Materials Used in the Construction, Conservation, and Restoration of Ancient Stupas in Sri Lanka

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INTRODUCTION

Stupas in Sri Lanka are monumental structures built to honour Lord Buddha. A stupa is an indispensable feature of any Buddhist temple, and architecturally the stupa is the most important Buddhist structure (Paranavitana 1946, Ranaweera 2004). Stupas house sacred relics of Buddha, or mark the sacred spots at which some important event connected with the religion had taken place, and they are venerated by the Buddhists. Their imposing, yet simple, features give one a feeling of stability, strength, nobility, and grandeur.

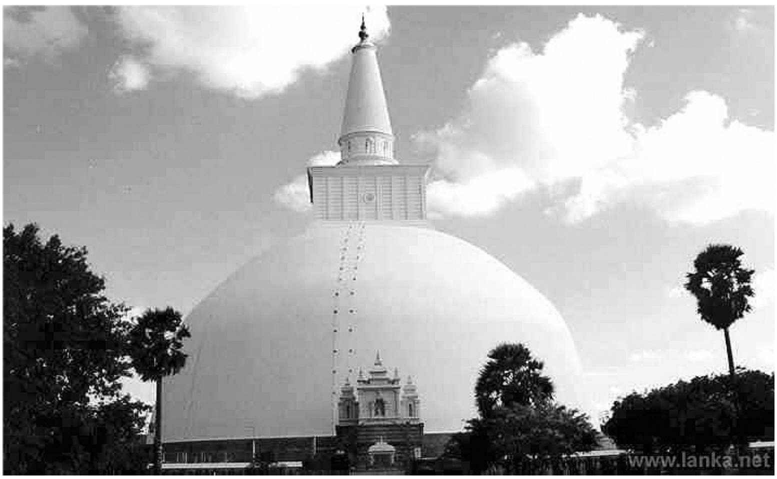

Figure 1. Ruvanveli stupa (height = 103.0 m, base diameter = 91.4 m)

The oldest stupa in Sri Lanka is Thuparama built by King Devanampiyatissa (250-210 BC) in the then capital city of Anuradhapura. With the passage of time more stupas were built by the Kings, notable ones being Ruvanveli **(fig. 1)** by King Dutugemunu (161-137 BC), Abhayagiri by King Valagambahu (89-77 BC), and Jetavana **(fig. 2)** by King Mahasen (276-303 AD). Jetavana, which attained a full height of 121.9 metres, and was at one time the third tallest structure in the world, surpassed only by the two great pyramids in Giza (Silva R 1982). Its present height is only 70.7 m, but with a volume of 233,000 cubic metres, Jetavana is arguably still the largest brick structure in the world. The most venerated stupa in Sri Lanka however is Ruvanveli, because it enshrines the most amount of corporal relics of Buddha.

Figure 2. Jetavana stupa under conservation (height = 70.7 m, base diameter = 111.9 m)

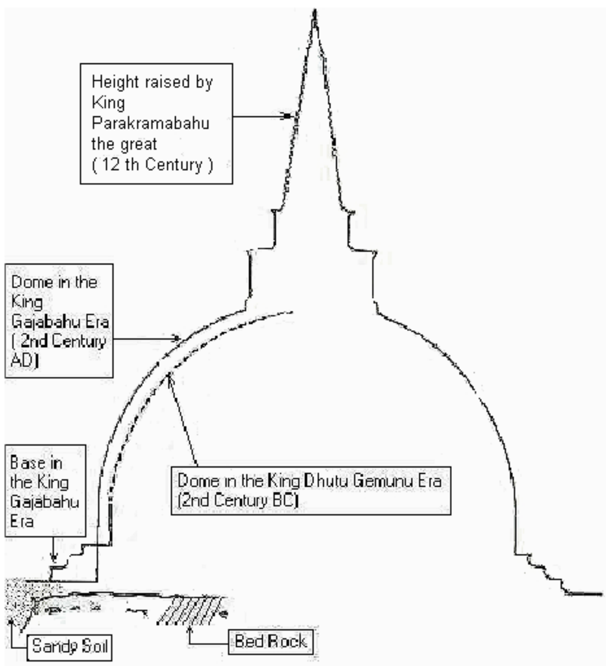

Figure 3. Development of Miriseveti stupa

Due to foreign invasions and the shift of the capitals from one place to another, the ancient stupas were neglected and became increasingly dilapidated. Various Kings carried out reconstruction/restoration/conservation of stupas built by their predecessors, increasing their sizes and sometimes changing their shapes **(fig. 3).** However, by the turn of the nineteenth century all the ancient stupas were in ruins **(fig. 4)**. During the colonial era, British rulers took a great interest in the ancient stupas and initiated programmes to restore/conserve them in the last decade of the nineteenth century (Silva WNG 2002). Presently a conservation programme is being carried out by the Central Cultural Fund of Sri Lanka.

