Ammonia as fuel for Gas Turbine

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Abstract. Ammonia has recently gained attention as a potential alternative fuel for gas turbines due to its relatively high energy density and mainly its low environmental impact since there is no CO_2 production during the combustion. In this study, we evaluate the integration of a Power to Ammonia to Power process(P2A2P) with a system for power generation and investigate the impact of the use of ammonia in gas turbines from technical, energetic, and environmental points of view. First, the P2A2P system layout is defined and then the scale-up of the process is evaluated to be integrated with a commercial medium-size Gas Turbine. The optimization of the size and Balance Of Plant (BOP) of the P2A2P process and the integration with the GT system are evaluated also considering the impact on the GT system. Moreover, a generic radial-tangential swirler representing a first design attempt to study the retrofittability of a natural gas-designed combustion chamber to operate with an NH_3-H_2 fuel blend is investigated. The results from dedicated experimental tests and the corresponding CFD simulations are discussed with a strong focus on the NOx pollutant emission representing one of the main limiting factors for ammonia as fuel.

1 Introduction

In the last decades, the world's population has assisted in the progressive increase of the global average temperature due to an intensification of the Greenhouse effect. This phenomenon, known as Global Warming, is recognized worldwide by the scientific community to be associated with the increase of CO_2 emissions in the atmosphere, mostly correlated to anthropogenic activities [1][2]. To face this global issue and try to limit the correlated Climate Changes, several actions have been undertaken by many countries: starting from the Kyoto Agreement to the more recent effective Paris Agreement. In particular, the European Commission has defined ambitious Climate and Energy goals for 2030 and 2050 in order to reduce the CO_2 emissions and reach the carbon-neutrality [3][4][5]. Since the Greenhouse Gases (GHG) emissions increase is mostly correlated to the use of fossil fuels, it is clear that a change in the energy paradigm is necessary. In this sense, a big effort has been put in place by the scientific and industrial communities and also by the regulators and politicians in order to define a sustainable alternative to the use of fossil fuels, especially in the energy and transportation sectors [3][6]. Among the others, hydrogen is considered as a promising alternative fuel option thanks to its relatively easy production via water electrolysis and the fact that its combustion is carbon-free. However, there are still several issues with the extensive use of hydrogen, mostly related to the very low energy density by volume that strongly impacts the storage and transport of large quantities of hydrogen for long distances. In response to that, ammonia has recently gained more and more attention as an energy vector and hydrogen carrier that can support and push the development of the up-and-coming hydrogen economy. Indeed, ammonia presents several advantages: (i) it is already a well-known chemical product worldwide produced and used, and hence, the know-how related to the synthesis, storage, transport, and handling is well developed; (ii) it is great hydrogen carrier considering that the H_2 content of liquid ammonia is more than 50% higher than liquid hydrogen and 6.7 higher than 200bar compressed H_2 [14]; (iii) it can be used as fuel for both internal combustion engines and gas turbines and its combustion is carbon-free [7-11]. In the next years, ammonia has the potential to become the key fuel to support the energy transition towards a Renewable Energy Sources (RES)-based system, by means of the Power-to-Ammonia-to-Power (P2A2P) process: the exceeding electrical energy from RES can be converted and stored into ammonia that, when required, can be used as fuel into traditional power plants reducing the environmental impact [12-15]. Indeed, conventional power plants are today compelled to be more and more flexible to support the RES penetration by contributing to grid stabilization, while reducing their carbon footprint and ensuring a clean, stable, and secure supply of energy. In this context, Natural Gas-fired plants are currently considered the most flexible power plants to operate in the European grid to facilitate the penetration of high-RES shares [16][17][18]. The injection of alternative fuels, such as ammonia (NH_3) in gas turbines will help the required fuel switch the EU is facing, drastically reducing $CO/CO_2/HC$ emissions. On the other hand, the P2A2P solution integration could help the Natural Gas Combined Cycles (NGCCs) to balance their load and reduce their environmental impact. An answer to this challenge is given by the H2020-FLEXnCONFU project [19] which offers an innovative solution to increase the flexibility and decarbonization of conventional NGCCs by integrating a P2X2P process based on Hydrogen and Ammonia [20]. The present work has been developed in the framework of the FLEXnCONFU project and investigates from technical, energetic, and environmental points of view the integration of a P2A2P with a commercial medium-size Gas Turbine (GT), and in particular the impact of using ammonia as alternative fuels. First, the P2A2P system layout is defined and then the scale-up of the process is evaluated to be integrated. The optimization of the size and the Balance Of Plant (BOP) of the P2A2P process and the integration with the GT system are evaluated also considering the impact on the GT itself. Moreover, a generic radial-tangential swirler representing a first design attempt to study the retrofitability of a natural gas-designed combustion chamber to operate with an NH_3-H_2 fuel blend is investigated. The results from dedicated experimental tests and the corresponding CFD simulations are discussed with a strong focus on the NO_x pollutant emission representing one of the main limiting factors for ammonia as fuel.

