# EXERGY ANALYSES OF RECUPERATED AND AIR PRECOOLED COGENERATION SYSTEMS

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**Abstract: In our study, air-fuel preheated cogeneration cycle, and inlet air cooling by using absorption cooling cogeneration cycle are evaluated with respect to energy efficiency (energy utilization factor), exergetic efficiency, electric and heat power, electric-heat energy rate, fuel energy saving ratio and artificial thermal efficiency. Those methods are compared with each other. In these analyses, the thermodynamic parameters such as compressing ratio, air and fuel mass ratio and compressor inlet temperatures of the cycles are used. It is concluded that these parameters can be listed from most effective to least effective as air fuel ratio, compression ratio and compressor inlet temperature. It is also concluded that the better cycle is found to be the air-fuel preheated cycle for obtaining more electric power and less heat power.**

**Index Terms: Cogeneration, exerg, air-fuel preheated, inlet air cooling**

## I.INTRODUCTION

Cogeneration is the concept used to indicate production of electricity and useful thermal energy in one operation by using fuel efficiently. Cogeneration systems have many advantages over the conventional ones such as lower weight per unit power, higher efficiency, dual fuel capability, compact size, safe and reliable operation, fast starting time, more economic and less environmental emissions. In gas turbine systems natural gas or mixed fuels such as biomass, alcohols, refinery residues, naphtha, etc., are used as fuel. The fuel flexibility for gas turbine systems is an important advantage [1, 2, 3]. Improving performance of gas turbine cogeneration cycles will be an important objective in the future.

Gas turbine cogeneration systems find applications in buildings, industry and others. The appropriate cogeneration system for a specific purpose is chosen with respect to some criteria such as efficiency, heat to power ratio and the grade of heat. Obtaining high efficiency depends on some factors such as reduced auxiliary power consumption, increased gas turbine inlet temperature, fuel preheating, advanced gas turbine cooling, inter-cooling, hydrogen cooled generators, low compressor inlet air temperature, high compressor inlet air pressure, high compressor inlet air humidity, multiple pressure cycle with reheat and better HRSG design [4, 5, 6]. There are many gas turbines cogeneration systems on the market, however they differ in efficiency, power output, pressure ratio, exhaust temperature, firing temperature, etc.

Khaliq and Kaushik in their study have analyzed thermodynamic performance evaluation of three selected gas turbine cogeneration systems with reheat, and found that the pinch point temperature has an effect on the fuel utilization efficiency, on the power to heat ratio and on the second law efficiency. They also found out that the process steam pressure affects the fuel utilization efficiency, the power to heat ratio and the second law efficiency [7]. Wang and Chiou, have studied the performance improvement of a simple cycle gas turbine GENSET- a retrofitting example, and found out that there is effect of compression ratio on power output, ambient temperature on generation efficiency and power output, and steam injection ratio on efficiency [8]. Akikur et al., have studied on the performance analysis of a co-generation system using solar energy and SOFC technology [9]. Karaali and Ozturk, have studied on the thermoeconomic optimization of gas turbine cogeneration plants. They found out that thermoeconomic analysis and optimization is a very useful and effective method to evaluate the power plants by finding the global optima [10]. Adding a recuperator rises the outlet temperature of the air of the compressor and that increases the efficiency of the cycle. The majority of the work produced by the turbine (work produced by the turbine to the compressor is called back work rate and is around 50-60 %) is spent by the compressor so that the compression ratios (compressor work) are very effective on the cycle efficiency.

Many publications are based on finding better evaluation criteria and the most effective parameters on efficiency for gas turbine cogeneration cycle. These studies generally contain fewer criterions, parameters and cycles therefore they are not satisfactory as a rule of thumb [7, 8, 9]. In this study, evaluation criteria for cogeneration cycles, such as energy efficiency (energy utilization factor), electric and heat powers, electric production efficiency, electric and heat energy rate, exergy efficiency and fuel energy saving ratio are studied with three parameters that are the compression ratio, the excess air rate and the inlet air temperatures for two different cogeneration cycles. Results are compared and discussed.

