EXERGY ANALYSIS USED IN PERFORMANCE TEST APPLIED AT A 532 MW COMBINED CYCLE POWER PLANT LOCATED IN THE NORTHEAST OF BRAZIL

Tales de M. Bezerra[1], talesmelo@yahoo.com.br
Fábio Magnani[2], magnani@ufpe.br

[1] - MsC – Technical Consultant
[2] - PhD – Federal University of Pernambuco

Abstract. *Thermoelectric generation in Brazil has been presented as an alternative to the security of the national power system, behaving as a complementary source that ensures the power supply. That source may be built near large urban centers and does not depend on adverse hydrological conditions, such as lack of rain. Through exergy analysis, it is possible to evaluate the use of an energy resource, allowing the identification of sub-systems that present the worst thermodynamic performance; in other words, the sub-systems with the greatest exergy destruction. Besides allowing this evaluation, through this analysis it is possible to construct a profile that matches the behavior of the cycle exergy efficiency along its lifetime. This profile can be obtained based on the values of degradation parameters of machines informed by the manufacturer - power output and heat rate degradation. The power plant used as a reference in this study is a combined cycle power plant, consisting of two 160 MW gas turbines and one 212 MW steam turbine, with their peripherals systems. Currently, in thermal plants, the performance tests only use the energy analysis. The great challenge of this work was to raise a profile of behavior of the cycle exergy efficiency in view of the gas turbines fired hours. Under this approach, this article aims to address all the exergy balance of the power plant used as the model, perform the exergy destructions calculation, as well as to plot the cycle exergy efficiency degradation profile.*

Keywords*: Exergy Analysis, Exergy Balance, Exergy Efficiency, Combined Cycle, Performance Test*

1. INTRODUCTION

Thermal power generation has been used in Brazil as a complementary source, in order to guarantee the supply energy for the national electric system. Its participation in the generation matrix becomes increasingly larger due to the ease of construction near major urban centers, unlike hydroelectric plants, since the use of dams is not required and there is no dependence on adverse hydrological conditions, such as lack of rain. One concern regarding the thermoelectric generation is the efficient use of fuel, aiming to reduce the marginal operation cost, which is predominantly tied to the fuel price. Other concern is a strict control of emissions, to eliminate or maximally reduce the aggressor wastes into the environment.

The adoption of a mixed system of power generation, which is able to explore the advantages between the thermal source and the hydropower source, contributes to increase the availability of energy supply by using these complementary resources. Regarding the thermal generation, the use of thermal power plants with combined cycle configuration, which includes Brayton and Rankine cycles, has increased due to their thermal efficiency compared to the simple cycle configuration. According to Yadav et al. (2004), advances in the technology of gas turbines used in thermal power plants are responsible for improving thermal efficiency and specific work, and also minimizing the emissions and the generation cost per kilowatt (kW).

The most important equipment of the combined cycle is the gas turbine (Sue and Chuang, 2004), whose performance has been improved with the use of intercooler in the compressor section (air cooling); chamber for reheating the combustion gases and steam injection into the combustion chamber (Khaliq and Kaushik, 2004). Other devices, such as compression or absorption chillers for cooling the inlet air of the gas turbine; use of pre-heaters to raise the fuel temperature and post-burn in the recovery boiler, to increase power in the steam turbine, are also being applied for improvement in the overall performance of the cycle (Sue and Chuang, 2004).

As the thermal machines tend to degrade during the continuous regime of operation, periodic monitoring of the combined cycle is necessary. The performance test is a tool that evaluates the behavior degradation of the cycle, by assessing two indicators: the heat rate and the cycle net-power. Over the plant lifetime, the heat rate tends to increase and the net-power tends to decline. Such trends can be verified through the degradation profiles of the thermal power plant, which are obtained through the degradation coefficients, declared by the machines manufacturer.

Other monitoring tool for the cycle degradation is the exergy analysis, which is based in the First and Second Laws of Thermodynamics. The basis of this analysis is the exergy, which means the useful part of energy. The exergy analysis has been considered a tool to help with three aspects of thermal plants: the project decision-making, the improvements of the operational efficiency, and also the identification of losses of each component. It means that the exergy analysis allows us to evaluate the energy conservation in thermal power plant (Khaliq and Kaushik, 2004). The exergy analysis has been largely adopted by designers and scientists, in order to assess whether the energy resources are being efficiently used or not. The advantage is to assess the potential of heat to perform work, because all work can be converted into heat, but not all heat can be converted into work (Sue and Chuang, 2004).