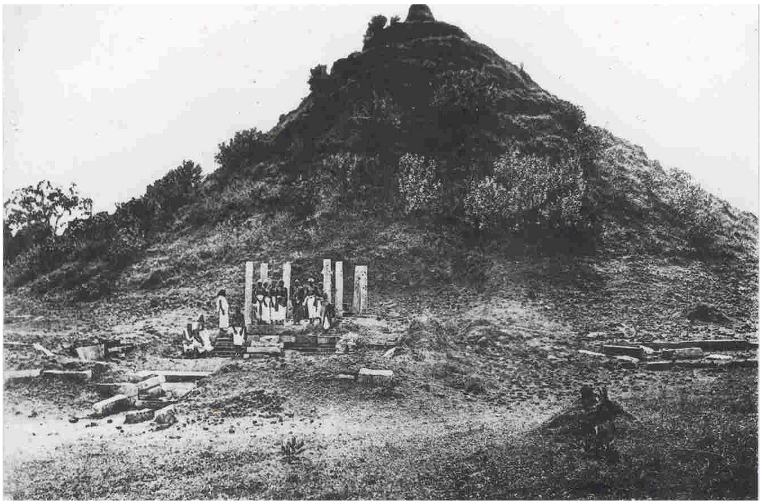

Figure 4. Mireseveti stupa in ruins

This paper deals with the materials used by the ancient builders of Sri Lanka in the construction of stupas and the materials used in recent times in the conservation and restoration of dilapidated stupas.

STRUCTURAL ASPECTS OF THE STUPAS

Ancient stupas in Sri Lanka are solid structures, built mostly of burnt clay bricks. Over the years, the structural form of the Sri Lankan stupa has changed from the original Indian form to a form of its own **(fig. 5).**

Main components of the Sri Lankan stupa are shown in **fig. 5**. The stupa dome has one, two or three cylindrical terraces or basal rings at the bottom, which sometimes form a plinth. At its top, the dome carries the square chamber, which is a solid structure having a square plan. Then come one or more cylinders, the spire and the pinnacle consisting of a minaret and a crystal. All these components, except the square chamber, are assymmetric.

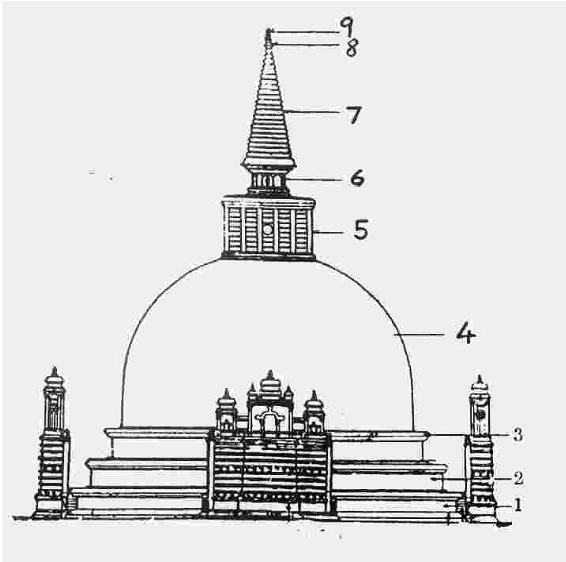

Figure 5. Main components of a Sri Lankan stupa (1,2,3-Basal rings, 4-Dome, 5-Square chamber, 6-Cylinder/s, 7-Spire, 8-Minaret, 9-Crystal)

The dome is the biggest component of a stupa and it contains the relics in a relic chamber, either at the level of the basal rings at the bottom, or in the square chamber at the top. Several shapes have been used for the dome, described as the bell, bubble, paddy heap, pot, and lotus. The bell and bubble shapes are the most common, and the mega stupas; Abhayagiri and Jetavana **(fig. 2)** are of paddy heap shape. This shape is the most stable from a structural point of view (Ranaweera 1998), as it produces no tension in the dome under self weight. The ancient Sri Lankan builders have arrived at this shape, maybe by trial and error, for the colossal stupas they built (Silva R 1982).

