} * 100$	Utilization efficiency- η_{SS} [%] Specific exergy of geothermal water -E_{GW} [kW/(kg/s)]
SFS	Flashing	$h_1 = h_2$	Isenthalpic process
	Separation	x_2	Vapor quality of flash outlet [-]
	Steam expansion	$w_t = h_4 - h_5$	Specific power-w_t [kW/(kg/s)]
	Condensation	$q_c = x_2 * x_5 * (h_7 - h_6)$	Specific condensing heat-q_c [kW/(kg/s)]
	Freshwater generation	$x_{fw} = x_2$	Freshwater to heat source ratio[(kg/s)/(kg/s)]
	Energy utilization	$\eta_{SFS} = w_t / E_{GW} * 100$	Utilization efficiency- η_{SS} [%]
TFS	Total-flow Expansion	$w_t = \eta_t * (h_4 - h_{5s})$	Pre-set average turbine efficiency-η_t[%]
	Condensation	$q_c = x_5 * (h_7 - h_6)$	Specific condensing heat-q_c [kW/(kg/s)]
	Freshwater generation	$x_{fw} = x_5$	Freshwater to heat source ratio[(kg/s)/(kg/s)]
	Energy utilization	$\eta_{TFS} = w_t / E_{GW} * 100$	Utilization efficiency- η_{SS} [%]

3.6. Modelling validation

Modelling of SS and SFS have been validated to previous work, as shown in Table 2, proving good modelling reliability, which also indirectly validates the TFS modelling, since both the expansion and condensation processes in TFS follow the same modelling rules.

Table 2 Modelling Summary

	Wellhead condition	Power output in Reference [kW/(kg/s)]	Power output in current work [kW/(kg/s)]	Deviation
SS	Pressure 0.9Mpa; Enthalpy 2800kJ/kg; Chapter 7 of Ref [8]	511.9	511.9	0.00%
SFS	Pressure 1.08Mpa; Temperature 183.3℃; Section 2.2 of Ref [7]	556.0	555.9	0.02%

4. Results and Analysis

4.1. Principal Influence Factors of System Performance

Average turbine efficiencies under the pressure range has been fixed as 20%, 30%, 40% and 50% for the trilateral flash system (TFS). The turbine inlet enthalpy of TFS is exactly the enthalpy of wellhead flow because the turbine in the system is a total-flow one. Average dry expansion efficiencies for both steam turbines in SFS and SS are set as 85%.

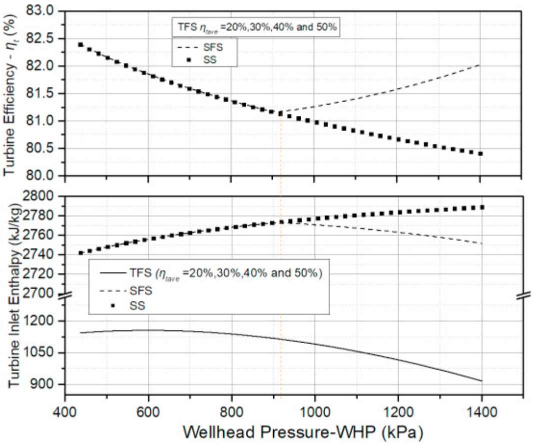

Fig. 3 Turbine efficiency and turbine inlet thermodynamic state

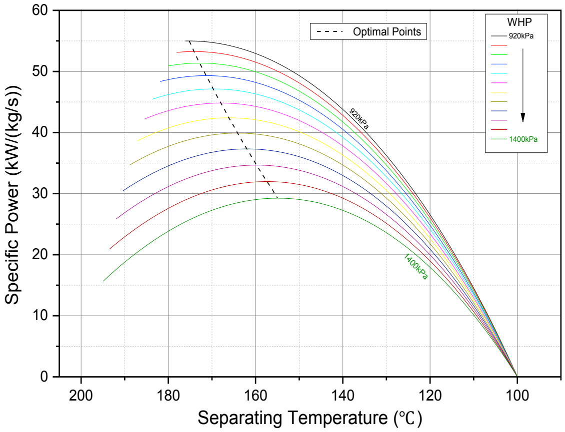

Fig.4 Thermodynamic performance of a single flash system against varying separating temperature

As shown in Fig.3, for a steam system (SS), turbine efficiency (wet efficiency) keeps decreasing as the wellhead pressure increases. The reason is that, turbine inlet vapor quality is always 1 while the outlet vapor quality decreases as the wellhead pressure increases, since the dry expansion efficiency is fixed. According to the Baumann rule, vapor quality is an essential parameter to determine the turbine wet efficiency. Therefore, the increasing wetness of turbine outlet flow reduces turbine efficiency. Besides, the turbine inlet enthalpy of SS keeps increasing as both the wellhead temperature and pressure increase. And it is 2 to 3 times higher than that of TFS since the inlet flow is only steam for SS as well as SFS.