2 Plant layout and scale-up

2.1 FLEXnCONFU P2A2P TRL6 pilot plant

The P2A2P pilot plant concept developed in FLEXnCONFU project is reported in Fig.1. It has been properly designed and developed to be highly flexible in following variable loads, modular and containerizable to be easy to install and integrate. The main innovation compared to traditional NG-based plants lies in the strong electrification of the process as extensively described in [21-22]. The P2A section is composed of a water electrolyzer for H_2 production and the storage of the N_2 supply. To improve the system flexibility and the thermal management during the partial/variable load, an electrical heater has been introduced before the synthesis reactor to control the syngas inlet temperature (around 400°C) and for the same reason, also the reactor has been equipped with different thermal resistance to keep it warm during the stand-by operation and optimized the working temperature. The synthesis reactor operates at 80 bar and 400°C. Regarding the A2P pilot plant, it is based on a T100mGT that is fuelled with 100% ammonia coming from the pressurized ammonia storage (element of connection between the P2A and the A2P). Considering that the fuel injection pressure of the T100mGT is around 6 bar, a fuel compressor is not required since it is possible to obtain the desired NH_3 outlet pressure for the storage by properly controlling the storage temperature (around 30°C).

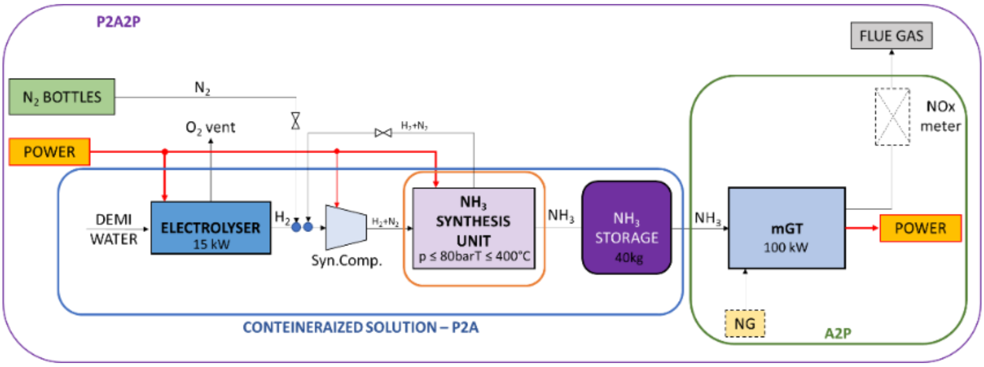


Figure 1 FLEXnCONFU P2A2P TRL6 Pilot plant layout

2.2 Process scale-up

In the present study, the scale-up of the P2A2P pilot is performed considering the integration with the medium-size GT NovaLT16 whose main technical data are reported in Tab.1.

Table 1 NovaLT 16 Specification

Power	17.5 MW
Fuel	Natural Gas (up to 15% C_{2+}, up to 15% inerts)
Emissions (burning NG)	NOx < 15 ppmvd 15% O_2 CO < 10 ppmvd 15% O_2
Efficiency	37.5 %
Fuel Consumption	46 MJ/s
Exhaust temperature	495 °C
Speed	3900-7800 rpm

The scale-up has been carried out based on the following considerations:

- Electrolyzer size: in this case, the size of the electrolyzer has been assumed equal to the maximum GT power (17.5 MW) unless the BOP requirement.
- Ammonia synthesis unit size: it is assumed that the synthesis unit size is proportional to the electrolyzer size and includes the gas compressors, the reactor, the heat exchanger, and the NH_3 storage.
- Nitrogen supply system: considering the N_2 hourly requirement rate (greater than 1000 Nm3/h), it is assumed to install a PSA unit with a specific consumption of 1.25 kWh/Nm3 and able to deliver gaseous N_2 at 6 bar.
- Storage size: since the size of the storage strongly depends on the operation profile of the GT that in the present work is not considered in detail, it is assumed the need to store

the amount of ammonia produced over 48 hours of operation at nominal load. An ammonia-pressurized storage system is considered for this application.

