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An Evaluation of R134a and R477 as the Working Fluid in Vapour Compression Cycle by Electrical Source of 1MW

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Abstract: ***The characteristics of vapour compression cycle (VCC) designed to operate by electrical power 1000 kW produced from cascade organic Rankin cycle by one of Benghazi Cement factory production lines. Thermodynamic model was schematically constructed using a commercial software package called IPSEpro. The model (using two environmentally safe refrigerants (R-134a, R-744)), was successfully simulated and could produce a cooling effect of 2997 to 3105 KW at COP of 3.0, 3.1 respectively with an outlet chilled water temperature of 5 °C.***

Keywords: Benghazi Cement factory;R-134a; R-744; vapor compression cycle; IPSEpro

1. Introduction

This paper examines of utilizing a high temperature exhaust gas by Benghazi Cement factory production lines as part of energy supply for organic Rankine cycle for electricity power which feed vapour compression cycle. The Benghazi Cement factory is located 15 km west of Benghazi city and one of the biggest cement manufacturers in Libya Surrounded by several shallow cold water reservoirs that contain water at a constant year round temperature of 22 ℃.

Industrial facilities could greatly benefit from exploitation of any readily available high potential exhaust gases sources. These sources could contribute to solving some local problems and could also motivate local societies to share the world's concern about producing clean green energy (even at small-scales), and reducing the growing demand for electrical power generation, rising cost of fuel and the environmental restrictions on thermal pollution.

Vapour compression refrigeration systems are the most commonly used among all refrigeration systems. As the name implies, these systems belong to the general class of vapour cycles, Vapour compression refrigeration systems are available to suit almost all applications with the refrigeration capacities ranging from few Watts to few megawatts.

The basis of modern refrigeration is the ability of liquids to absorb enormous quantities of heat as they boil and evaporate. Professor William Cullen of the University of Edinburgh demonstrated this in 1755 by placing some water in thermal contact with ether under a receiver of a vacuum pump. A wide variety of refrigerants can be used in these systems to suit different applications, capacities etc. The actual vapour compression cycle is based on Evans-Perkins cycle, which is also called as reverse Rankine cycle [1].

There are quite a number of research works on vapour compression cycle for more efficient energy utilization. However, within the last twenty years, the number of vapour compression cycles was remarkably increased due to a rapid development in physical and thermodynamic properties of working organic fluids. For instance G Venkatarathnam et al. [2] screened 38 pure components working fluids for VCC process. In their work the critical temperature, normal boiling temperature, and critical pressure of working fluids were arranged in specific order to give a first hint for the 43 application of the working fluids. Environment friendly refrigerants such as carbon dioxide, hydrocarbons have specific practical deficiencies that limit their universal use.

Al-Rashed [3] carried theoretical cycle simulations with 7 °C evaporator saturation temperature showed the COPs of the studied refrigerants to be in the order of their critical temperatures, i.e. low-pressure refrigerants had the best COPs. However, for the cycle simulations including evaporator effects (carried out at a different evaporator saturation temperature for each fluid), including R-134a.

The operating cycle with CO_2 is simple vapour compression cycle however when working with CO_2, The resulting operating cycle will be called as trans critical cycle, with supercritical conditions for CO_2 across the heat sink and subcritical conditions for CO_2 across the heat source. Subcritical cycle was proposed for air conditioning and heat pump applications [4]. The main design differences between the subcritical (traditional) cycle and the R744 transcritical cycle that the main differences lie in the pressure levels (both during operation and at standstill) and the methods implemented to ensure the control of high pressure and refrigerant flow rate [5].

This paper takes the evaluation of two working fluids by taking the system analysis further in simulating a complete VCC using the software IPSEpro from electrical source of 1000 kW with a cooling water supply at 22 ℃the fluids examined were R-134a and R-744.

2. General Characteristics of vapour compression cycle Working Fluids

The properties of the chosen working fluid have a significant impact on the performance of the vapour compression cycle. Ultimately appropriate thermodynamic properties can result in higher cycle performance andlow costs. In order to achieve a successful VCC process, the ideal organic working fluid should have the following general characteristics:

1) High molecular weight.
2) Small heat content (low enthalpy).
3) High critical pressure and temperature to allowengine operating temperature to absorb all the heat available up to that temperature.
4) Low operating pressure to avoid danger ofexplosion or rupture and avoid negative impact on the reliability of the cycle.
5) Small specific volume of fluid in its gaseous stateto avoid the need of large and costly turbines, evaporators, and condensers.
6) Has higher pressure inside condenser to preventair inflow into the system.
7) Inexpensive to avoid high overall system cost.
8) Low heat latency.
9) Non-flammable, corrosive or toxic.
10) Low environmental impact.