For a single flash system (SFS), the flow mixture after the flash process is separated into steam and brine liquid. There exists an optimal separating temperature to obtain the best thermodynamic performance if the heat source is saturated liquid [8]. However, this rule is not applicable when the heat source is a two-phase mixture. Results show that when the vapour quality of wellhead flow is higher than 0.18, the best power generating performance is obtained when the two phase heat source is separated directly behind wellhead, without going through a flash process. If a flash process is applied, the performance only keeps dropping if the separating temperature decreases from heat source temperature to condensing temperature. It means that under those conditions where the heat source has relatively high vapour quality and enthalpy, a flash process is not necessary for power improvement. Therefore, SFS will only be discussed in this work when it has a better power performance than SS, i.e. when WHQ is lower than 0.18, and WHP is higher than 920kPa, as shown in dash lines. Under these conditions, as further shown in Fig.4, there always exists an optimal separating temperature for each wellhead pressure. However, the optimal temperature decreases as the WHP increases from 920 kPa to 1400 kPa. Only the optimal point of SFS under each wellhead condition has been picked out and investigated. Thus, the turbine efficiency of SFS shows an increasing trend as WHP increases, because the decreasing optimal separating temperature leads to an increasing vapour quality of turbine outlet flow. The efficiency is thus increased according to the Baumann rule. Besides, the turbine inlet enthalpy decreases as the inlet temperature drops.

4.2. System Performance: Power Generation

Specific power outputs of all three systems show parabolic trends which increase first and then decrease as Fig.5 shows. However, reasons of the parabolic trends are not the same. For a steam system (SS), it shows obvious power generation advantages over the other two systems under low WHP conditions. As shown in the modelling part, specific power of SS is majorly affected by three parameters- wellhead quality (WHQ), turbine inlet enthalpy (WHH) and its wet efficiency. Thereinto, WHQ and turbine efficiency decreases along with the increasing WHP, while WHH changes in the opposite way. The parabolic trend is thus caused by mutual restrictions of the three indexes. The maximal power is 59.0kW/(kg/s) at 720.0kPa.

For a single flash system (SFS), it shows a bigger power generating ability over SS when the wellhead pressure is higher than 920kPa. However, the specific power keeps decreasing as the wellhead pressure increases further. Specific power of SFS is determined by the same three parameters as those of SS. Turbine efficiency is the only one that increases among the three parameters. The decrement of both WHQ and WHH leads to the decreasing specific power.

For a trilateral flash system (TFS), it shows a relatively more stable power generating performance under a wider WHP range comparing to other two systems. Variation of specific power output of TFS is majorly caused by the turbine inlet enthalpy. The pre-set turbine efficiency determines system's power potential. If the total-flow turbine has an average efficiency of 50% or higher, the system can generate more power than the two traditional systems under higher WHP and lower WHQ conditions. For a 50% efficiency, a maximum specific power 46.5kW/(kg/s) can be reached at around 875.0kPa.

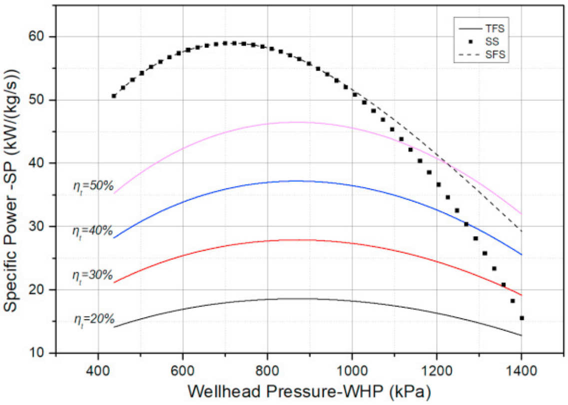

Fig. 5 Specific power generation against well head pressure

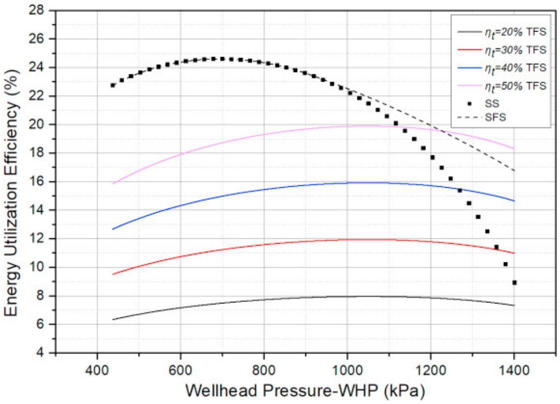

Fig. 6 Energy utilization efficiency against well head pressure

4.3. System Performance: Energy Utilization Efficiency

Variations of energy utilization efficiencies against well heat pressures are similar to those of specific power. For a steam system (SS), it has the highest energy utilization efficiency at 700kPa which is 24.6%. But when WHP gets to be higher than 1130kPa, and WHQ gets correspondingly lower than 0.13, the energy utilization efficiency of SS becomes lower than SFS and TFS. For TFS with a 50%-efficiency turbine, when the wellhead pressure is between 800kPa~1400kPa, in which range the WHQ is lower than 0.2, the system has a relatively promising and stable efficiency, which is between 18.3%~19.9%.