Great care was taken in selecting the sites and laying out the foundations. Most stupas have been founded on rock and for others elaborate preparations of the foundations have been made. *Mahavamsa* (Geiger 1950), describes how the foundation of the Ruvanveli stupa, was laid. “First the land was dug out to a depth of seven cubits (5.3 metres) and then crushed stones were stamped down by elephants whose feet were bound in leather. Then butter clay was spread over the stones and bricks were laid over the clay. Over these, a rough cement and a network of iron was laid. Finally a sheet of copper and a sheet of silver were laid”. This more or less gives a reinforced concrete foundation with damp proofing.

MATRERIALS USED IN THE CONSTRUCTION

The main building block of a stupa is the burnt clay brick, and different sizes of bricks have been used in different components of the stupa. Dome, the most bulky component of the stupa, has an outer layer of high quality bricks of large size, and towards its inside brickbats as well as earth has been used in some cases. The bricks were laid with a very thin mortar and the outside surface of the stupa has been protected from the elements with a thick plaster. Bricks were used for the foundations as well, with special precautions taken to prevent the ingress of moisture. According to *Mahavamsa* material used in stupa construction was subjected to strict quality control. King Dutugemunu employed the master builder who said that "he will pound the sand in a mortar and then shift it so that no grass or any such thing will grow in the stupa". King also appointed a committee to supervise the construction work.

Bricks

It is logical to assume that the earliest bricks used in the construction of stupas were un-burnt sun-dried mud bricks. These were later replaced with high-quality burnt bricks. *Mahavamsa* in fact states that when Thuparama - the first stupa - was built, mud-bricks were heaped over the sacred spot to form a stupa. Thermoluminescence (TL) dating of bricks from ancient stupas has established their dates of manufacture within 7% of the historical dates (Abeyratne 2005).

Size of bricks

The basal rings and the foundation below them, and the dome are the most voluminous parts of a stupa. For these parts the ancient stupa builders used large bricks which required both hands to handle, unlike modern bricks of much smaller dimensions. The size of these large bricks has reduced over time. The ones used in the third century BC are more than double the size of those used in the twelfth century AD. Measurements by Parker, some of which are given in Table 1, show that this reduction in size is monotonic, and this makes Parker to claim that the age of a stupa can be deduced from the size of the bricks used to construct it (Parker 1909).

Table 1. Variation of brick size with time

Stupa	Period (century)	Dimensions (in.)			Volume (in.^{3})
		Length	Breadth	Thickness	
Maha Seya(NCP)	Third BC	17.92	8.87	2.91	461
Yattala(SP)	Third BC	17.85	8.64	2.90	447
Sandagiri(SP)	Early second BC	17.14	8.67	2.81	418
Lankarama(NCP)	Early first AD	17.37	8.94	2.62	407
Millaewagala(NCP)	First or second AD	15.57	8.00	2.72	339
Padaviya sluice(NCP)	Late third AD	14.02	8.50	2.46	293
Dalada maligawa(NCP)	Early fourth AD	14.10	8.45	2.52	300
Sigiriya gallery (NCP)	Late fifth AD	13.09	7.32	2.31	220
Rankoth(NCP)	Twelfth AD	12.52	8.40	2.00	210
Thuparama(NCP)	Twelfth AD	12.00	8.36	2.00	201
Modern (specially made)	Twentieth AD	17.72	8.85	2.56	401
Modern (ordinary)	Twentieth AD	8.5	4.25	2.25	81

Mechanical properties of bricks

Ancient bricks from various stupas were tested for their mechanical properties using cylindrical core samples. Elastic moduli were obtained from resonant frequency testing and the tensile strengths were obtained by split cylinder testing. Some typical results are given in Table 2. It can be seen that ancient bricks are of much higher quality than the modern bricks.

