The Egyptian mud-brick silo. Technical and functional analysis of a grain storage device

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STORAGE IN ANCIENT EGYPT AND NUBIA

Earthen architecture and building techniques

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Published by Sidestone Press, Leiden
www.sidestone.com

Layout and cover design: Sidestone Press
Front cover: The *thēsauros* of Tebtynis in 2023. © Ifao/Mohamed Ibrahim Mohamed.

ISBN 978-94-6426-223-0 (softcover)
ISBN 978-94-6426-224-7 (hardcover)
ISBN 978-94-6426-225-4 (PDF ebook)

DOI: 10.59641/o29221ra

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Mud-brick silo, experimental archaeology, grain storage, building materials, building techniques, ancient Egyptian art, archaeology

Introduction

Adeline Bats & Nadia Licitra

Mud-brick silos are regularly identified in Egyptian archaeological sites and in "daily life" scenes depicted in private tombs since the Old Kingdom. They are present in several types of settlements and associated with various buildings such as temples or dwellings (Warden 2017; Bats 2022). Used for storing bulk goods such as cereals, malt, or fruits, these devices were designed to preserve foodstuffs over the medium and long term. In contrast to the grain pit[2] (Dachy 2014) – an underground device well known from the Bronze Age and medieval Europe[3] (Sigaut 1978) – the silo, built of mud-bricks, is mostly cylindrical or conical (Aurenche 1977, pp. 158-159), domed and provided with a shallow foundation.[4] Although it is still used today in some traditional societies in Africa and the Near East (see *infra*), the storage process is poorly documented and seems to correspond to that of a grain pit. Several hypotheses have been developed through comparisons, but the functioning of this type of structure remains largely unknown.

The free-standing silo preserves foodstuff by creating an airtight atmosphere, preventing exchanges between internal and external environments.[5] The bulk goods would then consume internal oxygen, release carbon dioxide, and go dormant. It has been assumed that, by absorbing the oxygen present, the cereals and legumes located against the walls of the structure would germinate, causing a partial loss of the crop but also creating a protective layer keeping the rest of the grains intact (Reynolds 1979).

1 This research was supported by a public grant overseen by the French National Research Agency (ANR) as part of the Nile's Earth project (ANR-21-CE27-0019-01), the *Fondation des Treilles,* and *Les Maîtres de mon moulin*.

2 For some examples of underground silos, see the contribution of Claes *et al.* in this volume.

3 Grain pits are also attested in many parts of the world and at different periods, see Bats, Licitra in this volume.

4 Quadrangular silos are attested for a very short period in Egypt, mainly during the First Intermediate Period and the early Middle Kingdom (Bats 2017, pp. 167-168). They will not be discussed in this article.

5 For a description of this process and the related bibliography, see Bats, Licitra in this volume.

in A. Bats, N. Licitra (eds.), *Storage in Ancient Egypt and Nubia. Earthen architecture and building techniques*, Leiden: Sidestone Press, 2023, pp. 151-172. DOI: 10.59641/029221ra

This interpretation has recently been challenged, since current experimentations in pit-silo operation show that this layer of germinated grains does not actually seem to be necessary for the proper conservation of the crops (Dominguez *et al.* 2022, p. 179). When the silo is open, the reintroduction of oxygen into the structure restarts the lifecycle of the seeds, forcing the grains to be removed in their entirety at once. This type of storage efficiently protects the crop against pests (Bats forthcoming) but, at the same time, affects the entire processing and consumption of the grain. Assuming that the operation of the mud-brick silo is similar to that of the pit-silo, several questions linked to the long-term conservation of seeds remain and need to be explored further. The first issue concerns the architectural elements: what was the role played by the building materials – essentially mud-bricks, earthen mortars and plasters – and the building techniques in insulating the crops from the outside atmosphere? As a matter of fact, unlike pit-silos, the external atmosphere is much more subject to variations in humidity and temperature than the underground. In addition, how long and how much do seeds retain their germinative properties when stored in a free-standing silo? This question is all the more relevant since, unlike grain pits, Egyptian silos sometimes had to store huge volumes of grain which favours spontaneous combustion and gas emissions. Finally, how were the silos plugged and hermetically closed?

To try to answer these questions, an experimental archaeology project was initiated in 2021, thanks to the financial support of the *Fondation des Treilles*[6] and the Labex AE&CC[7] (ENSAG/UGA). This project was divided in two parts: 1) the architecture of the mud-brick silo, and 2) its functioning. The project, led by Adeline Bats, gathered together archaeologists and architects specialised in earthen architecture: Nadia Licitra, Thierry Joffroy, several students of the DSA "Earthen architecture, constructive cultures and sustainable development"[8] (Mardjane Amin, Anna-Laura Bourguignon, Marion Denizart, Vanille Joséphine, Angèle Keserwany, Hugo Spack, Clément Venton), and María Lidón de Miguel (architect, PhD Candidate at the Universitat Politècnica de València).

During the first phase of the project, textual and archaeological data was collected by A. Bats and N. Licitra and is presented in the first two paragraphs of this paper. Then, during a series of working meetings with all the members of the team, the building protocol has been established (choice of building materials, shape and size of the silo, mud-brick dimensions, bonding, etc.) in light of this data. In the second phase of the project, a first mud-brick silo was built from 17 to 21 May 2021 during the *Grains d'Isère Festival* held at the *Grands Ateliers* in Villefontaine (France, Isère department).[9] The aim was to test the building protocol and to get acquainted with the building techniques and materials before the construction of a second prototype in which cereals could be stored for several months. The second silo was built from 20 to 27 June 2021 in Roland Feuillas' bakery-farm *Les Maîtres de mon Moulin*[10] at Cucugnan (France, Aude department) and was ensiled with barley in September 2021 to test its performance in preserving it. The experiment benefited from the participation of several volunteers who worked on the construction of the silo (Pauline Bordoux, Julie Depaux, Geoffrey Najda, and Jean-Pierre Najda) and the ensiling (Bastien Lamouroux, Gwendal Lagarde). Both these operations are presented in the following pages.

1. Silo architecture

Adeline Bats & Nadia Licitra

Despite the large number of mud-brick silos excavated on Egyptian archaeological sites, their conservation state – most of the time fragmentary – does not allow for a full understanding of their form, volume and construction. However, the elevation of these storage devices is mainly known thanks to the so-called "daily life" scenes decorating the walls of the tombs of members of the Egyptian social elite between the Old and New Kingdom.[11] In addition to these two-dimensional figurations, numerous clay or wood models belonging to the funerary furniture of private tombs also provide useful data on these storage devices.

1.1 Representations of silos in Egyptian art

The first depictions of Egyptian silos are terracotta models, more rarely in clay and stone, dating from the Early Dynastic Period.[12] Specimens in stone are still being

6 The *Fondation des Treilles*, created by Anne Gruner Schlumberger, aims to open up and foster dialogue between the sciences and the arts to advance creation and research at Les Treilles (Var, South of France) www.les-treilles.com.

7 https://aecc.hypotheses.org/105.

8 The DSA (Diplôme de spécialisation en architecture) "Earthen Architecture, Constructive Cultures and Sustainable Development" is a post-master course at the École Nationale Supérieure d'Architecture of Grenoble (ENSAG) http://craterre.org/enseignement:dsa-architecture-de-terre/.

9 https://www.lesgrandsateliers.org/.

10 https://lesmaitresdemonmoulin.com.

11 Several studies have been devoted to these sources, including Vandier 1978, pp. 198-203, 229-233 and 273-283; Siebels 2001; Masquelier-Loorius 2017; Bats 2017; Bardoňová 2018. Also a new classification has been proposed by J. Florès (2015, pp. 75-80), for scenes dated to the Old Kingdom.

12 From Turah (Śliwa 1983); Helwan (Saad 1947, pls. XIb, LVII); Tell el-Fakha (Kołodziejczyk 2009); Abydos (Petrie 1925, p. 7, pls. VII (no. 384), XI (nos. 123 and 124); Abu Rawash (Tristant 2018).

produced during the first part of the Old Kingdom.[13] These artefacts are known in different sizes, with a tall and cylindrical shape surmounted by a relatively flat dome, while a circular opening is visible on the top. Sometimes one or two lateral square openings, one above the other, are depicted on the object. The presence of these lateral trapdoors raises questions (Petrie 1925, pl. XI, nos 123 and 124; Saad 1947, pl. XIb; el-Khouli 1978, p. 325, pl. 83). According to W.F. Petrie (1925, p. 7), this arrangement allowed the grain to be removed at different levels.[14] By the middle of the Old Kingdom, the production of these models seems to be dramatically reduced (Tooley 1995, p. 37, but other iconographical sources provide information on silo shape and size for the following periods.

