ZIRCONIA

Material Properties and Surgical Principles for Dental Implants and Restorations

Corrado Piconi | Mutlu Özcan, DDS, DMD, PhD

QUINTESSENCE PUBLISHING

Zirconia: Material Properties and Surgical Principles for Dental Implants and Restorations

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FOREWORD

In recent years, dentistry has increasingly moved toward metal-free solutions, and ceramic implants have already established themselves as promising alternatives and supplements to titanium implants. The market for ceramic implants is also undergoing a dynamic change. Although titanium implants still hold the largest market share for dental implants, the demand for metal-free solutions is continuously increasing. Patients are not the only ones who appreciate the excellent biocompatibility and esthetic advantages of ceramic implants. An increasing number of dentists also recognize their potential as a long-term treatment option.

Despite growing scientific evidence to support ceramic implants and the expanding clinical experience with them, numerous questions remain regarding the material properties of ceramics, surgical protocols, standardized treatment concepts, and long-term success rates. This book is intended to help clinicians reach a new level of knowledge about ceramic implantology and to provide them with a sound understanding of this still quite new field. It makes a decisive contribution to the further establishment of ceramic implantology and offers valuable orientation for researchers and practitioners alike.

This work comprises 13 chapters that provide a comprehensive view of ceramic implantology. Starting with materials science, a detailed description of the biomechanical properties of ceramic implants is provided. Subsequently, modern implant designs, surface modifications, and current clinical studies are presented. The extensive clinical section, which describes surgical techniques, prosthetic treatment options, and proven treatment concepts, is particularly valuable. In addition, the book contains case reports that illustrate the application of various ceramic implant systems in practice. It is a reliable reference work to help clinicians integrate ceramic implants safely and successfully into daily practice.

This project was conceived by the members of the Scientific Advisory Board of the European Society for Ceramic Implantology (ESCI) to contribute to the society's goal to disseminate knowledge about ceramic implantology. Nearly all of the authors and contributors are members of the ESCI's scientific advisory board or board of directors, ensuring that the content is at the cutting edge of research and clinical practice. The case studies found in the final chapter were also contributed by ESCI company partners to provide a practical and cross-industry perspective. We would like to thank the authors, contributors, and everyone who has contributed to the creation of this work with their expertise and commitment.

Ceramic implantology has the potential to shape the future of dentistry—and this book is a guide for that exciting journey.

—Dr Jens Tartsch, ESCI President

FOREWORD

As a clinician-scientist, I am honored to be invited by the authors to write a foreword to their new textbook on zirconia. Certainly the current generation of clinician-scientists have been challenged by the rapid changes in dental therapeutics with the digital age. Technologies that existed in dreams have quickly become reality. The printing and milling of materials for the fabrication of complex advanced dental prostheses has become almost routine. Of course there have been bumps in the road with the introduction of new materials and technologies, and the task of Prof Corrado Piconi and Prof Mutlu Özcan and their research colleagues has been to correct and remediate these discovered flaws.

This textbook reviews the factors that make zirconia a reliable dental biomaterial in its first three chapters. It goes on to detail the biologic and biomechanical aspects of zirconia dental implants in chapters 3 to 6. The following three chapters elucidate the hard and soft tissue responses for one- and two-piece zirconia dental implants as well as provide the rationale for using zirconia dental implants. The final three chapters conclude with guided surgical techniques and the ceramic restorative options for zirconia dental implants, with the last chapter detailing case reports from members of the European Society for Ceramic Implantology.

This textbook is a wonderful source of current information regarding zirconia as a restorative and dental implant material, and the dental profession owes a debt of gratitude to the authors for curating the information in an informative and detailed manner.

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Professor Sami Sandhaus
1927–2019

This book is dedicated to the memory of Professor Sami Sandhaus, who created ceramic implantology.

01 CERAMICS AS DENTAL BIOMATERIALS

Corrado Piconi

This chapter reviews the behavior of the many ceramics used in dentistry. The general behaviors of ceramics are outlined and compared to those of metals. The materials used today in clinical settings are described from a historical perspective, with summaries of their main characteristics and some information on their development.