Table 2. Mechanical properties of some ancient and modern bricks

Source	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Compressive strength (MPa)	Tensile strength (MPa)
Sandagiri	1840	9.79	0.27	11.6	1.54
Jetavana	1723	4.5	0.25	8.50	0.85
Modern stupa brick	1768	1.92	0.21	5.30	0.55

In the case of Jetavana stupa, a linear elastic finite element analysis under self weight gave a maximum compressive stress of 839 MPa at the bottom centre of the dome and no tensile stresses in the dome (Ranaweera 2000). Hence the maximum stress in the dome is less than one tenth of the strength of ancient bricks used **(table 2)**. There are tensile regions in the square chamber which have tensile stresses reaching a maximum value of 40 kPa, which is also very low compared with the tensile strength of ancient bricks.

Composition of bricks

Thin section analysis carried out for the ancient bricks from Jetavana stupa and modern factory-made bricks (Siritunge 1982) gave the following results **(table 3).**

Table 3. Composition of ancient and modern bricks (Siritunge 1982)

	Component	Ancient bricks	Modern bricks
Mineral (percentages)	Sand (Quartz)	50 - 60	30 - 40
	Clay	35 - 45	55 - 65
	Voids	3 - 8	1 - 5
Sand size (percentages)	Silt (below 1/16 mm)	48.5	12.7
	Very fine (1/16 – 1/8 mm)	48.5	33.8
	Fine (1/8 – 1/4 mm)	-	17.8
	Medium (1/4 – 1/2 mm)	1.9	22.2
	Coarse (1/2 – 1 mm)	1.1	11.2
	Very coarse (1 – 2 mm)	-	2.3

These results show that the ancient brickmakers used a much higher content of sand than the modern ones, and that may be the reason for the higher strengths of the ancient bricks. The ratio of silt to sand is relatively constant in the ancient bricks, perhaps indicating better quality control in ancient brickmaking. In fact *Mahavamsa* mentions the process used by the King Dutugemunu to select the brick makers, very much like the way we select present day contractors.

Mortar

The mortar used in the brickwork of ancient stupas is a clay slurry type - called “butter clay” – with an adhesive from a tree and a solvent of sweetened water (*Mahavamsa* Geiger 1950). This was spread between different courses of bricks in very thin layers, unlike the thick layers used in modern brickwork, basically to fill the cavities between bricks and make them almost touch each other. Analysis of the original mortar samples from Abhayagiri (first century BC) and Jetavana (third century AD) stupas revealed that they consisted of finely crushed dolomitic lime mixed with sand and clay in a ratio 1:4 in Abhayagiri and 1:5 in Jetavana (Abeyratne 1982). This indicates that the lime mortar technology had also changed across the centuries (Abeyratne 2005).

Brickwork

In ancient stupas brick bonding principle was strictly adhered to and no vertical joints generally meet (Silva R 1982). With the slurry like mortar the thickness of mortar layer is reduced to almost zero, making the load transfer from one brick to another virtually by direct contact. The ancient brickwork and the brickwork used by the British in the nineteenth century renovations of Jetavana are shown in Figure 6. It can be seen that five courses of ancient brickwork match four courses of the British era brickwork with thick mortar.

Figure 6. Comparison of ancient and British era brickwork in Jetavana

Plaster

The outer surface of the stupa brickwork was water-proofed using a plaster layer. Some of the stupas have several layers of plaster, reaching overall thicknesses of 9 to 10 in. One of the best preserved examples is the Kirivehera at Polonnaruwa (fig. 7) built by King Parakramabahu in the twelfth century AD. These plasters are like lime-concrete rather than normal stucco (Silva R 1982).

Figure 7. Kirivehera (height = 24.4 m, base diameter = 25.6 m) showing thick original plaster

CONSERVATION AND RESTORATION OF ANCIENT STUPAS

Due to foreign invasions and the shift of the capitals from one place to another, the ancient stupas were neglected and started the process of dilapidation. This would have followed a progressively worsening process initiated by cracking of the surface, followed by rain water penetration, animal infestation, vegetation growth and root penetration in cracks, and would have been compounded by surface water erosion.

