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Influence of the coefficient of thermal expansion on the stress distribution in ceramic veneers after thermal simulation

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Abstract— *The aim of the study was to evaluate the stress distribution in the ceramic veneers in a full prosthetic crown with different framework after the sintering and cooling cycle through the thermal analysis by three-dimensional finite element analysis. Using images from a computerized microtomography of a central incisor, an anterior crown was constructed. The models were composed of 2mm thickness ceramics (feldspathic ceramics) and 0.4mm thickness frameworks(zirconia, alumina, lithium-disilicate, or metal). Ansys Workbench finite element software was used for analysis and mesh generation through a 5% convergence. The thermal loading was performed in 2 stages simulating the heating and cooling of the ceramic veneer sintering cycle: stage 1 - 403 to 750 degrees C; stage 2 - from 750 to 25 degrees C. The von Mises equivalent strain(σvM) was used for the quantitative and qualitative evaluation of the framework. The maximum (σmax) and minimum (σmin) stresses were used to evaluate the ceramic veneer and zirconia, alumina, and lithium-disilicate frameworks. The highest values of compressive stress (294,58 MPa) were found in the ceramic veneer in the models with alumina framework, followed by models with zirconia (253,65 MPa), palladium silver (239,74 MPa), and lithium disilicate (205,43MPa). The tensile stresses followed the same behavior presenting the highest values in the alumina prostheses (Al: 93,977 MPa, Zr: 76,358 MPa, Ps:68,193 MPa and Ld: 56,573 MPa). The ceramic framework alumina and zirconia cause a higher stress concentration in the ceramic veneers. The stress concentration in the ceramic veneers was affected not only by the coefficient of thermal expansion but also for the mechanical properties of the framework materials.*

Keywords— ***ceramic crown, finite element analysis, thermal analysis.***

I. INTRODUCTION

Metal-free prosthetic crowns have been highly appreciated in the dentistry, mainly in the anterior region, due to its ideal aesthetic characteristics, translucency close to the dental structure, and absence of the metal collar in the cervical region[1].

Besides these characteristics, the high resistance of the ceramic framework (lithium disilicate, alumina, and zirconia) associated with the feldspathic ceramic has become a relevant alternative for thin kind of restoration[2,3]. The zirconia, widely used as a framework material due to the high biocompatibility[4]and excellent mechanical properties, has an excellent tensile (1200 MPa) and compressive strength (2000 MPa)[5]. However, the zirconia frameworks present a high prevalence of ceramic veneer chippings[5–8].In this way, this failure is statistically higher when compared to the metal-ceramic crowns[9,10].

The incompatibility of the properties related to the thermal expansion between the framework and the ceramic veneer can induce the formation of residual stresses in these materials[11]. These residual stresses influence the fracture resistance of the ceramics used as aesthetic cover material[12]. Therefore, understand the possible contribution of the Coefficient of Thermal Expansion (CTE) in the development of the residual stresses in the ceramic veneer is crucial to avoid fractures and chipping after the heating and cooling cycles[13].

It is believed that the predisposition to long-term failures is related to thermal mismatch between zirconia and ceramic veneer, and not to the intrinsic characteristics, that are inherent to each material[14,15].Another point to take into account is the fracture propagation, which begins and expands in ceramics veneer and not in the framework[16].

During the preparation of prosthetic crowns, they are submitted to heating, firing, and cooling process. The concept of veneer ceramic application advocates that this has a CTE slightly lower (10% or less) then the CTE of the framework used to the metal-ceramic restorations and for all the ceramic materials, promoting a positive thermal mismatch, thus leading to compressive stresses between the two materials, avoiding in this way the ceramic veneer fracture during the cooling process[17–20].If the CTE of the ceramic veneer is significantly higher than that of the framework, tensile stresses are generated and the chipping of the ceramic veneer may occur[21]. Thereby, due to the differences in thermal behavior between the framework and ceramic veneer materials, its physical-chemical properties are adapted to expand and contract proportionately[22].

