WGCPARIS2015
WORLD GAS CONFERENCE
"GROWING TOGETHER TOWARDS A FRIENDLY PLANET"
IGU
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World Scale Boil-Off Gas Reliquefaction

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Background

Boil-off gas reliquefaction has become an industry standard for many LNG carriers, which no longer use gas as fuel for steam boilers, but tap others energy sources to generate power for propulsion. Well known examples are the ships of the Q-Flex and Q-Max class. Most of these vessels use simple nitrogen expander cycles with relatively high energy consumption (typically 800 kWh/t) and a moderate capacity of about 200 t/d LNG liquefaction.

Increasing LNG demand in Asia, especially in Japan after the nuclear catastrophe triggered innovative ideas to increase the LNG output of existing liquefaction plants. Boil-off gases and ship return gases from LNG tank farms have been identified quickly as promising source for additional LNG, as these gases are perfectly suitable for cryogenic processing. Obviously, dehydration and sweetening is not required. However, low pressure, low temperature and elevated nitrogen content pose challenges to an efficient design.

Linde Engineering has developed an innovative concept for a world scale boil-off gas reliquefaction unit with 0.3 to 1.0 mtpa capacity, which includes the following features:

- Boil-off gas compression starting from cryogenic conditions
- Mixed refrigerant cycle with two heat exchanger bundles only
- Load balancing between feed gas and refrigerant cycle compressors
- Nitrogen rejection into the gas turbine fuel gas with a double flash process
- Use of identical gas turbines as mechanical drive

Aim

Large LNG export terminals include an LNG tank farm with large LNG tanks providing storage capacity of several hundred thousand meters cubed. Low pressure gases at tank pressure (about 100 to 200 mbarg) originate from several sources like

- Boil-off gas caused by heat ingress through the tank walls and LNG pumps
- Flash gas generated in the run-down line between liquefaction and storage
- Ship return gas / displacement gas during ship loading
- Flash gas during cool-down of warm send-out systems

In total the overall LP gas (hereinafter called boil-off gas or BOG) flow rate may accumulate to about 1,000 t/d for a 10 mtpa LNG facility (this figure can be scaled almost linearly for larger plant capacities). The quality of the BOG may raise concerns as it will be enriched with nitrogen and may contain contaminants from ship return gases. The distance between the LNG liquefaction trains and the LNG storage may add up to a few kilometres depending on the site conditions. Thus, returning the BOG to the liquefaction trains and merging it with the end-flash gas may not be the optimum solution for every site.

The decision to install a dedicated BOG reliquefaction system for the entire LNG facility will depend very much on the specific site conditions including the fuel gas balance, the capacity of the existing refrigeration systems, availability of natural gas as feed stock, distance between liquefaction trains and jetty/tank area, and flare load especially during peak BOG generation as it happens for example during ship loading. Under all circumstances, however, BOG reliquefaction will generate a high value product starting from very favourable feed stock conditions, as the absence of water, sour gas components and heavy hydrocarbons in BOG simplifies cryogenic processing significantly.

Concept Selection

A BOG reliquefaction unit with a capacity between 0.3 and 1.0 mtpa LNG can be compared with mid-scale LNG plants. All land based LNG plants in this capacity range are using a single mixed refrigerant (SMR) cycle. This choice is based on its good efficiency (typically 350 kWh/t[i]), minimum count of rotating equipment and good safety records. Considerations to use nitrogen expander cycles for floating LNG concepts are not applicable for a land based BOG reliquefaction facility, mostly as compact design and readily available make-up supply are not likewise important.

Even if there is some discussion about the use of brazed aluminium plate-fin heat exchangers (PFHE) for SMR based mid-scale LNG plants, experienced operators prefer coil wound heat exchangers (CWHE) in this service, as especially load changes during ship loading will cause extra stress to the heat exchangers. All experience shows that CWHEs are more tolerant against frequent load cycles than PFHEs. The marginal cost adder to go with CWHEs is more than offset by the peace of mind, if downtime caused by heat exchanger repair is taken into account.

