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LOG BUILDINGS FROM THE PERSPECTIVE OF THE CURRENT REQUIREMENTS

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ABSTRACT

This contribution focuses on the verification of temperature and moisture content conditions inside perimeter walls of timber buildings as regards the temperature and humidity requirements in buildings intended for permanent residence. We assessed: a simple perimeter wall of solid timber, a wall of glued BSH profiles, a wall of an existing log building with additional thermal insulation in two options, and a sandwich log wall with a layer of embedded insulation. This study contrasts theoretical calculations with the values measured in a real buildings. The effect of the humidity changes on the strength and stability of dowelled joints is analysed.

KEYWORDS: Log building, building envelope insulation, wood moisture content, water vapour condensation, joints of timber elements.

INTRODUCTION

Decree no. 268/2009 Coll., on technical requirements for the construction, Clause 16 Energy Savings and Thermal Protection, stipulates that buildings must be designed and constructed so that the energy consumption related to their use is as low as possible. Requirements for thermal properties of buildings are becoming more stringent, and the current standard, ČSN 73 05 40-2 (2012) does not only relate to buildings newly built, but also those under reconstruction or modernization. Log buildings are assembled from hewn, cut or milled beams of various shapes and with various connections of individual elements. If the perimeter walls are to meet the thermal technical requirements, they must be supplemented by another envelope and embedded thermal insulation. As reported by Lokaj (Lokaj 2003), timber constructions have their own specifics and the attempt to reach the lowest possible heat loss must not impede the other essential requirements laid on these structures and buildings.

Limited water vapour condensation is allowed inside the buildings, but no condensed water vapour that would permanently increase the construction moisture content should remain in the annual balance (Fedorik et al. 2015). This requirement is verified by calculations in compliance with ČSN 73 0540-4 (2005). It follows from the above that without an appropriate solution of the wall composition as regards the thermal technology and the verification of hygrothermal conditions inside, the mechanical strength and stability of the construction cannot be guaranteed, nor the durability of wood and wood-based materials in terms of the threat of biological agents. (Havířová and Kubů 2005)

The aim of this study is to propose a recommended composition of log building perimeter walls to ensure that the thermal transmittance would reach the recommended values and at the same time, the risk of possible water vapour condensation in the walls is eliminated. As the calculation methods manifest relatively unfavourable values for the assessment of log walls (Al-Hajjar 2015), and, additionally, there are many ambient influences, a partial objective was to compare the theoretically set values of moisture of the incorporated timber with those actually measured inside the structure using several options of the thermal insulation of a log building. In addition, dependence was detected between the mass moisture content of the timber in the envelope and the hygrothermal changes of the internal and external ambient environments.

Log cabins comprise a separate category in the field of timber buildings for housing, in particular as regards the shape, dimensions and properties of the wooden material used. Structural details of these constructions are usually done as traditional carpenter's work, which, in addition to a static function, needs to take into account their unique (or specific) properties, such as the shape and, in particular, volumetric changes of wooden elements caused by their gradual long-term shrinkage. While the constructions of roofs, frame type timber buildings, buildings with wooden panels, and skeleton structures use "finished" material, i.e., wood dried to the required moisture defined by the service class, log buildings use “raw” material from the very beginning – logs, whose initial high moisture content significantly changes during the construction and the subsequent use. The gradual drying of the raw wood is accompanied by changes in the volume, so the structural analysis must comply with new volumetric and morphological characteristics to ensure the supporting function of the joints (i.e., to prevent their failure or additional loading of their elements induced by the wood shrinking and improve aesthetics).

MATERIAL AND METHODS

Calculations

The thermo-technical assessment of the proposed compositions of log walls in terms of heat flux and water vapour transmission (calculation of thermal resistance and thermal transmittance, internal surface temperature, decrease in contact temperature of the floor structure, distribution of temperature and pressure of water vapour in the construction, the areas of condensation, and the annual balance of condensed water vapour) was conducted using the TEPLO 2014 application, which takes into account the requirements of ČSN 730540-2 (2012) and the procedures set out in standards ČSN 730540-4 (2005), ČSN EN ISO 6946 (2008) and ČSN EN ISO 13788 (2013). Design values correspond to ČSN 730540-3 (2005).