The first two-dimensional representations of mud-brick silos appeared in Egyptian tombs during the Old Kingdom and developed markedly between the end of the V^th^ and the VI^th^ Dynasty (Siebels 2001; Bardoňová 2018). These scenes depict free-standing silos, often domed, cylindrical and elongated, provided with a top opening and a side hatch. The two trapdoors, already visible on some archaic silo models, are sometimes also found on wall reliefs, notably in the Kaemremet tomb (Mogensen 1921, p. 29, fig. 26, pl. IX). From the VI^th^ Dynasty onwards, a change is clearly visible in the composition: the silo gradually loses its predominant place in the representation to the advantage of the wider architectural context in which it is inserted (annexe buildings, courtyard, porch, etc.) and of the administrative activities linked to the ensiling of cereals (El-Hagarsa, tomb of Wahi, Kanawati 1995, pls. 28, 31; tomb of Meri-aa, Kanawati 1995, pl. 36). For instance, the stairs leading to the silo top opening as well as a door are depicted in a scene from the tomb of Iti and Neferu at Gebelein, (Turin S.14354/15, Montonati 2018, p. 12, fig. 11), indicating that the silo batteries are integrated into architectural complexes. During the Middle Kingdom the architectural context becomes increasingly detailed (see, for instance, the columns visible in the representation of a storage complex depicted on the Iqer's coffin from Gebelein and dated to the XII^th^ Dynasty: Turin S.15744, Montonati 2018, p. 12, fig. 10). Besides, the development of the representation of administrative activities in this architectural context led the artists to invest a new space by creating a register above the silos. This is well illustrated in the tomb of Antefoqer where the first register depicts a row of domed silos and the second one three scribes recording cereal amounts near a heap of grains (TT60, No. Davies 1920, pl. XV). In the tomb of Khnumhotep II at Beni Hassan a similar scene is even more detailed. Here, the representation of a storage complex includes a courtyard surrounded by a porch and provided with doors leading to the other sectors of the building (tomb no. 3, Newberry 1893, pl. XXIX; Kanawati, Evans 2014, pl. 117). While the surrounding architectural environment is clearly evoked by various architectural elements, such as columns, doors, and a staircase, a rectangular building can be identified as a group of silos only thanks to the four side openings depicted on one of its walls. In this scene, the scribes and the heap of cereals already present in the Antefoqer tomb have been moved to the first register, left of the silos, while the second register has been devoted to another counting operation. In both cases (Antefoqer and Khnumhotep II), it seems to us that the scenes of the first and the second registers have to be intended as separated activities, maybe with different temporalities, but occurring within the same space (the courtyard).

This iconographic evolution is perceivable through the clay and wooden models of the same period as well. Indeed, although dome-shaped silos continue to be attested through clay models[15], new wooden specimens of square silos appear in funerary furniture (Tooley 1989, pp. 89-126). It can be assumed that the material greatly conditioned how the storage devices were crafted, creating a clear distinction between round (clay) and square (wood) structures, since clay offers easy shaping of round structures, while wooden planks lead to rectangular shapes. To support this interpretation, one can mention one of the earliest wooden models showing a quadrangular building on which circular, domed silos have been painted (Cairo JE28839: Tooley 1995, p. 36, fig. 32).

To date, the storage of cereals in quadrangular silos is attested by archaeology only between the First Intermediate Period and the early Middle Kingdom (M. Adams 2007; Moeller 2016, p. 228, fig. 7.10, p. 230, fig. 12a; see also: Bats 2017, pp. 168-169). Despite the absence of openings identified by archaeologists in these constructions, the presence of a staircase at Abydos indicates that the foodstuffs were entered from the top (M. Adams 2007, p. 6, fig. 2). In addition, it is important to distinguish these square silos from the granaries with interconnecting chambers of the Middle Kingdom fortresses of the Second Cataract, where the internal circulation is clearly visible (Bats 2017, pp. 169-170). In the light of this archaeological evidence and the abovementioned wooden model Cairo JE 28839, it can be said that the Middle Kingdom wooden models could have had multiple influences: they could have been representations of actual quadrangular

13 Stone silo models from the III^rd^ Dynasty have been discovered in the underground gallery of the Djoser burial complex at Saqqara (Firth, Quibell 1935, pp. 133, 136, pl. 97, no. 3, pl. 104A, no. 2 ; Lauer 1939, p. 7, fig. 11, p. 18, fig. 30 ; el-Khouli 1978, p. 325, pl. 83).

14 Small silos (*ṣafat*) known for modern Egypt inside houses may also have different lateral compartments with their own openings (cf. *infra*).

15 See, for example, the set kept in the Norwich Cattle Museum (Blackman 1920).

mud-brick silos as well as, in other cases, depictions of circular silos adapted to a specific support (wood).

However it is important to stress that, in both cases (circular and square silos), we are dealing with airtight atmosphere (silos) and not with ventilated environment (granaries; Bats, Licitra in this volume).

The tombs of the XVIII[th] Dynasty, and more rarely those of the XIX[th] Dynasty, have provided representations of circular, domed grain silos. While the Middle Kingdom figurations highlight the features structuring the interior of the storage complexes (silo batteries, columns, staircases, doors, etc.), those of the New Kingdom tend to make these architectural elements disappear in favour of a wider view, where the silos are surrounded by an enclosure that is sometimes fortified and sometimes hosts a place of worship. The stored product is, for its part, well represented by dome-shaped heaps of grain. Some silos are nevertheless identifiable in some tombs of the mid-XVIII[th] Dynasty, such as those of Pehsukher (TT88, Virey 1891, p. 293, fig. 7), Ineni (TT81, Ni. Davies 1963, p. 20, pl. XXIII), and Nebamun (TT17, Säve-Söderbergh 1957, pl. XXII). The silos are depicted as large dome-shaped constructions, exceeding human height. The lateral opening, the trapdoor from which the grain is extracted, is systematically depicted: a quadrangular orifice located halfway up the structure or positioned at ground level, like a door in the tomb of Pehsukher. In the tomb of Ineni, this trapdoor seems to be closed, probably bricked up. The top opening is visible only in Pehsukher's tomb, where it is depicted as a quadrangular access in the upper part of the structure. However, unlike earlier depictions, it is not positioned in the centre of the dome but slightly on the side. Finally, we also note the representation of silos in the Djehouty-Nefer tomb (TT 104), for which only the hemispherical shape and especially the disproportionately large side door indicate the storage structure (Shedid 1988, pp. 125-127, pls. 5a, 27, 36a).

The access to the openings, both at the top and on the side, is signified in the tombs of Pehsukher and Nebamun. In the chapel of Pehsukher, a ladder provides access to the top opening, through which the grain was poured into the storage structure. More surprisingly, in Nebamun's tomb, a staircase leads to the side hatch, which also seems to be used for ensiling. This use of the side opening is also visible in the tomb of Ahmose (TT241, Shorter 1930, pl. XV), where, in this case, it is a bag of grain which is put into the silo.

The iconography analysis shows that no great change in the appearance of Egyptian mud-brick silos can be noted between the Early Dynastic Period and the New Kingdom. These storage devices had a cylindrical shape and were topped by a dome. Two openings are, in the vast majority of attestations, located on the top of the structure and on its side. In a few representations, mainly from the Early Dynastic Period and the Old Kingdom, two trapdoors are shown. These openings seem to have been blocked by a wooden board sliding inside the wooden frame before filling the silo, while the top opening was blocked after. The lid is sometimes signified by a diamond-shaped pattern.

1.2 Archaeological evidence

Circular built silos appear in Egypt during Naqada Period III. Although they are very common in Egyptian settlements, only few of them are preserved on more than a few brick courses. Despite this lack of information, it can be seen that these storage devices could have had very diverse forms (fig. 1).

1.2.1 Forms

Although few silos have been discovered preserved on more than one or two brick courses, some remarks on their form can be made on the basis of the archaeological evidence. Their bases are usually intended to be circular, even if a more or less irregular execution of the first mud-brick course can produce oval or uneven outlines. According to the height of the construction the inclination of the wall can give the silos a hemispherical (fig. 1, a-c), elliptical (fig. 1, d) or, in some cases, cylindrical (fig. 1, e) form. As the iconography shows, they were always dome-shaped (§ 1.1)

A small hemispherical silo has been discovered in the *shena* of Abydos (Middle Kingdom): the four layers of bricks preserved show that the courses were inclined inwards (Smith 2010, pp. 137-138). Similar silos are known at Balat/Ayn Asil (Late Middle Kingdom), where the great irregularity in their outlines depends on the unevenness in their construction. While some have a cylindrical body before the beginning of a cut to form the dome (see, for example, silo 1901, Marchand, Soukiassian 2010, p. 118, fig. 144), others show a sloping wall starting from the first brick course, giving them a hemispherical shape (Marchand, Soukiassian 2010, p. 118, fig. 144, silos 2298 and 2299).

Up to now, the best-preserved elliptic-shaped specimens, were discovered at Edfu and are dated to the Second Intermediate Period (Moeller 2010). Among them, silo 316 has a maximum external diameter of 6.12 m (north-south) and 5.5 m (east-west), while its total height was estimated at 5.2 m. At Kom Firin (Saite Period), the best-preserved silo – over a height of 2.38 m and a diameter of 2.5 m – has an irregular dome shape (Building X, silo 1065, N. Spencer 2014, pp. 164, 192, fig. 80, pl. 333).

Finally, the regular slender cylindrical shape, which is clearly visible in some representations, is attested in the Dahshur bent pyramid complex (Old Kingdom, Fakhry 1959, pp. 73-74, pls. 25 a and b; fig. 2).