BOG reliquefaction requires large compression systems for the refrigeration cycle and also for BOG compression, as liquefaction under low pressure would be very inefficient. A typical SMR process with a specific energy consumption of 350 kWh/t needs about 15 MW for a feed gas flow rate of 1,000 t/d under a pressure of at least 50 bar. Feed gas compression starting from tank pressure to at least 50 bar requires almost the same power. For compressor trains with more than 10 MW each gas turbines have been selected as driver in the past, if fuel gas is available under economically attractive conditions. Using electric motors instead of gas turbines seems to be preferable only, if and when electric power can be sourced reliably at low prices.

Process Optimisation

World scale BOG reliquefaction units have not been built so far. Thus, there is no proven template for a cost effective and robust process design. It is fair, however, to start with building blocks as they are known from mid-scale or world scale LNG plants.

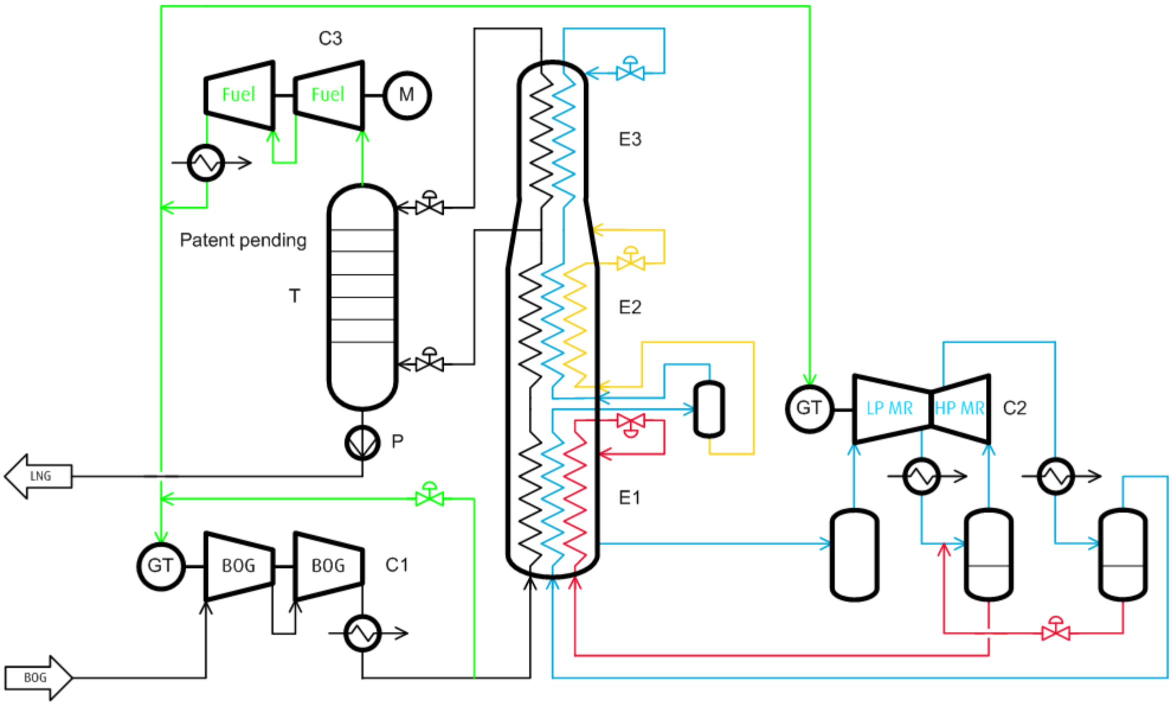


Fig. 1 Base concept with N2 stripper

Fig. 1 shows a conventional design for a BOG reliquefaction system. BOG from the LNG storage tanks has to be compressed first. The low molecular weight of the BOG and the high pressure ratio require two compressor casings for the single shaft, centrifugal compressor C1. In the absence of a need for sour gas removal and dehydration the compressed BOG will be sent directly to the cryogenic heat exchanger, which consists of a pre-cooling bundle E1, a liquefaction bundle E2, and a sub-cooling bundle E3. In most of the cases the nitrogen content of BOG will exceed the standard specification for LNG (<1 mol%) so that nitrogen rejection is required.

