EFFECT OF COMPRESSIVE LOAD ON SHRINKAGE OF LARCH BLOCKS DURING RADIO-FREQUENCY VACUUM HEATING

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ABSTRACT

This study was carried out to investigate the effect of a compressive load of 0.092 MPa on the shrinkage of the larch blocks with sides of 40 mm each, when subjected to vacuum combined with radio-frequency heating.

The shrinkages in the loading direction were significantly increased; for example, the tangential shrinkages of the blocks loaded compressively on their radial surfaces (loaded-RS), and the radial shrinkages of the blocks loaded compressively on their tangential surfaces (loaded-TS) were approximately one and one-half times as much as those for the load-free blocks.

The shrinkages perpendicular to the loading direction were restrained, for example, the radial shrinkage for the loaded-RS, and the tangential shrinkage for the loaded-TS.

Keywords: Loading direction, tangential shrinkage, radial shrinkage.

INTRODUCTION

The shrinkage of wood during drying is restrained, because wood is subjected to many different kinds of stresses, such as, a surface stress, a differential shrinkage stress, a hygrothermal recovery stress, and the internal stress caused by external loading. A restrained shrinkage or inelastic strain (Ugolev 1992; Wu and Milota 1994) is the sum of an instantaneous, a viscoelastic, a mechano-sorptive, and a free-shrinkage component. Much research on shrinkage behavior in conventional drying has been carried out (Barber 1968; Boyd 1974; Quirk 1984; Pang 2002).

In the case of vacuum drying, few studies on shrinkage behavior have been done. Harris and Taras (1984) reported that the shrinkage of red oak lumber dried in a radio-frequency/vacuum (RF/V) kiln was approximately 30% less than that dried in a conventional kiln. Lee and Hayashi (2000) found that sum of the tangential shrinkage and the radial shrinkage during RF/V drying of Japanese cedar log cross sections was about 40% to 70% less than that based on the ASTM method of shrinkage measurement. Other studies have reported similar results (Taniquchi and Nishio 1991; Liu, et al. 1994). However, no explanation was given for the reduced shrinkage that occurred during RF/V drying. Trebula, et al. (1993) found that vacuum-dried beech had a significantly larger shrinkage along the radial direction than that for conventional kiln-dried beech, while tangential shrinkage showed no significant difference between them. Therefore, it would appear that the shrinkage behavior of wood un-

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der vacuum, combined with RF heating, is not yet fully understood.

Hoffmeyer (1993) reported that the threshold level of stress for forming slip planes (the main cause of mechano-sorptive deformation) was at least 10 MPa corresponding to 10% of the ultimate stress parallel to the grain of *Picea abies*. Wu and Milota (1995) measured the mechano-sorptive deformation that occurred under 0.552 MPa corresponding to 26% ~ 40% of the estimated tangential strength perpendicular to the grain of Douglas-fir. However, there has been no report on the threshold level of stress for mechano-sorptive deformation in RF/V drying. In this experiment, the compressive load for larch was 0.092 MPa, corresponding to 0.17% of the strength parallel to the grain and 1.87% of the strength perpendicular to the grain, which is a fairly low level compared to previous reports in conventional drying. By applying a compressive load of 0.092 MPa perpendicularly to the tangential surface of Korean ash squares, the ratio of tangential shrinkage to radial shrinkage (T/R) was lowered to a value of one due to the tangential shrinking being restrained by mechanical pressure (Lee and Jung 2000). The lowering of the T/R ratio might help to reduce the deformation of lumber and the occurrence of V-shaped cracks in log cross section during RF/V drying; however, more information is required on the shrinkage behavior in the three fiber directions under a compressive load.

This study was carried out to investigate the effect of a low level of compressive load on the shrinkage of the larch blocks with sides of 40 mm each when subjected to vacuum combined with RF heating.

