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Indicators of energy efficiency in ammonia productions plants

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Abstract: - This paper presents and analyzes tools for the assessment of energy efficiency in ammonia production plants using key performance indicators (KPI). Monitoring the consumption of inputs in the industry could generate reductions in greenhouse gas emissions while simultaneously producing gains in energy efficiency in industrial operations. The continuous monitoring of performance indicators relative to emissions data and the consumption of natural resources allows for effective and direct intervention, resulting in improvements in production processes and operating practices. The use of such information by operating teams, in conjunction with management actions focused on continuous improvement, could lead to energy efficiency gains, a reduction in greenhouse gas emissions, and make production processes more profitable.

Keywords: - *Ammonia, Energy Efficiency, Greenhouse Gases, Key Performance Indicators (KPI).*

I. INTRODUCTION

With increasing demands for their products, industrial chemical manufacturers are being subjected to a number of national and international pressures to reduce greenhouse gas emissions. In addition, investors are demanding lower production costs in conjunction with higher production gains. Thus, advances in the control of production processes focused on reducing losses, the strict monitoring of resource consumption, and the energy efficiency of their production processes have become essential activities in the routine operation of chemical production plants.

Data published in 2007 by the Organization for Economic Co-operation and Development (OECD) show that global emissions of greenhouse gases will increase by 50% by 2050, mainly as a result of increased demand for energy and economic growth in large countries with emerging economies. According to the organization, emissions of carbon dioxide (CO_2), one of the main gases causing the greenhouse effect, are expected to grow by 70% by 2050 as a result of increasing energy use [1].

The industrial system is one of the largest energy consumers in Brazil and throughout the world. Energy costs may represent about 10% of the production costs. A common and very important input in the industry is water vapor. This input is used in the generation, transmission and use of energy. Much of the electricity generation in the northern hemisphere uses water vapor as the working fluid in thermodynamic cycles. About 40% of the fossil fuel burned in U.S. industry is used in the generation of steam. The steam generated is, in turn, used in heating processes to concentrate and purify liquids, but it can also be used directly as feedstock [2, 3, 4].

An analysis of steam systems indicates that in a typical industry that does not employ preventive or predictive maintenance techniques, 28% of steam traps have problems. To improve the use of steam, industries must employ an appropriate method for testing steam traps to identify leaks, making repairs or replacing faulty traps when required.

Electricity is an essential input for industrial activity, and ensuring its delivery, quality, safety and affordability is essential for the development of the global economy and the growth of industrial production. Figure 1 shows the electricity consumption in Brazil and in other countries of the world.