This article aims to raise the behavior profile of the exergy efficiency of the cycle in order to have one more indicator to evaluate the degradation of the thermal power plant along its lifetime. Besides the raised profile through exergy analysis, this article also addresses to verify the stretches with larger irreversibility, to get a photograph of their behavior when performing periodic performance tests.

2. METHODS

The thermal power plant considered in this study is located in the northeast of Brazil, with 532 MW of base capacity in combined cycle which arrangement is known as 2x1. The Brayton cycle is composed by two 160 MW gas turbines and two heat exchangers for heating natural gas, while the Rankine cycle is constituted by two 250 t/h recovery boilers, one 212 MW steam turbine, one condenser, two high pressure feed water pumps (one for each boiler), two medium pressure feed water pumps (one for each boiler), one condensate pump and one sea water pump for water circulation in condenser (cold source of the condenser).

From a macro point of view, the combined cycle under study was divided into three major groups: the first train (GT1 + HRSG1); the second train (GT2 + HRSG2) and the third train consisting of the steam turbine with the condenser. Values of the total exergy at the points mapped on air/gas and water/steam circuits were calculated.

Methodologically, for the calculations of exergy destruction and efficiency of major equipment, ten steps were obeyed:

1. Modeling the composition of atmospheric air, natural gas and exhaust gases (hot gases);
2. Calculation of enthalpies and entropies for all the points;
3. Calculation of physical exergy;
4. Calculation of chemical exergy;
5. Calculations of the exergy efficiency and exergy destruction of the cycle's main equipment, based on the values of total exergy.

2.1. <u>Exergy Analysis</u>

For the development of exergy analysis, we considered the equations of the First and the Second Laws of Thermodynamics. In this approach, the evaluation of kinetic and potential exergy was disregarded because these values are negligible compared to the calculated values of physical and chemical exergy.

2.1.1 <u>Exergy Balance</u>

The exergy balance equation for a given control volume has its origin from the energy balance equation (First Law of Thermodynamics) and from the entropy balance equation (Second Law of Thermodynamics). Through this equation it is easy to prove that the variation of exergy between input and output streams of the control volume corresponds to the maximum work that could be obtained between input and output states (reversible work) of a delimiting frontier. This ability to perform work is the sum of the following parcels (Negri et al., 1997):

- Work that would be obtained from a reversible heat engine operating between T and T_0 temperature levels, consuming $\dot{Q}$ and rejecting heat to the environment at T_0 (exergy associated with heat exchange);
- Work effectively performed (pure exergy);
- Available work destroyed due to the existence of irreversible processes (destructed exergy).

2.1.2 Total Exergy

The total exergy consists of four parcels (Tsatsaronis, 2007):

- Physical exergy – resulting from the difference between pressure and temperature of fluid inside a studied frontier, compared to those of the environment;
- Chemical exergy – resulting from the difference of chemical composition of the fluid inside the studied frontier compared to the elements found in natural state in the environment;
- Kinetic exergy - resulting from fluid velocity measured within the defined frontier, in relation to a reference in the environment;
- Potential exergy - resulting from the fluid height, measured inside the defined frontier, compared to a reference in the environment.

2.1.3 Exergy Efficiency

The exergy efficiency can be used for the following purposes (Moran et al., 2002):

- To determine the difference between the manner of use of resources, since some are thermodynamically effective and others less effective;
- To evaluate the effectiveness of the solutions adopted to improve the performance of the thermal system;
- To compare the potential of improvements in the performance of certain thermal system, with another similar.

Its value can be determined by the ratio between the exergy value attainable by a machine (useful exergy) to the value of available exergy to the equipment (input exergy). The higher exergy efficiency is associated to the better use of the energetic potential available by the input. It is important to note that the cycle can also be globally assessed by calculating its exergy efficiency.

3. RESULTS

The periodic monitoring tool for the combined cycle, currently adopted by the thermal power plant in study corresponds to the performance test. This tool is based on the energy analysis and two degradation profiles are considered: net power output profile and heat rate profile.