MATERIALS AND PROCEDURES

Preparation of blocks for determining shrinkage

Four green larch logs with a length of 180 cm and an average diameter of 26 cm were obtained from a sawmill. Each log was first live-sawn into several flitches, and then each flitch from the central part of the log was re-

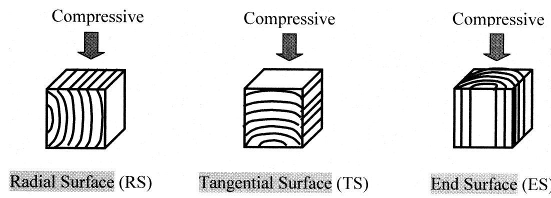

FIG. 1. Three types of compressive loading on the specimens with each side of 40 mm during RF heating in a vacuum chamber.

sawn into two squares, each with a cross section of 45×45 mm, from the outer section of the heartwood to minimize the ring curve effect. The squares were surfaced to a final cross sectional size of 40×40 mm. One of the squares was used for compressive loading and the other for loading-free. Then, an end-matched series of four blocks, each with a length of 40 mm along the grain, was cut from the surfaced square. Four blocks from each end-matched series, respectively, were used for determining shrinkage under compressive loading on the tangential surface (TS), on the radial surface (RS), and on the end surface (ES), and under loading-free condition (Fig. 1). Two reference lines, used for measuring tangential length and radial length, were drawn on the end surface, and a reference line, used for measuring longitudinal length, was drawn on the radial surface of each block. Twenty-four blocks were prepared for each treatment, respectively. The average green moisture content (MC) of the blocks was 43.2%.

Compressive loading and loading-free

For this experiment, the space inside a vacuum chamber was divided into a compressive loading part and a loading-free part (Fig. 2). The blocks stacked in the compressive loading part were compressively loaded by a pressure of 0.091 MPa to 0.093 MPa, corresponding to an ambient vapor pressure of 8 kPa to 10.3 kPa in the vacuum chamber, when a vacuum pump was turned on and off. The pressure, resulting from the difference in absolute pressure between the inside and the outside of the

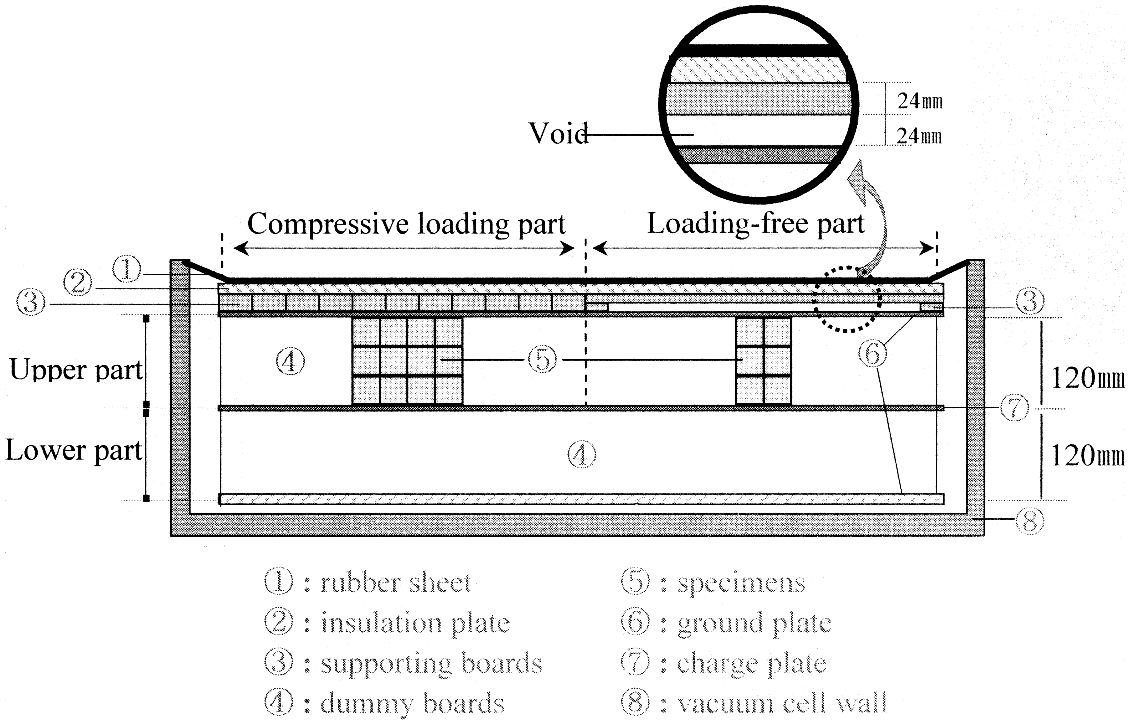

FIG. 2. A compressive loading part and a loading-free part in a vacuum chamber.