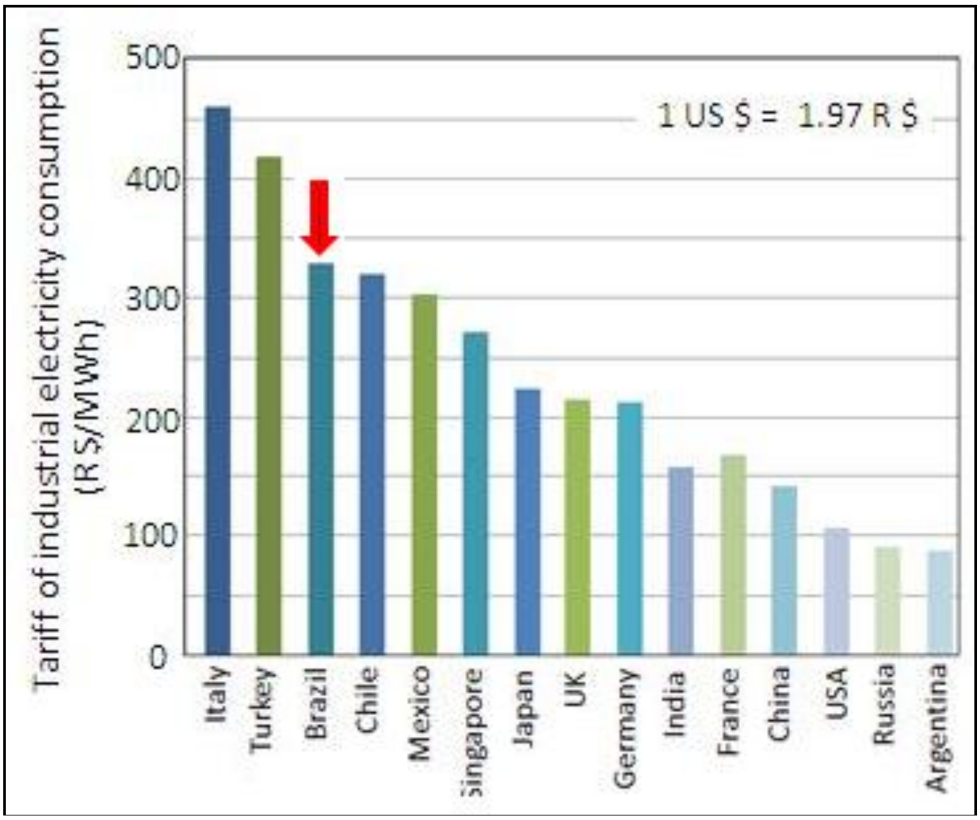

Figure 1- Tariff of industrial electricity consumption based on the Brazilian currency (Real $)

A more detailed analysis of production processes can identify potential areas for reducing manufacturing costs. An interesting strategy for reducing the consumption of inputs focuses on energy efficiency for both new and existing systems. Energy efficiency can be seen as an interesting means of reducing manufacturing costs. It can generate immediate and attractive returns, and may also provide robustness in the sustainability and profitability of operations. An effective management process begins with an analysis of energy consumption and greenhouse gas emissions. The results of such an analysis should be considered in any decision-making processes.

II. AMMONIA PRODUCTION PROCESS

Ammonia is one of the fundamental raw materials required for modern civilization. The raw materials for the production of ammonia are hydrocarbons, air, and energy, which is essential for all industrial operations. Commonly used energy sources are coal or hydrocarbons, which react with water vapor at high temperatures, and electricity, which is used in the operation of gas compressors. Natural gas (CH_4) is the hydrocarbon used most frequently in ammonia production, with about 80% of current global production being based on natural gas. There are three main types of processes currently used for the production of ammonia:

- steam reforming from natural gas or other light hydrocarbons (natural gas liquids, naphtha);
- partial oxidation of heavy oil or waste oil;
- gasification of coal.

Figure 2 illustrates the steam reforming process of ammonia production.

The natural gas produced in Brazil is contaminated with potentially poisonous sulfur compounds (H_2S). These compounds are typically removed from the natural gas stream, in a process known as desulfurization, using a cobalt molybdenum catalyst [5].

The resulting gas (CH_4), which still contains about 0.1 ppm (parts per million) sulfur after going through this process, is then blended with the steam. This mixture is heated to between 500 and 600 °C and introduced into the main reformer (in some cases, however, an adiabatic pre-reformer precedes the primary reformer).

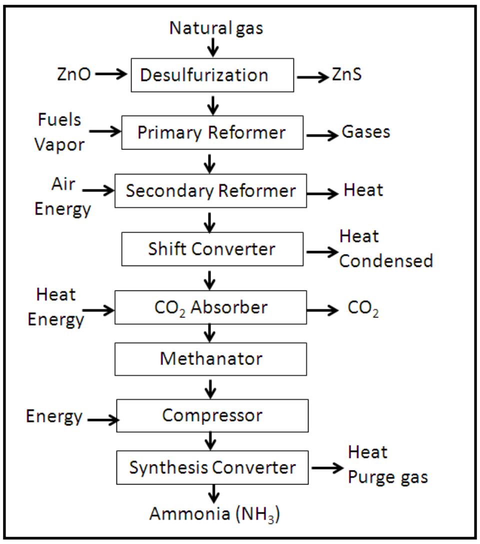

Figure 2 - Flowchart of ammonia production using the steam reforming process

The flue gases leaving the radiant section of the furnace reformer have exit temperatures approaching 1000 °C. Only 50–60% of the fuel heat is directly used in the ammonia production process itself, but the enthalpy of the combustion gases is utilized in the convection section of the reformer for the generation of steam or for other process requirements.

The process gas effluent from the primary reformer is directed to the secondary reformer, which receives the process air intake. The process air serves to enhance the combustion reactions and provide the nitrogen (N_2) necessary for the synthesis reaction. The gas/air mixture exits the secondary reformer at a temperature of 1000 °C, and 99% of the original gas feed is converted. The process gas is then cooled to between 350 and 400 °C and is used to power a steam boiler or a waste heat recovery boiler.

