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Unusual Examples of Sophisticated Iron Technology in the Heating Systems of Roman Imperial Baths

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In Roman imperial times, metallurgy reached a high degree of specialization and complexity. The use of iron extended even to building technology, leading to some very particular results, achieving a sophisticated mastery of the technology with a complete understanding of metal properties, in a social and economic context characterized by large financial resources and a high level of creativity applied to architectural projects. A still unpublished device was found in the construction of several floors in the Villa of Giulia, Augustus' daughter, in Ventotene (Italy). In the thermal area, the concrete floors of the bath tubs are supported by an iron grid held in place by vertical iron posts strongly fixed in the underfloor, allowing both widespread hot air circulation and support for superimposed loads. A curvilinear metal grid supported by metal hooks was also used to obtain a tile-line vault, creating an interspace for the circulation of hot air in calidaria; *a careful analysis of the remains of two vaulted systems in Villa Adriana, Tivoli (Italy), allows a clear reconstruction of this device. The building process was difficult and complex, requiring careful planning and great accuracy in execution. However, after nearly a century of experimentation, it is possible to propose the hanging ceiling built over the calidarium of the Baths of Caracalla in Rome as the most imposing example of the grid system ever realized.*

Keywords: buildings archeology, construction work, metal technology, economic context, iron grid

Introduction

By the Late Republic, Roman builders were employing iron dowels and cramps for connecting stone blocks, but under Augustus, at the end of the first century BC, they began to employ more advanced applications of iron devices, many of which have rarely been discussed. My aim is to show that some rare and little-known applications, which are poorly preserved because of the widespread reuse of metals over the centuries, demonstrate the sophisticated control Roman builders had over their materials and over the process of putting them into place. Iron elements typically appear only in projects characterized by both large financial resources and a high level of creativity.

An enlightening example is provided by metal grids, which are currently recorded only in thermal buildings. The grids, made up of iron or bronze elements linked with rivets or a dowel riveted at the end, were employed to create horizontal or curvilinear hollow airspaces, and they were always used alongside large bricks (i.e. *bipedales* or *sesquipedales*), or edge-trimmed roof tiles. Horizontal grids supported by vertical posts were employed to create stable raised floors in particular sections of

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bath buildings, and curvilinear grids hung from bars embedded in the core of the concrete vaults were used to create hanging ceilings that provided *calidaria* (heated rooms with a hot plunge bath) with better circulation of hot air.

The metal grids are found only in important thermal buildings, often of large size. Clearly, both the economic investment required for such technologically advanced structures and the cultural prestige associated with them created a highly stimulating context for the invention of new building solutions.

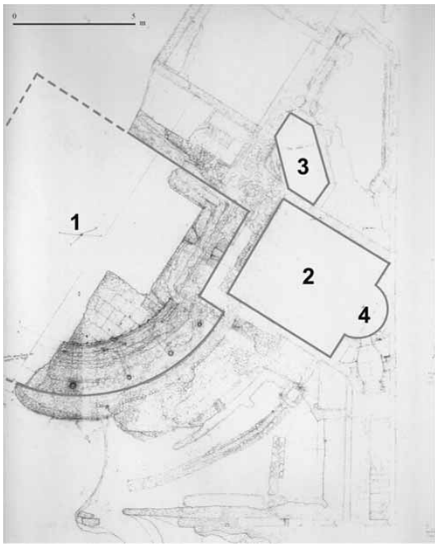

Figure 1. *Villa Giulia, Ventotene: original survey of the heated sector of the thermal building. 1:* piscina calida*; 2:* calidarium*; 3 and 4: heated tubs.* M.L. Tarabochia.

Horizontal Metal Grids

The proper heating of the hot sector of thermal buildings required the creation of a hypocaust with a raised floor (*suspensurae*), which was usually supported by small pillars or walls in stone or brick. These *suspensurae* allowed for the hot air produced in the furnace to circulate under the floor.