vacuum chamber, was applied to an insulation plate located underneath a flexible rubber sheet 3 mm in thickness, covering the vacuum chamber during evaluation, and transmitted to supporting boards, a top grounded plate, and finally to the blocks stacked in the compressive loading part (Fig. 2). The top load resulting from the insulation plate, the supporting boards, and the grounded plate was considered to be negligible. The blocks in the loading-free part were kept free from compressive loading, by the presence of a void of 24 mm in height between the insulation plate and the top grounded plate, even when a vacuum pump was operating (Fig. 2).

Stacking of blocks

The blocks to be used for the loaded-TS, RS, and ES were solid-stacked in three layers between an electric charge plate and the top ground plate in the compressive loading part, and the blocks to be used for loading-free were also solid-stacked in the loading-free part (Fig. 2). In order to be uniformly loaded during compression, the blocks to be used for the loaded-TS, RS, and ES were alternately stacked in each rank, each file, and each layer to ensure that the total amount of the shrinkage of each column would be nearly identical, in spite of differences in the amount of shrinkage of each block in each column (Fig. 3). The board with the temperature sensor was positioned in the lower part. The remainder of the space in the upper part and all of the lower part was filled with the dummy boards.

RF heating

The inside dimensions of the chamber containing the RF heater were 102 cm in width, 274 cm in length, and 40 cm in height. The blocks were heated in 10-min cycles, by a 7-kW RF generator at a fixed frequency of about 13 MHz, with the generator being turned on for 8 min and then off for 2 min. The center

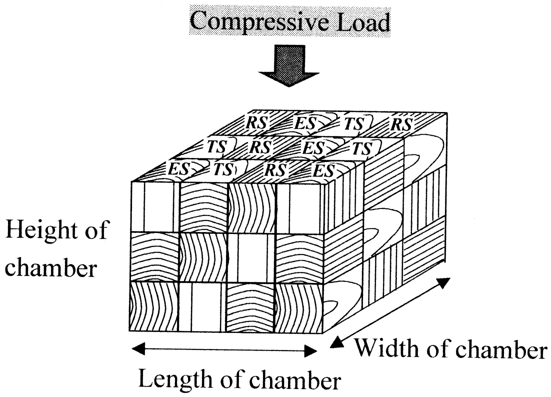

FIG. 3. Stacking of the specimens for determining shrinkages in the compressive loading part of a vacuum chamber.

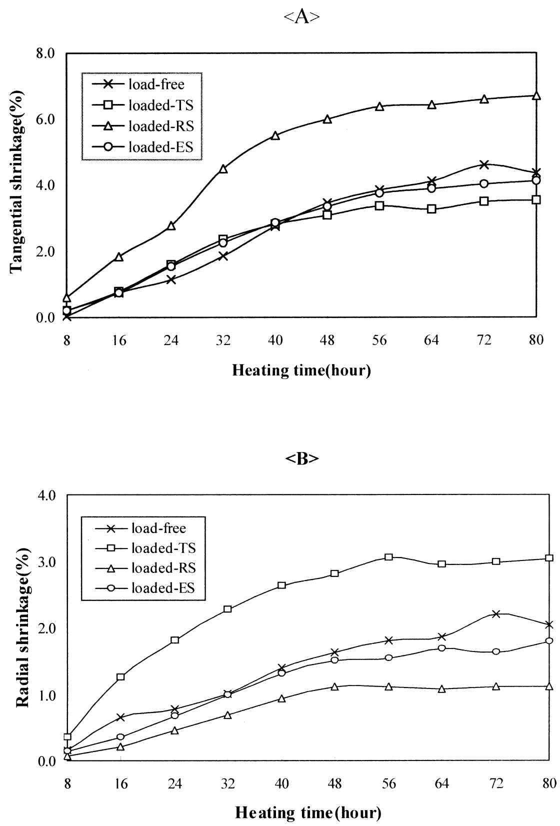

FIG. 4. Tangential shrinkage ⟨A⟩ and radial shrinkage ⟨B⟩ for the load-free, the loaded-TS, the loaded-RS, and the loaded-ES during RF heating in a vacuum chamber.

electrode plate connected to the RF generator was positive, while the top and bottom plates grounded to the chamber itself were negative. The heating temperature of the wood was set at 47°C throughout the heating period, and was automatically monitored and controlled by a teflon-sheathed platinum sensor inserted into a board.