After conversion of CO to CO_2, the gas, which generally contains about 20% CO_2, is subjected to either a chemical or a physical process. The absorption process is followed by adsorption facilitated by a pressure decrease with increasing temperature. CO_2 removed from the process is used mainly for the production of urea, injection wells in crude oil production, dry ice production, and in other industries.

At this point, only small amounts of CO and CO_2 remain in the synthesis gas stream. They must be removed, however, because they are poisonous to catalysts of ammonia synthesis.

In the next step (known as methanation), the small amounts of CO and CO_2 react with a given amount of hydrogen to produce methane (CH_4) and water in a reactor containing a nickel catalyst at a temperature of about 300 °C.

After separation of the condensate, the stream of process gas, called synthesis gas, reaches the ammonia synthesis section. This reaction occurs at pressures that are normally in the range of 100–250 bar. The ammonia synthesis occurs in an exothermic reaction that makes use of iron catalysts at temperatures of 350–550 °C. Because of the high exothermicity of the reaction, a comprehensive and efficient heat exchange mechanism is essential. Only 20–30% of the synthesis gas is converted to ammonia on each pass through the converter. For this reason, a synthesis loop is required, with the ammonia being separated by cooling and condensation, and the effluent vapor being mixed with fresh synthesis gas and returned to the converter.

The cooling and condensation of ammonia is achieved via an auxiliary refrigeration cycle using ammonia vapor in order to achieve satisfactory results at the low concentrations of ammonia gas returned to the converter.

In integrated plants, the ammonia that is synthesized can be used directly in, for example, the production of urea or nitric acid.

III. USE OF INDICATORS OF ENERGY EFFICIENCY IN INDUSTRY

The energy consumption in industrial processes can be determined by taking the level of activity, the industry structure and energy efficiency into account. Changes in energy consumption in industry are not only determined by energy efficiency in industrial processes but also by other political, economic and environmental factors. Additional factors, such as the production capacity and lifetime of the plant, should be considered in any analysis of energy efficiency [6, 7, 8].

The use of indicators aimed at evaluating the efficiency of processes in industry is growing in importance on a national and global level. The results of an analysis of energy efficiency indicators may be useful in the areas of strategic planning, management and environmental technology, and energy conservation. In practice, it is worth noting that the application of the analysis of these indicators and their relevance in describing the interrelationship between energy efficiency and resources consumed are associated mainly with the economic and political environment within the industry.

The use of indicators can have an impact on production processes. In industry, the analysis of energy efficiency indicators can help define relevant guidelines, such as:

- directing changes in energy consumption
- establishing energy-efficient policies
- indicating structural constraints that have an impact on increasing energy efficiency
- replacing technological processes
- changes in the use and choice of raw materials that are used in manufacturing processes, with the goal of reducing the demand for energy
- serving as a tool to assess goals for environmental policies aimed at the reduction of gaseous emissions

According to Abreu et al [9], indicators commonly used for the analysis of energy efficiency in industry can be subdivided into four groups: thermodynamic, physical-thermodynamic, economic-thermodynamic, and economic. Indicators that can be analyzed according to the laws of thermodynamics are included in the first group. The physical-thermodynamic indicators are also known as specific indicators. They are used to evaluate an input in relation to a particular production output. The third group provides a measure of the final product at market prices relative to thermodynamic units. The fourth group of indicators evaluates the changes caused by energy efficiency, in monetary terms, and can be considered to evaluate both the incoming and outgoing energy of a given process.

Based on thermodynamic laws, energy can be defined as the theoretical maximum useful work obtained when a system is brought to thermal equilibrium with the environment by means of processes in which the system interacts only with its environment [10].

According to Saidur et al [3, 4], the exergy is a direct function of the laws of thermodynamics. A property that determines the potential for useful work in a certain amount of energy in a specific state can be represented by Equation 1,

$$Ex = (H - H_O) - T_O (S - S_O) \qquad \text{(eq. 1)}$$

where the exergy (Ex) is a function dependent on the enthalpy (H) of the entropy (S), the absolute temperature (T) and also of the pressure and composition of the system. The subscripts represent the enthalpy and entropy conditions in the vicinity of the system.