## II.DESCRIPTIONS AND ANALYSES OF THE CYCLES

In inlet air cooling cycle (figure 1. b) inlet air is cooled by an absorption cooling device. The compressed air enter the combustion chamber and in recuperated cycle (figure 1. a) compressed air is heated by hot exhaust gases in the recuperator and then enter the combustion chamber. The hot gases that exit from the combustion chamber are then expanded at the gas turbine and from the gas turbine hot gases are the source of the recuperators and the heat recovery steam generator.

The thermodynamic analysis of the cycles and their components will be done and the mathematical modeling will be explained in this section. These cycles are fueled with natural gas; however it is taken to be methane for the sake of simplicity. The following assumptions are introduced in modeling each cycle: The pressure losses in the combustion chamber, air preheater and HRSG are known as 5 %. The environmental conditions are fixed and defined as $T_0 = 298.15$ K and $P_0 = 1.013$ bar.

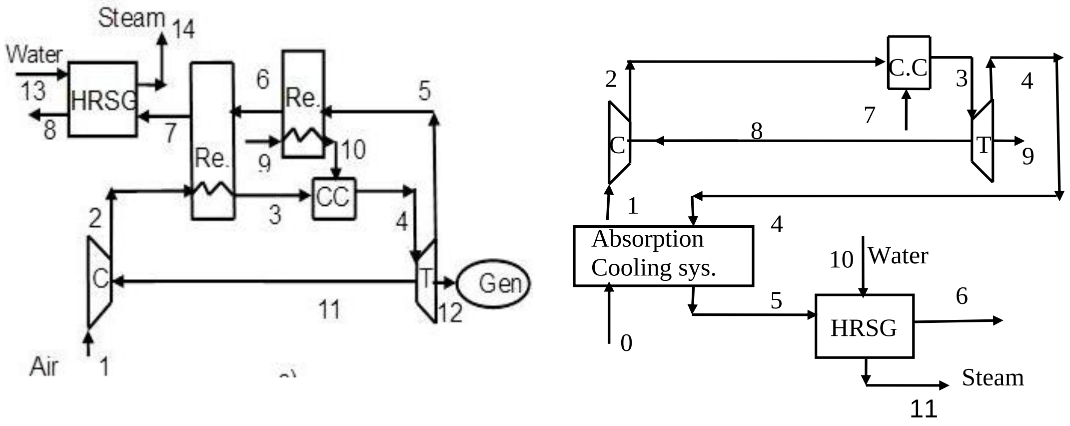

**Figure 1**. a) Air-fuel preheated b) Inlet air cooling cogeneration systems.

The chemical reaction in the combustion chamber can be written as follows [11].

$$\bar{\lambda} CH_4 + [0.7748 N_2 + 0.2059 O_2 + 0.0003 CO_2 + 0.019 H_2O] \rightarrow (1+\bar{\lambda})[X_{N2} N_2 + X_{O2} O_2 + X_{CO2} CO_2 + X_{H2O} H_2O] \quad (1)$$

The main capacity of the air compressors are $m_1 = 91.4$ kg/s, HRSG $m_s = 14$ kg/s saturated steam at 20 bar, gas turbine net electric power 30 MW (net electric power is equal to the mechanic power obtained from the gas turbine minus mechanic power used by compressor), combustion chamber's fuel $m_f = 1.64$ kg/s methane. The thermodynamic model and the calculation procedure are as follows for the CGAM cycle (air preheated cycle) [11, 12].

Fuel energy saving ratio directly measures the extent of fuel savings which the extent of energy utilization in a cogeneration plant. Increase in the rate of the fuel energy saving ratio provides information about the electric energy increases of the cogeneration system according to the first law. For the conventional system boiler efficiency $\eta_B = 0.9$ and the electrical efficiency $\eta_{el} = 0.4$ are taken [3, 6].

$$FESR = \left(\frac{Q}{\eta_B} + \frac{W}{\eta_{el}} - Q_{fuel}\right) / \left(\frac{Q}{\eta_B} + \frac{W}{\eta_{el}}\right) \quad (2)$$

In Table 1 and in Table 2 the mass, the energy, the entropy, the exergy and the exergy efficiency equations of the components of the air-fuel preheated cycle are given.