So then, it is important to emphasize that the literature is scarce about studies that quantify the stresses generated in the ceramic veneer after de complete sintering cycles of the materials addressed in this research. The finite element analysis can help the evaluation of the site where the stresses begin, thus allowing the comprehension of the CTE effects on the generated stresses in the ceramic veneer when using different materials as a framework. Therefore, this study aimed to evaluate the effect of the differences between the coefficients of thermal expansion of some materials used as a framework (alumina, zirconia, metal, and lithium disilicate) in the stress distribution of the ceramic veneers using the thermal simulation in a three-dimensional finite element analysis.

II. MATERIAL AND METHODS

Experimental Design

Three 3D models of an incisive single crown were virtually constructed. For these models, the crowns were divided into a framework and ceramic veneer. The framework materials were varied between Zirconia - Zr, Palladium-silver – Ps, Lithium-disilicate – Ld, and Alumina - Al. The models were thermally loaded assuming two conditions: a) firing rate: raging from 403°C to 750°C and b) cooling rate: raging from 750°C to 25°C. The finite element software was used to determine the tensile and compressive stress areas for the framework and ceramic veneer.

3D Models Construction

A 3D model of a maxillary central incisor was used for constructed a single crown using the SolidWorks 2013 software (Dassault Systèmes SolidWorks Corp, Waltham, Massachusetts, USA). The maxillary central incisor was prepared to receive a full prosthetic crown with 2mm of thickness, following the natural anatomy of the dental surfaces. The incisal edge was reduced 2.5mm and the margin designed was defined as a chamfer. After that, the prosthetic crown was obtained using boolean operations. The boolean subtraction operation was performed for the framework and ceramic veneer construction, which was defined with 0.4- and 1.6-mm thickness, respectively[23] (Figure 1).

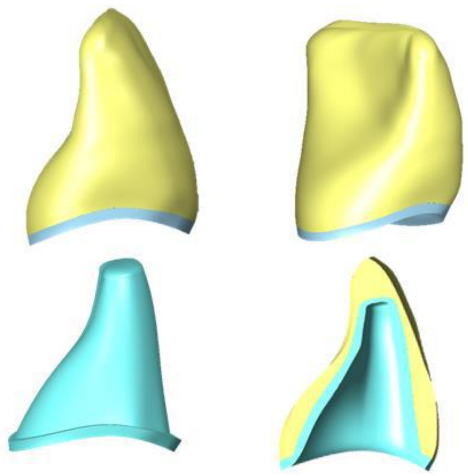

Fig.1: The 3D solid model of an incisor crown with a framework and ceramic veneer.

Numerical Analysis

The models were exported to Ansys Workbench 14.0 FEA software (Swanson Analysis Inc, Canonsburg, Pennsylvania, USA) for the finite element analysis. All structures were considered linear, isotropic, and homogeneous and its properties.

A convergence of analysis (5%) in all models was achieved using a tetrahedral mesh containing 0.5 mm elements and the final mesh for the models resulted in approximately 5300 elements and 10300 nodes for both solids (Figure 2).

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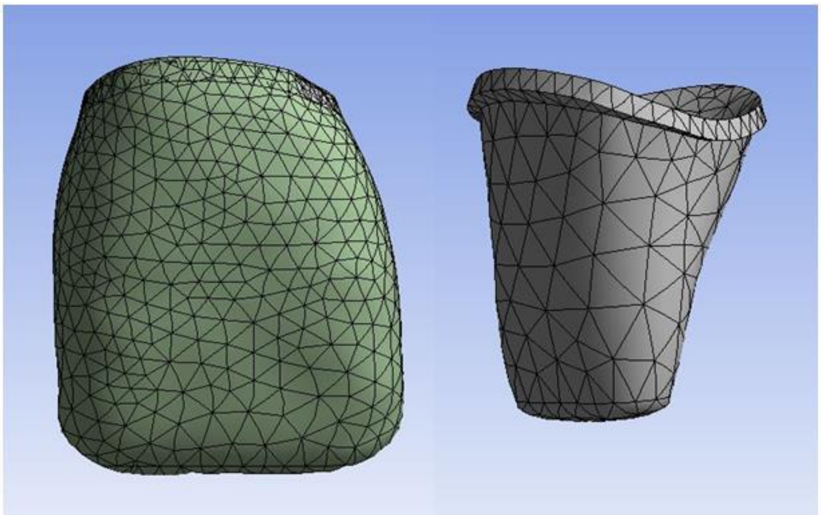

Fig.2: Tetrahedral 0,5mm elements mesh.