The two fluids chosen as the subject of this work and they have thermodynamic properties that make them suitable for use with electrical source. The important parameters of these fluids are shown in Table 1.

Table 1: Properties of working fluids.

Property	R-134a	R-744
Molecular mass, (kg/kmol)	102	44.01
Critical points	101ºC- 40.6 bar	31.06ºC- 73.84 bar
Boiling temperature at 1 atm., (ºC)	-26.4	-78
Safety	Non-flammable	Non-flammable
Atmospheric lifetime	14	29.3
ASHRAE level of safety	A1	A1
Ozone depleting potential ODP	≈ 0	≈ 0
Net Greenhouse warming potential GWP 100 year	1320	1

3. Thermodynamic Analysis of the VCC Cycle

The schematic of vapor compression refrigeration cycle components and T-s diagram are shown in Figures 1 and 2 respectively. The cycle is entirely in the sub-critical region of the T-S chart and operates between two pressure limits Pc and Pe and consists of four stages under which refrigerant circulates continuously .In the first stage the low temperature, low pressure vapor at state 1 is compressed by a compressor to high temperature and pressure vapor at state 2, this is called the compression stage. In the next stage the compressed vapor is condensed into high pressure vapor at state 3 in the condenser and then passes through the expansion valve, this is stage is called the condensation stage. Here, in the expansion stage the vapor is throttled down through a throttle valve to a low pressure liquid and passed on to an evaporator, where it absorbs heat from the surroundings from the circulating fluid and vaporizes into low pressure vapor at state 1. The fluid here is the refrigerant. The cycle then repeats in a similar fashion [7, 8]. The detailed cycle processes are identified in Fig. 2 and explained as follows:

1-2 isentropic compression in a compressor
2-3 Constant-pressure heat rejection in a condenser
3-4 Throttling in an expansion device
4-1 Constant-pressure heat absorption in an evaporator

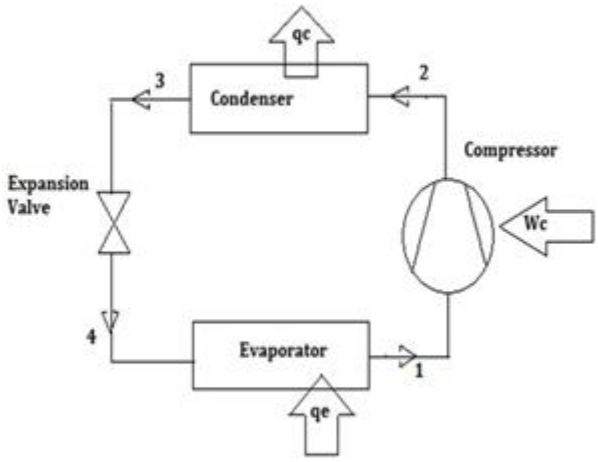

Figure 1: Basic vapor compression refrigeration cycle

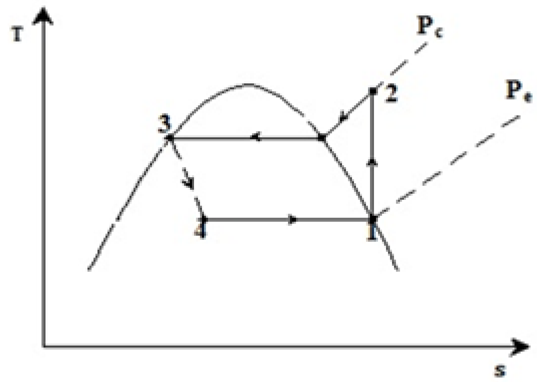

Figure 2: Basic vapor compression refrigeration cycle T-s diagram

It can see that refrigerant such as carbon di-oxide, have symmetrical saturation curves (vapor dome), as a result both the superheat and throttling losses are significant. That means deviation could be significant when these refrigerant is used as working fluids but Refrigerant such as HFC134a, these refrigerant has small superheat losses but large throttling losses [1]. The analysis of the cycle consists of applying mass and energy balances to each of the processes mentioned above.

