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FIRST AND SECOND LAW EFFICIENCIES OF A THERMOELETRIC POWER PLANT

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Abstract: This work presents a methodology for energy and exergy evaluation of a thermoelectric power plant fuelled by blast furnace gas and tar. The methodology was applied to evaluate Barreiro Thermoelectric Power Plant, a co-generation unit located in the State of Minas Gerais, Brazil. The plant comprises, as main equipments, boiler, turbo-generator system, condenser, high-pressure pump and regenerative heat exchangers. Computer simulation was executed using data obtained from the power plant. The results show the efficiency of each individual equipment and that for the whole cycle as a function of the power supplied.

Keywords: thermoelectric power plant, Rankine cycle, availability analysis.

1. Introduction

The U.S. Department of Energy 2002 report (DOE, 2002) estimates the global energy demand will reach petroleum equivalent 15.41 million ton by the year of 2020, with an average annual increase rate of 2.26%. In this context, the industrialized countries will present an energy consumption annual increase rate of 1.27%, the under-developed countries, 3.86%, and the Eastern Europe/ Former Soviet Union countries (EE/FSU), 1.64%. Brazil is estimated to reach an energy consumption of petroleum equivalent 424 million ton by the year 2020, with 3.3% annual increase rate on demand (Fig. 1).

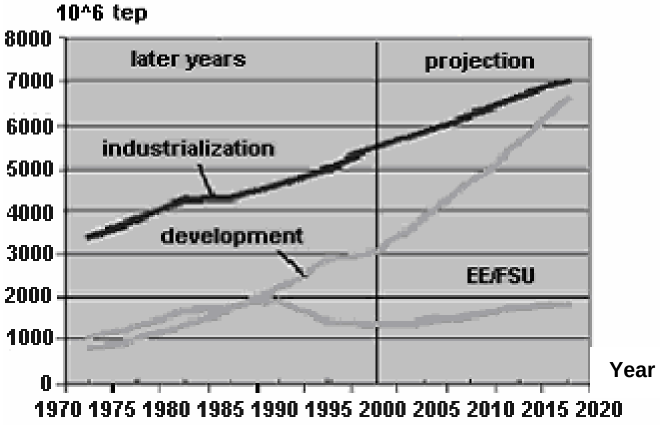

Figure 1 – 1970-2020 Internal energy offer forecast (DOE, 2002).

The global energy intensity, measured by the relationship between the energy demand and the Gross Domestic Product (GDP), is estimated to decrease at the annual rate of 0.95% up to 2020 (Fig. 2). That means an effort to energy saving in comparison to the period from 1970 to 2000, when this indicator showed an annual decrease rate of 0.92%. The EE/FSU will present the highest rate of energy intensity reduction, of 2.58% per annum. The industrialized countries will present a reduction of 1.34% per annum, and the under-developed countries, 1.15% a year. In the same period, Brazil is expected to present a reduction in energy intensity of 1.59% a year, as a result of a less intensive industrial growth and usage of more efficient processes and energy sources (MME, 2003).

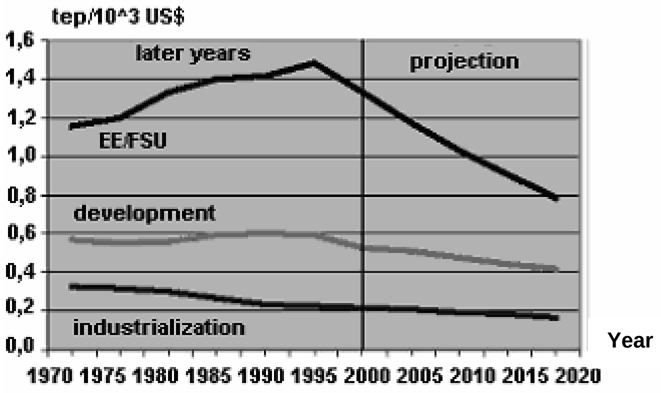

Figure 2 – 1970-2020 Energy intensity (MME, 2003).