The underground silos also offer important elements of comparison. Whether it is silo 096 from Elephantine

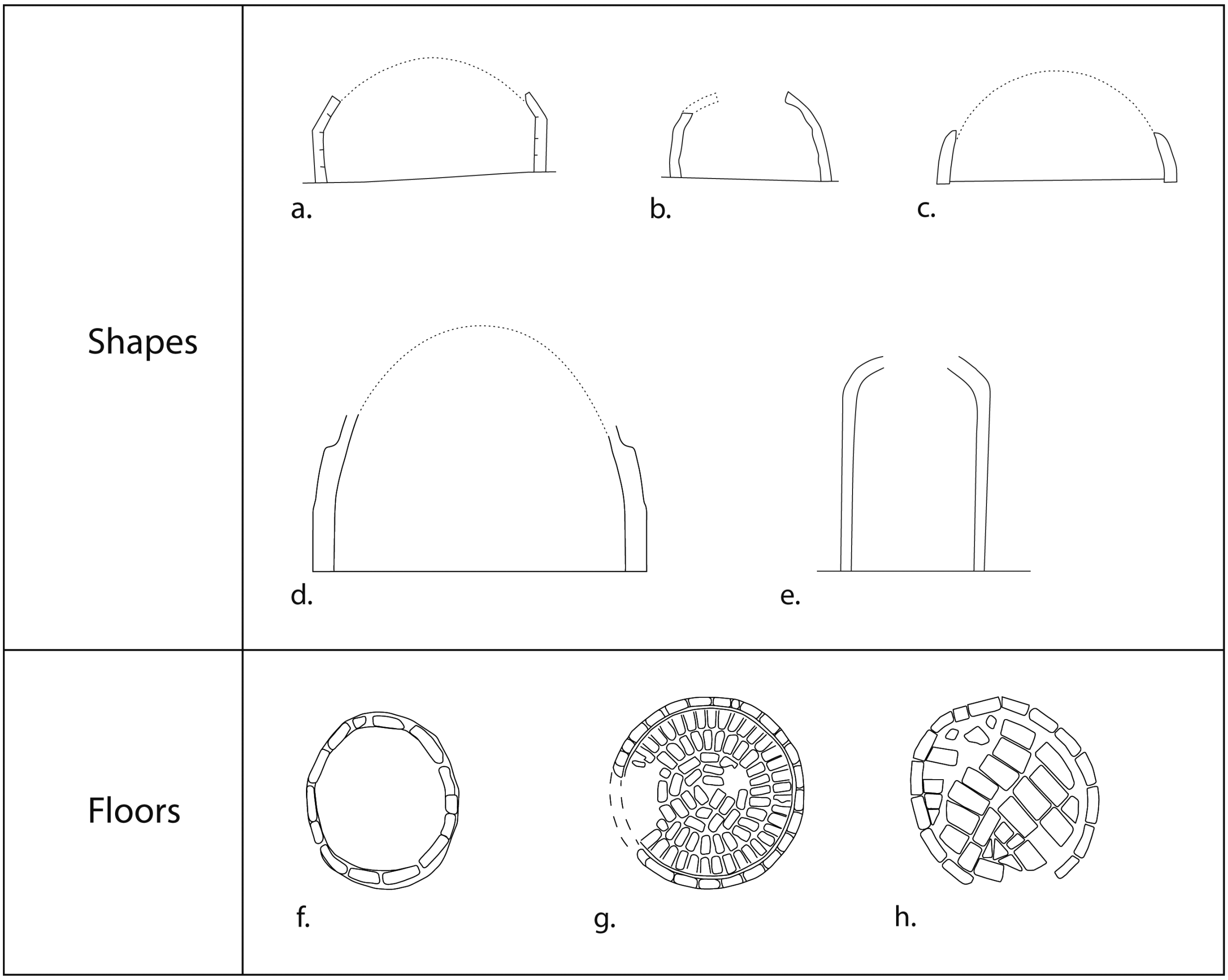

Figure 1. Variability of silo shapes and floors.

(Middle Kingdom; von Pilgrim 1996, p. 146, fig. 58) or silo 2131 from Balat/Ayn Asil (Late Middle Kingdom; Marchand, Soukiassian 2010, p. 117, figs. 141-142), one notices that the walls are straight, before a rapid narrowing of the shape, contrary to the free-standing silos. This cylindrical shape is also found for silos inserted in the masonry of tomb 3038 at Saqqara (Early Dynastic Period, W. Emery 1949, pp. 82-94, fig. 50), which have a slender profile similar to a bottle. A shallow dome crowns the high vertical wall.

The wall of a silo from Kom Firin, dating to the Saite Period, has been reinforced with four mud-brick buttresses, one of which is partly bonded with the silo brickwork (Building X, silo 1065: N. Spencer 2014, pp. 164, 189, 191-192, 215-218, figs. 75, 77, 80, pls. 328-331, 333-334, 336).

1.2.2 Foundations

Archaeological evidence shows that silos did not always have foundations. Foundation trenches are sometimes identified by archaeologists (see, for example, Millet in this volume), but in some other cases, they are indiscernible and their presence is only pointed out by the silo internal floor being located lower than the external one. As a matter of fact, most of the time the first mud-brick courses were laid inside the foundation pit, against the trench walls. In some cases, the silo first course has been laid 1 m below the external floor (Peet, Woolley 1923, p. 11).

When the trench is visible, it is often filled with soil mixed with ash and, sometimes, potsherds. The proportion of ash varies from one site to another. In House E of the Khentkawes town at Giza (Old Kingdom; Yeomans, Mahmoud 2011, p. 49), but also at Elkab (Early Old Kingdom: Claes *et al.* in this volume), at Balat/Ayn Asil (Late Middle Kingdom; Marchand, Soukiassian 2010, p. 111, figs. 139-140), and at Tell Hebua (Early New Kingdom; Abd el-Maksoud 1998, p. 115) an ash layer had been spread all over the base of the foundation. As a desiccant, ashes are generally considered to be an effective insecticide repelling certain pests in so far in several traditional societies they are added and mixed with the crops stored in the silo

Figure 2. Silos from the Dahshur bent pyramid complex. © Courtesy of the DAIK <D-DAI-KAI-A-FAK-062-001-111.

(Miller 1987; Hakbijl 2002; Scheepens *et al.* 2011, p. 39; Levinson, Levinson 1998, p. 141-142; Malleson 2013). It is likely that a similar precaution was taken by ancient Egyptians as some evidence from underground silos in Tell el-Amarna seems to indicate (Peet, Woolley 1923, p. 49).

1.2.3 Floors

At Edfu (Second Intermediate Period; Moeller 2010, p. 95) as well as some of the specimens of Tell Hebua I, the preserved internal floors of the silos are made of compact mud (silos SI.1, SI.16-SI.19, SI.9, SI.11-SI.15: Abd el-Maksoud 1998, pp. 60, 63-66, 136-137, 140-141, figs. 11-12, 15-16, pl. VA). At East-Karnak, archaeologists have identified a mud plaster and a bed laying of clean white sand 2 to 3 cm thick on top of that (Middle Kingdom – Second Intermediate Period; Redford *et al.* 1991, p. 95). Others silos are paved with bricks, notably at East-Karnak (Middle Kingdom; Millet, in this volume, fig. 6, silo SI1), at Balat/Ayn Asil (Marchand, Soukiassian 2010, pp. 111 and 116, fig. 140) or also at South Abydos in the annexes of Senwosret III's Temple (end of the Middle Kingdom; Wegner 2021, pp. 324-326, fig. 35). Bricks can be more or less well organised, jointed, and sometimes laid in rows of headers with half-bricks or fragments of bricks used to fill the gaps (Abd el-Maksoud 1998, pp. 61, 137, 140, figs. 12, 15: silo SI.6). At Tell el-Daba', similar arrangements are also documented (Second Intermediate Period; Bader 2020, plan 1 [Silos L158 and L172], plan 5 [Silo H-M1]) as well as a concentric one (Bader 2020, plan 3 [Silo G4-M22]). Silos paved with bricks laid in circles are also known in *Haus* 84 at Elephantine (Middle Kingdom; von Pilgrim 1996, pp. 92, 231-234, fig. 26) and at Tell Hebua I (Abd el-Maksoud 1998, pp. 61, 137, 140, figs. 12, 15: silos SI.4-SI.5). Finally, it is noteworthy that at Umm Mawagir (Middle Kingdom, J. Darnell, C. Darnell 2016, p. 46, fig. 14), in the Western Desert, silo 406 is paved with local limestone slabs that are rough but fitted together to create a smooth floor. The archaeologists believe that the small size of the structure and the paving indicates a storage space for flour or bread dough.

1.2.4 Walls

Circular silos are normally built with bricks laid as stretchers. At Edfu, silo 316, dated to the Second Intermediate Period and, up to now, the best-preserved silo of the Pharaonic period, has been built by alternating courses of headers and stretchers instead. Starting from the nineteenth course, where the dome started, the thickness of the wall has been reduced to a single row of bricks (14 cm), probably to lighten the upper part of the structure (Moeller 2010, pp. 91-93). Silo inner and outer surfaces were usually coated with plaster, right down to the foundations. The water tightness of the silo was thus reinforced by the application of this layer, which could be re-applied regularly. The well-preserved silos of Edfu, as silo 1065 discovered at Kom Firin (Saite Period, N. Spencer 2008, fig. 30, pl. 333), show that the constructions were very irregular, contrary to what the iconography indicates. This impression is also perceptible when only the foundations are preserved since circles on the ground are often uneven.

1.2.5 Openings

The top opening, used to put the foodstuff into the silo, has not been archaeologically documented to date, due to the poor state of preservation of the silos. At Balat/Ayn Asil, the diameter of a silo top opening has been tentatively estimated at 31 cm (Marchand, Soukiassian 2010, p. 111, n. 5). At Umm Mawagir, in Kharga Oasis, a 9 cm thick potsherd, found near a silo, has been interpreted as the cap of the top opening (J. Darnell, C. Darnell 2016, p. 46). Access to this top opening can be challenging to understand. It can be assumed that for small silos, an adult could easily put the grain in them from above. The representations of the tombs show the existence of ladders (see above, Pehsukher tomb). However, at Tell el-Amarna, small spiral staircases around some silos have been discovered (for example, Houses T35.3, T35.6, T35.9 and T.36.11: Frankfort, Pendlebury 1933, p. 37, pls. VII, XVII; Lloyd 1933, p. 3, fig. 1).