Table 1. The mass, the energy and the entropy equations of the components of the air-fuel preheated cycle.

| Component | Mass Equation | Energy Equation | Entropy Equation |
|---|---|---|---|
| Compressor | $\dot{m}_1 = \dot{m}_2$ | $\dot{m}_1 h_1 + \dot{W}_C = \dot{m}_2 h_2$ | $\dot{m}_1 s_1 - \dot{m}_1 s_2 + \dot{S}_{gen,C} = 0$ |
| HRSG | $\dot{m}_7 = \dot{m}_8$<br>$\dot{m}_{13} = \dot{m}_{14}$ | $\dot{m}_7 h_7 + \dot{m}_{13} h_{13} = \dot{m}_8 h_8 + \dot{m}_{14} h_{14}$ | $\dot{m}_7 s_7 + \dot{m}_{13} s_{13} - \dot{m}_8 s_8 - \dot{m}_{14} s_{14} + \dot{S}_{gen,HRSG} = 0$ |
| Recuperator1 | $\dot{m}_2 = \dot{m}_3$<br>$\dot{m}_6 = \dot{m}_7$ | $\dot{m}_2 h_2 + \dot{m}_6 h_6 = \dot{m}_3 h_3 + \dot{m}_7 h_7$ | $\dot{m}_2 s_2 + \dot{m}_6 s_6 - \dot{m}_3 s_3 - \dot{m}_7 s_7 + \dot{S}_{gen,R1} = 0$ |
| Recuperator2 | $\dot{m}_5 = \dot{m}_6$<br>$\dot{m}_9 = \dot{m}_{10}$ | $\dot{m}_5 h_5 + \dot{m}_9 h_9 = \dot{m}_6 h_6 + \dot{m}_{10} h_{10}$ | $\dot{m}_5 s_5 + \dot{m}_9 s_9 - \dot{m}_6 s_6 - \dot{m}_{10} s_{10} + \dot{S}_{gen,R2} = 0$ |
| Combustion Chamber | $\dot{m}_3 + \dot{m}_{10} = \dot{m}_4$ | $\dot{m}_3 h_3 + \dot{m}_{10} h_{10} = \dot{m}_4 h_4 + 0.02 \dot{m}_{10} LHV$ | $\dot{m}_3 s_3 + \dot{m}_{10} s_{10} - \dot{m}_4 s_4 + \dot{S}_{gen,CC} = 0$ |
| Turbine | $\dot{m}_4 = \dot{m}_5$ | $\dot{m}_4 h_4 = \dot{W}_T + \dot{W}_C + \dot{m}_5 h_5$ | $\dot{m}_4 s_4 - \dot{m}_5 s_5 + \dot{S}_{gen,T} = 0$ |
| Overall Cycle | $\bar{h}_i = f(T_i)$<br>$\bar{s}_i = f(T_i, P_i)$<br>$\dot{m}_{air} h_{air} + \dot{m}_{fuel} LHV_{CH4} - \dot{Q}_{Loss,CC} - \dot{m}_{eg.,out} h_{eg.,out} - \dot{W}_T - \dot{m}_{steam}(h_{water,in} - h_{steam,out}) = 0$<br>$\dot{Q}_{Loss,CC} = 0.02 \dot{m}_{fuel} LHV_{CH4}$ | | |

Table 2. The exergy and the exergy efficiency equations of the components of the ai-fuel preheated cycle.