These profiles can be assessed by the first performance test results and from the cycle degradation coefficients informed by the machines manufacturer. All the performance test procedures follow the recommendation of ASME PTC-22, ASME PTC-46 and ASME PTC-6.

The application of the performance test allows to assess the cycle in compliance with the profile raised, in order to identify deviations between the calculated values and the estimated values.

From a technical and practical standpoint, this test constitutes a hallmark instrument for the thermal power plant, which permits to infer some conclusions about the system's operating cycle as a whole, allowing us to know the causes that may justify the shown behavior. Nevertheless, this single analysis does not allow a more accurate and conclusive diagnosis that points the equipment where the largest irreversibilities occur. That is the reason why it is necessary to perform the exergy analysis, to identify losses and destructions through the exergy balance in each part of the cycle, focusing specific corrective actions on the local of interest.

With the cycle operating at base load, we determined the composition and concentrations of elements on air, fuel (natural gas) and exhaust gas, whose results are presented in Tab. 1.

From the balance of the chemical reaction of combustion, we calculated the molar fractions of reactants and products in the air/gas circuit. With these values it was possible to calculate the enthalpy and entropy of the substances, considering the pressure and temperature of the mapped points into this circuit. These results were used in the physical exergy calculation. Similarly to physical exergy, chemical exergy of the air/gas circuit was determined by using molar fraction and the tabulated values of standard molar chemical exergy.

With respect for the water/steam circuit, through the pressure and temperature of the mapped points into this circuit, it was possible to calculate the enthalpy and entropy, used to obtain the physical exergy. The chemical exergy at these points could be calculated from the standard molar chemical exergy of the water.

After calculating the values of physical and chemical exergy of air/gas and water/steam circuits, we obtained the value of the total exergy. Total exergy allowed to calculate the destroyed exergy and exergy efficiency of major equipment of the cycle and to determine the exergy balance, which results are presented in Tab. 2. This analysis helped to confirm higher cycle's exergy destruction in the combustion chambers of the gas turbines, which can be attributed to the irreversibility resulting from combustion. The exergy destruction in the recovery boiler was not as pronounced, possibly because the post-burn did not come into operation during data collection. The irreversibility of the recovery boiler is related to its inside heat transfer.

Table 1 – Fluids composition and chemical concentrations of combined cycle in base load

Item	Parameters	Concentration
	Air	
1	Oxigen (O2)	20,45%
2	Nitrogen (N2)	76,93%
3	Water (H2O)	2,62%
	Natural gas	
4	Methane (CH4)	88,67%
5	Etene (C2H6)	7,03%
6	Propane (C3H8)	0,04%
7	Nitrogen (N2)	3,43%
8	Carbon dioxide (CO2)	0,82%
	Combustion gases GT1	
9	Nitrogen monoxide (NO)	6,32 PPM
10	Nitrogen dioxide (NO2)	1,86 PPM
11	Carbon monoxide (CO)	6,98 PPM
12	Sulfur dioxide (SO2)	0 PPM
13	Oxigen (O2)	13,35%
	Combustion gases GT2	
14	Nitrogen monoxide (NO)	6,33 PPM
15	Nitrogen dioxide(NO2)	1,87 PPM
16	Carbon monoxide (CO)	6,99 PPM
17	Sulfur dioxide (SO2)	0 PPM
18	Oxigen (O2)	13,37%

Table 2 – Exergy destruction and efficiency

Equipments	Exergy destruction - $\dot{E}d$ (MW)	$\dot{E}d$ distribution_function of total $\dot{E}d$ (%)	$\dot{E}d$ distribution_function of total fuel (%)	Exergy efficiency (%)
Compressor GT1	10,61	2,66%	1,17%	93,79%
Turbine GT1	14,96	3,76%	1,65%	95,59%
Combustion Chamber GT1	135,38	34,00%	14,92%	77,94%
HRSG1	16,85	4,23%	1,86%	87,19%
Compressor GT2	9,71	2,44%	1,07%	94,24%
Turbine GT2	14,53	3,65%	1,60%	95,68%
Combustion Chamber GT2	137,64	34,56%	15,17%	77,53%
HRSG2	17,64	4,43%	1,94%	86,58%
ST_HP	3,05		0,34%	92,70%
ST_IP	0,13	8,76%	0,01%	99,81%
ST_LP	31,71		3,49%	69,04%
Condenser	6,01	1,51%	0,66%	57,57%
TOTAL	**398,00**	**100,00%**	**43,88%**	**-**

To determine and close the exergy balance of the cycle, the flow exergy of input and output to the air/gas and water/steam circuits were calculated.