The focus of this work is the development of a methodology for energy and exergy evaluation of thermoelectric power plants with co-generation. Such methodology allows for evaluation of thermal losses and energy quality. Energy availability is compared to measured data. As a case study, the methodology is applied to Barreiro thermal power plant, a co-generation unit located in the State of Minas Gerais, Brazil. The plant has a nominal power of 12.9 MW, and uses blast furnace gases and tar as fuel in a Rankine cycle. Natural gas is also used to startup the boiler or in case of interruption of blast furnace gas or tar supply. The unit operates continuously, providing electrical power to the primary loads of the plant (blower and pumps of the blast furnace and cooling system) in parallel to the electrical network.

2. Literature Review

Wall (1986) applied the concepts of exergy in a paper and cellulose industry, calculating the exergy losses costs for the main equipment.

Balestieri (1994, 2002) presented a multi-objective optimization for cogeneration plants that allow analyzing several types of configuration based in mathematical programming.

Horlock (1997) defined the criteria for thermodynamic analysis of combined heat and power plants.

Coelho et al. (1995) developed a study on cogeneration impact in the Brazilian energy matrix. Steel, sugar, alcohol, paper and cellulose sectors were analyzed. Cogeneration was seen as an alternative to expand the electric system, due to its potential and the investment difficulties the power companies face. Similar studies were done by Janson et al. (1997).

Nascimento et al. (1997) analyzed cogeneration in Brazil, Europe and USA. The authors related the potential for cogeneration in different sectors and its perspectives with respect to institutional changes. The existence of a good potential for cogeneration in Brazil and changes in legislation that were favorable to private sector participation in the production of electric power were highlighted.

Barros et al. (1998) analyzed the potential for electric power generation using blast furnace gas in steel industries. The authors described the advantages and existing technological options for this purpose.

Negri et al. (1999) applied the concepts of exergy in a thermal power plant operating with natural gas. The efficiencies of several equipments were evaluated. The method of availability analysis was proven to be a good tool to identify the magnitude and the probable reasons for thermodynamic losses in the equipments.

From thermal-economic analysis of cogeneration systems, Cerqueira and Nebra (1999) pointed out the economic viability for self generation and cogeneration for several configurations of heat/power production.

Iglesias and Vasconcelos (1998) presented technical-commercial aspects of Barreiro cogeneration thermal power plant. The viability to use is low-cost residual blast furnace gas and tar as fuel was demonstrated.

3. Mathematical Modelling

Based on thermodynamics concepts, specific equations were developed for efficiency calculations for the main equipments of Barreiro thermal plant to determine the energy availability. In Fig. 3, the cycle of Barreiro thermoelectric power plant is presented schematically with its main equipments: boiler, turbo-generator system, condenser, high-pressure pump and regenerative heat exchangers (air purge, high pressure and low pressure heat exchangers). Numbers in the figure correspond to the thermodynamic states in the equations.