At elevated nitrogen levels in the BOG a nitrogen stripper T operated at low pressure will be the right solution for this purpose. An elegant manner to provide strip gas[ii] for the stripper is the use of 'warm' LNG after the liquefier E2, which will generate a sufficient quantity of gas, when it is flashed into the column. On-spec LNG will be sent by pump P via run-down lines to the storage tanks. The nitrogen rich stripper overhead gas has to be recompressed in compressor C3 to the required fuel gas pressure of the selected gas turbines. The chosen single mixed refrigerant cycle is the LIMUM® process, which has been developed and patented[iii] by Linde Engineering and is successfully in operation since many years in different locations. It is built around a single casing, barrel type compressor C2 with two compression stages.

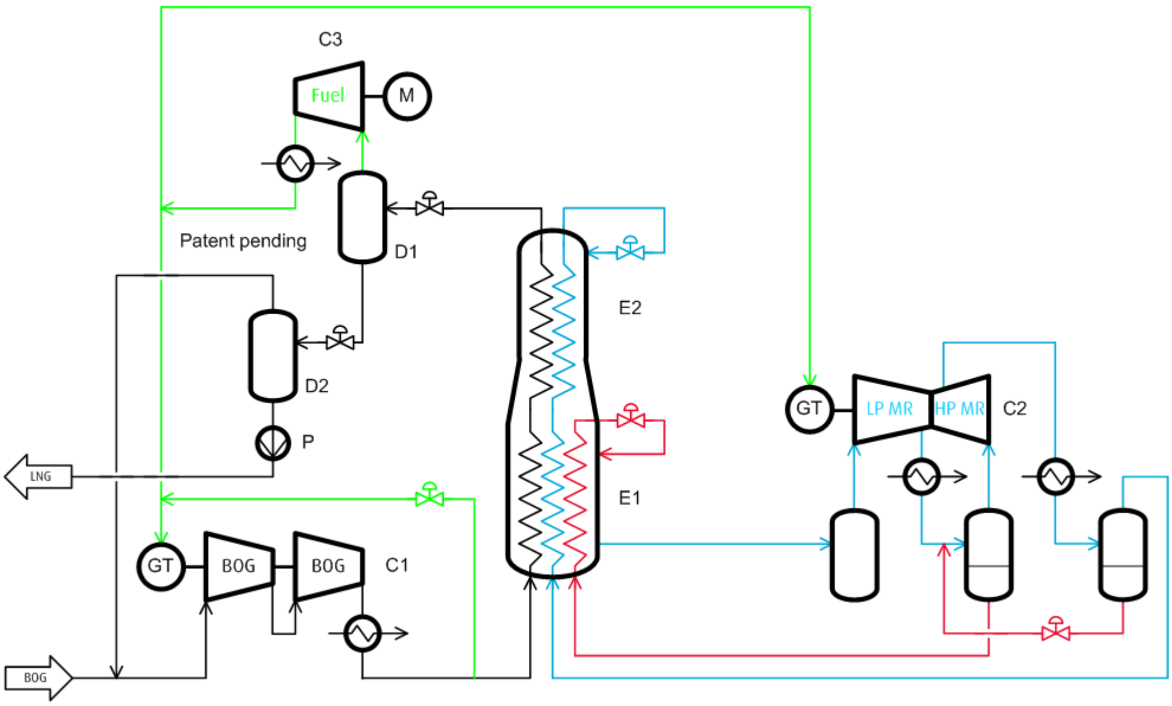


Fig. 2 Final concept with double flash system

This conventional design was scrutinized with value engineering methods with the following findings:

- Shaft power of C2 is about 150% of shaft power of C1, identical duties are desirable
- LP suction conditions of C3 result in an expensive multi casing design
- Stable operation of stripper T under frequent load changes is hard to achieve