A lateral door – the original dimensions of which are unknown – was discovered partially preserved in silo 316 from Edfu (Moeller 2010, pp. 91-92, fig. 5), while L. Borchardt documented the remains of a rectangular (60 cm large and 90 cm high) lateral opening on a silo from el-Lahun (internal diameter: 2.64 m; Arnold 2005, pp. 96-97, fig. 11, pls. 11-12. Similar proportions are documented at Amarna where four silos from the house of Ranefer (N49.18) measuring about 2.5 m in internal diameter were provided with lateral openings 50 cm large (Peet, Woolley 1923, p. 11, pl. VII/2).

On the contrary, the silos discovered in the XIII[th] Dynasty settlement of Balat/Ayn Asil were devoid of any lateral trapdoor: since their total height should not have originally exceeded 1.50 m, these devices were likely emptied through the top opening, as would have been done for underground silos (Marchand, Soukiassian 2010, pp. 111, 121, fig. 150). Similarly, at Kom el-Firin (Saite period, N. Spencer 2008, p. 164, fig. 80, pl. 333), no side trapdoor was identified, despite the preserved height of 2.38 m of silo 1065. The archaeologists considered that the only access must have been from above, especially as the space left between the northern edge of the silo and the wall 1174/1676, 1.24 m wide, would have allowed for the positioning of a ladder. Finally, silos inserted in the masonry of tomb 3038 at Saqqara (Early Dynastic Period, W. Emery 1949, pp. 82-94, fig. 50) have two openings. A ceramic cover plugged the top opening, while the side opening was closed by a stone and sealed with a clay plate.

1.3 Building materials

1.3.1 Mud-bricks

For a detailed description of mud-bricks as building materials, see Bats, Licitra in this volume.

1.3.2 Mortars and plasters

In the same way, for a general description of mortars and plasters used in mud-brick architecture, see Bats, Licitra in this volume.

In silo construction, mud mortar was used for brick joints, while mud plaster was employed to coat internal and external surfaces, as well as floors. Sometimes they are both preserved (see, for instance, Moeller 2016, p. 92 and fig. 6). Macroscopic observation regularly shows the presence of a levelling coat applied directly onto the silo wall, and one or more layers of finishing mud plaster. In some cases the latter is whitewashed with a gypsum-based coat.

1.3.3 Ashes

As previously said (§ 1.2.2), ashes were often used to fill foundation trenches because of their desiccant properties repelling pests. In some cases, they also filled voids between adjacent silos (see, for instance, Yeomans, Mahmoud 2011, p. 49) or between silos and contiguous walls (Moeller 2010, p. 94). At Balat/Ayn Asil, considerably amount of ashes have been added to the mix used for the mud-brick of the square silos in the annexes of the governors' chapels (Soukiassian *et al.* 2002, p. 289). As a desiccant, ashes probably played a role in the absorption of moisture as well (Scheepens *et al.* 2011) and kept the silos dry. It is noteworthy in fact that they were used in the *chaussées absorbantes* of the streets of Mari and the cities of northern Mesopotamia to absorb rainwater (Margueron 2004, p. 142).

1.3.4 Sand

Sand, acting as a capillarity barrier, has sometimes been used in silo foundation trenches (Millet in this volume). For the same reasons, in some cases, a sand layer has also been spread over the clay floors (N. Spencer 2014, pp. 41, 92, fig. 48 [Silo 0693]).

1.4 Silo capacity

Silo internal diameter (not the external one) and internal height were the two dimensions needed to calculate the original internal volume, i.e., the silo capacity.

With regard to the silo dimensions, as it has already been stated (§ 1.2), for the time being, there is no archaeological evidence of a silo wholly preserved and only the iconography gives an idea of the silo's overall shape and proportions. Because of the state of conservation, the original height of a silo has therefore never been archaeologically recorded, even if, in some cases, it has been supposed with a very good approximation (Marchand, Soukiassian 2010, pp. 111-121). On the contrary, diameter is the only dimension that is usually documented in the field. Nevertheless, with some exceptions (as an example, for 10-cubits silos see: Bietak *et al.* 2001, pp. 60-61, fig. 19; for 5-cubits silos: Arnold 2005, p. 96), no regular correspondence of internal diameters with ancient Egyptian units of measurement – cubits, palms and digits – could have been recognised, not even in a large and chronologically uniform group such as the 46 silos of Balat/Ayn Asil, whose (internal) diameters vary from 1.24 to 2.90 m (Marchand, Soukiassian 2010, p. 121, fig. 150). As a matter of fact, most of the time, conversion of recorded metric diameters into Egyptian cubits does not reveal any significant correspondence, which could satisfy our, often unconscious, expectations for exact figures.

Concerning the internal volume, a wide variety and variability of silo profiles can be observed as well, while seeking some rule or proportion does not yield any significant results either. This frequent lack of conformity in silo dimensions with predetermined numeric values could be surprising, especially since it can be argued that silo construction demands a quite precise execution of the original plan to know its size/capacity and calculate the exact amount of cereals stored in it.

Problems reported in mathematical papyri seem to relate to the calculation of internal volumes of cylindrical (Papyrus Rhind nos. 41-43: Peet 1923, pp. 80-83, pls. M and N; Papyrus UC 32160-2/Kahun IV.3: Imhausen, Ritter 2004, pp. 84-89, see also Michel 2014, pp. 385-393) or rectangular (Papyrus Rhind nos. 44-46, Peet 1923, pp. 84-87, pl. N, see also Michel 2014, pp. 374-384) grain containers. The volume (in cubic-cubits) is firstly calculated on the base of their linear dimensions and is then converted into their respective capacity units (bags *ḫꜣr*; C. Rossi, Imhausen 2009, p. 444; Pommerening 2005, pp. 135-136).

However, archaeological evidence shows that the precision of the dimensions was not sought during the building process, which leads to assume that the capacity of a silo was accurately estimated only at the time of ensiling using the number of grain bags poured into it. This interpretation is supported by the systematic representation of scribes during the ensiling operations both in the models and in the two-dimensional representations mentioned above (§ 1.1).

As it has been pointed out (C. Rossi 2020, pp. 236-238), this is only an apparent discrepancy due to our modern conception of planning and building, since for ancient Egyptians, the accuracy of the measuring operation was more important than the resulting figures. One can therefore suppose that the mathematical formula for calculating the volume capacity of cylindrical containers was used to have a rough estimate of the size of a silo to be built. Close adherence to the plan would not have been sought during the building process since the calculation of the grain stored was made employing the number of bags.

In addition, the silos were not perfect cylinders with flat tops. On the contrary, if their base was circular, their walls were inclined, and the top was domed. This outline did not allow for exact calculations but only approximate ones. It can be assumed, by comparison with the variability of the Ramesseum's vault outlines (Goyon *et al.* 2004, p. 128, fig. 132d) that also domes were built freehand with empirical methods (still used nowadays in the construction of the Nubian vaults: Fathy 1996, p. 36, pls. 7-8).

Finally, in light of the silo operation in an airtight atmosphere and in order to minimise the amount of oxygen inside the construction (Bats, Licitra in this volume), it has to be stressed that the capacity of these storage devices likely corresponded to their full capacity rather than their two-thirds as it has been sometimes assumed (Marchand, Soukiassian 2010, p. 115; N. Spencer 2014, p. 32).

1.5 Brick size and bonding

Archaeological reports usually describe the bricks of the silo walls, while no dome fragments could have been identified as such. Therefore, it is unknown whether the same bricks were used for the wall and the dome.

In most of the archaeological data there is no conformity between brick size and silo dimensions. It seems more likely that, at least in domestic contexts, silos were built with bricks (and brick fragments) available at that moment (new and/or reused).

Moulded rectangular mud-bricks are primarily used in silo construction, even if some exceptions are known. Slightly trapezoidal specimens are documented in the remains of a large silo (external? diameter: 5.80 m) in the Pharaonic town of Sai Island (area SAF5; Azim 1975, pp. 113-115 and pl. XI, fig. 1). Three sizes have been recorded: 51 x 37 cm, 34 x 29 cm and 44 x 32 cm (Adenstedt 2016, p. 35). Their date remains uncertain, but they preceded the storerooms' construction in the area SAF5 at the beginning of the XVIIIth Dynasty. Four other silos (diameter: 5.45 up 7.20 m), erected in the same area after the abandonment of the storerooms, have been built with square mud-bricks measuring 35 x 35 cm (Adenstedt 2016, p. 35).

At Amarna, curved bricks (39 x 16 cm) have instead been used for a silo in the house Q44.1, showing the existence of special moulds used for this production (Kemp 2012, p. 70, fig. 2.26).

With regards to rectangular mud-bricks, the standard brick length:width ratio is 2:1 (J. Spencer 1979, p. 143, 147 and pls. 41-43) since the origin of the Egyptian mud-brick architecture (Buchez *et al.* 2021, pp. 117, 122-123; Buchez *et al.* 2022, pp. 63, 68-69). The size of the bricks used in silo construction does not seem to differ from the ones employed for mud-brick walls. For instance, at Edfu, mud-bricks used in silo construction are between 28 and 34 cm long (Moeller 2010, p. 90, table 2), while silos from Tell Hebua I have been built with bricks up to 38 cm long (Abd el-Maksoud 1998, pp. 60-61, 63-66, 73: silos SI.1-SI.6, SI.16-SI.17, SI.9-SI.15, SI.01-SI.03).