The compressive of the working fluid through the compressor, withthe power input to the compressor:

$$\dot{W}_{in} = \dot{m}_{wf} * (h_2 - h_1)$$

With a condensation process occurred within counter flow heat exchanger using cooling water at 22ºC,the rate of heat rejection from the refrigerant to the environment is:

$$Q_{co} = \dot{m}_{wf} * (h_2 - h_3)$$

The throttle is simply an expansion valve which is adiabatic and does no work, however enables a significant reduction in temperature of the refrigerant:

$$h_4 = h_3$$

The heating process in the evaporator where heat removal from the refrigerated space transferred to the working fluid:

$$Q_{ev} = \dot{m}_{wf} * (h_1 - h_4)$$

The coefficient of performance of the refrigerator is:

$$COP_R = \frac{Q_{ev}}{W_{in}}$$

4. ModellingTool

Computational modeling and simulation have become the most basic part in most of nowadays studies and applications. In this research work, simulation commercial software called IPSEpro of Sim.Tech® was used. It is an extremely powerful package [6]. It is highly flexible and comprehensive for modeling and analyzing processes in energy engineering, chemical engineering and many other related areas. IPSEpro is based on overall balances of mass and energy and is capable of simulating the whole system. In order to perform a thermodynamic analysis for a component in the modeled systems, the principle of mass conservation and the first law of thermodynamics are applied to each individual component. Each component can be treated as a control volume with inlet and outlet streams, heat transfer, and/or work. The electrical source of 1MW has been simulated using this software package as shown in Figure 3.

During various modeling stages, a parametric study was carried out to find out the most effective parameters that have great influence on the performance of the cycles. In addition, pinch point analysis of the most important equipment of VCC model, evaporator heat exchanger, was conducted. As the most modeled cycle equipment were counter and cross flow heat exchangers, all related effectiveness (ε) and Number of transfer units (NTU) explicit relations were used to confirm their validity and to make sure that these components are within acceptable manufacturing ranges.

5. Simulated Models Results and Discussion

Vapor compression cycle model was schematically built as shown in Figure 3, it was vapor compression cycle powered by electric energy 1 MW, simulation was chilled water at constant temperature of 12 ºC and The rejected heat from the condenser was carried by water at fixed temperature 22ºC.The objective of the impact of refrigerant (R-134a and R-744) has on the cycle components for a desired level of performance. The simulated results showed that Produced refrigeration capacity of 2997kW and 3105kW were produced at COP of 3, 3.1 respectively. The result obtained from simulated vapor compression cycle models are shown in Table 2.