Introduction to Ceramics

Ceramics are "solid articles which have as their essential component, and are composed in large part of, inorganic nonmetallic materials."[1] In comparison with metals, ceramics exhibit low thermal and electrical conductivity, higher melting temperatures, and no plastic deformation before rupture (Box 1-1). They have been used for centuries to produce bricks and tableware. Only in the last century, however, has their use been extended to other applications. One of the main advances in ceramic technology that made this change possible was the switch from using natural materials to using synthetic raw materials. This expanded the applications of ceramics in many aspects of modern life, ranging from electronics to medicine.

The properties of ceramic oxides are derived from the oxygen atoms present in their molecules. These oxides include magnesia (MgO), titania (TiO_2), zirconia (ZrO_2), and alumina (Al_2O_3), among others. In metals, atoms are bonded together in a cloud of free electrons within the space of the crystal lattice. Ceramic molecules, on the other hand, are directly linked with directional ionic or covalent chemical bonds.

Ceramics can be crystalline solids or amorphous solids. Crystalline solids are characterized by a long-range ordered microstructure formed by atoms arranged in a regular 3D lattice, with the angles and distances between atoms varying according to the specific material. This long-range order is absent in the microstructure of amorphous solids, which exhibit only short-range order. The amorphous microstructure is sometimes termed *glassy microstructure* because it is characteristic of glasses. Crystalline structures are more compact than amorphous ones, and crystalline solids are usually stronger than glassy ones because it is more difficult to break the ordered network of atomic bonds. Figure 1-1 shows the typical microstructure of various ceramic materials.

BOX 1-1 › General behaviors of metals and ceramics

Metals	Ceramics
• High number of free electrons	• Absence of free electrons
• Metallic chemical bonds	• Ionic/covalent chemical bonds
• Good electrical conductivity	• Electrical insulators
• Good thermal conductivity	• Thermal insulators
• Opaque to visible light	• Can be transparent or translucent
• Plastic strain before fracture	• No plastic strain before fracture

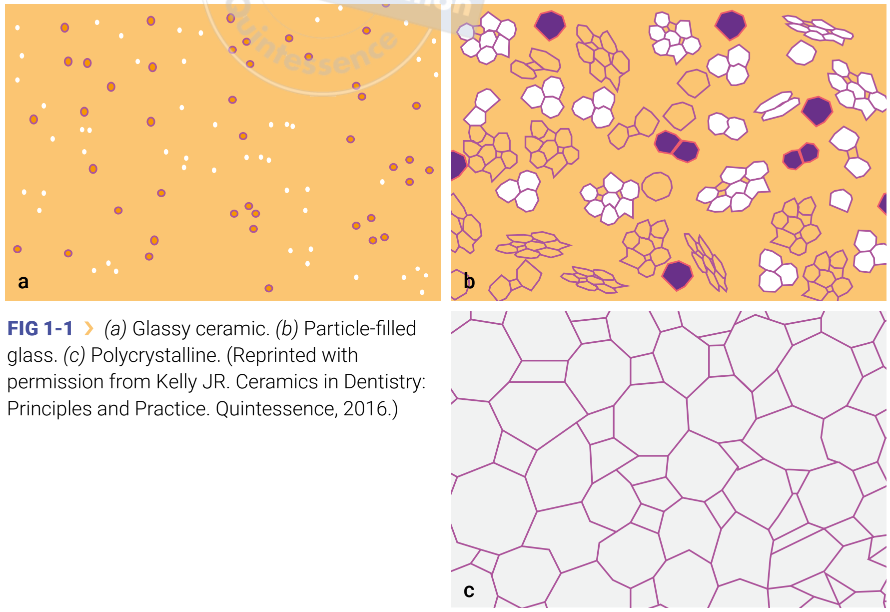

FIG 1-1 › *(a)* Glassy ceramic. *(b)* Particle-filled glass. *(c)* Polycrystalline. (Reprinted with permission from Kelly JR. Ceramics in Dentistry: Principles and Practice. Quintessence, 2016.)