Table 3 presents the values of the flow exergy summed with the useful work for the first, second and third trains. In the same table, we can observe the values of exergy corresponding to inputs (natural gas) and losses.

Table 3- Results of flow exergy, useful work, loss exergy and fuel exergy

	Flow exergy + Useful work (MW)	Losses (MW)	Insume (MW)
First train			
	268,50	7,50	453,40
Second train			
	267,00	7,00	453,60
Steam turbine / Condenser			
	-49,00	8,00	-
TOTAL	**486,50**	**22,50**	**907,00**

To facilitate the analysis of exergy destruction, we chose to express it as percentage distribution, based on the total exergy destruction of the cycle, equal to 398 MW, which is presented in Tab. 2, as well as in Fig. 1.

The analysis of Fig. 1 allowed identifying that the greatest contribution of cycle's total exergy destruction corresponded to the combustion chambers of the gas turbines, equating to 34% in the combustion chamber of GT1, and 34.56% in combustion chamber of GT2.

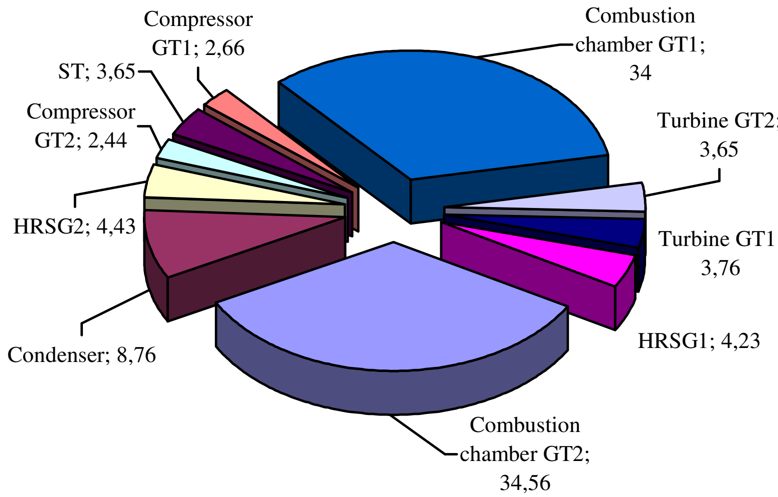

Figure 1 – Percent distribution of exergy destruction of equipment in function of destructed total exergy

For details of the exergy analysis, it was determined the percentage distribution of the destruction of each equipment, based on the total exergy of used fuel, which values can be seen in Tab. 2, as well as in Fig. 2.

It was found that in 43.88% of total exergy destruction of the cycle, according to fuel exergy, 30.09% was destroyed in the combustion chambers of the gas turbines in amounts of 14.92% at the GT1 chamber and 15.17% at the GT2 chamber.

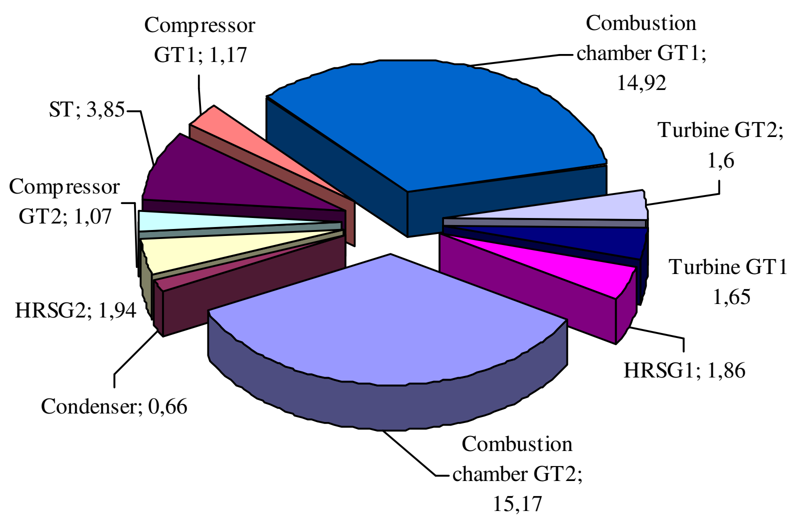

Figure 2 – Percent distribution of exergy destruction of equipment as function of fuel total exergy

In Tab. 4, we summarized the results of the cycle's exergy balance closure, with the values of exergy destruction, losses and net-flow added to the net useful work, expressed in MW, and also the percent distribution of these values according to fuel exergy.