As for silo size, for mud-brick size a discrepancy exists between written sources and archaeological evidence. Papyrus Reisner I (I, 21) generically mentions "large-size brick" (*ḏb.t ꜥꜣ.t*) without any additional information on the brick measurements (Simpson 1963, pp. 57, 76). On the other hand, an El-Lahun papyrus (Khaun III.1 A recto: F. Griffith 1898, p. 59, pl. 23, ll. 38-39; Simpson 1960) recording mud-bricks of 5 palms (= 37 cm) and 6 palms (= 45 cm) shows that exact units of measurements could be chosen for brick size. Nevertheless, the dimensions of bricks discovered in the field rarely correspond to an exact number of palms or digits.

The reuse of mud-bricks is a well-known phenomenon that archaeologists constantly observe in several kinds of buildings, especially in domestic contexts. The practice is also attested in a written source, a Greek papyrus (P.LilleDem. III, 102 = Inv. Sorb. 276) relating a mud-brick account where the distinction is made between new and old bricks to be used in the construction of temple annexes (de Cenival 1984, pp. 55-61). As regards to silo construction, reused mud-bricks or mud-brick fragments have often been documented: for instance, at Elephantine (von Pilgrim 1996, p. 92, figs. 26, 59, 65), Elkab (Claes *et al.* in this volume), Karnak (Millet in this volume), Zawiet Sultan (Moeller 2016, pp. 217-218, fig. 7.2) Tell el-Dab'a (Bader 2020, pp. 151-152, fig. 5.1 [silo H-1], plan 1 [Silos L158, L159, L132, L134, L171, L172], plan 2 [Silo G3-M23], plan 3 [Silos G4-M5 and G4-M22], plan 5 [Silos H-M1 and H-M2]), and Kom Firin (silos 0864 and 1096: N. Spencer 2014, pp. 37, 69, 164, 197, figs. 24, 92). This is not surprising, especially since, as the examples mentioned above show, in silo construction, brick fragments limited the width of vertical joints along the external side of the wall and thus ensured a regular profile and bricklaying of better quality.

Finally, with no silo dome being preserved, it is impossible to say if bricks of smaller size were used for the upper courses of the construction.

In the absence of preserved elevations, only the first courses of the archaeologically attested silos bear witness to the bonding used for these storage devices. According to the available archaeological evidence presented above (see also Millet in this volume), the silo's wall was usually made of stretchers or bricks laid on edge. Even for silos with large diameters, the wall is usually thin, often not exceeding 10 cm. Nevertheless, some notable exceptions are known, among others, at Kom Firin where the wall of silo 0864 was up to 25 cm thick (N. Spencer 2014, p. 37, fig. 24) and at Edfu, with silos Si 303 and Si 316 built by alternating courses of headers and stretchers (Moeller 2010, p. 86, fig. 3).

For floor bonding, see § 1.2.

2. Historical comparatism and ethnographic parallels

Adeline Bats

Circular earthen silos are known from other civilisations, both ancient and modern, in Africa and the Near East. Remains of free-standing silos are also attested in ancient Sudan and Near East. Likewise, as in the northern Nile Valley, several models of silos have been discovered in the Near East, Crete and Greece (Muller 2016, pp. 122-124). These regions offer relevant comparisons for the study of silos in ancient Egypt, to better understand their architecture and construction principles, but also to apprehend the modes of conservation of foodstuffs. However, care should be taken not to transpose this information without due caution.

Silos built of mud-bricks appear in Sudan in the Ancient Kerma period (Marchi 2017), a little later than in Egypt. Similar to the northern silos, many examples have been found in the city of Kerma. Circular or oval, these storage devices are built of mud-bricks laid as stretchers or on the edge. In the centre, the floor is made of rammed earth or stones of uniform dimensions. These silos are found in the courtyards of houses, sometimes protected by a canopy. Some are raised about twenty centimetres above the floor of the house, while low walls can support the larger ones. During the Classical Kerma period, the silos become wider and the walls thicker. In Sudan, silos are still found at several sites from the Meroitic period such as Muweis and Meroë (Choimet, forthcoming). Finally, in modern Egypt, mud-brick silos – or similar storage devices – are known. These buildings have not been published.

In addition to the silos located outside the houses, small silos are also positioned inside. The *ṣafat* is an earthen construction located inside houses for storing grain or for serving as a storage chest (Castel 1984, pp. 147-148). These containers are raised with stones or bricks to protect the food from rodents. Grain stores are cylindrical, consisting of two or three spaces, with an internal volume of 1 and 2 m^3. The grains are poured in through an opening at the top. When the *ṣafat* is filled, this opening is hermetically sealed. Side openings – one for each internal compartment – allow the grain to be recovered. Nevertheless, ethnographic observations point to recurrent openings and, thus, a different functioning of the airtight silos. Similar facilities are also known in Sudan as *gossi* (Tahir *et al.* 2015) or *quseba* (W. Adams 2000, p. 35) where they seem to have appeared during the Christian period. They are usually built with alluvial soil mixed with donkey or cattle dung and placed on stones to isolate them from the ground. To reduce the risk of stock deterioration, the grain is exposed before storing to the sun to reduce the moisture content and kill any insects in the stock. Nubian women waterproof the interior with sticky mud mixed with lime. Plant fibres can be incorporated into the walls to strengthen them and prevent erosion during rainfall.

In the Near East, the first free-standing silos appeared during the Neolithic period (Van der Stede 2010, pp. 363-365). These structures were built of brick or stone and could have had flat or domed roofs. Several seals dated to the 4th millennium give a more precise idea of the elevations. The silos are integrated into rectangular buildings and are individually covered with a dome. The cereals are then stored in the top part, accessible by a ladder or a staircase[16] (Faivre 2017; Patrier 2009).

Olivier Aurenche lists cylindrical or conical modern silos in Turkey and Syria, for which two openings (top and side) are known (Aurenche 1977, s.v. "silo", pp. 158-159). The recorded examples show small mobile earthen silos positioned inside houses (Aurenche 1977, fig. 432, Sumatar, Turkey). These silos are cylindrical in shape with a top opening and they are similar to the Egyptian *ṣafat* (cf. *supra*). Other earthen silos are located outside the houses (Aurenche 1977, figs. 433 and 434, Mureybet, Syria). They have a conical shape with an opening on one side. Finally, a rectangular silo for storing straw is also recorded outside the houses (Aurenche 1977, fig. 435, Mureybet, Syria). Other ethnographic parallels show two possible top coverings: the dome, as described above, and the flat roof built of plant materials. It has been stressed that the domed roof generally used to cover large structures has the undeniable advantage of favouring the outward radiation of the heat accumulated in the bricks (Seeden 1982; van der Stede 2010, p. 365). Smaller silos were variable in shape, from a half-sphere to a cylinder, and without a trapdoor. In the 1930s, Taufik Canaan documented a methodical description of the construction of silos made of plant fibres or stone in Palestinian land. It is a *šūneh* for storing straw for fuel or construction (*qaṣwal*). The stages of construction of this building are described:

> "A circle of the size of the base of the *šūneh* is made of bundles of dry sesame stalks. They are laid horizontally on a hard layer of earth and the bundles must first be tied together. In one side – generally the south or east – a small opening not larger than 40 x 50 cm is left as a door, *bāb eš-šūneh*. It is made of three stones, the two vertical serving as the jambs and the horizontal as the lintel. They are held together by clay mud. The circle is filled with *qaṣwal*. A second layer of sesame-stalk bundles is laid on the first one. The bundles of the second layer interlace with those of the first and with each other, thus making a firmer structure. The higher the layers are raised the more *qaṣwal* is introduced and the smaller the circles become. At time maize stalks, *ʿuram ḍurah* and other brushwood may be used instead of, or with the sesame bundles. This is only done when the latter material is not found in sufficient quality, for sesame stalks are preferred above all the other material. When the whole conical structure is complete sometimes the outside of the *šūneh* is covered with a layer of *djilleh*, called also *laṭ* (cow's manure), to prevent rain water from leaking in. From the top of the *šūneh* protrudes a perpendicular piece of wood (*Qbāb*) or a stone (*el-Barriyeh*). This is known in the Ramleh and Jaffa districts as *rās* (or *rāsiyet*) *eš-šūneh* and in some villages of the Djenīn district as *qassīs*. Some *šūnehs* are very large and symmetrically built. In el-Barriyeh the present writer saw some with diameter of 3-3.5 m and a height of 4 m. In poorer villages they are smaller and carelessly built. The small opening left at the bottom serves for drawing the *qaṣwal* as needed. The *bāb eš-šūneh* is closed by a wooden door or by stones" (Canaan 1933, pp. 47-49).

T. Canaan also presents alternative constructions:

> "A substructure 1-1.50 m high is built of rubble stones held together by mud. This structure may have a round or a square ground plan. The walls are raised perpendicularly. The conical part, of sesame stalks, rests on the walls.
>
> A simple wooden frame is erected in cone-shape fashion. The several boughs (*ʿūd, ʿīdān*) are united by sesame or maize stalks. The whole is covered by *djilleh*. This method of making a *šūneh* is rare" (Canaan 1933, pp. 47-49).