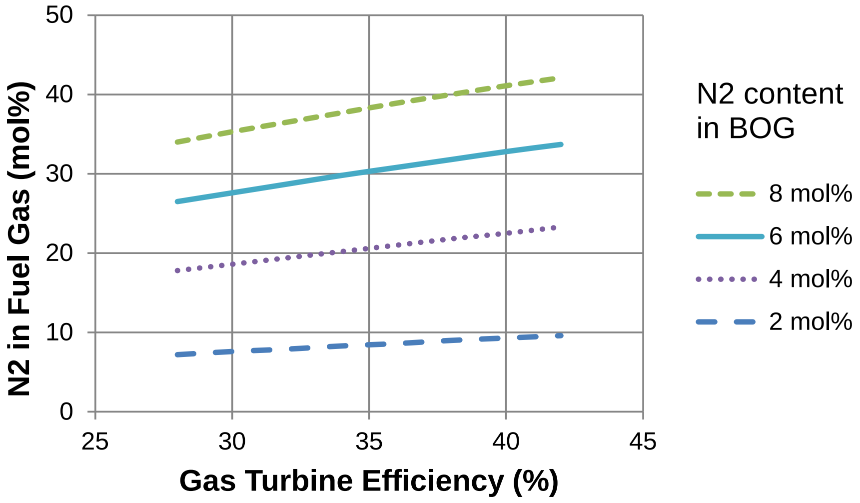


Fig. 3 Correlation between GT efficiency and fuel gas quality

The result of the subsequent process optimization is shown in Fig. 2. The MRC compressor C2 is unloaded by shifting part of its duty to the BOG compressor C1. This can be achieved by replacing the sub-cooling refrigeration duty of the MRC, which was used in E3, by an open methane cycle. Instead of sub-cooling LNG to such a low temperature that only the desired fuel gas stream is generated, a larger methane rich flash gas rate is deliberately accepted, which is recycled to the suction side of the BOG compressor C1. Thus, a very good match between the shaft power of C1 and C2 could be achieved[iv].

In a second step the nitrogen stripper T was replaced by a medium pressure flash drum D1 and a low pressure flash drum D2. The operating pressure of D1 can be selected such that the fuel gas can be compressed in a single casing, single stage compressor C3, which can be operated optionally at ambient temperature suction conditions, as the elevated suction pressure allows for a warm-up of the fuel gas before it is compressed.

In total the value engineering exercise helped to eliminate the sub-cooling bundle E3 and the low temperature LP casing of the fuel gas compressor C3. The stripper column T was replaced by two simple flash drums D1 and D2 and the main compressors C1 and C2 can be hooked up to drivers of identical rating.

After a successful streamlining of the process the suitable equipment had to be selected. One very complex decision was the selection of the best fitting gas turbine. In a situation, where the BOG is worked up into only two products, LNG and fuel gas, obviously most of the nitrogen has to go with the fuel gas, as LNG can accept only a very small amount (max. 1 mol% N_2). As a result highly efficient gas turbines with a low heat rate have to be operable with higher nitrogen content in the fuel gas and vice versa. This correlation is plotted in Fig. 3 for different BOG compositions.

Low BTU gas turbines

The combination of DLE (Dry Low Emission) requirements with a low heating value of the fuel gas requires certain measures to guarantee the flame stability. Fig. 4 shows a suitable concept as it is used e.g. in the Siemens industrial gas turbine family SGT-600/700/800 being equipped with eighteen 3G fuel nozzles, also called burners, in an annular combustor. The burners use pilot gas, which is fed at the burner outlet and is burned around the main flame for flame stabilization. Typical for DLE combustion, which is used by Siemens for more than 20 years, fuel is burned with twice the amount of air in comparison to stoichiometric combustion. The large amount of air keeps the flame temperature low reducing emissions of nitrous oxides, but on the other hand increasing the risk of combustion instabilities and incomplete combustion leading to emissions of CO.

At load levels exceeding 50 % most of the gas is burned in the main flame, which has a low ignition temperature producing low concentrations of CO and NOx. At lower power output, more gas is burned in the pilot flames, which operate at a higher temperature and thus create more NOx. At all levels of power output the amount of pilot flame gas is limited to the amount needed to ensure stable operation of the turbine.