Table 4 – Exergy balance of the cycle and percent distribution as function of fuel exergy

EXERGY BALANCE		
Parcels	Values (MW)	Distribution as function of fuel exergy (%)
INSUME EXERGY	**907,00**	**100,00**
EXERGY DESTRUCTION	398,00	43,88
NET FLOW EXERGY + NET WORK	486,50	53,61
EXERGY LOSSES	22,50	2,51
TOTAL	**907,00**	**100,00**

Within a global analysis, it is observed that the exergy losses did not generated strong impact on the percentage distribution shown in Tab. 4, while the portion related to the exergy destruction has become very powerful. Considering a 43.88% weight in the percent distribution, we proceeded a thorough evaluation on equipment which had higher irreversibility to allow certain improvements for reducing this parcel.

Aiming to get a second tool for monitoring the cycle degradation, based on exergy analysis, we raised the profile of exergy efficiency as a function of gas turbines fired hours, represented in Fig. 3, which can be used as one more tool for future periodic performance tests of the thermal power plant.

The steps for determining the behavior profile of the cycle exergy efficiency along its lifetime were:

1. Determining the specific consumption of the cycle for the first performance test;
2. Determining the specific consumption of the cycle relative to zero hour (starting point);
3. Determining the specific consumption of the cycle along its lifetime;
4. Determining the fuel consumption (mass flow) of the cycle along its lifetime;
5. Determining the exergy efficiency of cycle along its lifetime.

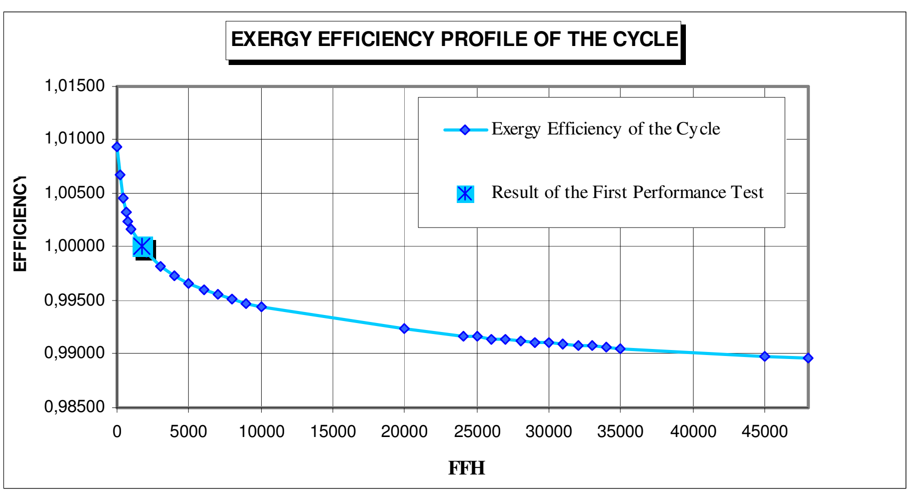

Figure 3 - Profile of exergy efficiency of combined cycle

Note: Due to a request of the thermal power plant, the actual values of exergy efficiency of the cycle could not be inserted. The values in the ordinate axis, kept proportionality with the actual value of the exergy efficiency of the cycle on the first performance test

Through the behavior profile of the exergy efficiency of the cycle and with the determination of top and bottom boundary lines, it is possible to develop a management tool of cycle degradation. A major issue is the decision making of programmed outages when there is an operational interference caused by the full need for cycle generation, ie, this profile allows us to infer whether the thermal power plant should really have a partial or total shutdown, in occasions of a request of the electrical system for generation.

The lines of upper and lower limit delimit the tolerance range within the variation of exergy efficiency becomes acceptable to the thermal power plant and constitutes an internal decision. For example, in Fig. 4, the green line represents the upper limit and the red line, the lower limit of the allowable range, built to a tolerance of 2.5% compared to the profile shown in Fig. 3.