Whatever their structure, ceramics generally have low tensile and bending strength (much lower than those of metallic alloys), although their compressive strength is generally high. Ceramics are also more brittle (less tough) than metals. Material toughness describes how difficult it is for fractures to propagate in a material and eventually lead to rupture. Material toughness is especially relevant in ceramics because linear elastic fracture mechanics tell us that the strength of a material *(σ_R)* is dependent on the ratio between the toughness *(K_{IC})* and the size of the principal critical flaw in the material *(c)*, following Griffith's law[2]:

$$\sigma_R = \frac{K_{IC}}{\sqrt{\pi c}}$$

In addition, ceramics are sensitive to intrinsic flaws in their microstructure—grain boundaries, pores, and inclusions—and to internal stresses and surface defects that may occur during the production process of ceramic devices. This explains why efforts to enhance the strength of ceramics for structural applications are focused on two main areas: *(1)* improving the production process to reduce the number and size of intrinsic flaws and *(2)* developing materials with higher intrinsic toughness.

Although ceramics have low strength and toughness in comparison with metals, ceramics have clear advantages over metals in the oral environment in terms of esthetics and corrosion resistance. From an esthetic viewpoint, metal substructures are limited by their lack of translucency, the metallic ring they exhibit at tooth margins, and the grayish hue they lend to gingival tissues.

Metals are also vulnerable to general and localized corrosion. Local and systemic reactions to the release of metallic ions due to dental device corrosion have been reported in the literature.[3–8] Another benefit of ceramic devices is reduced bacterial surface adhesion.[9,10]

The ceramics currently used in dentistry are essentially composite materials, with some having a glassy phase in their structure. We define a *composite material* (or simply a *composite*) as the combination of two or more materials with different physical and chemical properties into one new material with properties different from those of its components. Two basic types of ceramics are used: those with glass as a component and those without glassy phases in their microstructure. In this book, we devote special attention to zirconia-containing ceramics. Although glass-containing ceramics with metallic structures for added strength are still popular for dental restorations, zirconia ceramics are preferred because of their excellent strength and toughness (important for one- and two-piece dental implants) and their good esthetics (important for metal-free crowns, partial dentures, and complete dentures). Other ceramics, including hydroxyapatite, tricalcium phosphate, calcium sulfate, and bioreactive glasses, are also used in dentistry as scaffolds for the regeneration of bone and to fill bone defects, but these topics are outside the scope of this book.

Glass-Containing Ceramics in Dentistry

A BIT OF HISTORY

The eve of ceramic use in dentistry came during the second half of the 18th century as a consequence of Böttger's discovery of the process to obtain porcelain, which took place in Saxony in 1709.[11] Porcelain was the most sophisticated material available at that time. White, hard, and heat resistant, porcelain seemed to be the ideal denture material to Alexis Duchateau, a Parisian pharmacist who is rightly regarded as the inventor of dental ceramics.[12] After several attempts, Duchateau succeeded in developing a ceramic paste in 1744, from which he manufactured a number of dental appliances, but he was not fully satisfied. He turned to a dentist in Paris, Nicholas Dubois de Chemant, to improve his products from a functional point of view.

De Chemant immediately understood the importance of the discovery and performed extensive experiments in the laboratories of the Manufacture Royale de Porcelaines in Sevés, France, to improve Duchateau's basic mixture. De Chemant published the results of this work in 1789 in his treatise on artificial teeth,[13,14] but the French Revolution forced him (a man who had been awarded a royal patent giving him the exclusive right to produce removable prostheses in porcelain) to move to England, where he perfected his technique in collaboration with Josiah Wedgwood. During construction of the terminus of the Channel Tunnel Rail Link in London, a denture likely made by de Chemant was discovered in the burial place of the Archbishop Richard Dillon.[15] Each arch of this device consisted of a single piece of porcelain with a glassy finish applied to the teeth and the flange colored to represent the gingival tissues. Giuseppangelo Fonzi, an Italian dentist working in France, later improved this construction in 1806. He constructed single artificial teeth to be fixed in the sockets with metallic hooks.[16] Later on, Fonzi produced complete dentures by welding metallic pins hosting porcelain teeth to a metallic substructure.[17]

Porcelain teeth were introduced in the United States by Planteau in 1817, and S. Wesley Stockton started production of porcelain teeth in 1825. Vulcanized rubber was discovered in 1839 and was subsequently adopted for the bases of dentures with porcelain teeth. In 1844, Samuel Stockton White founded the S.S. White Company in Philadelphia for the industrial production of dental instruments and porcelain denture teeth. By 1867, the company was turning out 4 million teeth per year.[18]