Determining shrinkage of blocks

The green lengths of the reference lines for the three fiber directions were measured by a digital vernier caliper with an accuracy of 0.01 mm. All blocks were removed from the chamber, and then their lengths and weights were measured every 8 h until the end of the 80-h heating period. The heating time excluded the dead time required for measuring. Finally, all the blocks were oven-dried in an air-circulating oven, and weighed, and the MCs of the blocks during heating were calculated. The shrinkages from the green state to any MC during heating and to 11% were analyzed.

RESULTS AND DISCUSSIONS

Linear shrinkage along the transverse direction

The tangential and radial shrinkages as a function of heating time are shown in Fig. 4 ⟨A⟩ and ⟨B⟩, respectively. Over the entire heating time, the tangential shrinkage for the loaded-RS and the radial shrinkage for the loaded-TS were approximately one and one-half times as much as those for the load-free blocks. This indicates that the shrinkages in the loading direction are significantly increased, which might be due mainly to mechano-sorptive deformation (Wu and Milota 1995), resulting from the combinations of the compressive load and the change in the moisture content. The greatly enhanced shrinkage occurring at such a low level of load might be explained by the fact that there are weaker hydrogen bonds among the molecules in the blocks in a vacuum chamber than in an atmospheric oven; thus the hydrogen bonds can be easily affected by such a low level of load (Skaar 1972; Hoff-

TABLE 1. *Shrinkage of larch under RF/V heating from the green state to 11% MC.*

Shrinkage	Load-free	Compressively loaded: Tangential surface	Radial surface	End surface
Tangential (%)	4.37	3.54	6.70	4.13
Radial (%)	2.03	3.02	1.11	1.78
Longitudinal (%)	0.02	−0.03	0.01	0.33
T/R	2.15	1.17	6.03	2.32
T+R	6.40	6.56	7.81	5.91
T−R	2.33	0.52	5.59	2.35
ASE[a]				
Tangential (%)	—	19.0	−53.3	5.5
Radial (%)	—	−48.8	45.3	12.3
Longitudinal (%)	—	250.0	50.0	−1550.0

Note: The ASE meant antishrink efficiency, and was determined by the following equation:

$$\mathrm{ASE} = \frac{S_n - S_p}{S_n} \times 100\ (\%)$$

S_n: shrinkage from the green state to 11% MC for the load-free.
S_p: shrinkage from the green state to 11% MC for the compressive-load.

meyer and Davidson 1989; Hoffmeyer 1993; Wu and Milota 1995).

However, the radial shrinkage for the loaded-RS was 0.1% less during the initial stage and 0.92% less during the end stage of RF heating than that for the load-free blocks; and the tangential shrinkage for the loaded-TS was slightly less than that for the load-free blocks. This indicates that the shrinkages perpendicular to the loading direction are restrained.

The antishrink efficiencies (ASE) from the green state to 11% MC were 45.3% in the radial direction for the loaded-RS and 19% in the tangential direction for the loaded-TS (Table 1). This can be explained by means of the earlywood-latewood interaction theory (Pentoney 1953). The radial shrinking for the loaded-RS is restrained more than the tangential shrinking for the loaded-TS, because the radial shrinkage is a summation of the weighted contributions of the earlywood and latewood parts of the annual increment, and the radial shrinkage includes that of the low-shrinking earlywood component.

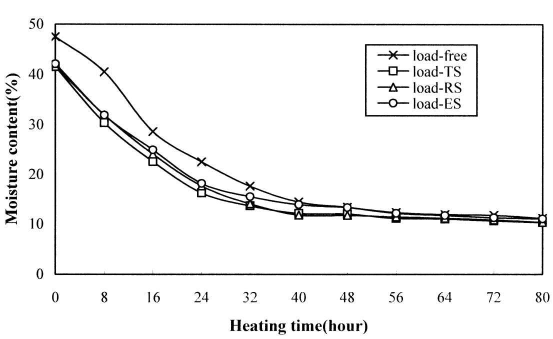

FIG. 5. Drying curve of RF vacuum drying of 40×40×40 mm larch cube.