Various Kings of Sri Lanka carried out reconstruction, restoration or conservation of the stupas built by their predecessors. King Prakramabahu (1140 – 1173 AD) is credited with the restoration of many stupas including the mega stupas, Ruvanveli, Abhayagiri and Jetavana. After the twelfth century there were hardly any work on stupas until the British started documentation and reconstruction work on ancient stupas, in the latter half of the nineteenth century (Silva WNG 2002). Around the same time Buddhist organisations undertook restoration works on many important stupas, the most important among them being Ruvanveli (fig. 1). Ruvanveli restoration started in the 1870s but only finished in 1940. The stupa was restored to its full conjectured height of 103 m, from a height of 47 m. These early restorations used whatever construction materials available.

Miriseveti restoration

Mirisaveti, built by King Dutugemunu in the second century BC was reconstructed by several Kings (fig. 3), the last major enlargement done by King Parakramabahu in the twelfth century. It is the first stupa to be reconstructed by the British, and when they started their investigation work in the late nineteenth century, the stupa was in ruins (fig. 4). Even though the plans were prepared for its full restoration, the work was not completed, and only the dome was reconstructed (fig. 8).

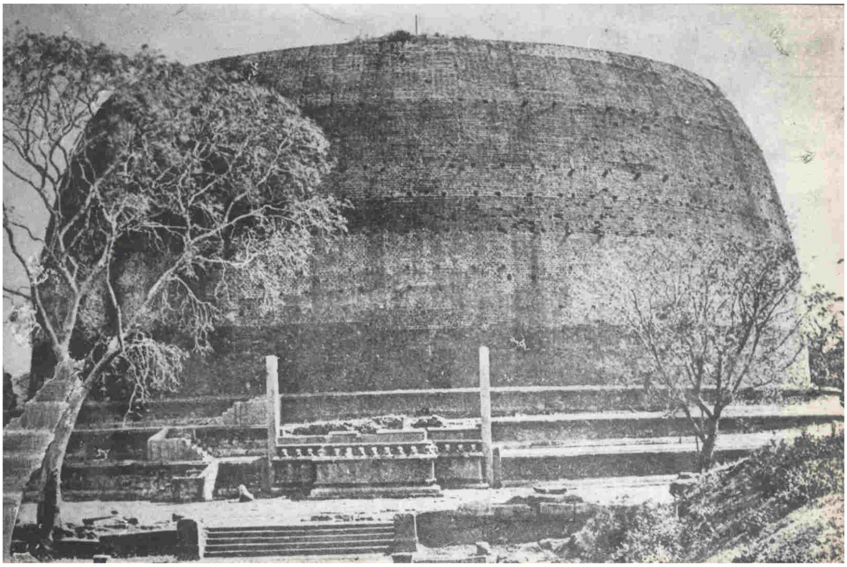

Figure 8. Mireseveti stupa during reconstruction by the British in 1906

The second attempt at the restoration of Mirisaveti stupa, to its full conjectured dimensions, commenced in 1979 (Silva WNG 2002). The concept was to restore the stupa as a solid brick dome, and a set of reinforced concrete rings was to be incorporated onto the periphery of the dome to take any hoop tension. Brickwork carried out in the previous attempt was to be removed and the new brickwork started from the original brickwork. Cement mortar was to be used in the general proportion of 1:5. However the stupa failed catastrophically in 1987 when the restoration work reached the dome top level, breaking into several segments through vertical (meridional) cracks. This tragic event led to various discussions among the engineers and archaeologists, leading to several engineering studies being conducted to ascertain the reasons for the failure. The stress analyses (Ranaweera 1993) showed that the self weight causes radial and circumferential tension in the hemispherical dome and that the new brickwork imposes excessive pressure on the inner ancient brickwork which is very weak.

Hence in the third attempt to restore the stupa, a design concept where the new brickwork is acting as a thick shell without bearing on the remaining ancient brickwork was used, and the new brickwork was constructed with radial and circumferential ring beams of reinforced concrete **(fig. 9)** to take up tensile stresses. The construction work started in 1990 and completed in 1992 with the unveiling of the pinnacle **(fig. 10)**.