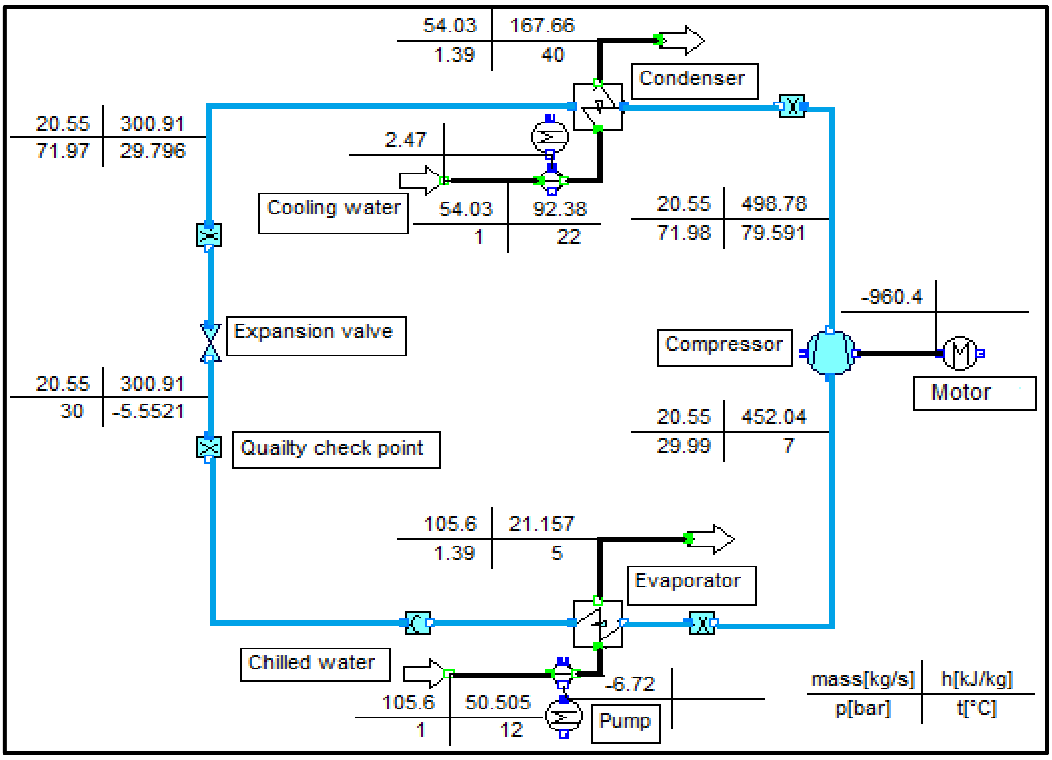

Figure 3: Refrigeration capacity produced by R-744 vapor compression cycle model

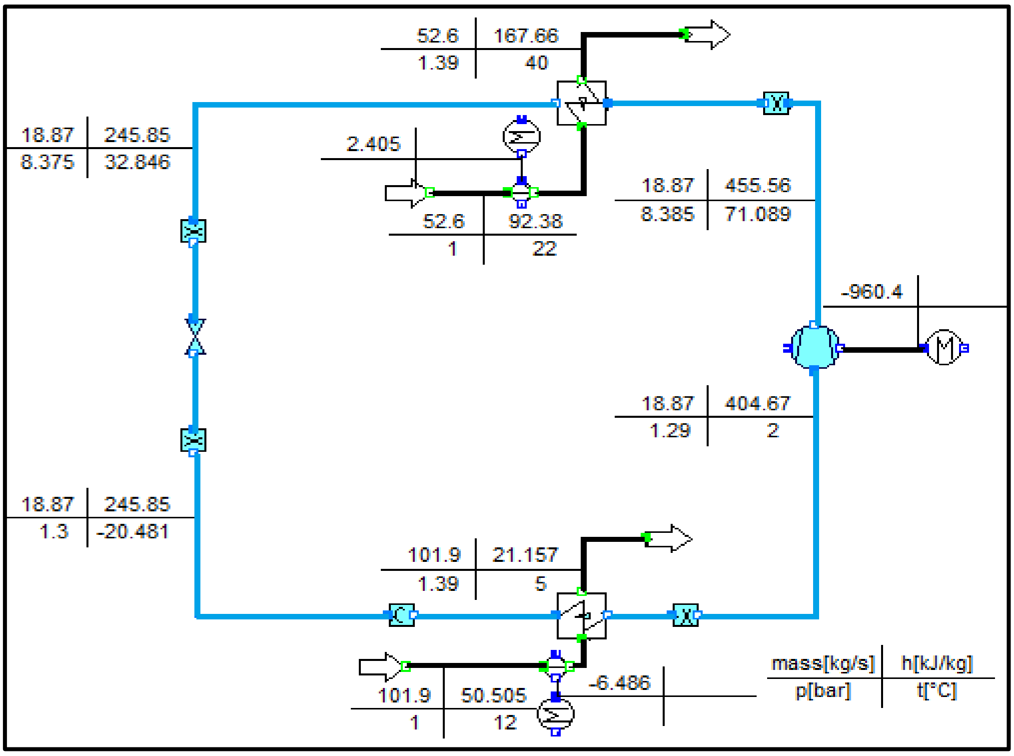

Figure 4: Refrigeration capacityproduced by R-134a vapor compression cycle model

Table 2: Output results of both modeled refrigerants

Parameters	R-134a	R-744
Coefficient of performance (COP)	3	3.1
Electrical power input, KW	1000*	1000*
Pressure ratio of the compressor	6.5	2.5
Produced refrigeration capacity, KW	2997	3105
Condenser UA value, kW/k	206	208
Evaporator UA value, kW/k	181	416
chilled water inlet temperature, °C	12*	12*
Chilled water mass flow, Kg/s	102	105
Cooling water mass flow, Kg/s	52.6	54
Evaporator effectiveness value, ε	0.69	0.71
Evaporator Number of transfer Units value, NTU	1.17	1.24
Condenser effectiveness value, ε	0.77	0.86
Condenser Number of transfer Units value, NTU	1.47	1.96