- Fuel supply system from the ammonia storage to the GT combustor: considering that the GT requires a fuel pressure of 40 bar, a pump able to compress the liquid ammonia at working pressure has to be installed followed by an evaporator since the ammonia need to be injected in the gaseous form inside the GT-CC

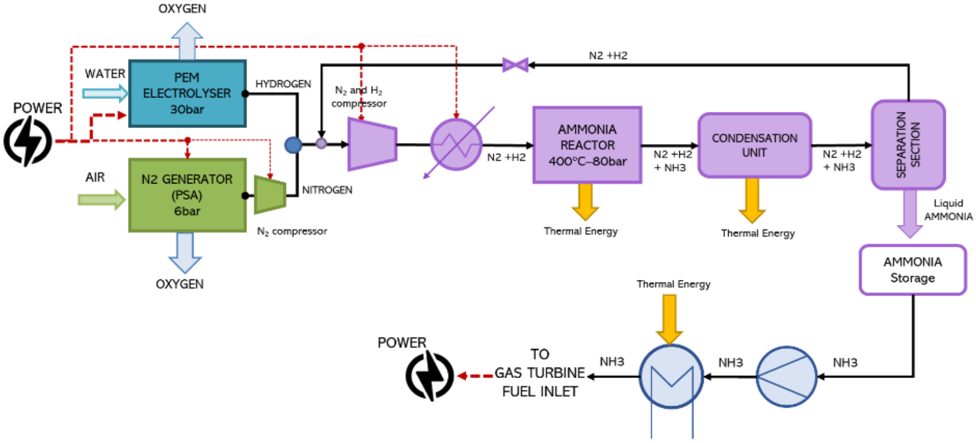


Figure 2 Scaled-up system layout.

The following table reports the results of the scale-up process in terms of component sizes and energy requirements.

Table 2 P2A2P system process scale-up for the NovaLT16: Mass Balance and Power Balance

Mass Balance		
Water Feed	2261	kg/h
H_2 produced	251	kg/h
N_2 required	1172	kg/h
Fresh Feed	1424	kg/h
Feed Loop	3915	kg/h
Feed in	5338	kg/h
NH3 production	**1281**	**kg/h**
O_2 co-produced total	2290	kg/h
NH_3 Storage 48hrs		
Mass content	61496	kg/48h
Energy content	322.9	MJ_{48h}
Eq. Tons of NG	23246	kg/48h

Power Balance		
Electrolyser	14	MW
PSA - N_2 generator	1.17	MW
Compressor train	0.89	MW
Syngas Compressor (30 to 200 bar)	*0.8*	*MW*
N_2 Compressor (6 to 30 bar)	*0.09*	*MW*
Electrical Heater	0.77	MW
NH_3 pump	0.03	MW
TOTAL	**16.86**	**MW**
Heat of Reaction	1	MW_{th}
Condensation Unit Thermal Duty	2	MW_{th}
NH_3 evaporator	-3.4	MW_{th}
TOTAL	**-0.5**	$\mathbf{MW_{th}}$
P2A Efficiency	40%	

The results showed that the BOP of the P2A2P system is about 20% of the electrolyser installed power for a resulting system efficiency (at the GT fuel inlet) of around 40%. Regarding the fuel injection system from the NH_3 tank to the GT combustor, a pump and an evaporator are needed. The thermal energy requirement is about 0.2 MW_{th} per MWe produced by the GT. The overall efficiency of the P2A2P system (at the GT combustor inlet) is around 40%. Regarding the NH_3 storage, considering 48 hrs of operation at nominal load, the total amount of ammonia stored is about 61.5 ton/48hrs or 23.3 ton of NG_{eq}/48hr (based on LHV). Using such amount of ammonia as fuel, in place of NG (at 100%), the 48 hrs storage duration results in around 7 hrs at nominal load operation with a storage charge/discharge factor of 6.8. Considering 7 days of operation, the use of such ammonia could bring a reduction of 4% of the CO_2 emission at the stack.