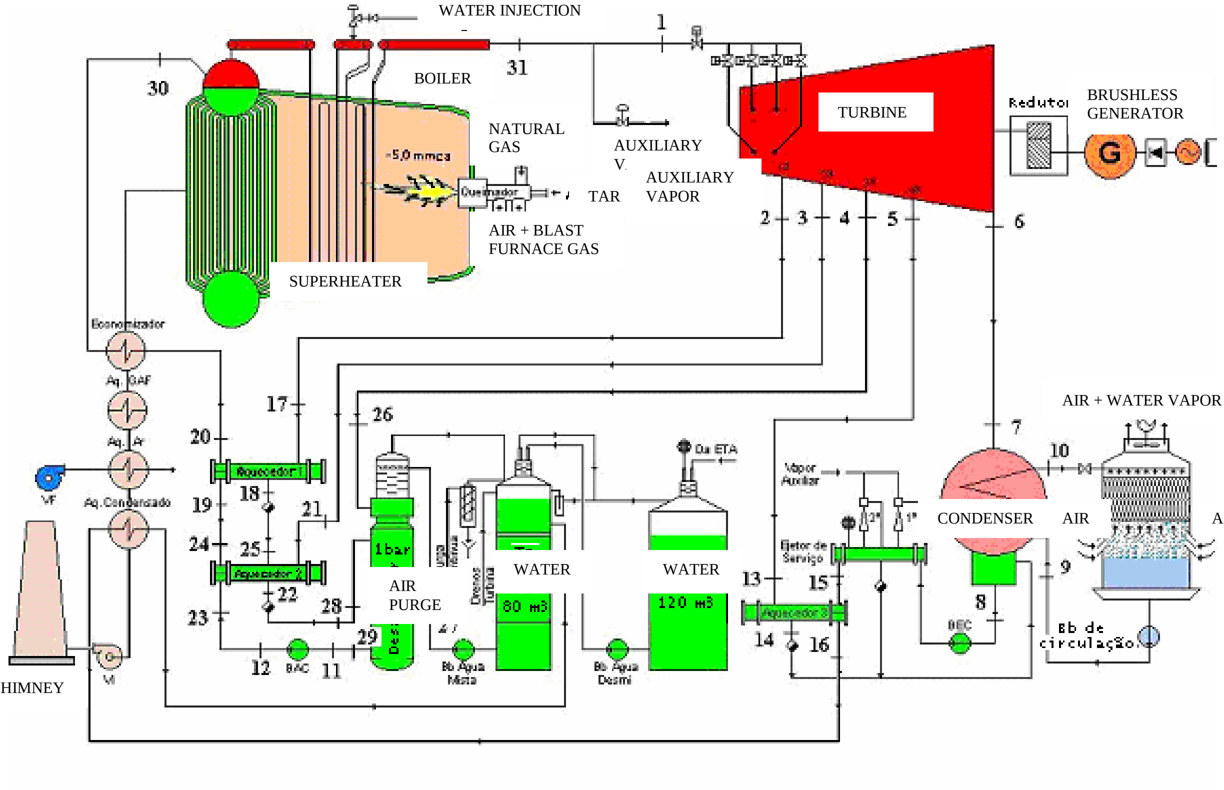

Figure 3 – Regenerative Rankine cycle of Barreiro thermoelectric power plant.

4. Boiler

The efficiency of the boiler, ηb, is defined by the First Law of Thermodynamics as:

$$\eta_b = \frac{\dot{Q}_b}{\dot{m}_{bfg} Q_{LHV,bfg} + \dot{m}_{tar} Q_{LHV,tar}} \qquad (1)$$

Heat transfer rate to the boiler is defined as:

$$\dot{Q}_b = \dot{m}_{31} h_{31} - \dot{m}_{30} h_{30} \qquad (2)$$

Subscripts 30 and 31 refer to the entry and exit of the boiler, respectively.
The efficiency by the Second Law of Thermodynamics is defined by:

$$\varepsilon_b = \frac{A_b}{\dot{m}_{bfg} . a_{bfg} + \dot{m}_{tar} a_{tar}} \qquad (3)$$

The rate at which the availability of the boiler water varies is equated as:

$$A_b = \dot{m}_{31} a_{31} - \dot{m}_{30} a_{30} \qquad (4)$$

The availability balance for the boiler is reduced to:

$$A_h + I = A_{total}^{ch} - A_b \qquad (5)$$

5. Turbo-Generator System

The turbine, illustrated in Fig. 3, has four steam extractions, two of which are directed to the regenerative high-pressure heaters, the third to the air purge and the last to the low-pressure heater. The efficiencies of the turbo-generator system, by the First and the Second Law of Thermodynamics, are expressed as follows:

$$\eta_t = \frac{\dot{W}_g}{\left(h_1\dot{m}_1\right) - \left(h_{2I}\dot{m}_2\right) - \left(h_{3I}\dot{m}_3\right) - \left(h_{4I}\dot{m}_4\right) - \left(h_{5I}\dot{m}_5\right) - \left(h_{6I}\dot{m}_6\right)} \qquad (6)$$

$$\varepsilon_t = \frac{\dot{W}_R}{\left(a_1\dot{m}_1\right) - \left(a_2\dot{m}_2\right) - \left(a_3\dot{m}_3\right) - \left(a_4\dot{m}_4\right) - \left(a_5\dot{m}_5\right) - \left(a_6\dot{m}_6\right)} \qquad (7)$$

Indexes 1 to 6 refer to the inlet and exit of the turbine, as shown by Fig. 3.