The models were thermally loaded in 2 steps simulating the firing and cooling process. The firing temperature was varied from 403° to 750°C and the cooling temperature was varied from 750° to 25°C. The CTE of each material was obtained from the manufacturer and is also demonstrated in Table 1.

Table 1: Mechanical properties of materials used.

MATERIAL	Young's Modulus (Gpa)	Poisson's ratio	Coefficient of thermal expansion (10-6/K)
Ceramic veneer	70	0.24	9,5
Zirconia	205	0.22	11
Palladium-silver	150	0.33	13,5
Alumina	370	0.22	8
Litium-dissilicate	95	0,30	10,2

The results were evaluated using maximum and minimum principal stress for the ceramic veneer.

III. RESULTS

The results were obtained using the maximum (tension) and minimum principal stress criteria for ceramic veneers, the quantitative analysis of which is shown in Figure 3. The highest values of compressive stress (294,58 MPa) were found in the ceramic veneer in the models with alumina framework, followed by models with zirconia (253,65 MPa), palladium-silver (239,74 MPa), and lithium-disilicate (205,43MPa). The tensile stresses followed the same behavior presenting the highest values in the alumina prostheses (Al: 93,977 MPa, Zr: 76,358 MPa, Ps:68,193 MPa and Ld: 56,573 MPa).

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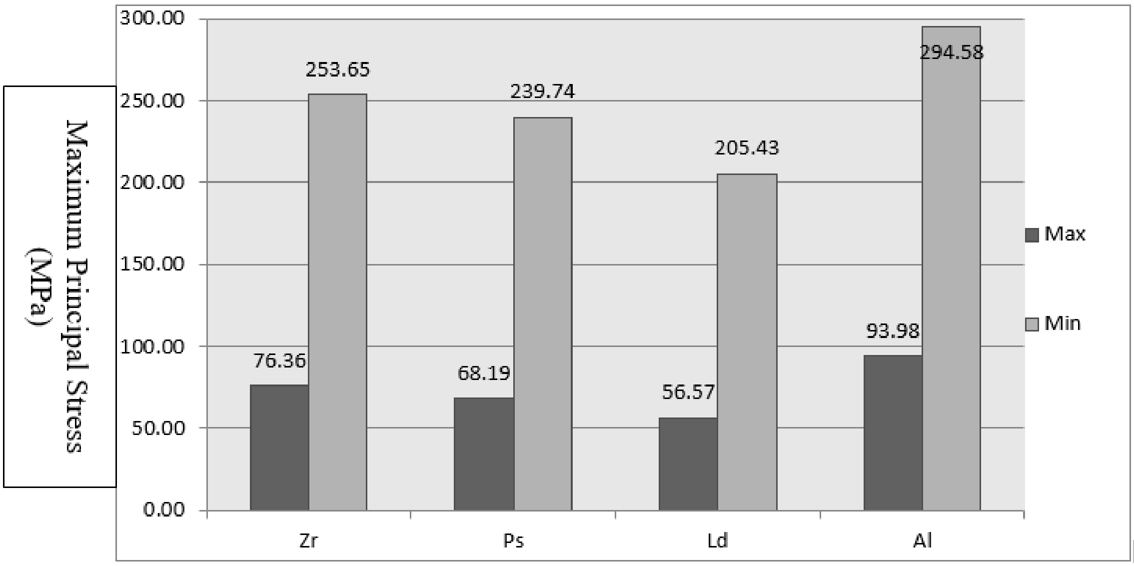

Fig.3: Maximum and Minimum Principal Stress in the ceramic veneer for the different core materials.

The maximum tension and compression were located on the external lingual face of the ceramic veneers in all models. The pattern of stress distribution did not change with the use of different materials (Figure 4,5 and 6). It was observed that the peak stress was located in the area of the lowest volume of the ceramic veneer, indicating that the thickness of the restorative material may influence the stress distribution.