3 Ammonia blends combustion

The environmental impact of the P2A2P solution presented above should focus on the combustion system and the corresponding emission of nitrous oxides derived from the cracking of NH_3. To characterize the ammonia-hydrogen combustion from this standpoint, tests have been executed with a generic swirled burner in a single-cup test facility. The experimental data have also been leveraged to validate a CFD model whose post-processing can help explain the role of important engine parameters, like the operating pressure.

3.1 Combustion test set-up

An optically accessible test rig is employed for the execution of the pressurized tests [23-24]. Fig. 3 shows the arrangement around the quartz flame tube enclosed by the external casing and highlights the most important sections, such as the inlet of the reactants and the radial-tangential swirler whose detailed geometry is summarized in the bottom part of the picture. The nature of the mixture can be considered as perfectly premixed once it reaches the primary zone

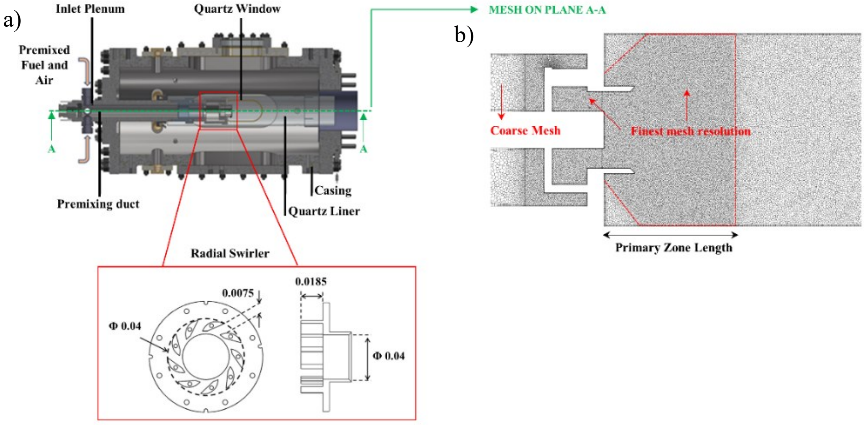


Figure 3 a) Test rig detailed geometry with close-up on the radial-tangential swirler having a swirl number of 0.8. b) the computational mesh on the longitudinal plane A-A is shown.

Two main measures are performed to characterize the flame during the test. The first is the OH* chemiluminescence executed through a high-speed camera equipped with a 310 nm narrow bandpass filter. The time average of more than 2000 snapshots constitutes the mean flame position the numerical results will be compared. Secondly, the pollutant emissions are measured by sampling the combustion products downstream of the quartz liner.

The investigated conditions refer to a blend of NH_3-H_2 with a volumetric concentration of 25%-75%, respectively. Being the hydrogen the substance with the higher volume fraction within the fuel mixture, the global Equivalence Ratio (ER) of the mixture is kept in the ultra-lean regime (ER 0.287). Table 1 reports the main information about the three recorded Test Points (TP). In addition to the equivalence ratio, the temperature of the combustion air is kept constant at 500 K while the operating pressure is increased from atmospheric up to 2 bar with the goal to quantify the impact in terms of NO_x emission reduction. The mass flow rate scales to maintain the specific power constant at about 12.5 kW/bar-a.

Table 3 Operating conditions summary.

	TP1	**TP2**	**TP3**
Fuel Gas Composition	75% H_2 – 25% NH_3 % vol.		
Unburnt Air Temperature	500 K		
Equivalence Ratio	0.287		
Operating Pressure [bar-a]	1.1	1.5	2.0
Air Flow Rate [g/s]	13.0	17.73	23.98
NH_3 Flow Rate [g/]	0.205	0.28	0.382
H_2 Flow Rate [g/s]	0.073	0.099	0.132