Total destruction of availability in the turbine is caused by internal irreversibility and heat loss to the environment and can be calculated through the availability balance as follows:

$$A_h + I = A_1 - (A_2 + A_3 + A_4 + A_5 + A_6) - A_w \qquad (8)$$

6. High-Pressure Pumps

Efficiencies of the First and Second Law of Thermodynamics for pumps are written as follows:

$$\eta_p = \frac{\dot{m}_{11}\left(h_{11} - h_{12I}\right)}{\dot{m}_{11}\left(h_{11} - h_{12R}\right)} = \frac{\left(h_{11} - h_{12I}\right)}{\left(h_{11} - h_{12R}\right)} \qquad (9)$$

$$\varepsilon_p = \frac{\dot{m}_{11}\left(a_{11} - a_{12}\right)}{\dot{W}_R} \qquad (10)$$

Subscripts 11 and 12 refer to the entry and exit of the high-pressure pumps. The availability balance for the adiabatic pumps is reduced to:

$$I = A_{11} - A_{12} + A_w \qquad (11)$$

7. Condenser

In the condenser, the steam flow and dissolved gases flow to the ejector were not taken into account. Thus, the condenser efficiency using the Second Law is calculated as follows:

$$\varepsilon_c = \frac{\dot{m}_9\left(a_{10} - a_9\right)}{\dot{m}_7\left(a_7 - a_8\right)} \qquad (12)$$

The availability balance for the condenser is reduced to:

$$A_h + I = A_9 + A_7 - \left(A_{10} + A_8\right) \qquad (13)$$

8. Regenerative Heater Exchangers

The equations employed for calculating the efficiency and availability balance for the high-pressure heater, according to the numbering in Fig. 1, are as follows:

$$\varepsilon_{hph01} = \frac{\dot{m}_{19}\left(a_{20} - a_{19}\right)}{\dot{m}_{17}\left(a_{17} - a_{18}\right)} \qquad (14)$$

$$A_h + I = A_{17} + A_{19} - \left(A_{18} + A_{20}\right) \qquad (15)$$

9. Regenerative Rankine Cycles

The global efficiency of the thermoelectric regenerative cycle is the result of the product between the cycle efficiency and the respective boiler efficiency (Li, 1996), and is expressed by the First and Second Law of Thermodynamics as:

$$\eta_{global} = \eta_{cycle} . \eta_b \tag{16}$$

$$\varepsilon_{global} = \varepsilon_{cycle} . \varepsilon_b \tag{17}$$

10. Results and Discussion

Figure 4 shows boiler efficiency for several loading conditions. It is noticed that boiler efficiency by the First Law exceeds the efficiency given by the Second Law. This occurs because the First Law only takes into account the energy balance in the boiler, whereas losses due to heat transfer through the sides and unburned fuel amount approximately 12% of the ideal condition. When calculating the efficiency by the Second Law, the total availability of the fuels used is compared to the availability that is effectively absorbed by the working fluid.

The efficiency of the turbo-generator system using the First Law of Thermodynamics for the ideal load of 12.904 MW is equal to 74.69%, including the speed reducer, generator and bearings (Li, 1996). This value was confirmed by the simulations done in this work, which also included the determination of the efficiency using the Second Law, as shown by Fig. 5. An expected decrease in efficiency is observed with reduction of the applied load, since the turbine is designed to work primarily at the nominal load of 12.907 MW. Besides, an increase in irreversibility is noticed resulting from the expansion control valve at lower powers.

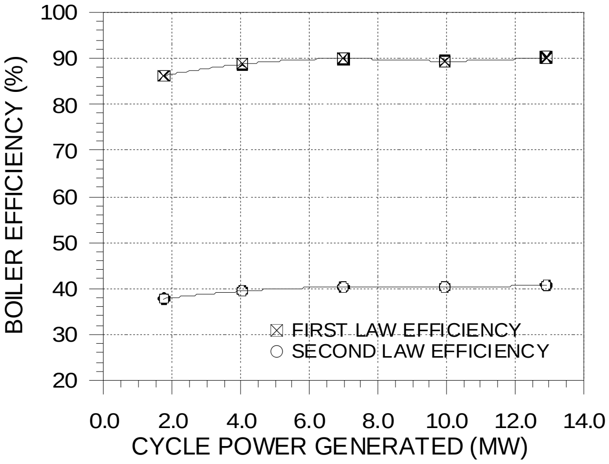

Figure 4 – Variation of boiler efficiency with load.