Another step forward was thanks to Dr Charles Henry Land (grandfather of the aviator Charles Lindbergh), who by the end of the 19th century had developed all-porcelain crowns and is thus considered the father of modern metal-free prosthetics. His invention was continuously improved upon and was still in use as late as 1950.[19]

FELDSPATHIC PORCELAIN

Feldspathic porcelain is a potassium aluminosilicate glass obtained by melting feldspar, quartz (15%), kaolin (4%), and other oxides. It is called "porcelain" because it is made of a glassy matrix containing several crystal phases, though *porcelain* really refers to a class of ceramic-based composites made mostly of kaolin (70%) joined to feldspar and quartz (each 14% to 15%). The esthetic properties of feldspathic ceramics are due to their amorphous (glassy) matrix, while their mechanical strength is due to leucite ($K_2O{\bullet}Al_2O_3{\bullet}4SiO_2$) crystals. These porcelains were used in denture teeth and in powder form for inlays and partial dentures.

Although feldspathic ceramics provide excellent esthetics and have good compressive strength, they fracture easily under shear stresses because of their low flexural strength (< 60 MPa).[20] To improve the mechanical reliability of feldspathic porcelain restorations, Weinstein et al[21] developed porcelain-fused-to-metal (PFM) restorations, consisting of porcelain fused to a thin metallic substructure (a crown core or partial denture framework). PFM technology has since been continuously improved, and today it is the standard for crowns and partial denture restorations.

Several types of dental porcelains are currently used, with their applications determined by their melting temperature. High-fusing porcelains (melting temperature 1,250°C–1,350°C) and medium-fusing porcelains (melting temperature 1,100°C–1,250°C) are especially suitable for denture teeth, whereas low-fusing porcelains (melting temperature 850°C–1,100°C) are used for metal-ceramic crowns and partial dentures. Porcelains with a melting point below 850°C (very low-fusing porcelains) can be used with an expanded selection of metal alloys for support.

REINFORCED FELDSPATHIC PORCELAINS

The major limitation of feldspathic porcelains is their low strength. To improve the material strength of feldspathic ceramics, McLean and Hughes[22] proposed the addition of 40% to 50% alumina to the porcelain, increasing strength to between 120 and 150 MPa. The alumina-reinforced porcelain was used for the core of jacket crowns with porcelain veneers to improve their esthetics. Notwithstanding the increase in strength obtained by the introduction of alumina, successful outcomes with these early devices were limited because of the residual porosity of the cores after sintering, and the cores were further reinforced with platinum foils.[23,24] Different reinforcing agents were introduced in the following years, including fibers or leucite crystals added to feldspar glass as a powder or grown in situ during melting of the feldspar.

GLASS-CERAMICS

Dr S.D. Stookey discovered glass-ceramics (GCs) in the late 1950s while working for Corning Glass Works.[25] The discovery was the result of a chain of serendipitous events that occurred while Dr Stookey was developing a different product.[26] The application of GCs are manifold, ranging from household appliances to smartphone screens and from radomes to telescope mirrors. As dental materials, GCs offer both the esthetic properties of glasses and the mechanical properties of crystalline ceramics. Their microstructure is characterized by a fine and homogeneous distribution of ceramic crystals in the glass matrix that are grown directly from the glass through a controlled crystallization process known as *ceraming*.

Ceraming is a two-step thermal treatment to develop the crystalline phase within the glassy matrix. It is achieved by fine-tuning the heating temperature, heating rate, and annealing time. Any crack that eventually develops in the material must follow the contours of the crystals created during ceraming. This results in a longer path and the dissipation of propagation energy as the crack travels through the material. This microstructural feature results in a material with improved fracture strength and hardness.[27–29]

The first dental GC (Dicor, Dentsply International) was developed in 1972 by Grossmann and introduced in 1984 as a GC ingot for castings with a flexural strength of 150 MPa.[30] Dicor was constituted of fluormica (55 vol%), giving the material its high translucency and flexural strength. Dicor was later available as a machinable block (Dicor MGC) for the CEREC system (Dentsply Sirona) and used for inlays, onlays, and crowns.