3.2 CFD model

Fig. 3b shows the computational mesh on a longitudinal plane cutting the 3D domain. The latter starts upstream of the swirler and ends at the position where the products are experimentally sampled, it is discretized with 8 million polyhedral cells. The highest mesh resolution (600 μm) is applied inside the swirler and the primary zone while the characteristic size of the grid inside the flame tube is 1.2 mm. Such resolution is calibrated according to TP3 conditions that is the most demanding due to the highest pressure. Steady-state Reynolds Averaged Navier-Stokes (RANS) model simulations are performed in this study with the $k-\varepsilon$ realizable turbulence model. The Eddy-Dissipation Concept [25], assuming that the reactions take place in fine structures where the conditions of a perfectly stirred reactor are reached, is used as a combustion model. The corresponding finite-rate chemistry is based on a skeletal mechanism of 27 species and 154 reactions derived by CRECK [26] whose validation is summarized in [27]. This chemistry set embeds the NO_x kinetics: the mole fraction of NO and NO_2 are directly calculated solving the transport equations of these two species.

3.3 Test Results and CFD validation

3.3.1 Flame Morphology

The Abel deconvoluted OH* maps reported in Fig. 4 characterize the flame morphology as a function of the operating pressure from an experimental point of view. It can be observed that the flame length gets shorter with increasing pressure while the radial extension of the heat release region does not change significantly. In particular, the flame stabilizes only in the inner recirculation zone. The numerical model is able to reproduce the flame length reduction above atmospheric conditions. An excellent agreement is obtained for TP1 and TP2 while a slightly shorter flame is predicted for TP3.

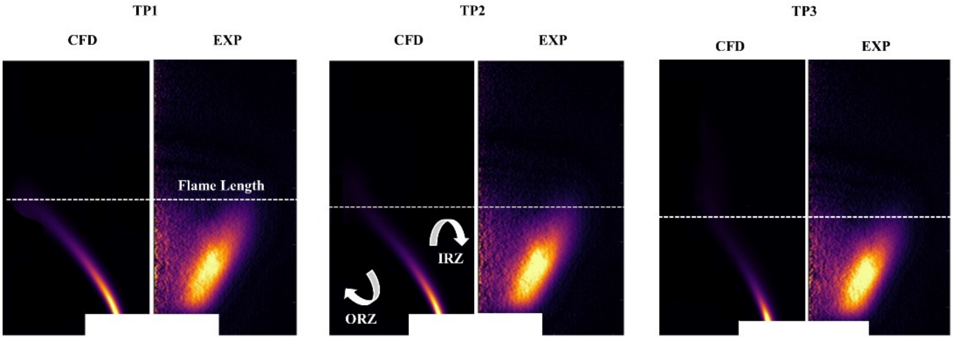
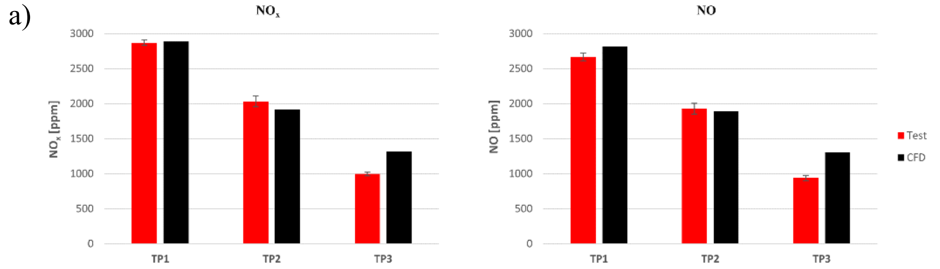


Figure 4 Flame morphology comparison for the three test conditions: OH* mole fraction from CFD (left) vs Abel-deconvoluted OH* from the tests (right).

The shortening of the heat release zone with the pressure increase, which can be primarily related to the higher turbulence level is also related to the lower specific heat loss of the rig operating at higher pressure.

3.3.2 NOx Emission

The graph reported in Fig. 5-a summarizes the comparison between both the NO_x and the NO emissions recorded during the test with the values predicted by the CFD model. Considering the experimental trend only, it is quite evident that the majority of the NO_x is related to the NO alone while the NO_2 represents a very limited amount of the global emission, quantifiable in about 7% at atmospheric conditions and about 5.5% at higher operating pressure. The numerical trends are able to predict the experimental measures quite well. It can be observed that for TP1 the NO overprediction is compensated by the NO_2 underprediction leading to a perfect match of the NO_x. Instead, a slight underprediction of both NO and NO_2 characterizes TP2. The major difference is visible at TP3 conditions where the NO_x reduction related to the pressure rise is not fully captured and the emissions remain higher (+35%). The contour plots of NO on the longitudinal plane reported in Fig. 5-b allow the effect of the pressure to be visualized. It can be noticed that with increasing pressure the NO concentration drops both in the inner and the outer recirculation zones inside the primary zone.