Although the materials used for these silo constructions differ from those used by the ancient Egyptians, some similarities can be noticed, such as the circular and conical shape, a lateral opening for the collection of straw, and an external plaster for waterproofing. On the contrary, these

16 Louvre SB 2141; Louvre SB 2027; Louvre SB 1979; Louvre SB 1964; Louvre SB 6302; SB 1958.

silos were built with plant stems mixed with raw earth or stones with raw earth and were used to store straw. The straw was stored as it was built, a process that does not require the construction of a top opening. Straw storage in a silo was still practiced in Europe at the beginning of the 20th century (Chancrin, Dumont 1921, *s.v.* "silo", p. 577).

A wide variety of storage devices, often designated as "granaries" without considering the storage technique that induces a distinction between "granary" and "silo", are attested in West Africa.[17] In her article on this subject, Labelle Prussin indicates that the construction technique of these storage devices is similar to that used for shaping ceramics (Prussin 1972). In Cameroon today, several storage devices are known: *banco*[18] silos (the most common), wickerwork silos, grain-pits / underground silos, small containers stored in indoor granaries or hanging jars, sacks, and even metal barrel (Seignobos 2005). *Banco* silos have different storage capacities (between 1m^3 and 4.5 m^3). In his article, Christian Seignobos discusses the role of silos in the management of food stocks. They are part of the complex management of reserves, where the use of storage devices is alternated. For example, granaries made of plant materials are intended for short-term storage and conservation. The silo is used for the long term. In practice, the storage strategy follows that of millet consumption. "Dirty millet" (badly winnowed) is consumed first, and then millet stored by women in their granaries is eaten. Afterward, the silo of the head of the family is unsealed. The author also indicates:

> "La conservation ne pose pas de problèmes pendant la saison sèche où le grain est dur, sa faible teneur en eau limitant les effets des insectes ravageurs. La saison des pluies, avec l'humidité qui ramollit les grains, ravive, en revanche, les attaques parasitaires à partir de larves ou d'œufs présents depuis la récolte. Les dégâts sont généralement plus importants sur les sorghos que sur les petits mils, et sur ces derniers que sur les éleusines, qui ont la réputation d'être quasi inattaquables. Les réserves entamées semblent plus vulnérables que celles des silos pleins, dans lesquels il se crée un microclimat relativement indépendant des changements hygrométriques extérieurs et de la composition chimique du milieu ambiant, la diminution du taux d'oxygène renforçant la conservation" (Seignobos 2005, p. 107).

Finally, in protohistoric and medieval Europe, silos were built underground (see Bats, Licitra in this volume). However, in modern times, several built silos can be found in the countryside. These are semi-subterranean buildings made of baked bricks or cement. The roof is made of wooden boards that are then covered with earth (Chancrin, Dumont 1921, s.v. "silo", pp. 577-579; Sigaut 1978).

3. The experimentation[19]

Adeline Bats, Nadia Licitra & Thierry Joffroy

3.1 Working with architects specialised in earthen architecture

The data collected during the first phase of the project and presented in the previous paragraphs has been discussed with all the participants in the project in order to set a scientific protocol for the construction of the first silo prototype. A 3D model created by Angèle Keserwany (ENSAG, DSA student) with the software Rhinoceros®-Grasshopper® to test the different hypotheses and propositions as the conception process went along has also been useful to estimate the number of mud-bricks needed and to plan the bonding principles.

The main difficulties encountered in the prototype design concerned, firstly, those parts of the construction for which sufficient data was missing (the dome in particular). Secondly, the lack of ancient Egyptian know-how in building the silo according to its elliptic profile free-hand has led to the use of a specific tool. Thanks to his expertise and experience in the construction of vaults, Thierry Joffroy proposed to use a mechanical arm of his invention drawing ellipses in space as a guide to lay down the upper mud-brick (inclined) courses. At the same time, this was a good method for the team to get acquainted with the construction of architectural elliptical profiles. The benefits of this choice already appeared during the construction of the second prototype, when the mechanical arm was abandoned in a very natural way, the experience with the first prototype having provided a good understanding of the inclination which had to be given to the upper courses of the construction.

Quickly during the exchanges, a divergence clearly emerged between the ancient Egyptian practices and the approach used in contemporary architecture concerning in particular the idea of accuracy. The bonding initially conceived by the architects, with bricks of different lengths regularly and carefully alternating to avoid too large joints, was too "clean" compared to the archaeological evidence. During the experimentation, it has become clear that ancient Egyptian builders worked with a more significant degree of what we would wrongly

17 On the different storage devices identified in West Africa by enthoarchaeology, see Mayor, Pelmoine in this volume and Seignobos 2017, pp. 54-59.

18 *Banco* is a mixture of mud, straw and water.

19 More pictures illustrating the different stages of the experimentation can be found here: https://stockagenil.hypotheses.org/.

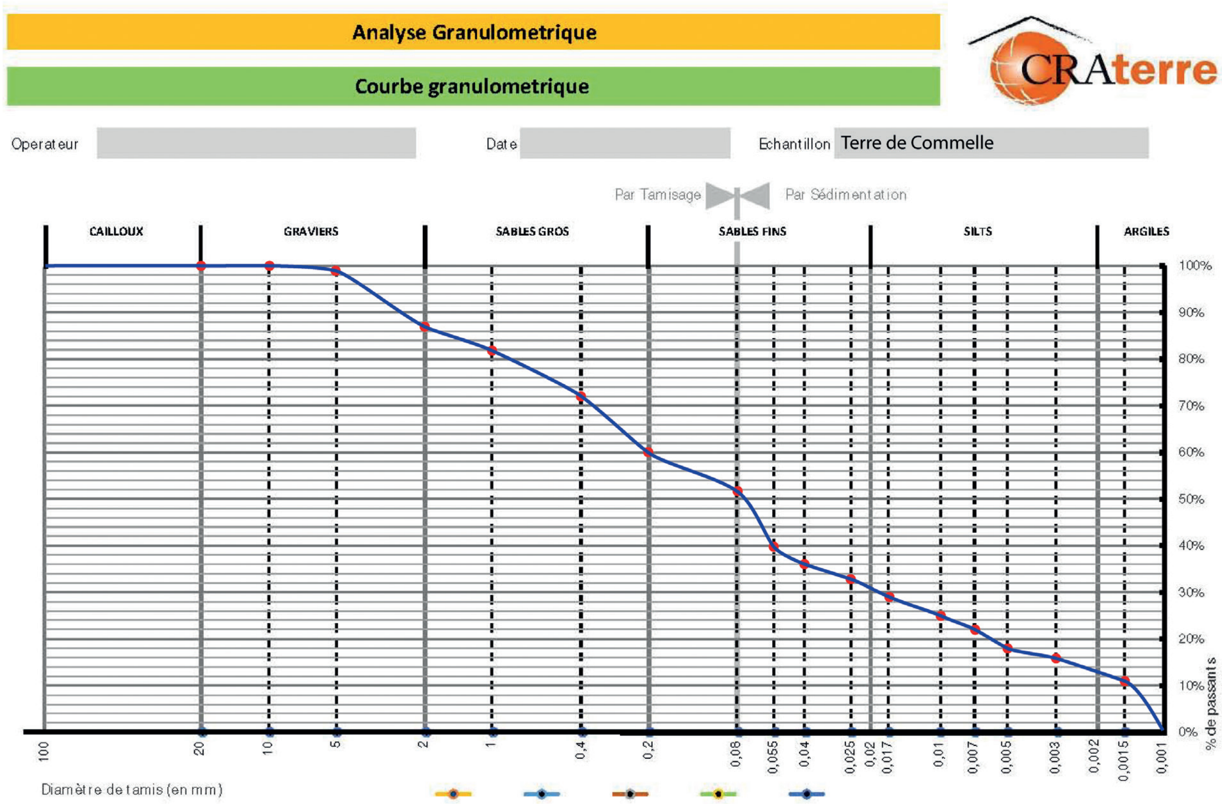

Figure 3. *Terre de Commelle*: particle-size distribution curve. © CRAterre.

call "approximation". Actually, the place of a brick or the width of a joint was more set by experience than based on a predetermined design.

3.2 Technical choices and implementation

For the first prototype, several hundred bricks – made of earth, straw, and sand – were produced in the week before the experiment by the students of the DSA "architecture de terre" of the École Nationale Supérieure d'Architecture of Grenoble (ENSAG).

The chosen soil used was the *terre de Commelle*, a sediment whose sources are located near the Commelle village (about 60 km north-west of Grenoble). As shown in fig. 3, it has a high percentage of fine fractions presenting similarities in particle-size distribution with Egyptian soils. The mix used has been prepared according to the following recipe: 1 volume of *terre de Commelle* + 2 volumes of sand + 0.5 volume of straw + 3-4 litres of water. The shrinkage rate observed did not exceed 1.4%.

The same ingredients have been used for the joint mortar of the silo's wall, but with a slightly higher percentage of sand: 1 volume of *terre de Commelle* + 2.25 volumes of sand + 0.5 volume of straw. Conversely, a less sandy mortar has been produced for the dome courses to improve its adhesive properties: 1 volume of *terre de Commelle* + 1 volume of sand + 0.25 volume of straw.

No sand was added to the mix for the plaster and only 1 volume of *terre de Commelle* + 1 volume of straw were used.

The mixtures were kneaded through a compulsory mixer, while the bricks were moulded by hand with wooden, single (for large bricks) and double (for small bricks) moulds crafted for the purpose (fig. 4).

With regards to the conception of the construction, in accordance with the archaeological data evoked in the previous paragraphs (§ 1.2 and 1.3), the silo's dimensions have been established in ancient Egyptian units of measurement in order to adopt a "historically correct point of view" (C. Rossi 2020, p. 230). For financial reasons – the aim of the experiment being the grain ensiling – a silo of small size has been preferred, in order to ensile a reasonable volume of grain while limiting the costs linked to the price of cereals. Therefore, the chosen size for the prototype was 2 Pharaonic cubits (i.e., 104 cm) in internal diameter and 3 cubits (i.e., 156 cm) in internal height for an internal volume of ca. 1.5 m^3.