The tangential shrinkage for the loaded-TS was slightly greater than that for the load-free blocks during the early stage of RF heating (Fig. 4 ⟨A⟩); however, after the first 40 h of heating, this situation reversed itself, although there was little difference in the average MC of the specimens (Fig. 5). It should be noted that even though a compressive load of 0.092 MPa is not enough to restrain the dimensional change perpendicular to the loading direction, resulting from moisture loss during the early stage of RF heating, it contributes to reducing shrinkage within the low moisture region owing to the set built up during high moisture.

From the green state to 11% MC, the shrinkages of 4.39% in the tangential direction and 2.03% in the radial direction for the load-free blocks (Table 1) were lower than those observed under conventional drying conditions (Shin 2001). This might be due to the fact that the free shrinkage of wood under vac-

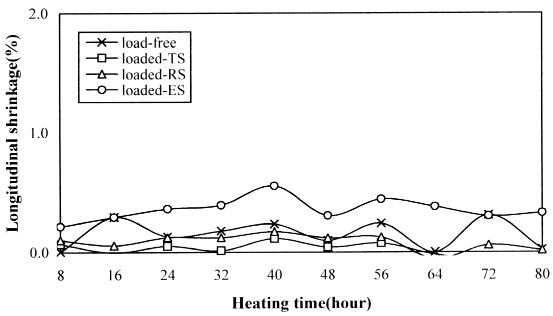

FIG. 6. Longitudinal shrinkage for the load-free, the loaded-TS, the loaded-RS, and the loaded-ES during RF heating in a vacuum chamber.

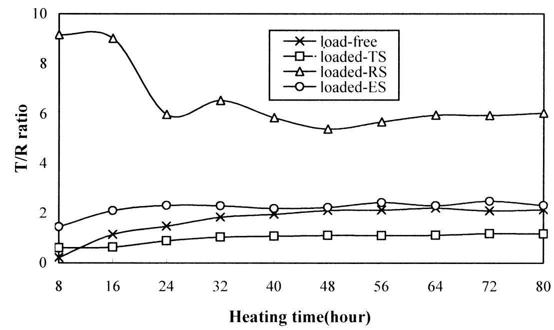

FIG. 7. Ratio of tangential shrinkage to radial shrinkage (T/R) during RF heating in a vacuum chamber.

uum is restricted by the difference in absolute vapor pressure between the inside and the outside of wood. However, additional experiments need to be carried out in order to clarify the shrinking behavior of wood when the pressure is below ambient vapor pressure.

Linear shrinkage along the longitudinal direction

The longitudinal shrinkages as a function of heating time are described in Fig. 6. The longitudinal shrinkage for the loaded-ES was dramatically 14.4 times as much as that for the load-free blocks during the entire heating time. This supports the hypothesis that shrinking along the longitudinal direction is affected more by deformation due to compressive load than by free shrinkage due to moisture loss. Nevertheless, the longitudinal shrinkages for the loaded-TS and the loaded-RS represented lower values than that for the load-free blocks. This is a typical rheological behavior. Under the combined conditions of compressive loading and changing moisture content in a vacuum chamber, there is much more longitudinal shrinkage along the loading direction due to slip-plane formation (Armstrong 1972; Hoffmeyer and Davidson 1989), than that for the case of load-free blocks.

Dimensional changes of end surface

Ratio of tangential shrinkage to radial shrinkage.—The curves corresponding to the ratio of tangential shrinkage to radial shrinkage (T/R) during RF heating are given in Fig. 7.

The T/R ratio for the loaded-RS was even higher than the ratios for the others during the entire heating period. The reason for this is that the tangential shrinkage is largely increased by the compressive load on the radial surface, whereas in contrast, the radial shrinkage is effectively restrained by it. After the first 16 h of heating, corresponding to about 24% MC, the T/R ratio for the loaded-RS represented an approximate value of nine, and then became stable with a value of about six. The tangential shrinkage observed in Fig. 4 ⟨A⟩ is caused mainly by the instantaneous and creep deformations (Wu and Milota 1994), although the MC of the specimen is above the hygroscopic range.

The T/R ratio for the loaded-TS was less than that for the load-free blocks during the entire heating period, having a value of 0.61 to 1.18. This means that a compressive load on the tangential surface during RF/V heating is advantageous in preventing the formation of warping.