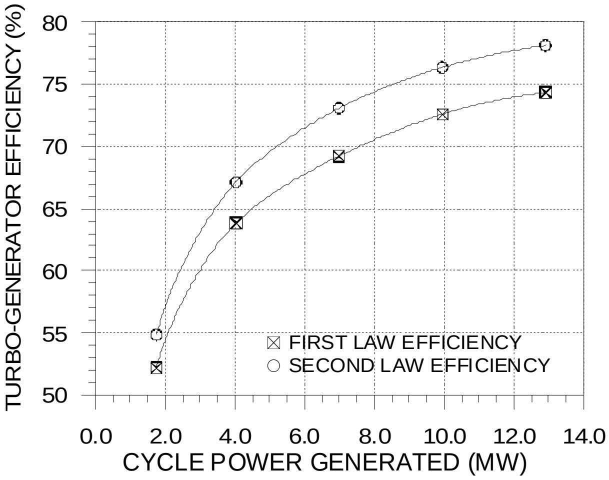

Figure 5 – Variation of turbo-generator efficiency with load.

Use of the Second Law, in this case, gives an unusual higher efficiency than the First Law, as documented by Li (1996). This occurs because the First Law uses the isentropic power as the maximum, whereas the Second Law uses the maximum power limit as the variation of the availability between two real states. In this case, only part of the availability flow can be transformed into work; the rest is consumed in the process due to its irreversibility.

The high-pressure pumps First Law efficiency at the nominal power is 73.3%. Analogous to the turbine, Fig. 6 shows that pump Second Law efficiency is higher than First Law efficiency. This phenomenon is also described by Li (1996).

Figure 7 shows that a reduction in Second Law efficiency happens for higher loading conditions. This is explained by the increase in irreversibility of the working fluid. This behavior is associated to the difference between the saturation and working fluid temperatures at the condenser exit. For higher loads, an increase is observed in both the difference between temperatures and the rejected heat transfer rate. These factors contribute to an elevation of the irreversibility in the thermal equipment and, subsequently, the lowering of its efficiency. The condenser Second Law efficiency calculated is 47.24% at the nominal condition (12.907 MW) and 72.62% at the minimum load (1.751 MW).

Figure 8 shows the high-pressure heat exchanger Second Law efficiency increasing when load is augmented, staying nearly constant beyond 6.985 MW. The trend observed is the same as that for the mean temperature difference between the hot and cold working fluids. At 12.907 MW, the Second Law efficiency is 88.42%. All other heat exchangers show similar behavior.

Figure 9 shows large variations in global efficiency using both Laws of Thermodynamics with varying load. This occurs primarily because of the expansion of the turbine inlet valve and the influence of the steam extractions. The Second Law efficiency for all conditions is lower than that obtained using the First Law. This is explained by the large irreversibility created by the boiler (Li, 1996). The First Law system global efficiency is equal to 25.79% for the nominal load of 12.907 MW, which is in accordance to Toshiba (2001).

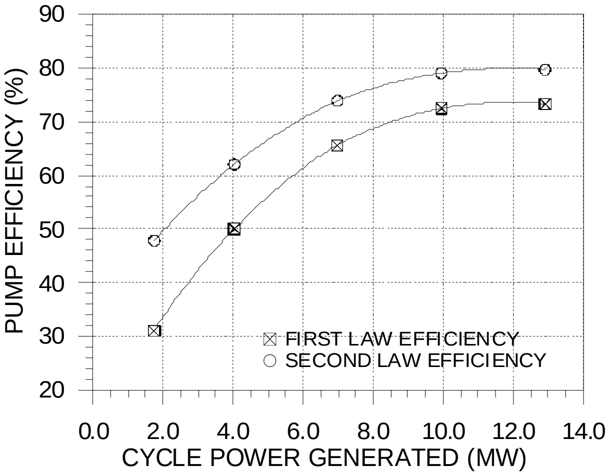

Figure 6 – Variation of high-pressure pump efficiency with load.