Starting from an exergetic balance for a hypothetical system, it becomes feasible to direct the construction of an indicator. The exergy (Ex) is the difference between the sum of flows entering the exergetic system ($\Sigma\ Ex_e$) through sources of fuel and raw materials, their losses ($\Sigma\ Ex_s$) and losses that are consumed in the process ($\Sigma\ Ex_c$) as represented by Equation 2.

$$Ex = \Sigma\ Ex_e - \Sigma\ Ex_s - \Sigma\ Ex_c \qquad \text{(eq. 2)}$$

The concept of exergy can be useful in analyzing aspects related to the life cycles of products as the exergetic content can determine the flow of energy lost. According to Dincer et al [11], exergy can be considered as a link between the thermodynamic concepts and systems engineering processes in relation to the environment from the viewpoint of energy efficiency.

The literature presents several studies that define and characterize the energy efficiency of industrial processes on the basis of macro indicators, which report on the economy as a whole (macroeconomics), or on the basis of individual industrial sectors with their specific production outputs [12, 13].

IV. METHODOLOGY

To calculate net energy efficiency, the annual production of ammonia and the energy used in its manufacture were taken into account. All feedstocks (direct and indirect) and fuels consumed in an ammonia production plant were considered in this study.

The energy plots considered in the calculation of the indicators were, among others, those relating to energy for the production of ammonia, the energy used for starting the plant, the energy consumed during unplanned shutdowns, and any reduction in the lifetime of the catalysts (possible deteriorations). We also considered the annual performance against the expense of efficiency projects.

To facilitate the analysis between the different ammonia production plants, it was necessary to develop a basis for comparison. This normalization was performed according to the different configurations of the plants analyzed. The following are some of the considerations that were taken into account:

- imported electricity was converted to its heat equivalent, assuming 40% efficiency based on the lower calorific value of the fuel;
- the import and export of steam corresponding to a 90% conversion efficiency was considered as a reference for saturated steam at 150 °C;
- the baseline for the production of liquid ammonia was considered to be 100% under atmospheric pressure conditions and a temperature of -32 °C;
- the energy used to produce and pump cooling water was considered in the calculation for the share of energy use;
- the amount of energy used to produce and pump feed water for boilers was considered in the calculation for energy use;
- No adjustments were made on the basis of different technologies, climate conditions, catalysts used or operational problems.

To analyze energy efficiency, 50 ammonia production plants and their individual annual product outputs were included in the study. The energy efficiency indicator was calculated according to Equation 3,

$$\eta = (R + C_f + Z)/M_{NH3} \qquad \text{(eq. 3)}$$

where:
η = energy efficiency (GJ/t_{NH3})
R = the conversion of raw materials consumed in equivalent energy, assuming the lower calorific value
C_f = the conversion of fuel used in the process in equivalent energy, assuming the lower calorific value
Z = other energies involved in the process, such as electricity and steam imported, export credit for energy (steam) generation, and pumping water to supply boiler and cooling water
M_{NH3} = ammonia production in metric tons

The part related to ammonia production was considered to be the maximum daily production at the expense of the production capacity of the plant design. The plants were divided into three categories. Of the 48 conventional plants (plants that utilize steam reforming), 12 were classified as small, with ammonia production values of less than 1000 t/day (metric tons per day), 17 plants were classified as intermediate, with production values of 1000–1500 t/day, and 19 plants producing more than 1500 t/day were classified as large.

V. RESULTS AND DISCUSSION

The annual production capacities of the ammonia plants analyzed are shown in Figure 3. The production capacities ranged from 91,000 t/y to 749,800 t/y. The values found in the evaluation of the energy efficiency indicator ranged from 23.8 GJ/t NH_3 to 51.9 GJ/t NH_3. Of the 50 plants analyzed, two used high purity hydrogen as a feedstock. These plants typically have higher levels of efficiency when compared with other plants. The 48 conventional ammonia production plants use various raw materials such as natural gas or heavy oil derived from petroleum fractions.