The application of CAD/CAM technology to dentistry has resulted in the development of an array of processes to obtain ceramic cores for the milling of crowns, partial dentures, and complete dentures. This technologic breakthrough is due to the French dentist François Duret, who patented his "process to obtain a dental prosthesis" in 1982.[31] Unfortunately, the system he developed (Sopha, Hennson SA) was removed from the market in 1993, when the manufacturing company was dissolved.[32] Later, Mörmann et al significantly developed this approach, resulting in the well-known CEREC system that made the success of CAD/CAM in dentistry.[33–36] Today, a number of CAD/CAM systems and machinable materials are available for the production of dental appliances.[37,38]

Difficulties encountered in the lab (eg, long workflow, product inhomogeneity) eventually led to the discontinuation of the early castable GCs and stimulated the development of new ones that were easier to handle in a dental laboratory. The first of these new systems was a GC obtained by the crystallization of leucite in a feldspathic porcelain enriched with K_2O and ceraming performed at a higher temperature. IPS Empress (Ivoclar Vivadent), a well-known leucite GC, is manufactured at a temperature of about 1,050°C to enhance the growth of leucite crystals, resulting in a material with a flexural strength of 160 MPa and excellent esthetics.[26]

LITHIUM DISILICATE GLASS-CERAMICS

Lithium disilicate GCs for dental applications were obtained in the system SiO_2–Li_2O–K_2O–ZnO–P_2O_5–Al_2O_3–La_2O_3 by Höland et al.[39] The material consists of a glassy matrix containing a homogeneous dispersion of randomly oriented rod-like $Li_2Si_2O_5$ crystals. A small fraction of lithium orthophosphate (Li_3PO_4) crystals is present because P_2O_5 is a process additive that promotes the nucleation of lithium silicate phases in the volume of the glass.[40] Two different processing routes are used for the nucleation of crystals of lithium disilicate. A two-stage process is used to obtain pressable ingots with the lost wax hot pressing technique, whereas a three-stage process is used to produce CAD/CAM milling blocks.

The first step to produce pressable ingots is performed at the factory and involves nucleating the glass. The second step is performed in the dental laboratory and involves hot pressing the crystallized ingot in a viscous state at about 920°C into a dental mold shaped like the desired restoration. The elongated $Li_2Si_2O_5$ crystals give the pressable ceramic 400 MPa in strength and a fracture toughness of 2.75 MPa $m^{1/2}$.

For machinable blocks, lithium disilicate is precipitated in a three-stage process. The first stage consists of forming lithium orthophosphate nuclei for the successive crystal growth of metasilicate crystals. In the second stage, the glass block is heated to form lithium metasilicate (Li_2SiO_3) crystals. After cooling, the intermediate metasilicate phase—evenly dispersed small platelet-shaped crystals—accounts for 40 vol%. This material is strong enough to be milled to form the desired restoration. During the third stage, the material undergoes an additional thermal treatment at 850°C for 20 to 31 minutes to precipitate small rod-like and interlocked 1.5-μm-long crystals of lithium disilicate in a volume fraction of up to 70%. The resulting GC has 360 MPa in strength and a fracture toughness of 2.25 MPa $m^{1/2}$. Figure 1-2 shows the microstructure of lithium disilicate.[41]

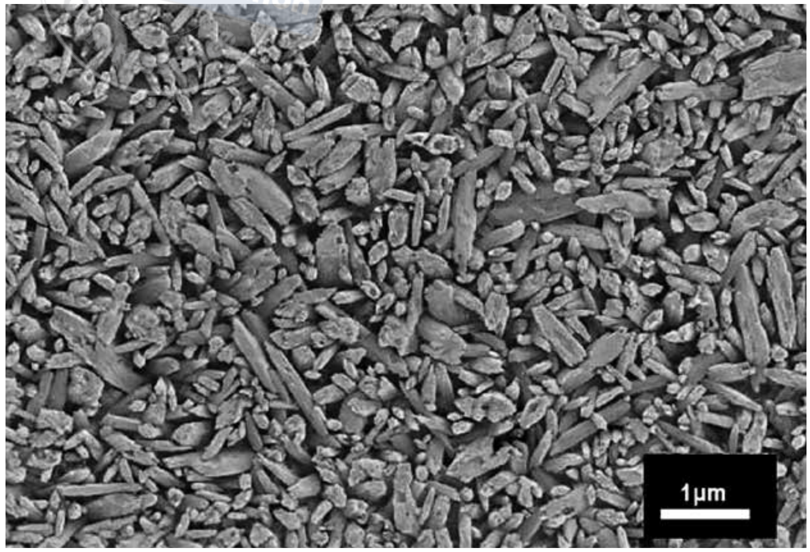

FIG 1-2 › Scanning electron microscopy (SEM) image of the microstructure of a lithium disilicate–type GC (IPS e.max CAD, Ivoclar Vivadent). (Modified with permission from Ritzberger et al.[41])