Figure 9. Mireseveti stupa restoration – new brickwork and groves for RC beams

Figure 10. Mireseveti stupa after full restoration (height = 43 m, base diameter = 54 m)

Jetavana & Abhayagiri conservation

Jetavana and Abhayagiri are the two largest stupas in Anuradhapura, which was declared a World Heritage Site by UNESCO in 1985. Restoration work on the Jetavana stupa commenced in 1981 by the Central Cultural Fund, which was established in 1980. In the beginning the plan was to fully restore the Jetavana stupa, to its full conjectured height of 122 m. However after the complete restoration of Mireseveti stupa, there were objections from archaeologists to complete restorations using modern materials like reinforced concrete. Much discussion took place and it was finally decided that a conservation rather than a restoration of the stupa should be done, after a study of the stresses in the stupa.

The aim of conservation is to preserve the as-found nature of the structure with minimum intervention, retaining as much as possible the original structure. Any repairs done should use like-for-like materials, and should be reversible. These rules of archaeological conservation are used in the present work on Jetavana and Abhayagiri stupas.

Figure 11. Jetavana stupa dome restoration showing pointed brickwork

Finite element stress analyses (Ranaweera 2000, 2001) of the stupas under self weight showed that the paddy heap shaped domes (ellipsoid in the case of Jetavana, and paraboloid in the case of Abhayagiri) have no tensile stresses and that the square chambers have tensile stresses at the top surfaces. Some tensile hoop stresses are present in the cylinders, too. Hence no provision to take tension is needed for the domes, which are covered with vegetation. They are cleaned and a layer of especially made new bricks is added, on top of old bricks where necessary, using mortar which does not contain cement. The bricks at the outer surface will be pointed and no plaster will be used (figs. 2 & 11). However major repairs have to be done on square chambers which had undergone serious damage, and are developing tensile regions. This required the use of a reinforced concrete ring beam at the top and an especially designed concrete layer on the top surface of the square chamber. Some concrete rings are also being used to resist hoop tension in the cylinders.

Materials used in conservation work

Materials for conservation have to be especially prepared in keeping with conservation principles. As far as possible the materials should be similar to the ancient materials and it should be possible to remove them without damage to the ancient structure. Materials used in the conservation work at Jetavana and Abhayagiri are described below.

Bricks

Bricks to the same size as ancient bricks are made in a special kiln designed for that purpose. Typical properties of new bricks are given in Table 2.

Mortar

Investigations on mortar extracted from construction in Sri Lanka during the seventh century AD revealed that pozzolanic materials had been used along with lime in making mortar. According to Brohier (Brohier 2000) who refers to the findings of Hughes (Hughes 1918), this mortar showed superior properties to the Roman mortar, which had long been accepted as the best ancient product.

Following that line, a number of mixes comprising different proportions of slaked lime, rice-husk ash, termite mound clay, ground brunt clay tile fragments, and water were investigated for the soaked and dry strengths. Table 4 contains a description of a couple of mixes so investigated (Abeyruwan 2001). The investigation revealed that both rice husk ash and ground burnt clay roofing tiles had pozzolonic action, whereas the ground burnt clay bricks did not show such significant effect. The typical mix used for the conservation is Mix 5. Sand was omitted in the mixes, in order to ensure thin layer of bedding, replicating ancient bricklaying practice (fig. 6).

Table 4 Properties of bedding mortar

Mix Id.	Mix proportions by volume					90-day compressive strength (N/mm^2)	
	Slaked lime	Rice-husk ash	Ground burnt clay bricks	Ground burnt clay roofing tiles	Termite mound clay	Dry	Soaked
Mix 5	1	1	-	2	2	1.2	0.8
Mix 6	1	1	2	-	2	0.3	0.1

Concrete

Portland cement was used rarely in restoration work. Nevertheless, concrete members reinforced with stainless steel bars were used at locations where the stress analyses showed substantial tensile stresses. The objective of using Portland cement was to get significant early strength, to enable the speeding-up of restoration work. In order to prevent leaching of hydrated lime liberated from hardened Portland cement, silica fume was added, as a lime-fixing agent, to the concrete mix at a dosage of 10% by mass of cement.

CONCLUSIONS

Ancient builders in Sri Lanka used high quality materials and strict quality controls, in constructing the mega stupas. They used bricks of larger sizes than modern bricks and these were found to have higher strengths than present day bricks. The use of a very thin layer of mortar made the brickwork stronger. A thick plaster layer was used to water proof the surface and prevent the deterioration of the stupa under the action of elements. The present repairs are done in keeping with conservation principles using similar materials as much as possible.

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