During the modelling phase, we could already observe that this diameter/height ratio resulted in a shape perfectly

Figure 4. Moulding small mud-bricks. © María Lidón de Miguel.

corresponding to the elliptical one illustrated by some iconographic representations (see § 1.1).

The same concern for consistency with the Egyptian units of measurements led to the choice of bricks of 4 x 2 x 1 palms (30 x 15 x 7.5 cm) for the silo wall. Nevertheless, because of the lack of data concerning brick size and bonding of the upper part of most ancient Egyptian silos (§ 1.5), after careful discussion within the team, Thierry Joffroy's advice was followed and it was decided to build the dome with smaller bricks measuring 2 x 1 palms (15 x 7.5 cm) and 5 cm in thickness. The use of lighter elements along with a more adhesive mortar, previously mentioned, would have facilitated the laying down of the upper, inclined courses and prevented the bricks from slipping during the drying of the mortar. Such a variation in brick size in the same construction would not be unusual since bricks thinner than those employed for the walls were also used in the construction of the inclined courses forming the Nubian vaults (J. Spencer 1979, pp. 141-142).

3.3 Construction of the silo prototypes

The construction of the first prototype built at the *Grands Ateliers* in Villefontaine started by drawing the silo's circumference (1.04 m) on the floor. A string, 52 cm long, was fastened to a wooden pencil set in the centre of the circle while a small piece of chalk tied to the other end has been used to stretch the string straight and trace out the circle.

Then the first course was built by laying bricks, half-bricks and fragments of bricks as edger-stretchers along this drawn outline. The second and third courses have been laid down similarly by alternating bricks and half-bricks. Once the third course was built, at about 45 cm from the floor, a square opening measuring 30 x 30 cm was put in place in the side wall (courses 4 and 5), its wooden lintel being laid on the fifth course of bricks (§ 1.2.5). Since the prototype was not intended for ensiling, the wooden hatch usually closing it was not crafted and only the construction process of the opening was tested.

Starting from the fourth course, the mechanical arm was put in the centre of the silo's circumference to help, first, with the inclination of the next courses and, then, the dome construction (fig. 5). Courses from fourth to seventh were gradually inclined following the profile outlined by the arm. From the eighth course, small bricks were used to form the dome and seven more courses were added. A second circular opening (about 30 cm in diameter) was set on the top and an earthen hand-shaped stopper with a high percentage of vegetal fibre was crafted to close it.

Finally, the silo external surfaces were coated with mud plaster (fig. 6).

Figure 5. Bricklaying the mud-brick courses with the help of the mechanical arm. © María Lidón de Miguel.

Figure 6. The first silo prototype at the end of the experimentation. © Adeline Bats.

The second prototype, of the same size as the first one (1.04 m in internal diameter, 1.56 m in internal height), was built a few weeks later, in June 2021 in Roland Feuillas' bakery-farm *Les Maîtres de mon Moulin* in Cucugnan (France, Aude department). The building protocol followed was very similar to the one implemented in the *Grands Ateliers*, as well as the building materials – especially mud-bricks and mortar – which had been mostly reused from the first prototype. The mortar in particular was prepared by crushing, rewetting and mixing the remains of the mortar used for the first silo, along with some bricks from the same work.

Since the silo was built outdoors, after the clearing of the construction site, a foundation pit measuring 1.60 m in diameter was dug to a depth of about 20 cm (16 cm at the front and 23 cm at the back) and partially filled with a layer (about 2 cm thick) of wood ash from Roland Feuillas' bread ovens.

The first course of edger-stretcher mud-bricks (30 x 15 x 7.5 cm) was laid directly on this ash layer and the following four were erected vertically, without any side opening (fig. 7). Then, the mechanical arm was installed in the centre and guided the laying of the following two courses, increasingly inclined towards the interior of the silo. It has to be noted that despite the use of the mechanical arm to lay down courses 1-8, the circular shape of the silo in the first vertical courses was gradually lost becoming oval in the upper courses. At the same time, during the construction process, less and less assistance from the arm was needed and the bricks were laid intuitively. From the eighth course onwards, smaller bricks (15 x 7.5 x 5 cm) were used, laid as stretchers.

Figure 7. The second silo prototype. The bricklaying of the first mud-brick courses. © Aurélie Feuillas.

Figure 8. The second silo prototype at the end of the experimentation. © Aurélie Feuillas.

As the courses were laid, the external and internal surfaces were coated with mud plaster identical to the mortar used for joints between bricks.

During the construction, a plastic pipe was installed in a mortar joint between two courses of bricks to set later a probe to record temperature and relative humidity variations inside the silo. Once the construction was completed (fig. 8), the silo dried for several weeks before the grain ensiling. Contrary to the first prototype, no side opening has been built since it was planned to disassemble it and excavate it – course after course – to observe and document any areas of rotting or infestation of the grain. If the grain had been wholly evacuated through the side opening, no observation could have been possible.

3.4 Grain ensiling

Texts and iconography point to several commodities stored in Egyptian silos. Food grains, starch wheat, and common barley are widely mentioned, although malted barley, hulled wheat, tubers, and even fruits could also be kept in these storage devices (Bats 2019, pp. 224-226).

The ensiling of cereals in the second prototype was made on 1 September 2021 due to a particularly wet summer that resulted in a late harvest (fig. 9). According to organic farming principles, the agronomist Bastien Lamouroux selected "Bérénice barley", a semi-ancient and organic two-row common barley grown in the Gers department (France). Having noticed rising dampness inside the silo during the weeks of its drying, he suggested placing a straw layer

Figure 9. Pouring the barley into the second silo prototype. © Adeline Bats.

about 3 cm thick at the bottom of the structure. Using straws to slow down the rising dampness of the soil is well-attested by ethnography.[20] In total, 580 kg of barley were poured into the experimental silo. The progressive pouring of the barley caused the spread of a lot of chaff and dust, which made the atmosphere above the silo cloudy. Final mulching was then carried out before the silo was closed to reduce the oxygen level inside to a minimum. In the absence of historical data on the closing system of the Egyptian silos, the stopper previously mentioned was put in place and the prototype was sealed with the same mortar used to construct the silo.

Two sensors have been used to record temperature and humidity measurements: PeakTech® 5185 for the interior and Lecxin TempU 03 for the exterior. The internal sensor probe was placed in the centre of the silo, 45 cm above the floor level, during the filling. The flexible plastic tube, inserted through it, was then sealed on the outside with adhesive tape to keep the structure airtight. In addition to this recording, regular monitoring was carried out in the following months by Julie Depaux, Aurélie Feuillas, and Bastien Lamouroux, collaborators of the bakery-farm *Les Maîtres de mon Moulin*.

20 In some parts of the world, straw is placed at the base of the top opening to protect the food from rain (Seignobos 2017, p. 108). See also Sigaut 1978, p. 14.

4. Grain monitoring

Bastien Lamouroux, Julie Depaux & Aurélie Feuillas

4.1 The choice of the cereal for the experiment

For this experiment, we selected common barley (*Hordeum vulgare*), cultivar "Berenice", a 2-row spring cultivar registered in 1972. This robust variety is particularly interesting in organic mixed farming systems for its high-quality straw and protein-rich grain. Cultivated for 20 years on Thierry Lamouroux's farm, this spring cereal makes it possible to integrate a shorter cycle into the rotation: grassland (2 to 3 years) / winter cereal or fava beans / "Bérénice" barley or flax. Its straw is crushed to enrich the soil with carbon; its grain, once harvested, is a food supplement for the farm's ewes, fattening lambs, and horses. Part of the harvest is reserved for sowing until next winter (in February). Since this farm seed has adapted to the clay-limestone soil and the relatively dry summers of the Gascony hillsides, it appeared particularly suitable for the experimental silo prototype in Cucugnan.

4.2 Silo monitoring

The silo was located at the foot of a slope planted with trees, with partial natural protection against rain and wind. However, as we approached December, we realised the importance of covering the silo because the first winter's rains were starting to wear away the silo wall, the site having little shelter from the elements. In the end, the tarpaulin installed above the silo in June served its purpose as long as there was no strong wind but the Tramontane wind from the Hautes Corbières, known for its strong gusts, proved fatal. In December, this protection was gone. We decided to let the silo uncovered while continuing to take readings from the two probes. Following the heavy winter rains, the erosion of the silo increased and its walls gradually soaked up the water from the ground by capillarity without us being able to intervene. The silo was then brutally ripped open on Wednesday 12 January 2022 (fig. 10) on the north-western part (the part most exposed to the weather) and badly cracked in various places (fig. 11).

However, of the 580 kg of barley ensiled, the majority of the grain was recovered, bagged, and stored immediately. Indeed, the grains were healthy at the time of release except those in contact with air and moisture germinated. A tiny blue fungus of the *Penicillium* (not analysed) developed on these sprouted grains. On the contrary, the healthy grain remained undamaged (fig. 12) until April 2022 – the date corresponding to the writing of this part of the article – and could be used as a seed or otherwise, which confirms our forecasts and means that the storage conditions in the centre of the silo were favourable.

Figure 10. January 2022, the second silo prototype ripped open. © Aurélie Feuillas.

Figure 11. January 2022, cracks in the second silo prototype wall. © Aurélie Feuillas.