Experimental measurement

To verify the theoretical results obtained from the calculations, a log building was selected and fitted with sensors for the measurement of internal temperature and air humidity, external humidity and air temperature, and wood equilibrium moisture content, in the places where the risk of water vapour condensation was expected. We used resistance hygrometers with drilled-in sensors and temperature compensation. The walls were then insulated. The measurement was carried out in three consecutive winter seasons.

Thermal insulation option

For the purposes of measurement, three different compositions of thermal insulation of the building envelope have been designed. The selected room was located in the corner of the building, and it included the kitchen with the dining room, where a higher relative humidity was assumed. The influence of the wall insolation was avoided by choosing north-west and north-east oriented walls. Two options of the insulation composition were designed for the interior side and one for the exterior.

Options I and II are versions with the internal insulation. The composition of the wall is shown in Fig. 1.

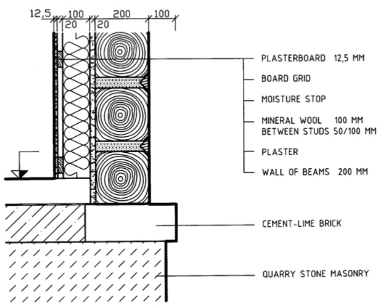

Fig. 1: Detail of the interior insulation of the log wall (option I and option II).

Fig. 2: Interior insulation of the log wall (left - option I; right - option II.)

In the first option, a vapour barrier - G + H Isover Difunorm - is inserted between the internal lining and thermal insulation. In the second option, a more effective vapour barrier is used - a bubble polyethylene foil, 4 mm thick, with an aluminum film - DAPE AB. (Fig. 2)

Option III has the additional insulation from the outside. Detail of the composition is presented in Fig. 3. All three options are designed as diffusion-closed.

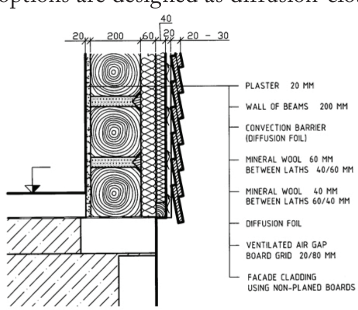

Fig. 3: Detail of the exterior insulation of the log wall (option III).

Constructional details

In addition to wall, floor and roof structures, the load-carrying systems of log cabins may contain truss girders, trimmers and brace members, which are predominantly loaded by tensile and compressive axial forces – see Fig. 4.

Fig. 4: Trusses in the log cabin structures.

The transfer of forces in the connections, loaded by compressive axial forces is usually resolved by machined contact surfaces whose position is secured mostly by steel fasteners.

The transfer of tensile forces in the truss members can be efficiently addressed using steel joint elements. A number of proven structural solutions are used, such as a connection based on slotted in-steel plates with dowel and bolt fasteners. This is a solution which is suitable for the statics (possible transfer of forces of greater intensity), fire prevention (the slotted in-steel plate is protected by wood) and aesthetic reasons. It is also relatively easy to implement. (Kala et al. 2012).

The static design of the joint can be done in compliance with EN 1995-1-1 (2006) as the double shear dowelled connection of "steel-to-timber" type. A problem that may occur during the design is high moisture content, which increases the risk of major radial and longitudinal drying cracks in the places where dowelled joints are located. These occur as a consequence of the local weakening of the material (Straka and Šmak 2008). Also the design procedures in standard EN 1995-1-1 (2006) do not sufficiently reflect the higher level of moisture in these structural elements.

RESULTS AND DISCUSSION

The measured values were compared with the calculated values using statistical methods. The boundary conditions used for the calculation were the average values of the temperature and the moisture content of the exterior and the interior from the steady state. For further verification of the moisture conditions in the construction we used the assessment methodology for the equilibrium moisture content of wood developed within VZ MSM 6215648902 part VZ no. 5 at Stage no. 7 - Timber elements and constructions. Energy diagnostics of buildings made of timber - within the solution of the task "Analysis of hygrothermal conditions inside the envelope of a timber building in dependence on the changes in the temperature of the external environment" (Kotásková and Havířová 2011).

Comparison of the measured and calculated values of wood moisture content

Out of the series of the monitoring periods we select the period from January 5 till January 12 (Fig. 5). The results of the balance of moisture and the values of thermal transmittance are listed in Tab. 1 for the comparison of the different options.