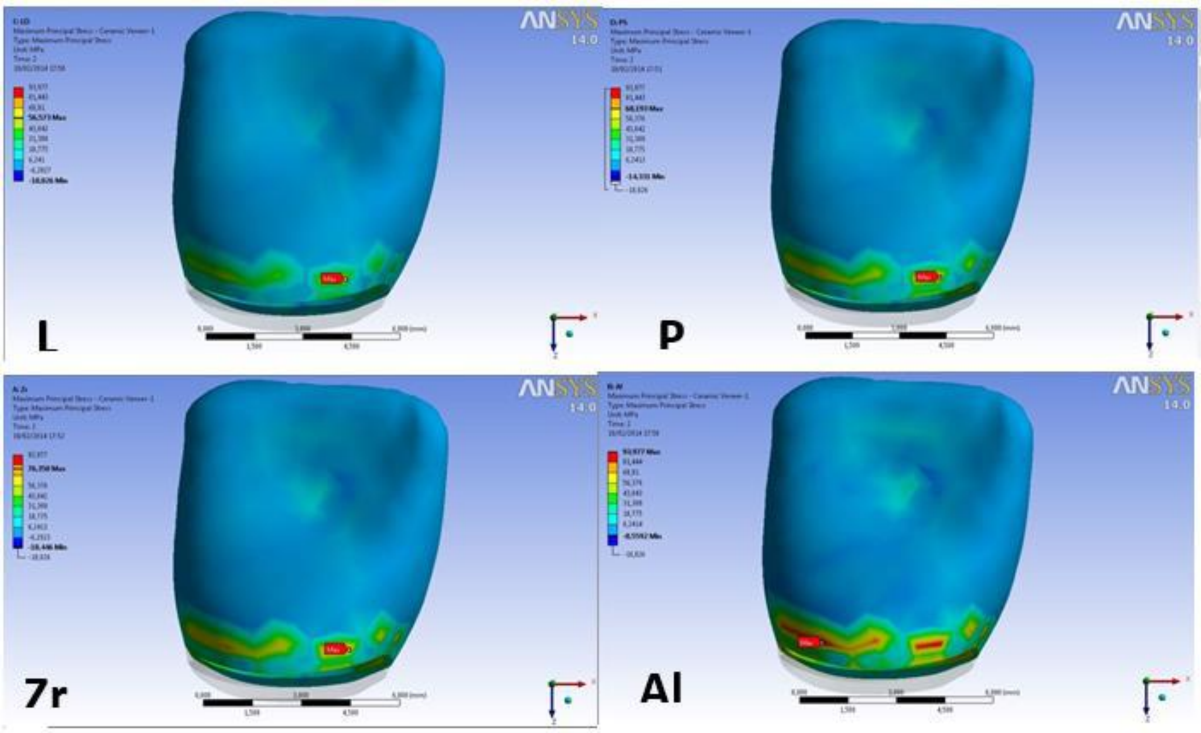

Fig.4: Maximum Principal Stress for the ceramic veneer in the lingual view.