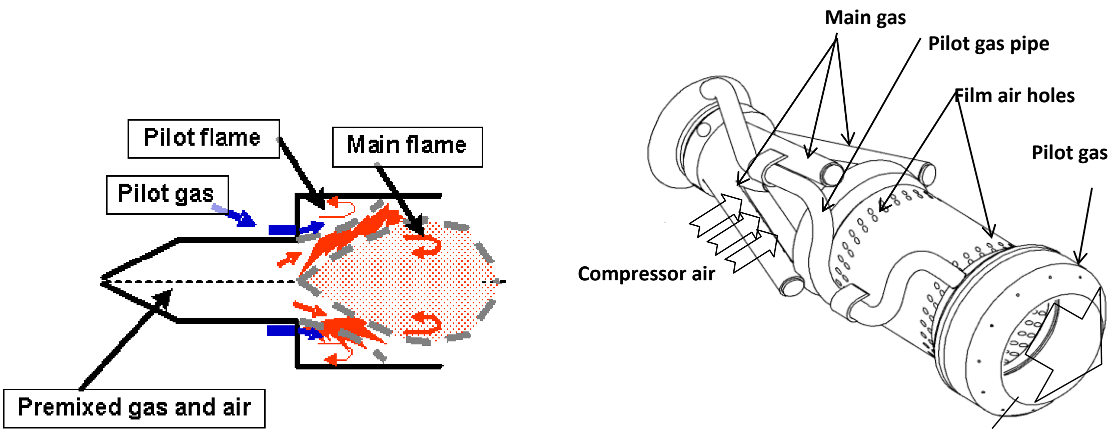


Fig. 4 3G burner schematic (left) and details (right)

The unique fuel nozzles of the Siemens industrial gas turbines have been proven to be very flexible in terms of the heating value of the fuel, respectively the Wobbe index. A high N2 content in the fuel acts just as ballast since N2 does not contribute to the combustion. Results from test beds and from actual operation in LNG plants[v] show that up to 40% N2 in fuel gas can be accepted without changes in the standard configuration. This feature comes with the full capability to accept substantial changes in Wobbe index. However the starting gas needs to be correlated with the control system for safe start-up, but once in operation a very reliable operation can be achieved with this system.

BOG compressor

Among all turbo compressor applications the cryogenic BOG compressor service is one of the most demanding applications. Due to the nature of the BOG service the compressor trains are periodically exposed to large fluctuations regarding volume flow and suction temperatures. The proprietary Siemens design features (see Fig. 5) include variable Inlet Guide Vane (IGV) control (blue) in front of the impeller (red), protected dry gas seals (green) in a heated and cooled seal carrier (yellow), extensive expertise in material selection, compressor design, manufacturing and testing.

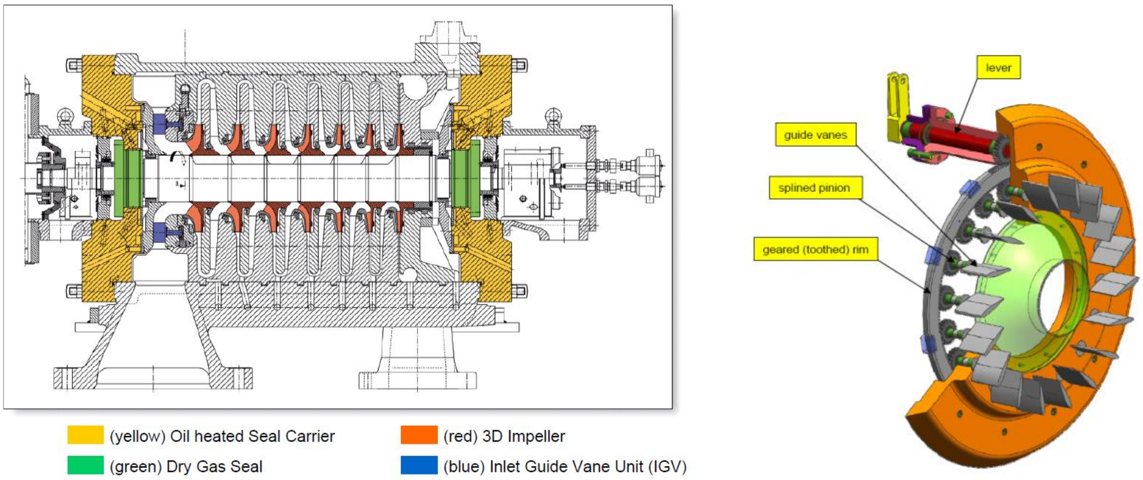
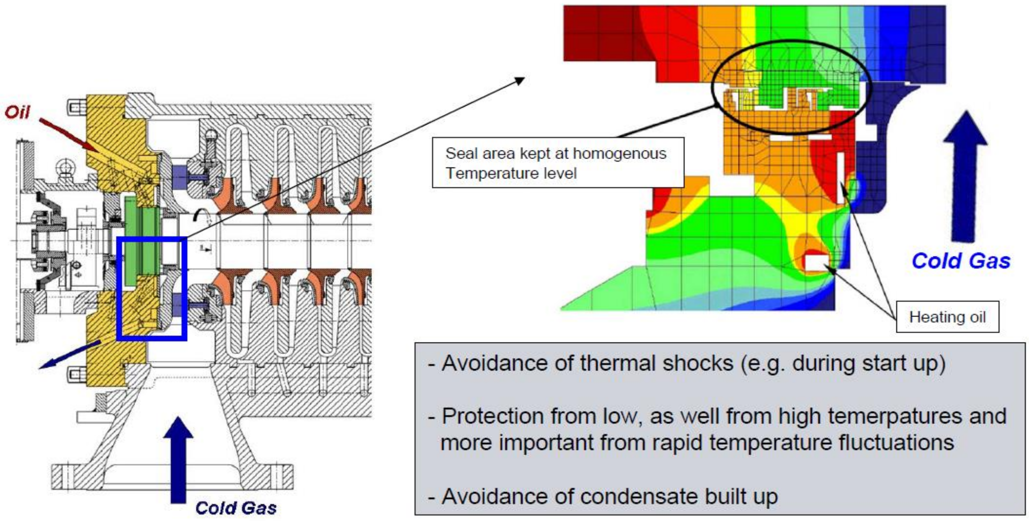