Figure 12. Grains in the middle of the second silo prototype. © Aurélie Feuillas.

Indeed, when looking at temperature and humidity readings, it can be noticed that when a major storm occurred, the inside of the silo was affected very little by the significant increase in outside humidity (e.g. 4/09/21, 09/09/21 storms). Similarly, despite the erosion and humidity of the silo wall, the grains located in the centre remained dry. The silo therefore isolated the grains from the moisture in the outside air and its masonry could withstand a few rainy episodes. On the other hand, temperature variations seem to have been less well absorbed since this is the element that has varied the most inside the silo (table 1).

Date	Outdoor probe		Indoor probe		Observations
	Temperature (°C)	Moisture (% in air)	Temperature (°C)	Moisture (% in air)	
01/09/2021	28	41.4	22.5	52	Ensiling.
04/09/2021	23.3	95.6	22.9	58	
06/09/2021	26.5	75.8	22.8	56.9	Big storm the day before.
09/09/2021	21.9	90.7	23.5	57.1	
13/09/2021	24.6	83	23.2	55.7	Big storm. Water flows directly onto the silo and its base.
18/09/2021	23.8	81.5	20.8	58	
27/09/2021	26.2	50.8	21.1	57.3	
06/10/2021	18.7	54.2	19.7	57.4	
22/10/2021	18.2	61.4	18.2	56.9	
06/11/2021	12.9	57.3	17.4	56.5	
05/12/2021	7.6	100	8.4	53.5	The protective tarpaulin over the silo has been blown away by the wind.
24/21/2021	10.3	100	8.1	52.4	The tarpaulin is repositioned. The silo is still wet at the base.
10/01/2022	11.6	90.4	12.3	53	Rain with heavy showers for several days.

Table 1. Table of relative temperature and humidity provided by the two probes placed inside and outside the silo prototype. Temperatures below 10°C are shown in blue, while red indicates relative humidity above 90°C. It is important to note that the devices chosen for data recording were programmed to record temperatures and percentage humidity in the air every 12 hours. However, with the destruction of the silo this data could not be retrieved. The data presented in the table was collected manually during monitoring, to prevent any potential following loss of information.

Figure 13. Barley at the flooded bottom of the silo and sprouted grains. © Aurélie Feuillas.

Figure 14. Sprouted grains with some mould. © Aurélie Feuillas.

4.3 Taking grain out of the silo

During the emergency removal of the common barley, we noticed that the grain was immersed in the lower part of the silo for about 10 cm, and that germination occurred along the inner part of the construction – on the floor and against the damp wall – due to high humidity that had accumulated during the months of rain (figs. 13-14). The internal probe, placed in the heart of the silo, unfortunately, did not allow anticipating so much infiltration, the humidity being relatively constant (figs. 15-16). Seeds stuck to the inner wall of the silo were at different stages of germination, indicating that the wall had been moist for a long time and that the moisture had spread.

General conclusions

As with any experimental research programme, it is essential to consider this investigation of the ancient Egyptian mud-brick silos over the long term: a single test cannot be considered as representative of reality. Indeed, in addition to the numerous biases introduced voluntarily for convenient reasons (for example, local French soil for bricks; the climate of the south of France; different cereals from those grown in ancient times – although we looked for grains that were as close as possible), or involuntarily due to a lack of archaeological data, part of the knowledge can only be acquired through the repetition of actions and the research questions accumulated as one goes along.

The construction of two experimental mud-brick silos, built in collaboration with CRAterre's architects

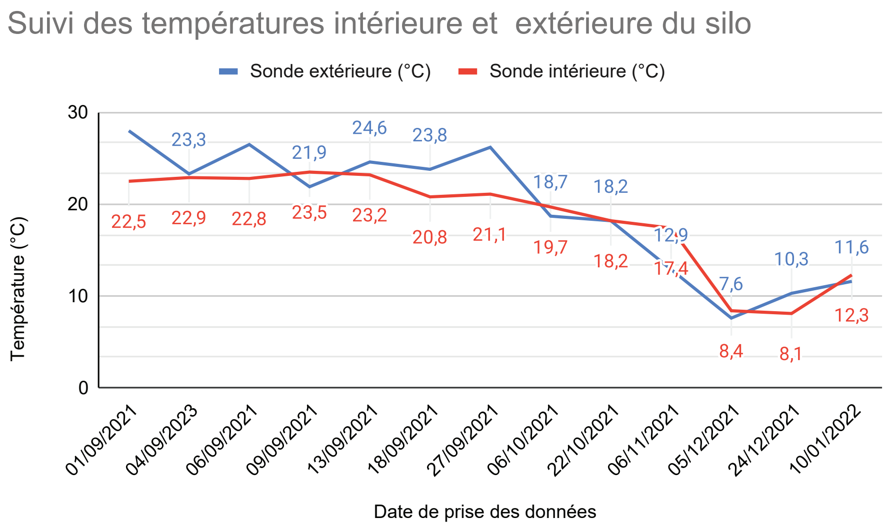

Figure 15. Diagram showing silo inner and exterior temperature variations during the experimentation.

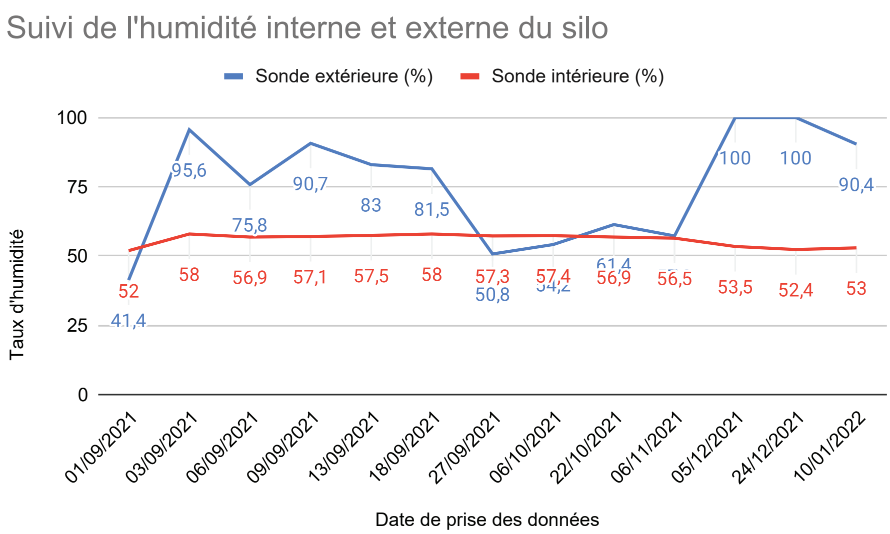

Figure 16. Diagram showing silo inner and exterior humidity variations during the experimentation.

and students, has been an original and interdisciplinary undertaking which has provided better understanding of the architectural practices and technical gestures associated with these common storage buildings in ancient Egypt and Sudan.

The comparison between the archaeological evidence and the building of the two prototypes has concretely shown that silo construction in ancient Egypt was the result of an empirical know-how, enabling the builder to erect elliptical, dome-shaped silos by laying down intuitively inclined courses made of alternating bricks and fragments of bricks. The mechanical arm used during the construction of the first prototype, as we have seen, was abandoned during the erection of the second silo, which has a lesser regular outline than the first but, at the same time, resembles the ancient specimens more.

As far as the questions stated in the introduction of this paper are concerned, some preliminary remarks can be made. First of all, earth has proved to be a suitable building material for silos, since, apart from the grains located near the water infiltration; the rest of the barley has been kept safe and this preserved grain could have been used later as fodder for small livestock.

Secondly, because of the growing humidity inside the second prototype due to the rainy season, cereals have germinated all along the moist silo wall. One therefore can assume that the grains, in good hygrometric conditions, were not bound to germinate. The phenomenon, already observed by P.J. Reynolds (1979), is currently under study within the framework of an interdisciplinary research on airtight pit-silos aiming to better apprehend its actual impact on crop long-term conservation (Dominguez *et al.* 2022).

As a final remark, the use of a mud stopper to plug the second prototype along with mud mortar showed that this simple method is quite adapted to hermetically close the construction.

The small size of the first two prototypes, although documented by archaeological evidence, was mainly determined by financial reasons. The structural data collected during the experimentation encourages a reiteration of the experimentation in the future with larger constructions in order to understand the building issues involved (shallow foundations, thin wall, height and width of the vault, etc.).

The environmental and climatic contexts in which the second prototype took place, apart from being a main bias, has also played an essential role in the experiment duration and silo performance. The next stage of this experimental project will therefore take place in Sudan – where mud-brick silos are also attested – under climatic conditions closer to the ones of the ancient Nile Valley. This new phase of the experimentation will be carried out in collaboration with the Kerma Doukki-Gel mission led by Séverine Marchi (CNRS, UMR 8167 Orient & Méditerranée) and Xavier Droux (University of Geneva).

For the third silo prototype, the methodology for temperature and humidity measurements will have to be improved. The probe used for the second prototype has clearly been insufficient, since it provided only data concerning the innermost part of the construction and did not record the humidity increase along the silo's wall leading to the cracking of the latter. Accordingly, it will be necessary to install at least three probes inside the silo, not only in the centre, but also against the interior wall and near the side opening. Furthermore, an additional probe will be needed to monitor the decreasing oxygen level inside the silo once sealed and to observe the potential impact of this phenomenon on interior temperature and humidity. Finally, during the following grain removal, it will be necessary to analyse the cereals to determine whether they are still suitable for human or animal consumption and can still be sown.