GLASS-INFILTRATED CERAMICS

VITA Zahnfabrik developed a class of glass-infiltrated dental ceramics (In-Ceram) during the 1980s. In-Ceram crown cores were made in the dental lab by slip casting alumina slurries in porous gypsum dies, followed by sintering of the green body. Sintering process parameters were selected to result in 20% to 25% porosity. After shaping, the alumina porous cores (copings) were infiltrated with molten lanthanum aluminosilicate glass. The composition of the cores may be alumina, magnesium spinel ($MgAl_2O_4$), or a ceramic composite of alumina and zirconia (zirconia-toughened alumina [ZTA]). The ZTA system (In-Ceram Zirconia) is obtained by adding 33 vol% of 12 mol% ceria-stabilized zirconia (12Ce-TZP) to In-Ceram Alumina.

In-Ceram Alumina can be used for three-unit anterior fixed partial dentures (FPDs) and can thus be regarded as the first all-ceramic restorative system.[42,43] In-Ceram Zirconia has a bending strength that is 20% higher than In-Ceram Alumina, and it is recommended for three-unit posterior FPDs.[44] Initially used for ceramic copings, In-Ceram Alumina and In-Ceram Zirconia were later available as presintered porous ceramic blocks for CAD/CAM and prosthetic abutments infiltrated by lanthanum glass. Table 1-1 provides an overview of some basic material properties of glass-containing dental ceramics.

Oxide Ceramics in Dentistry

PURE ALUMINA

Applications of alumina (aluminum oxide, Al_2O_3) as a biomaterial are based on its microstructural properties, which may occur in many metastable phases eventually leading to irreversible transformation into alpha-alumina if heated above 1,200°C. Alpha-alumina is a close-packed hexagonal arrangement of oxygen

TABLE 1-1 › **Properties of glass-containing dental ceramics**

Material	Strength at rupture (MPa)	Fracture toughness (MPa m½)	Young modulus (GPa)
Feldspathic porcelain	60–70	0.92–1.26	70
Leucite GCs	160	1.4–1.5	65
Lithium disilicate GCs	360–400	2.25–2.75	95
Glass-infiltrated spinel	400	2.7	185
Glass-infiltrated alumina	500	3.9	280
Glass-infiltrated zirconia	600	4.4	260

ions that constitutes a very high thermodynamically stable phase. Known also as *corundum* (or *emery* if containing impurities), alpha-alumina is the alumina material used for biomedical application.

In the lattice of alpha-alumina, each aluminum cation Al^{3+} is surrounded by oxygen anions O^{2-} forming two regular triangles on both sides, twisted by 180 degrees and lying on parallel planes. The surface layer of O^{2-} anions allows the chemisorption on the surface of OH^{+} groups, then the bonding of water molecules or proteins. In other words, the surface has high wettability (higher than several metallic alloys).

One of the physical properties to be controlled to achieve the best clinical outcomes with alumina bioceramics is the residual porosity of the product. The porosity fraction influences the mechanical properties, as explained in the following section. The open porosity fraction especially must be controlled because it allows the permeation of liquids and gases.

Alumina restorations

Andersson and Odén[45] reported the use of high-purity (> 99.9%) alumina ceramic for the manufacture of single crowns (Procera AllCeram, Nobel Biocare) in the early 1990s. Developments in the production system later allowed for the manufacture of partial dentures and abutments. In this ceramic, there is no glassy phase present between the grains, a feature that differentiates it from former dental ceramic materials. Procera Alumina has a flexural strength of about 600 MPa. The Procera AllCeram cores (99.9% polycrystalline alumina) are obtained via an industrial process performed at a centralized manufacturing plant. After milling and sintering, single-crown and multiunit frameworks are veneered with feldspathic ceramics to provide the desired color and form of the restoration.[46]

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