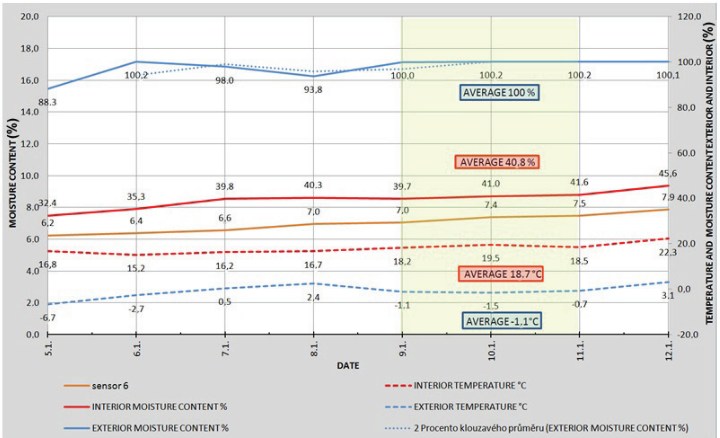

Fig. 5: Progress of wood moisture content based on the average daily values measured by sensor 6 in dependence on the temperature and moisture content of the interior and the exterior for the selected steady-state period.

Tab. 1: Comparison of the calculated thermal technical values for the particular options

	OPTION 1	OPTION 2	OPTION 3
The thermal transmittance of the construction U ($W.m^{-2}K^{-1}$)	0.292	0.282	0.300
Wood moisture content provided by calculation (%)	13.4	13.0	8.3
The average value of the measured wood moisture content (%)	11.6	10.3	7.9

The average measured values are lower than the calculated ones, i.e., the calculation is conservative (Havířová and Kubů 2005). The reliability of the timber construction of options 2 and 3 verified by the calculation is also visible in the graphs (Figs. 6 and 7); no condensation zone arises in the construction.

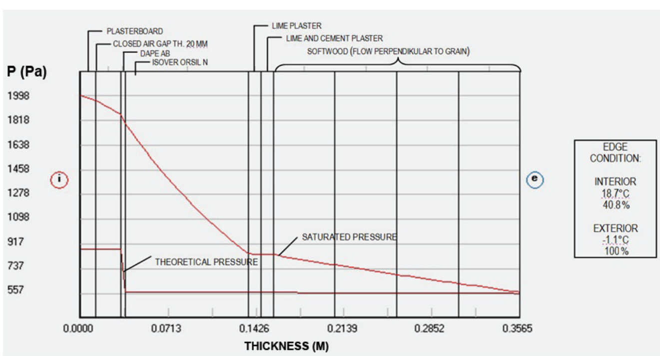

Fig. 6: The distribution of water vapour pressures in a typical place of the construction for option 2 with modified boundary conditions [μ 100 % μ of wood 157 (-)].

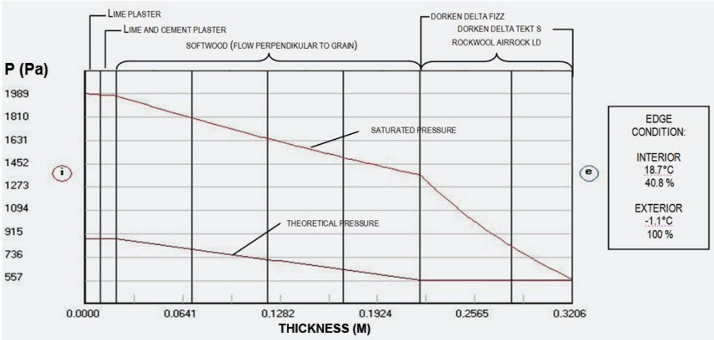

Fig. 7: The distribution of water vapour pressures in a typical place of the construction for option 3 with modified boundary conditions [μ 100 % μ of wood 157 (-)].

The measured values show that the insulated walls are without risk; however, it is necessary to verify this by calculation with standard boundary conditions in compliance with ČSN 73 0540-3 (2005).

The results of the calculations with the standard boundary conditions of the external and internal environments

The results show how the wall will behave at extreme values, particularly of the air temperature in the exterior. The calculation and the graph (Fig. 8) of option 1 demonstrate that a condensation zone occurs in the wood.