| Component | Exergy Equation | Exergy Efficiency |
|---|---|---|
| Compressor | $\dot{E}_{D,C} = \dot{E}_1 + \dot{W}_C - \dot{E}_2$ | $\eta_{ex,C} = \frac{\dot{E}_{out,C} - \dot{E}_{in,C}}{\dot{W}_C}$ |
| HRSG | $\dot{E}_{D,HRSG} = \dot{E}_7 - \dot{E}_8 + \dot{E}_{13} - \dot{E}_{14}$ | $\eta_{ex,HRSG} = \frac{\dot{E}_{steam,HRSG} - \dot{E}_{water,HRSG}}{\dot{E}_{in,exhaust,HRSG} - \dot{E}_{out,exhaust,HRSG}}$ |
| Recuperator1 | $\dot{E}_{D,R1} = \dot{E}_2 + \dot{E}_6 - \dot{E}_3 - \dot{E}_7$ | $\eta_{ex,R1} = \frac{\dot{E}_{out,air,R1} - \dot{E}_{in,air,R1}}{\dot{E}_{out,exhaust,R1} - \dot{E}_{in,exhaust,R1}}$ |
| Recuperator2 | $\dot{E}_{D,R2} = \dot{E}_5 + \dot{E}_9 - \dot{E}_6 - \dot{E}_{10}$ | $\eta_{ex,R2} = \frac{\dot{E}_{out,air,R2} - \dot{E}_{in,air,R2}}{\dot{E}_{out,exhaust,R2} - \dot{E}_{in,exhaust,R2}}$ |
| Combustion Chamber | $\dot{E}_{D,CC} = \dot{E}_3 + \dot{E}_{10} - \dot{E}_4$ | $\eta_{ex,CC} = \frac{\dot{E}_{out,CC}}{\dot{E}_{in,CC} + \dot{E}_{fuel}}$ |
| Turbine | $\dot{E}_{D,T} = \dot{E}_4 - \dot{E}_5 - \dot{W}_C - \dot{W}_T$ | $\eta_{ex,T} = \frac{\dot{W}_{net,T} + \dot{W}_C}{\dot{E}_{in,T} - \dot{E}_{out,T}}$ |
| Overall Cycle | $\dot{E} = \dot{E}_{ph} + \dot{E}_{ch}$<br>$\dot{E}_{ph} = \dot{m}(h - h_0 - T_0(s - s_0))$<br>$\dot{E}_{ch} = \frac{\dot{m}}{M}\left\{\sum x_k \bar{e}_k^{ch} + \bar{R}T_0 \sum x_k \, ln x_k\right\}$<br>$\eta_{ex} = \frac{\dot{W}_{net,T} + (\dot{E}_{steam,HRSG} - \dot{E}_{water,HRSG})}{\dot{E}_{fuel}}$ | |

## III.RESULTS AND DISCUSSIONS

All the analysis results are presented in Figure 2 to 7. In Figure 2 variation of energy and exergy efficiencies with compression rates for constant combustion temperature are given. In the same way, outlet temperature of the combustion chamber is kept constant and recuperator outlet temperature is taken 7-15 K below the turbine outlet temperature. Adding second recuperator for fuel decreases the energy efficiency however increases the exergy efficiency of the cycles. Increasing the compression ratio of these two cycles increases the energy efficiency, but decreases the exergy efficiency for constant outlet temperature of the combustion chamber. The energy efficiency increases about 12 % but the exergy efficiency decreases about 7 % by compression rate range of 6 to 16.

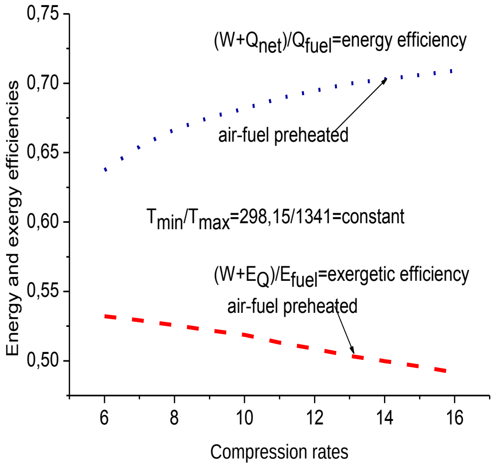

Figure 2.

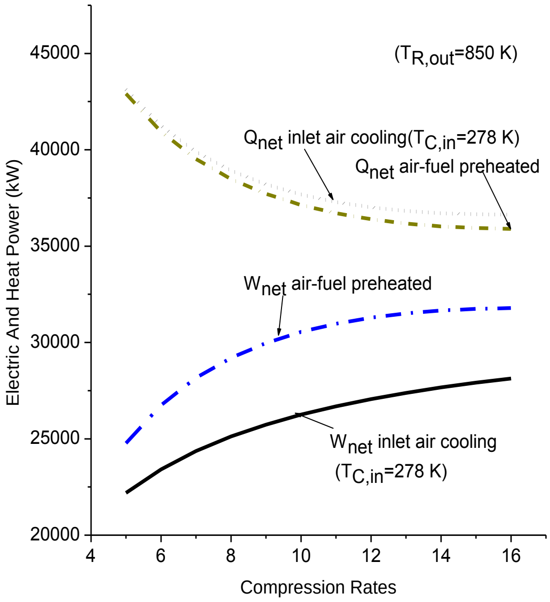

Figure 3.