* Set values

6. Sensitivity analysis of Proposed models

The model of vapor compression cycle using (R-134a and R-744) was found to be communicated with the environment at point the cooling water sink. The cooling water temperature is assumed to be fixed at 22 ºC, and the only external variable that will most likely affect the performance of other cycle parameters such as: refrigeration capacity, chilled water mass flow, cooling water mas flow, condenser heat transfer, and refrigerant mass flow is the electric power input. Figures 5 to 9 show the effect of the variation of the electric power input on various cycle parameters for two refrigerants.

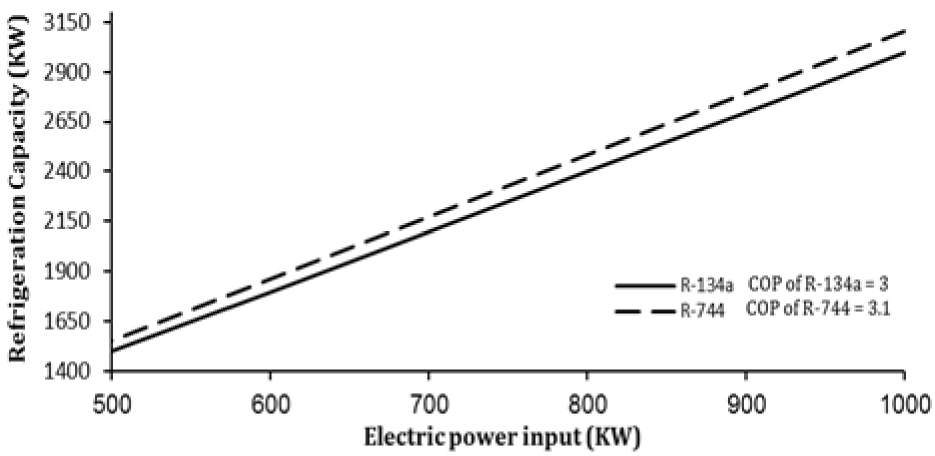

Figure 5: Effects of the electric power input variations on the refrigeration capacity

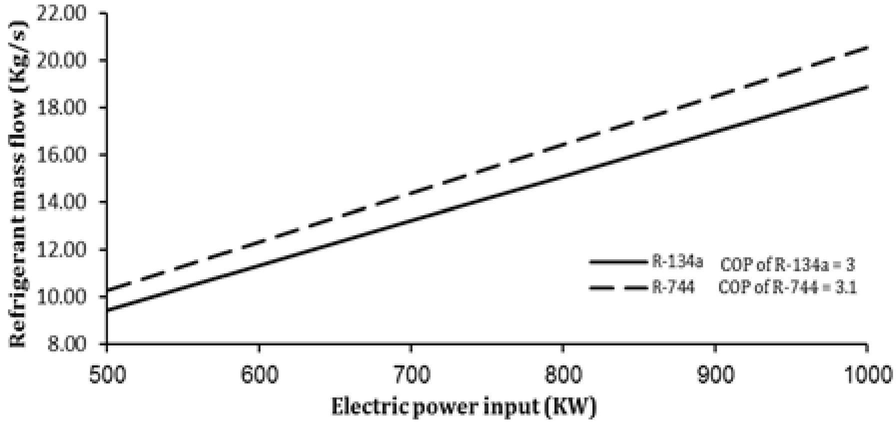

Figure 6: Effects of the electric power input variations on refrigerant mass flow