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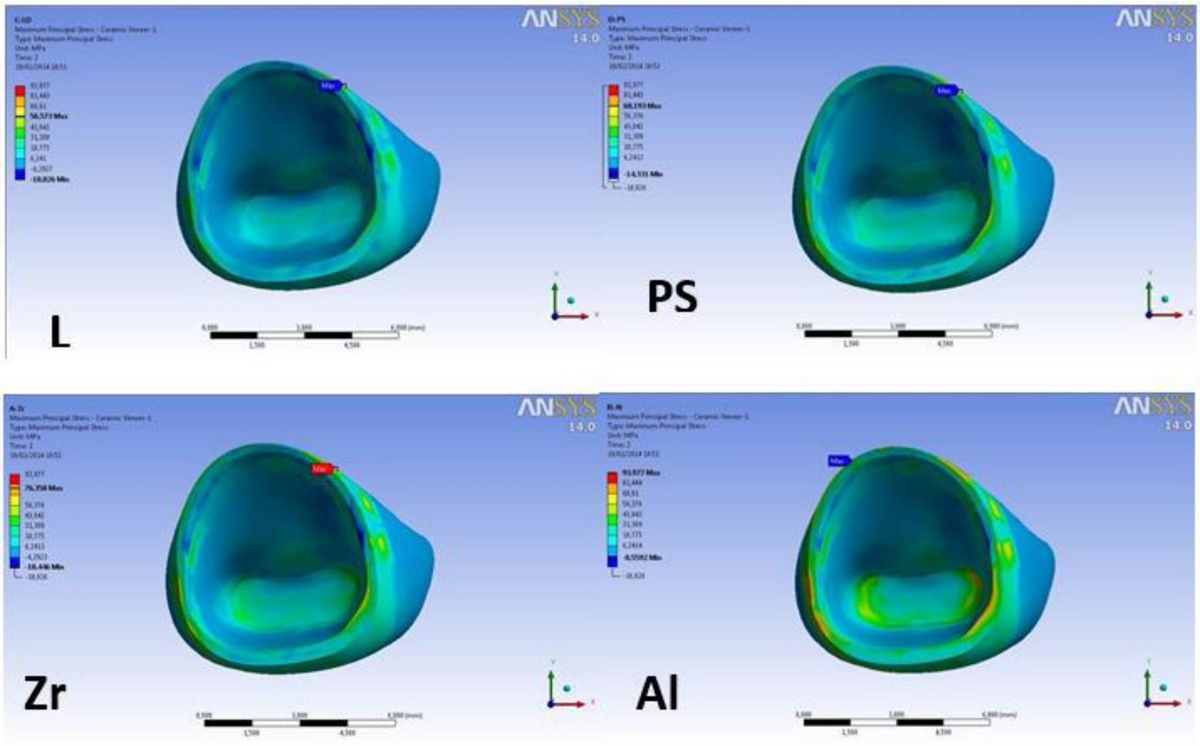

Fig.5: Maximum Principal Stress for the ceramic veneer in the intaglio surface.

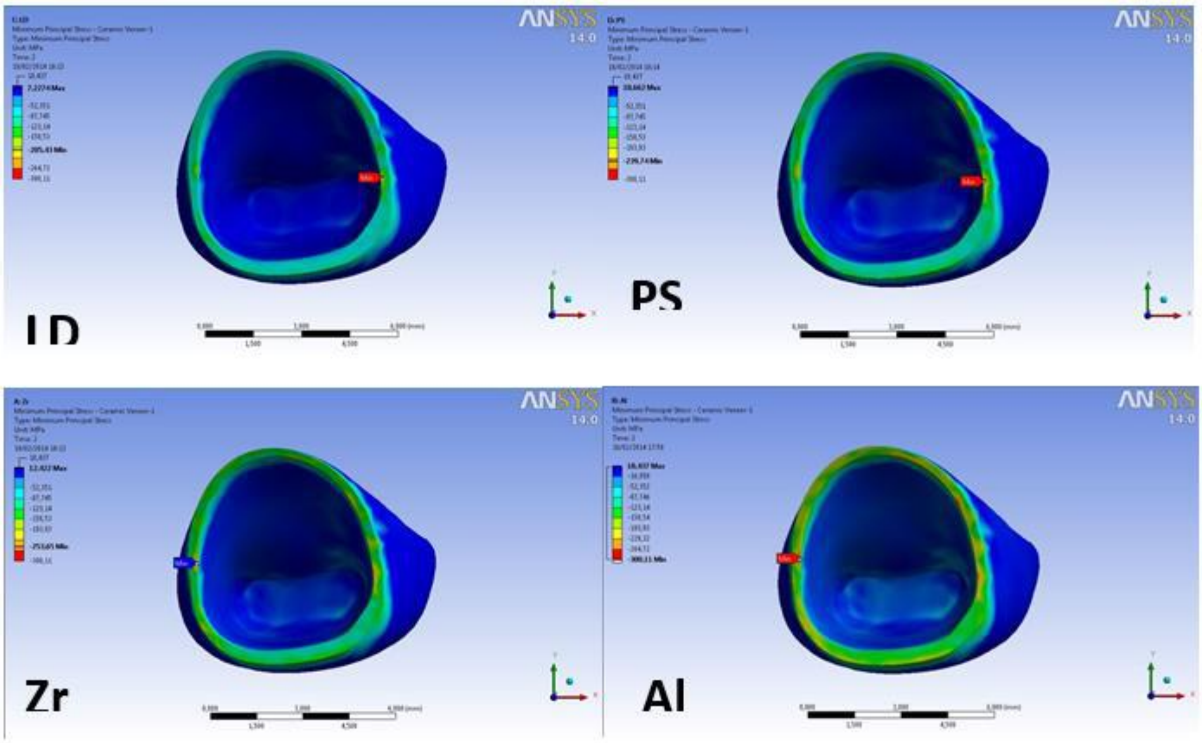

Fig.6: Minimum Principal Stress for the ceramic veneer in the intaglio surface.