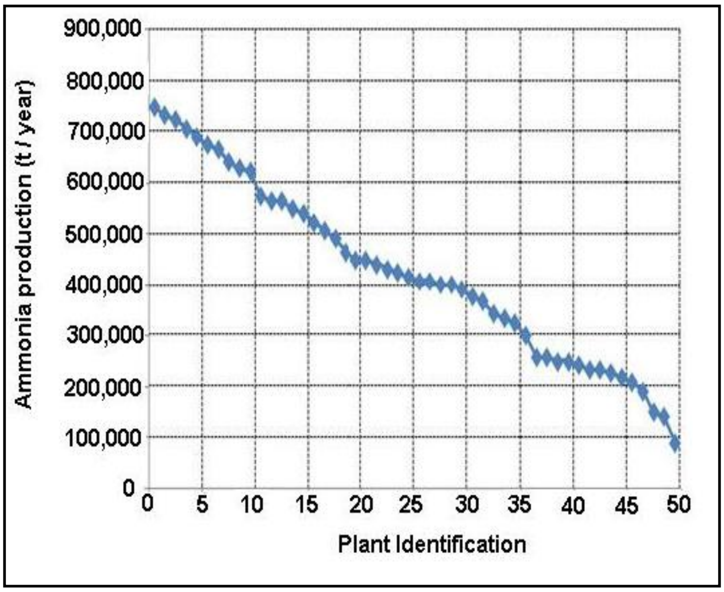

Figure 3 - Annual production of ammonia (metric tons)

Figure 4 shows the energy efficiency indicator for each ammonia plant.

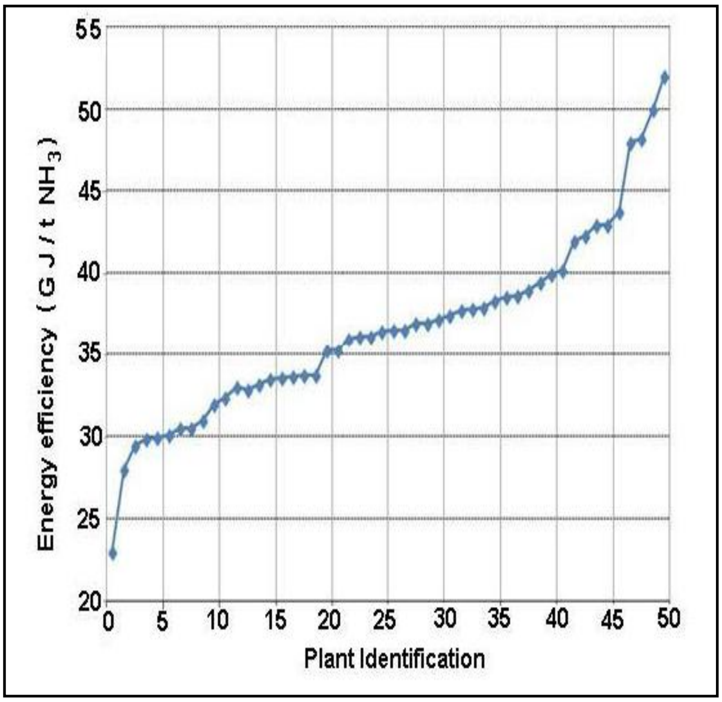

Figure 4 - Energy efficiency (GJ/t NH_3) for ammonia production plants

The relationship between capacity and energy efficiency for the 48 conventional ammonia production plants is shown in Figure 5.