4.4. System Performance: Fresh Water Generation

For trilateral flash system (TFS), the biggest advantage over traditional power systems is its fresh water generating capacity, as shown in Fig.7. With a 20% of turbine efficiency, specific freshwater of TFS can reach up to be 1.7 and 4.9 times higher than that of SFS and SS respectively. However, higher turbine efficiency leads to slighter lower specific freshwater quantity, because of lower turbine outlet vapor quality. The considerable amount of fresh water generated in the condensing stage is an extra benefit of the power system, especially for remote arid geothermal terrains. The geothermal heat source is better utilized without adding separate water desalination systems. Three power systems have similar fresh water variations. They all decrease with the increase of WHP and the decrease of WHQ.

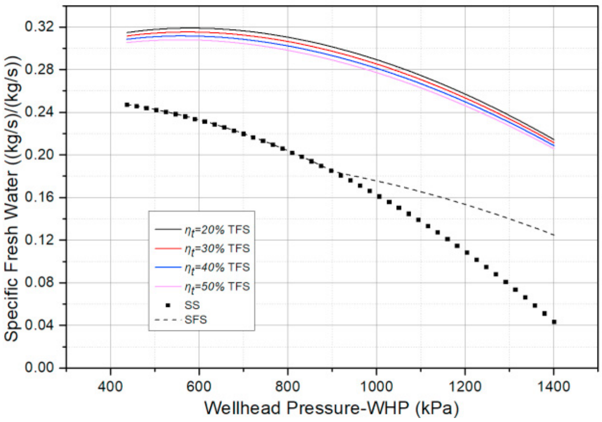

Fig. 7 Specific fresh water generation against well head pressure

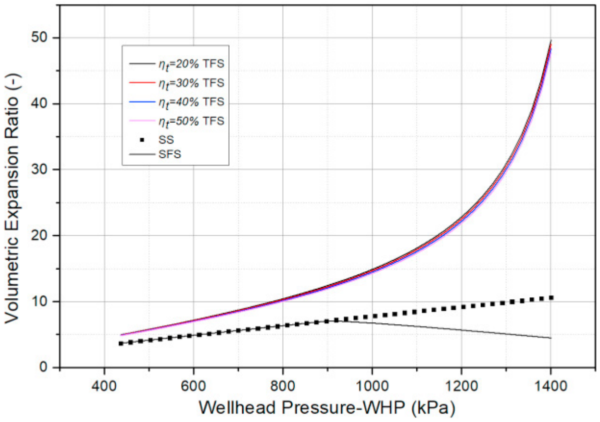

Fig. 8 Volumetric expansion ratio against well head pressure

4.5. Key Component: Turbine Selection

Volumetric expansion ratio (VR) is a major criterion for turbine selection. Fig.8 shows that, for traditional SS and SFS, their volumetric expansion ratio are mostly lower than 10, which is easier for the application of single-stage turbines. However, VR of a trilateral flash system is much higher than those two systems, and it increases substantially with WHP, especially when WHP is higher than 1000kPa. The reason is that the total-flow turbine in a TFS uses original two-phase geothermal source for expansion, and the specific volume of turbine inlet is an order of magnitude smaller than that of the other two systems. For this reason, displacement expanders such as screw expanders may not be a good choice since the VR is the major restriction. Total-flow dynamic turbines which allow bigger volumetric expansion ratio should be explored and developed.

5. Conclusions

To seek after solutions for the twin challenges of energy shortage and water-scarcity challenges in geothermal field, three combined power and freshwater generation configurations have been proposed and compared in this work, including two traditional power plant systems and a novel trilateral system. Both power generating and water producing performance are investigated, conclusions are drawn as following:

1. For liquid-dominated geothermal wells, steam system (SS) has absolute power generating advantage over single flash system (SFS) and the novel proposed trilateral flash system (TFS) under low wellhead pressure and high wellhead vapor quality conditions, and a flash process is not necessary under these heat source conditions.
2. However, The TFS shows more stable power-generating and freshwater generating performance under various wellhead conditions, especially when WHQ reduces to a certain level.
3. Efficiency of the total-flow turbine in a TFS determines the system power potential. 50% of efficiency enables the trilateral flash to obtain comparable specific power with traditional power systems. Efficient total-flow dynamic turbines which also allow relatively bigger volumetric expansion ratio should be explored and developed

4. Specific freshwater of TFS can reach up to be 1.7 and 4.9 times higher than that of SFS and SS respectively. Freshwater generation is an advantage of the trilateral flash system which qualifies it a better comprehensive choice in remote arid geothermal terrains.

Acknowledgements

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