IV. DISCUSSION

The contribution of the cooling rate, differences in CTE between the core and veneer material, and a complex tooth geometry need to be considered as potential sources of residual stresses causing the fracture of ceramic veneers. The present study evaluated the stress generated in the ceramic veneer of the full crown using four different core materials. The results indicate that core material with

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a high difference with ceramic veneer material can induce stress in the cervical area of the ceramic veneers. The greater the incompatibility of the CTE, the greater was the tensile and compression stress observed in the ceramic veneer.

All-ceramic systems are widely used to achieve excellent esthetic restorations. Especially for zirconia and alumina restorations, they need to be covered by feldspathic ceramic to decrease the opacity of the framework[24].If the core/ceramic veneer interface exhibits an incomplete bond, chipping or fracture is expected to initiate in the veneer margins[25]. The literature reports that the interface between the ceramic veneer and the framework affects the mechanical performance of the ceramic veneer [24], showing the importance of this interface in the integrity of the restorations.

The framework/veneer interface may suffer from many variables that can affect the bond strength, such as the surface of the core. The surface can affect the mechanical retention and residual stresses generated by the mismatch of the CTE between the ceramic and framework structures[25].

The CTE mismatch variation and the cooling rate had a greater impact on the failure of the ceramic veneer [16]. Sebastiani in 2015 observed that the cooling rate and the thickness of the ceramic veneer influence the thermal gradient during the cooling process and residual stress, however, the study did not use crowns, due to this fact, the anatomical conformation it was suggested as a reason for the change in the distribution of residual stress[26]. This study presents a three-dimensional model simulating a crown in its anatomical aspects and the distribution of residual stress was better elucidated. The hypothesis that the thickness of the ceramic veneer influences the thermal gradient during the cooling was confirmed since the higher stress was observed in the cervical area of the crown, where the ceramic had lower thickness.

The residual stress generated can be modulated by the slow cooling protocol [8,27,28] but this factor has been controversial in the related literature. Some studies show less resistance to fracture when the ceramic was cooled quickly, suggesting that tensile stress is generated as a consequence of a high-temperature gradient during solidification and that residual stress develops on the surface of the quickly cooled ceramic[12]. Another study found no significant differences between fast and slow cooling protocols[9,19,29]. In this study, the cooling process was simulated as a fast cooling process, since this process appears to be the most challenging to the ceramic veneer. The results prove that the fast cooling process produces high stress in the ceramic veneer and can be harmful to the success of the restoration, especially on crowns with alumina or zirconia frameworks. Bonfante et al. evaluated the cooling process using finite element analysis and found that the all-porcelain system presented high-stress concentration compared with metal ones. However, in the study, the authors did not compare the residual stress generated between the firing and cooling process [21].

When evaluating the results of this present study with the CTE of the materials, the alumina crown showed a negative mismatch between the veneer and framework material and present high stress in the ceramic veneer. The palladium-silver material a greater mismatch and presents lower stress that zirconia material. This can be explained that not only the CTE but also elastic modulus and Poisson's ratio of the material can influence the stress distribution.

Fatigue, different framework designs, and different veneer layer thicknesses were not considered in the present study. These factors should be evaluated in future investigations. Therefore, although further virtual simulations are required to gain a better understanding of the mechanical behavior of the zirconia core/ceramic veneer interface, the results of the present study add useful data to previous in vitro findings.

V. CONCLUSION

The differences between the CTEs influence the mechanical behavior of the ceramic veneers. The differences between the systems indicate that the compatibility between the CTEs is fundamental, but also the mechanical properties (elastic modulus) to maintain a mechanical performance of the veneering ceramics. The lithium disilicate frameworks cause lower stress in the ceramic veneers, while the alumina the higher stress.

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