Fig. 5 turbo compressor cross sectional drawing (left) and variable IGV unit (right)

The IGV unit is an aerodynamic device and induces a vortex onto the flow increasing the compressor head respectively adjusting the angle of attack (incidence) to the impeller blading. The IGV concept improves the turbo compressor performance control and increases the operating range (turndown). The IGVs provide a map of individual performance curves within the IGV setting range, where the volume/head adjustment is quick and smooth. Main advantages of IGV control for BOG applications are

- Direct Online (DOL) start-up possible (start-up without any prior static cool-down, therefore no gas needs to be flared)
- Compact design, less space required, less weight, minimum equipment count, less spare parts, minimized footprint
- The IGV concept for cryogenic BOG compressor applications is well backed-up by references
- Largest turndown (highest process flexibility)
- Lowest maintenance

This design was first executed in 1972 for the first single shaft compressor train supplied for BOG service (Brunei) and in 1992 the first time also for cryogenic (-160 degree C) temperatures (Qatar). Since then, this design has become industrial standard and today all new BOG single shaft centrifugal compressor trains have been equipped with this advanced technology.



- Avoidance of thermal shocks (e.g. during start up)
- Protection from low, as well from high temerpatures and more important from rapid temperature fluctuations
- Avoidance of condensate built up

Fig. 6 oil heated/cooled dry gas seal carrier

Due to the nature of the BOG service the turbo compressor train is periodically exposed to very low suction temperatures (even down to -170 degree C) as well as to ambient and even high discharge temperatures during start up, compressor run in, or performance test. In order to eliminate or minimize thermal tension/stress for the dry gas seals caused by the extremely low suction temperature and periodically occurring temperature fluctuations (e.g. start/stop) resulting out of the different operation modes it is essential to keep the seal area at an almost constant temperature level during all possible operating modes. The required constant temperature level is achieved by providing oil heated/cooled seal gas carriers (see

Fig. 6, the oil heated/cooled seal gas carrier is marked in yellow colour on the left hand side drawing).

The heating oil is split from the regular lube oil flow and the fluid is circulating around the dry gas seal cartridge in seal-welded channels inside the compressor seal carrier (casing cover) forming a thermal shield. This design was first executed in 1991 for the first single shaft compressor train supplied with dry gas seals for cryogenic temperature BOG service. Since that time all new single shaft BOG centrifugal compressors provided with dry gas seals are equipped with oil heated/cooled seal carriers (in 2013 total 83 compressor casings) ensuring highest reliability (safety) and start-up availability, long-life service periods and lowest operation, inspection and maintenance cost.

Conclusions

World-scale BOG reliquefaction has become reality. Linde Engineering has successfully developed a new product for the LNG industry. Siemens contributed with innovative compressor and gas turbine designs, which are proven in service and are highly respected worldwide. The first plant, which is based on this novel concept is under execution for Malaysia LNG and is scheduled for start-up in mid-2015.

Acknowledgements

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