In Figure 3 variation of electric and heat power with compression rates for different cogeneration cycles and variable combustion temperature (where $m_{fuel} = 1{,}64$ kg/s, $m_{air} = 91{,}3$ kg/s, excess air rate = 2,5, $\eta_{is,C} = \eta_{is,T} = 0{,}86$, $T_{rec.out} = 850$ K, $T_{steam} = 485{,}57$ K, $T_{eg.} = 426$ K) are given. Increasing compression ratio increases the electric power but decreases the heat power, because increasing the compression ratio increases combustion chamber outlet temperature which increases the turbine work but decreases the amount of heat obtained from HRSG. Air-fuel preheated cycle has the highest electric power but the lowest heat power among the two cycles.

Electric power increases about 22 % but heat power decreases about 28 % for air-fuel preheated cycle and electric power increases about 20 % but heat power decreases 12 % for air cooling cycle by compression rate range 6 to 16.

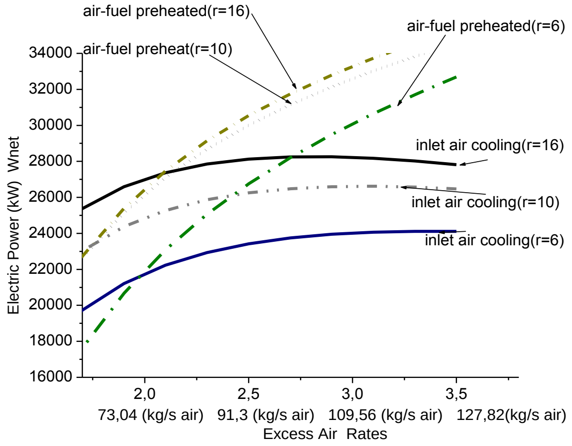

Figure 4.

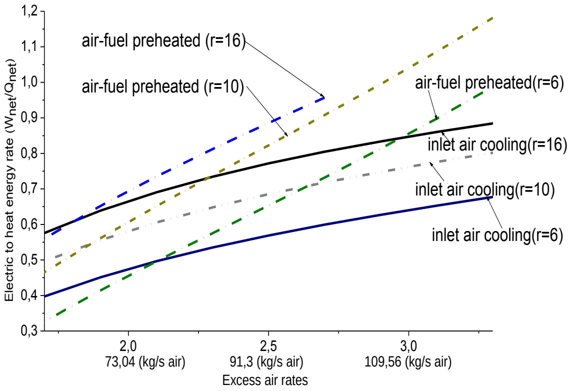

Figure 5.

In Figure 4 variation of electric power with excess air rates for different compression rates are given. The inlet air cooling and the air-fuel preheated cycles have the maximum electric power around 3.0 and 3.5 excess air rates, however increasing excess air rates of the air-fuel preheated cycles increases electric power. The two cycles have higher electric power output at higher compression ratios. However air–fuel preheated cycle works at 10 to 16 compression rate until at excess air rate 3 to 2.75.

In Figure 5 variation of electric to heat energy rate with excess air rates for different compression rates are given. Recuperated cycle use some of the exhaust energy that decreases the energy of the heat recovery steam generator and that decreases the heat power. Increasing compression ratio increases electric to heat energy rate of the two cycles. Increasing excess air rates increases electric to heat energy rate for the two cycles, however this increase is greater than the other for the air-fuel cycle.

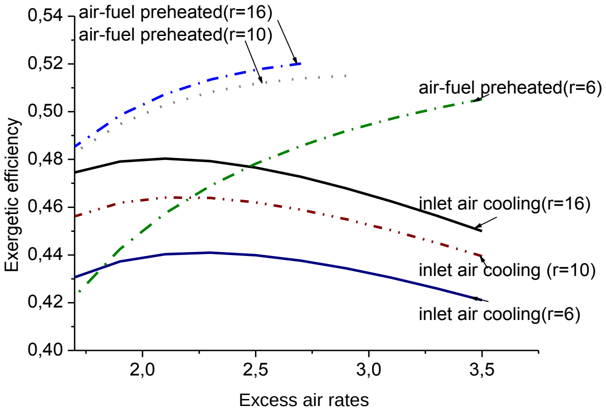

Figure 6.