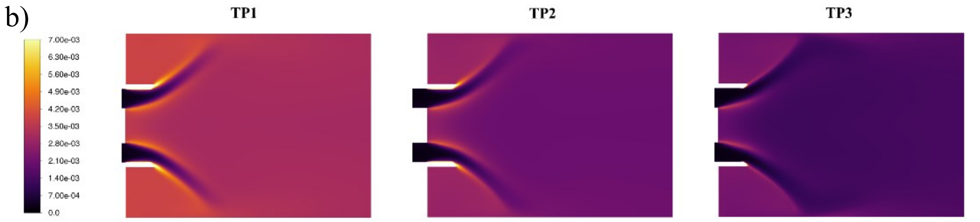


Figure 5 a) Experimental vs numerical NO_x (left) and NO (right) mole fraction. b) Contour plot of NO on the longitudinal plane.

Such effect is related to the lack of oxygen at higher pressure: the enhanced interaction of third bodies with radicals like OH ($H + OH(+M) \leftrightarrow H_2O(+M)$) subtracts oxygen for the NO formation. It has been found that this phenomenon is present till moderate pressure (less than 10 bar) and negligible above [28].

4 Combustion system retrofitting requirements.

The resulting high NO_x emission represents a limit from an industrial perspective of the introduction of ammonia blends in combustion system architectures based on lean premixing strategy, as presented in this paper.

One of the most promising alternative solutions for a Dry-Low NO_x ammonia blends burnability is the modification of the primary zone air split such that a rich mixture is achieved in the flame region (mimicking the rich-quench-lean concept) and the remaining part of the air flow rate is injected downstream to abate the flame temperature. As a consequence of the lack of oxygen in the primary zone, the NOx formation rate drops and the final emission can be minimized. This aspect represents a contrasting requirement in an eventual redesign of the combustion system aimed to extend the gas turbine fuel flexibility from natural gas and hydrogen fuels also to ammonia blends, meaning that still a huge joint effort between industry and academia is still needed to industrialize this concept. Adoption of post-treatment units to gas turbines developed with lean premix Dry-Low NOx combustion system can be seen as a mitigation solution to enable the ammonia blends combustion.

5 Conclusion

In this study, the integration of a P2A2P system with a commercial medium-size GT has been investigated from technical, energetic, and environmental perspectives. At first, the P2A2P scale-up is carried out considering the technical requirements of the NovaLT16 Gas Turbine. Then retrofitting of the GT combustion chamber and the impact in terms of NO_x emission have been investigated from both CFD modelling and experimental points of view. The main results can be summarized as follows:

- Regarding the P2A2P scale-up - the resulting Electrolyser size is 14 MW and the BOP accounts for 20% of the electrolyzer size, including the PSA unit to produce the N_2 required. The resulting efficiency of the P2A system and the fuel supply system is around 40%, while the roundtrip efficiency of the P2A2P integrated process is around 15%. The P2A system capacity is 30 ton/day that, considering the GT energy requirement (46 MJ/s), it corresponds to around 3.4 hrs at full load operation. Regarding the fuel supply system, it is required a pump to pressurize the liquid ammonia up to the fuel inlet pressure and then an ammonia evaporator to be able to inject chamber a fuel in gaseous form inside the combustion.
- Regarding the CFD simulations of a combustion system fed by ammonia-hydrogen blends in atmospheric conditions, the numerical model is able to reproduce the flame

length and the NOx emissions. The availability of such validated tool can be employed to conceive and verify the performance of preliminary design modifications.

- At this regard, the preliminary evaluation of the combustion system retrofitability and the high NO_x emission associated with hydrogen-ammonia blends combustion represent limits from an industrial perspective, suggesting changes of the primary zone air split to move toward a sequential rich-quench-lean combustion concept that could be preliminary investigated numerically.
- Adoption of post-treatment units to gas turbines developed with lean premix Dry-Low NOx combustion system can be seen as a mitigation solution to enable the ammonia blends combustion.

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