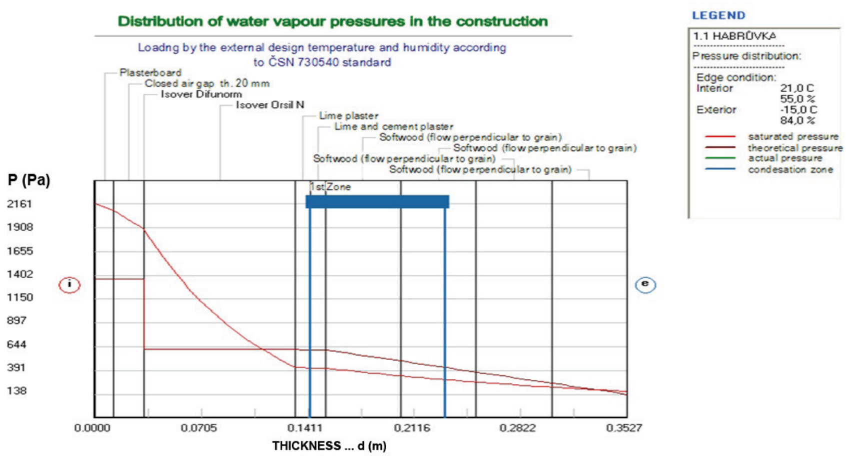

Fig. 8: The distribution of water vapour pressures in a typical place of the construction based on calculation 1.1-Habrůvka Option 1 [μvapor barrier 100 %, μwood, 157 (-)].

As regards the second and third options of insulation, the calculation and the graph show that water vapour will not condense in the construction with the design boundary conditions for rooms for habitation. The equilibrium moisture content of wood embedded in the construction is very low.

Comparison of the values of the year-round moisture balance

The composition options of the walls for newly designed log buildings were proposed so that they meet the requirements of the above-mentioned standard. Calculations verified various options of double log walls with embedded thermal insulation. (Fig. 9).

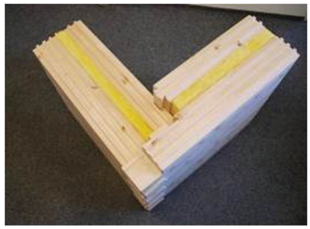

Fig. 9: Corner joint - double log walls with embedded thermal insulation.

These are all diffusion-open compositions; we searched for the optimal combination of the interior log wall thickness, thermal insulation thickness, and the exterior log wall thickness.

Tab. 2 presents the values of the moisture balance of the walls, which use the required value of thermal transmittance U = 0.30 $W.m^{-2}K^{-1}$. For comparison, the values for a solid wood wall, all three options of the insulated building, and double log walls with embedded thermal insulation are presented.

Tab. 2: Comparison of year-round moisture balance at standard boundary conditions (U = 0.3 $W.m^{-2}K^{-1}$).

	Log wall	**Measured insulated building**			**Composition of a double log wall with insulation from interior to exterior wood/insulation/wood**	
Thickness in meters	0.58	OPT. 1	OPT. 2	OPT. 3	0.2/ 0.06/0.1	0.1/0.06/0.2
Thermal transmittance of the construction U ($W.m^{-2}K^{-1}$)	0.295	0.292	0.282	0.30	0.30	0.30
The amount of water vapour condensed with the specified standard boundary conditions Mc,a ($kg.m^{-2}.year^{-1}$)	0.0005	0.002	0	0	0.0092	0.0243
The amount of evaporable water vapour Mev, a ($kg.m^{-2}.year^{-1}$)	0.1407	0.123	0	0	0.1819	0.1975
Condensation occurs when the exterior temperature is	-10°C	-5°C	does not occur	does not occur	0.0°C	5.0°C

Tab. 3 compares the amount of water vapour condensed, when calculated with the recommended value U = 0.25 $W.m^{-2}K^{-1}$. If a thicker wall is designed from the interior, the thinner wall with insulation has the same function as the external thermal insulation. If the interior wall is thinner, it is the internal insulation.

Tab. 3: Comparison of year-round moisture balance under standard boundary conditions (U = 0.25 W.m^{-2}K^{-1}).