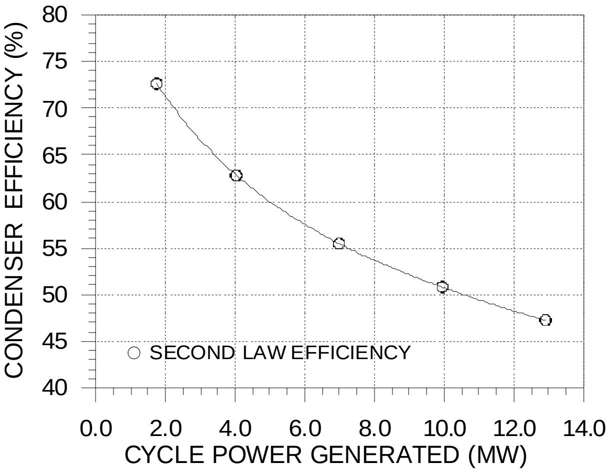

Figure 7 – Variation of condenser Second Law efficiency with load.

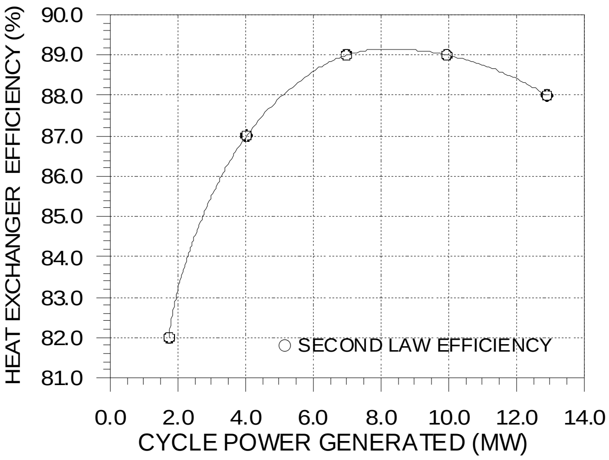

Figure 8–Variation of high pressure heat exchanger 1 efficiency with load.

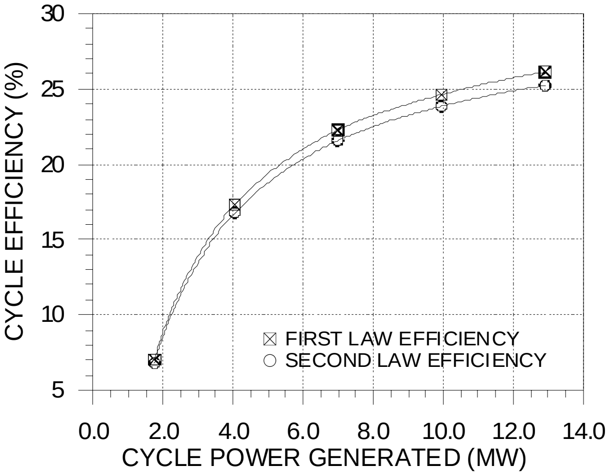

Figure 9 – Variation of system global efficiency with load.

Figure 10 shows the participation of the equipments in the total irreversibility generated at the nominal load of 12.907 MW. Boiler and turbo-generators are the equipments with the largest potential for optimization. For other loads, participation of the equipments was very similar. On-line monitoring of the boiler and other equipments make it possible to evaluate the best operational conditions for the existing system, and, to a certain extent, can help to decide on future alterations to boost performance.

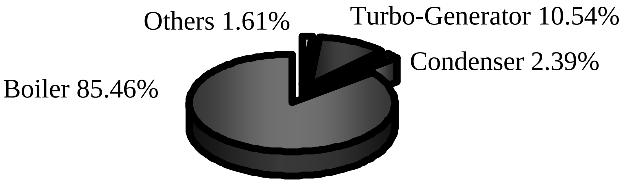

Figure 10 – Influence of each equipment in the total irreversibility for nominal loading conditions.

11. Conclusions

- A routine calculation for energy and exergy analysis of a co-generation thermal power plant has been presented.
- The calculated efficiencies for the boiler, turbo-generator, pump, and heat exchangers showed and increase with the total load, while a decrease in efficiency with increasing load was noticed for the condenser.
- System global efficiency reached a maximum of 26.1%, at the nominal load of 12.907 MW.
- Boiler large influence on the irreversibility of the co-generation cycle was verified, contributing to nearly 85.5% of the total availability destruction for all loading conditions analyzed.

- The turbo generator has also shown to be an important source of irreversibility in the cycle, contributing to about 10.5% l, followed by the condenser, which accounted for 2.4%.
- All other sources contributed with less than 2% of the cycle total irreversibility.

12. Acknowledgements

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