To exemplify the management of data obtained in performance tests to be conducted during the lifetime of the plant, in Fig. 4, besides the point for the first performance test (blue), six other points were inserted, graphed in green, yellow and red.

The points graphed in green indicate that the result of the exergy efficiency, obtained during the performance test, exceeded the expected value of the trend line graphed in blue, thus representing good performance. The points graphed in yellow indicate less efficient results, because they are in the interval between the trend line (blue) and the lower intake (red), pointing to the need for actions that promote increased exergy efficiency. The points graphed in red represent poor performance of the cycle, since it hit the lower allowable limit, requiring the scheduling of corrective action to promote the recovery of exergy efficiency value.

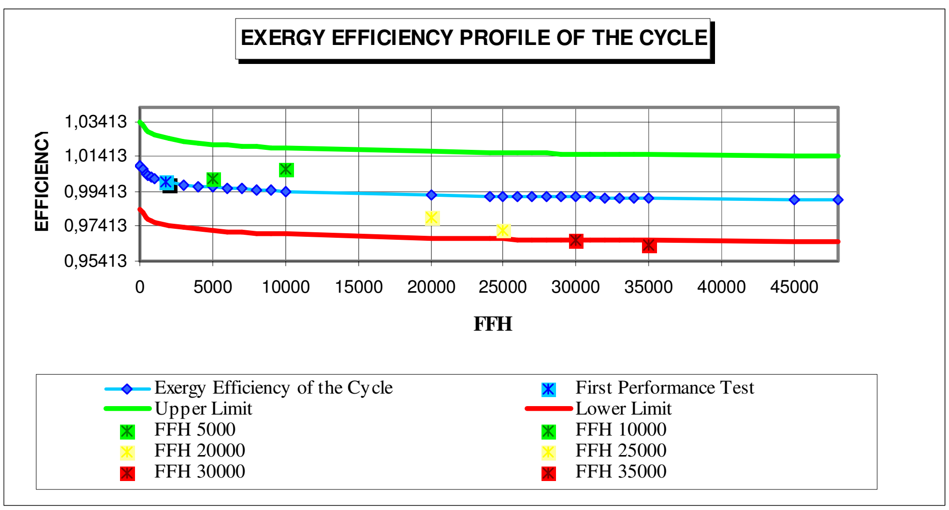

Figure 4 - Profile of the exergy efficiency of combined cycle with boundary lines

4. CONCLUSIONS AND SUGGESTIONS

Currently, the exergy analysis has been adopted in the systems of thermal power generation as a tool for identification of the points that constitute the major sources of exergy destructions in order to mitigate them. In this regard, this work could prove that the exergy analysis, applied to a combined cycle power plant, was a tool to facilitate the identification of areas with larger irreversibility as well as serve as a basis for decision making regarding the most efficient operation of the cycle.

In developing the exergy balance of the cycle, operating at base load, the stretch that showed the highest exergy destruction corresponded to the combustion chambers of gas turbines, due to irreversibility in the combustion. Recovery boilers had no very high exergy destruction due to the fact that post-burn was not triggered for the case study.

Regarding the exergy efficiency, the condenser was the equipment that showed the lowest value, due to the considerable difference between steam and water exergy, inherent to function of the equipment itself. This difference becomes substantial, which impacts the denominator of the ratio of exergy flow of water circulation and flow exergy of steam/water, since the calculation of the exergy efficiency of the condenser is obtained for this reason. It is noteworthy that while the exergy efficiency of the condenser has not presented a high value, its exergy destruction was pretty small, considering the total exergy destruction of the cycle, therefore, this equipment is not considered one of the focuses in which should conduct studies on mitigation of exergy destruction and, yes, the combustion chambers of the gas turbines. Through a number of tools currently used, for example, the injection of diluents, one can achieve the reduction of exergy destruction in this equipment.

Aiming to follow the natural evolution of the exergy destruction of the combined cycle of the plant under study, we determined the behavior profile of the degradation of cycle's exergy efficiency, to serve as a hallmark instrument for the thermal power plant, which allowed us to determine the expected value for the exergy efficiency of the cycle throughout the lifetime of the plant. The plant, operating at base load, had a better use of available energy resource, which allowed reiterating that this assumption should always be taken into account when carrying out the schedules of generation plant.

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