The T/R ratio for the loaded-ES maintained an almost constant value of 2.0. The T/R ratio for the load-free blocks, however, was below 1.0 during the initial stage of heating, and then gradually rose after the first 48 heating hours, and then followed the same curve as the loaded-ES.

Summation of transverse shrinkages.—Fig-

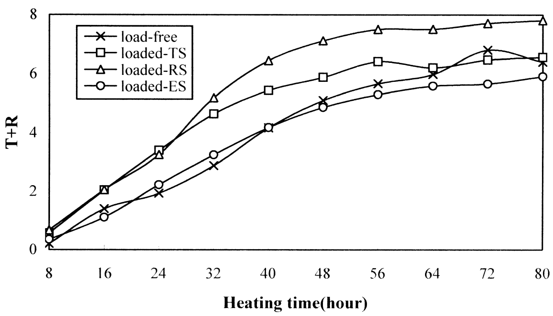

FIG. 8. Sum of tangential shrinkage to radial shrinkage (T+R) during RF heating in a vacuum chamber.

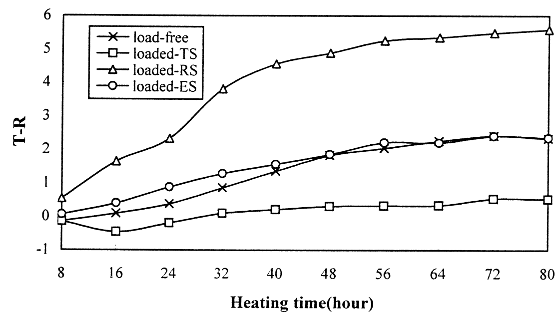

FIG. 9. Difference of tangential shrinkage to radial shrinkage (T−R) during RF heating in a vacuum chamber.

ure 8 shows the curves corresponding to the summation of tangential shrinkage and radial shrinkage, (T+R), during RF heating in a vacuum chamber.

The dimensional change on the end surface for the loaded-RS followed the same curve as that for the loaded-TS until almost 24 heating hours, with approximately 16% to 17% MC, and became greater than that for the loaded-TS thereafter. This means that the contribution of the compressive load to tangential shrinking, in the case of the loaded-RS, is greater than the restraint of tangential shrinking for the loaded-TS. It was observed that the mechano-sorptive effect increased with decreasing moisture content of the specimen (Hoffmeyer and Davidson 1989).

The value of (T+R) from the green state to 11% MC was 6.56% for the loaded-TS and 6.40% for the load-free blocks (Table 1). This means that for the loaded-TS, the contribution of the compressive load to radial shrinking is offset by the restraint of tangential shrinking due to the load.

Differences between transverse shrinkages.—The differences between the two transverse shrinkages (T-R) as a function of heating time are described in Fig. 9.

The curves of (T-R) had a similar tendency to those of the T/R ratio. The (T-R) for the loaded-TS had the lowest value, being almost zero or negative, which would lead to reduction in the loss of volume during the machining process of squares dried with proper compressive load on their tangential surfaces.

A compressive load of 0.092 MPa applied on the end surface of the block may be insufficient to reduce the value of (T-R), and it might not be effective in preventing the formation of V-shaped cracks during the drying of a log cross section. However, the effect of compressive load on the shrinkage behavior of a log cross section with pith is worthy of further detailed study.

CONCLUSIONS

This study was carried out to investigate the effect of a compressive load of 0.092 MPa on the shrinkage of the larch blocks with sides of 40 mm each, when subjected to vacuum combined with radio-frequency heating.

The shrinkages in the loading direction were significantly increased; for example, the tangential shrinkage for the loaded-RS and the radial shrinkage for the loaded-TS, which were approximately one and one-half times as much as those for the load-free blocks, because a large amount of rheological or inelastic deformation was formed, as a result of the compressive load and the change in moisture content.

The shrinkages perpendicular to the loading direction were decreased—for example, the radial shrinkage for the loaded-RS and the tangential shrinkage for the loaded-TS, because of Poisson's ratio.

The contribution of the compressive load to tangential shrinking for the loaded-RS was larger than the restraint of tangential shrinking for the loaded-TS.

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