	Solid wood	**The composition of the log wall from the interior to the exterior -wood/insulation/wood**			
	Thickness in meters				
	0.7	**0.21/0.08/0.12**	**0.12/0.08/0.21**	**0.22/0.08/0.12**	**0.12/0.08/0.22**
Thermal transmittance of the construction U (W.m^{-2}K^{-1})	0.246	0.250	0.250	0.246	0.246
The amount of condensed water vapour at standard boundary conditions Mc,a (kg.m^{-2}.year^{-1})	0.0004	0.0107	0.0261	0.0095	0.0252
The amount of evaporable water vapour Mev, a [kg.m^{-2}.year^{-1}]	0.1174	0.1538	0.1630	0.1516	0.1620
Condensation occurs when the exterior temperature is	-10°C	5.0°C	5.0°C	0.0°C	5.0°C

The balance of the condensed and evaporated moisture shows that the amount of condensed water vapour is less than 0.1 kg.m^{-2}/year and the annual amount of evaporated water vapour is larger than the annual amount of the condensed water vapour. This means the proposed compositions meet the requirements of relevant standards.

However, if condensation occurs when the temperature outdoors is lower than 5°C, which according to standard ČSN 73 0540-3 (2005) corresponds to approximately 180 days in a year, such a composition is to be considered risky (Havířová and Kubů 2005). As a consequence of the condensation, the equilibrium moisture content of wood in the existing log wall under the specified conditions will increase. The most appropriate composition seems to be: interior log wall thickness of 0.22 m, exterior wall thickness of 0.12 m, and the embedded thermal insulation Isover Orsik thickness of 0.08 m. In this composition, condensation occurs when the air temperature is 0°C and lower, as the calculation shows.

Besides the condensation of water vapour in the perimeter wall, it is possible to find condensation inside the ceiling or roof structures (Solař 2011). In particular, low air exchange may result in increased mass moisture of timber elements. The greatest risk occurs above unheated area of the loft which is not ventilated sufficiently.

Analysis of dowelled joints

Experimental research was carried out on the actual behaviour of the selected types of joints made from round wood with slotted in-steel plates and dowel and bold fasteners (Fedorik et al. 2015, Kala et al. 2012). One of the goals was to verify the influence of the moisture content of the basic material (solid wood) and partial strengthening on the load-carrying capacity of the joint under loading by axial tensile forces (Šmak and Straka 2008, 2014).

To validate the properties of the joints, we selected elements from solid spruce (*Picea abies*) - planed logs of quality class S10, which were planed to the same diameter (160 mm) to allow for an objective comparison of the examined effects.

The steel plate, 8 mm thick, was inserted into the slot in the direction of the connected member axis. The plate was made of steel strength class S355 (11523), holes were drilled 1 mm larger than the diameter of the bolts, which corresponds to normal conditions.

Three bolts were used in the joint - 12 mm in diameter - made of threaded rod M12, strength class 8.8, fitted in the timber element axis (bolts cannot be fitted in two rows, due to the dimension of the timber element). The spacing between the bolts and distance from the ends of the timber element comply with the conditions stipulated in EN 1995-1-1 (2006), including the recommended slenderness of bolts inhibiting the formation of brittle fracture in the wood.

The design of the analysed joint is displayed in Fig. 10.

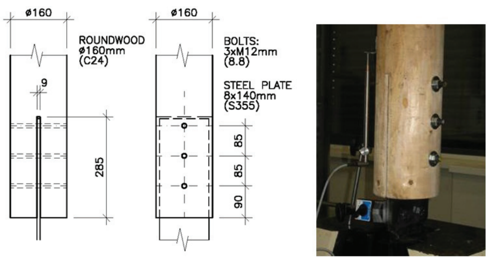

Fig. 10: The assessed joint with a slotted in-steel plate and bolts.

Fig. 11: The arrangement of the loading tests.

The joint was strengthened in the selected test samples to limit the formation and propagation of longitudinal cracks in the timber element. For this purpose, punched metal plate connectors were used, fitted at the end of the timber profile.

The analysed joint was loaded by an axial tensile force until complete failure. The force and the joint elongation were recorded continuously during loading.

The overall arrangement of the experiment is presented in Fig. 11.