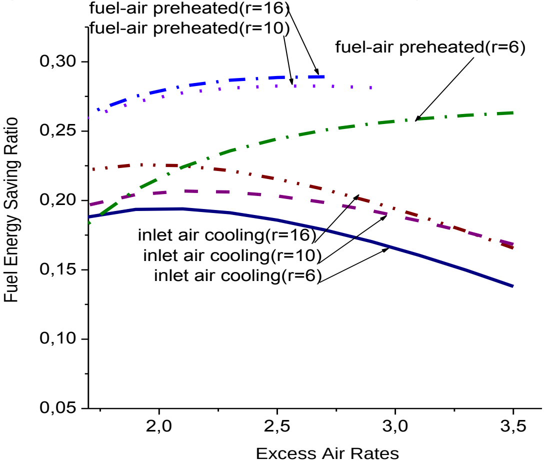

Figure 7.

In Figure 6 variation of exergetic efficiency with excess air rates for different compression rates are given. As can be seen in this figure that increasing compression ratio increases the exergetic efficiency for the two cycles. The reason for this is that increasing compression ratio increases the outlet temperature of the combustion chambers which means that increasing the inlet temperature of the turbine which increases the exergetic efficiency. The better exergetic efficient cycle is found as air-fuel preheated cycle. The exergetic efficiencies of the air-fuel preheated cycle is continuing increasing with increasing excess air rate. Maximum efficiencies are obtained about 2 and 2.5 excess air rates for the inlet air cooling cycle. For the air-fuel preheated cycle increasing excess air rates increases the exergetic efficiency. Some of the curves are cut because of the unsuitable working conditions of the systems. Exergy efficiency increases about 16 % for air fuel preheated cycle by excess air rate range 1.3 to 3.5 at 6 compression rate.

In Figure 7 variation of the fuel energy saving ratio with excess air rates for different compression ratios are given. As can be seen here that increasing compression ratios increase the fuel energy saving. The maximum values of the fuel energy saving ratio for the absorption cooling cycle are obtained in the excess air ratios of 2-2.5. These ratios are about 2.5-3.5 for the air-fuel preheated cycle. Fuel energy saving ratio increases about 16 % for the air-fuel preheated cycle for the compression rate of 6 of the excess air rate range from 1.3 to 3.5.

As can be seen in the figures given above increases in the compression ratio, results in higher electrical power that means slight increase in the fuel causes more electricity production. It appears that the air-fuel preheated cycles have much better performance than the absorption cooling cycle. Increases in the excess air rate increase the amount of the fuel for per unit electricity, which these increase are more for the absorption cooling cycle.

Adding recuperators decreases the energy efficiency, however increases the exergy efficiency of the cycle. Increasing the compression ratio of the two cycles increases the energy efficiency, but decreases the exergy efficiency for the constant outlet temperature of the combustion chamber.

Increasing the excess air rates increases the net work, the compressor work and the exhaust energy loss but decreases the heat energy, the combustion chamber outlet temperature and the energy efficiency. Increasing the compression ratio increases the exergetic efficiency for the two cycles.

## IV.CONCLUSIONS

In our study, air-fuel preheated cogeneration cycle, and inlet air cooling by using absorption cooling cogeneration cycle are evaluated with respect to energy efficiency (energy utilization factor), exergetic efficiency, electric and heat power, electric-heat energy rate, fuel energy saving ratio and artificial thermal efficiency. Those methods are compared with each other. In these analyses, the thermodynamic parameters such as compressing ratio, air and fuel mass ratio and compressor inlet temperatures of the cycles are used.

The results presents that by changing compression rate from 6 to 16, the energy efficiency and electric power increase about 12 % and 22 %, but exergy efficiency and heat power decrease about 7 % and 28 % respectively for air-fuel preheated cycle.

Fuel energy saving ratio increases about 16 % for air-fuel preheated cycle at compression rate 6. The effectiveness of parameters on cogeneration cycle can be ordered as air fuel ratio, compression ratio and compressor inlet temperature. According all the evaluating criteria the most efficient cycle is found as the air-fuel preheated cycle for obtaining more electric power and less heat power. It is concluded that these parameters can be listed from most effective to least effective as air fuel ratio, compression ratio and compressor inlet temperature. It is also concluded that the better cycle is found to be the air-fuel preheated cycle for obtaining more electric power and less heat power.

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