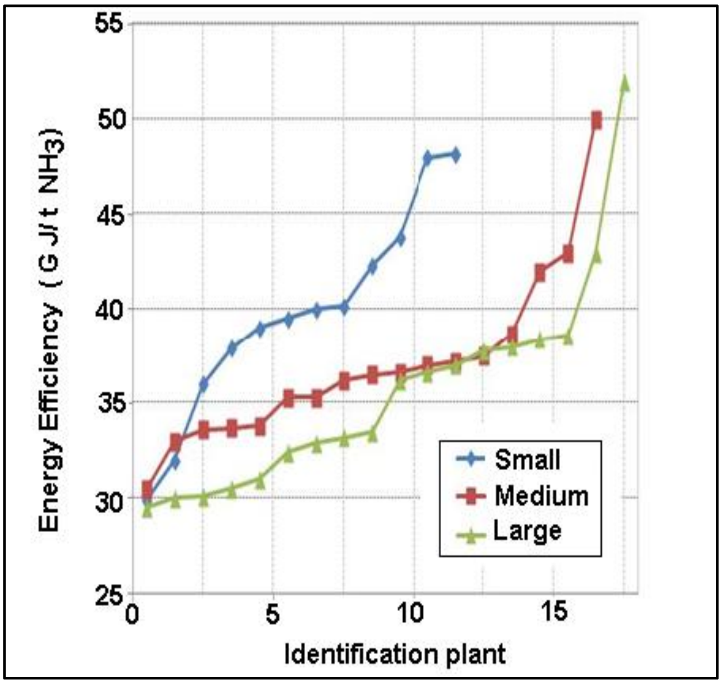

Figure 5 - Energy efficiency (GJ/t NH_3) in the capacity of ammonia production plants of varying production capacities

From the analysis of Figure 5 we see that there is a relationship between the production capacity and efficiency of the plants analyzed. In general, plants with higher capacity have higher energy efficiency and plants with smaller capacity are less energy efficient. However, the best plants in each group have energy efficiency rates ranging from 29.5 GJ/t NH_3 to 30.6 GJ/t NH_3, indicating that plants with a capacity lower than

1000 t/d may still be energy efficient.

Figure 6 shows the calculation of the energy efficiency indicator as a function of the age of each plant. The age of each plant varies from between 1.5 and 39 years. The plants were divided into three categories. Those classified as new are less than 14 years old. Plants between 18 and 29 years old were classified as intermediate, and plants older than 30 years were classified as old.

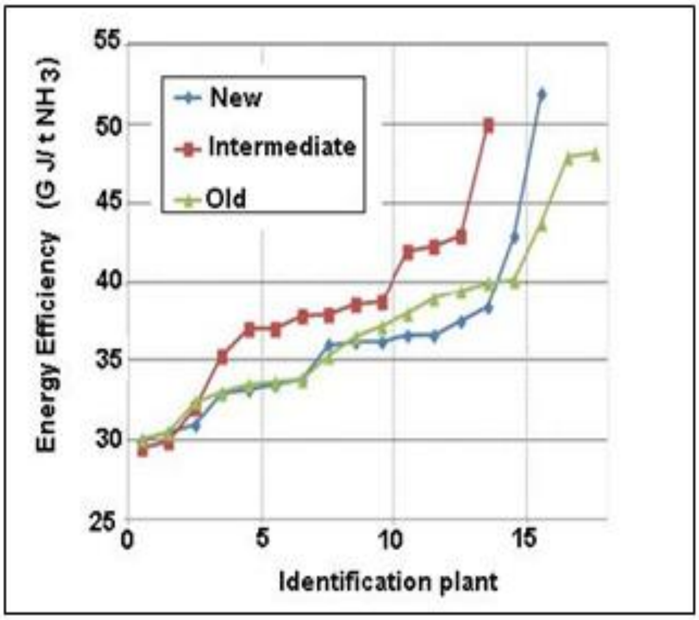

Figure 6 - Energy efficiency as a function of the age of the ammonia production plants

Of the 48 conventional ammonia production plants analyzed, those classified as new showed better average energy efficiency indicators, with a net energy efficiency of 36.0 GJ/t NH_3 for 16 plants analyzed in this group. Plants classified as intermediate (14 plants) displayed an average energy efficiency of 37.7 GJ/t NH_3. The plants classified as old showed an average result of 37.4 GJ/t NH_3.

The best plants in each group have energy efficiency ratings of about 30 GJ/t NH_3. This observation indicates that even plants that have been operational for longer periods of time can, through modifications and improvements in their processes operate at good levels of energy efficiency.

VI. CONCLUSIONS

This work presents an evaluation of the energy efficiency of ammonia production plants through the use of indicators. Data from 50 ammonia plants were considered in this study. The energy efficiency indicator was based on the annual production of ammonia and took into account the equivalent amounts of energy consumed in the consumption of raw materials, fuels, and other forms present in the process, such as the energy consumption equivalent of the generation and distribution of cooling water, and the import or export of steam, among others.

Comparisons were made on the basis of the designs of the plants and the production processes used. Other comparisons took into account the energy efficiency of the plants. We presented energy efficiency rates as a function of the age of plants and also as a function of annual production. It was found that there is a direct relationship between production capacity and energy efficiency.

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