As has been verified, the measurements yield more favourable values of wood moisture content than calculations. It is therefore likely that the amount of the condensed water could be lower in reality. However, when adding insulation to an existing log wall or designing a sandwiched wall, it is highly necessary to consider well whether the insulation will be fitted to the exterior side, which will impair the external appearance of the building, or the interior side with a greater risk of water vapour condensation inside the structure and the subsequent increase in the wood moisture content above 20 %. Some companies prefer log walls with a thicker layer of wood from the exterior, mainly for aesthetic reasons.

Fig. 12 shows the tested samples (or connection details) after the tests.

Series of tested samples:

- K1: wood moisture 24 %, without strengthening
- K2: wood moisture 32 %, without strengthening
- K3: wood moisture 24 %, strengthening of ends of members using a pair of punched metal plate connectors
- K4: wood moisture 32 %, strengthening of ends of members using a pair of punched metal plate connectors.

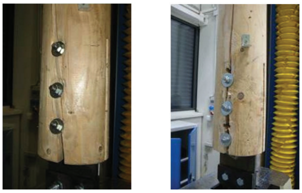

Fig. 12: Failure of tested samples (connections) after loading (on the left with strengthening on the right without strengthening).

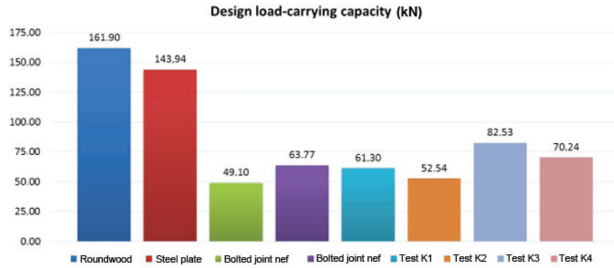

Fig. 13: Connection analysis results – design load-carrying capacities of connections for service class 3 and instantaneous loading (roundwood: Design load-carrying capacity of the basic timber member; steel plate: design load-carrying capacity of the slotted-in steel plate; bolted joint 'nef' design load-carrying capacity of the connection with reduced number of bolts in a row; bolted joint 'n': design load-carrying capacity without reduction of number of bolts; experimental tests K1- K4:load-carrying capacities determined by the loading tests).

Fig. 13 summarizes the results of connection analysis – design load-carrying capacities determined according to EN 1995-1-1 (2006) and EN 1993-1-8 (2006) (Lokaj 2003) and those obtained from the design load-carrying capacity of experimental measurement (test K1, K2, K3, K4).

CONCLUSIONS

The major objective was to design the composition of the envelope of a log building so as to avoid water vapour condensation and consequent moistening of the incorporated timber inside the construction, which can result in the wood degradation and thus depreciate the whole building or reduce its service life. The values of wood moisture content of the particular layers calculated by methods stipulated by ČSN 73 0540-4 (2005) were compared with those actually measured inside the construction using specific options of thermal insulation of the investigated building.

The examination of the proposed options implies that the correct dimensioning has a decisive influence on the service life and functional reliability of timber buildings. The results obtained lead us to a conclusion that additional insulation of log buildings from the internal side is, practically always, risky. In addition, the log wall is exposed to the weather and is not protected from rainwater leaking into the drying checks. On the contrary, it can be unequivocally stated that the proposed insulation of the log building envelope from the external side can guarantee mechanical resistance and stability of the construction, thermal protection of the building and energy savings. Short-term fluctuations in the temperature and humidity of the exterior and the interior have no significant effect on the changes in the wood moisture content, which is affected by longer-term changes in the internal and external environments.

It is obvious from the results that:

- Wood moisture significantly affects the load-carrying capacity of the dowelled connection. If the wood moisture grows from 24 (limit for the service class 3) to 32 %, then the load-carrying capacity is reduced by about 16 %. In all loading tests a higher load-carrying capacity was measures than the design load-carrying capacity according to EN 1995-1-1 (2006), even if the instantaneous loading (k_{mod} = 0.90 service class 3) was considered.

- Member strengthening at the end of the profile has a principal impact on the load carrying capacity of the dowelled connection. If a pair of punched metal plate connectors of nail thickness 1 mm and length of 10 mm are used, the load-carrying capacity is increased by approximately 35 % as compared with the connection without strengthening. The identical load-carrying capacity increase was recorded for the members with wood moisture 24 and 32 %.

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