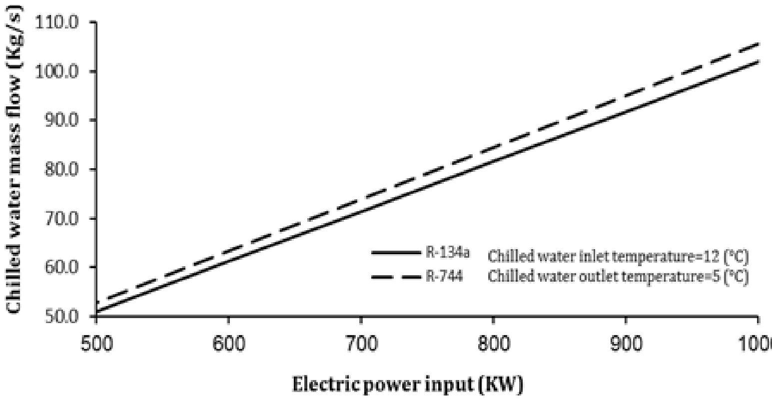

Figure 7: Effects of the electric power input variations on the chilled water mass flow

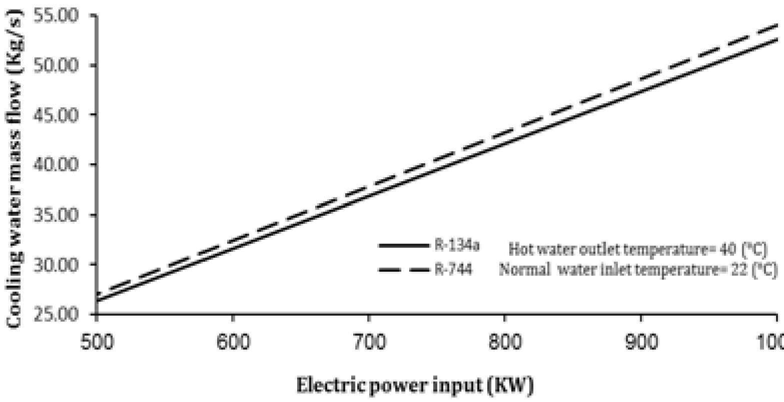

Figure 8: Effects of the electric power input variations on cooling water mass flow

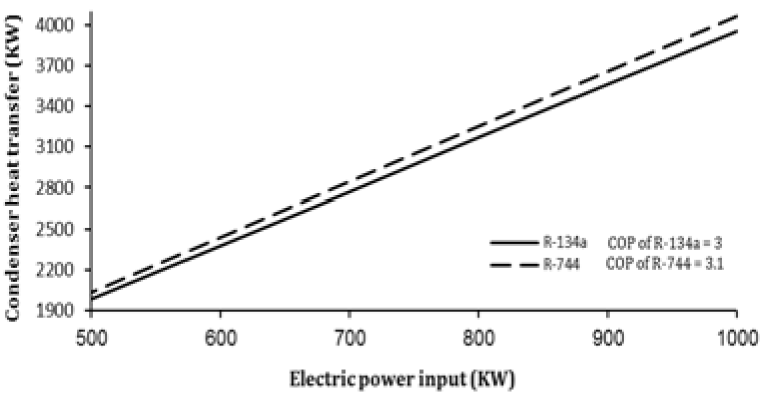

Figure 9: Effects of the electric power input variations on condenser heat transfer

7. Conclusions

Modelling simulation of vapour compression cycle using two refrigerants R-744 and R134a was schematically built and well performed in order to produce cooling effect. This cooling capacity was produced when the cycle powered by 1000 kW of electricity. The results showed that refrigerant R-744 at COP of 3.1 and refrigeration capacity of 3105 KW were performed well and better than R-134a which was at COP of 3.0 and refrigeration capacity of 2997 KW. It has been noticed that refrigerant R-744 was operated at higher cycle pressure values in comparison with other refrigerant-R-134a. This could lead to drawback from using R-744 as a working cycle refrigerant. However using R-134a is better than R-744 when lower operation pressures, technical and environmental aspects are favourable.

Abbreviations	
WHRS	Waste heat recovery system
CO_2	Carbon dioxide
SimTech	Simulation Technology
VCC	Vapor compression cycle
Nomenclature	
COP	Coefficient of performance -
NTU	Number transfer units -
ε	Effectiveness -
Q	Heat transfer kW
T	Temperature° C
W	work transferkW
h	Specific enthalpy kJ/kg
m	mass flow ratekg/s
Subscripts	
co	Condenser
ev	Evaporator
m	Mechanical
p	Pump
C	compressor
wf	Working fluid

8. Acknowledgments

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