At the Villa Giulia in Ventotene, Italy (De Rossi, 1986: 154–61), where Julia, the daughter of Augustus, was exiled, the floors of some of the heated areas in the Augustan-period thermal baths were built in a different manner: they were supported by an iron grid raised on iron posts fixed into the subfloor of the hypocaust. A careful analysis of the planimetric survey drawn during the excavation in 1984 (Figure 1) shows that the metal grid system was used in at least three rooms – a *piscina calida* (hot plunge bath) and two tubs – each of which contained water that imposed an additional load; elsewhere, traditional *suspensurae* were used.

The traces left by the rust from the horizontal bars in tub 3 (Figures 2 and 3) are particularly evident in the subfloor, paved with trimmed tiles. The pattern of the grid can be put in relation to imprints left by the vertical posts, thus allowing the entire metal structure to be reconstructed. The marks left on the perimeter walls of the tub also indicate the thickness of the layers composing the floor above (Figure 4). The metal grid was fairly regular, with horizontal bands about 6 cm wide, crossing orthogonally every 50–60 cm. These bands were supported and connected at the intersections by quadrangular posts, about 6 cm each side, which were firmly embedded in the subfloor. The upper floor was made up, as usual, of several layers of *cocciopesto* (lime mortar with crushed pottery and/or bricks), to an overall thickness of about 40 cm. It was supported by a layer of trimmed tiles, of which several pieces have been found in the excavation of the room. Fragments of marble slabs have also been found, suggesting a floor and a wall covering of *opus sectile* (marble slabs), probably with plaster frames. The tub would have held around 5.5 m^3 of water, which would have weighed about 5.5 tons.

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Figure 2. *Rhomboidal tub of the* calidarium *at Villa Giulia, measuring about 4.5 × 1.75 m. Traces left by the iron grid, about 7 cm wide, and the vertical imprints in the edge-trimmed tiles in the subfloor.* De Rossi (1993).

A similar system must have been used also in the semi-circular tub of the second *calidarium*, which was in direct contact with the *praefurnium* (heating room), judging from the analysis of the original drawing (Figure 1.4). The imprints for the vertical posts supporting the grids are reported at a regular distance of about

Figure 3. *Rhomboidal tub of* calidarium *at Villa Giulia, detail. Apparently the suspended floor was already partially damaged when the oxidation of the bars left the traces on the subfloor.* De Rossi (1993).

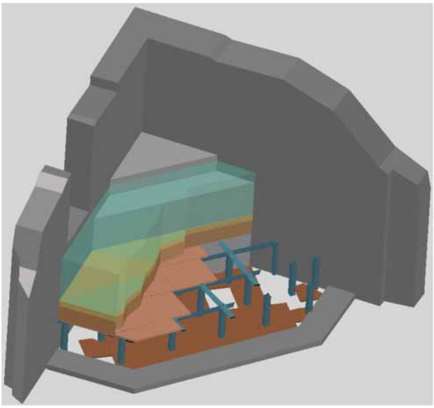

Figure 4. *Rhomboidal tub of the* calidarium *at Villa Giulia and reconstruction of the suspended floor, based on the evidence of the preserved remains.*

55–60 cm. They only occur on the subfloor bricks or trimmed tiles of the tub. Other specific details are lacking.

A mixed system was applied in the *calidarium* with *piscina calida*, which is only partially preserved, the remains of which have been obscured by a drastic restoration (Figure 1.1). The room had a remarkable size, about 12.6 × 9 m, and opened onto a semi-circular structure with a radius of 7.5 m. It was delimited by a brick wall with a thickness of 0.6 m, which makes a vaulted roof extremely doubtful in spite of the support provided by half-columns placed on the outside of the wall every 3.6 m.

The interpretation of the building is made possible by comparing the analysis of the original planimetric survey,[1] photographs of the excavation, and an eighteenth-century drawing from the State Archive in Naples, which reproduce the construction in a better

[1]Plans published in De Rossi (1986: figs. 243–244) are very schematic and clearly not drawn by the person who actually carried out the survey; the documentation is inaccurate, incomplete, and, sometimes, even misleading. The original survey is drawn by Dr Maria Luisa Tarabochia, with skill and attention to noteworthy details.

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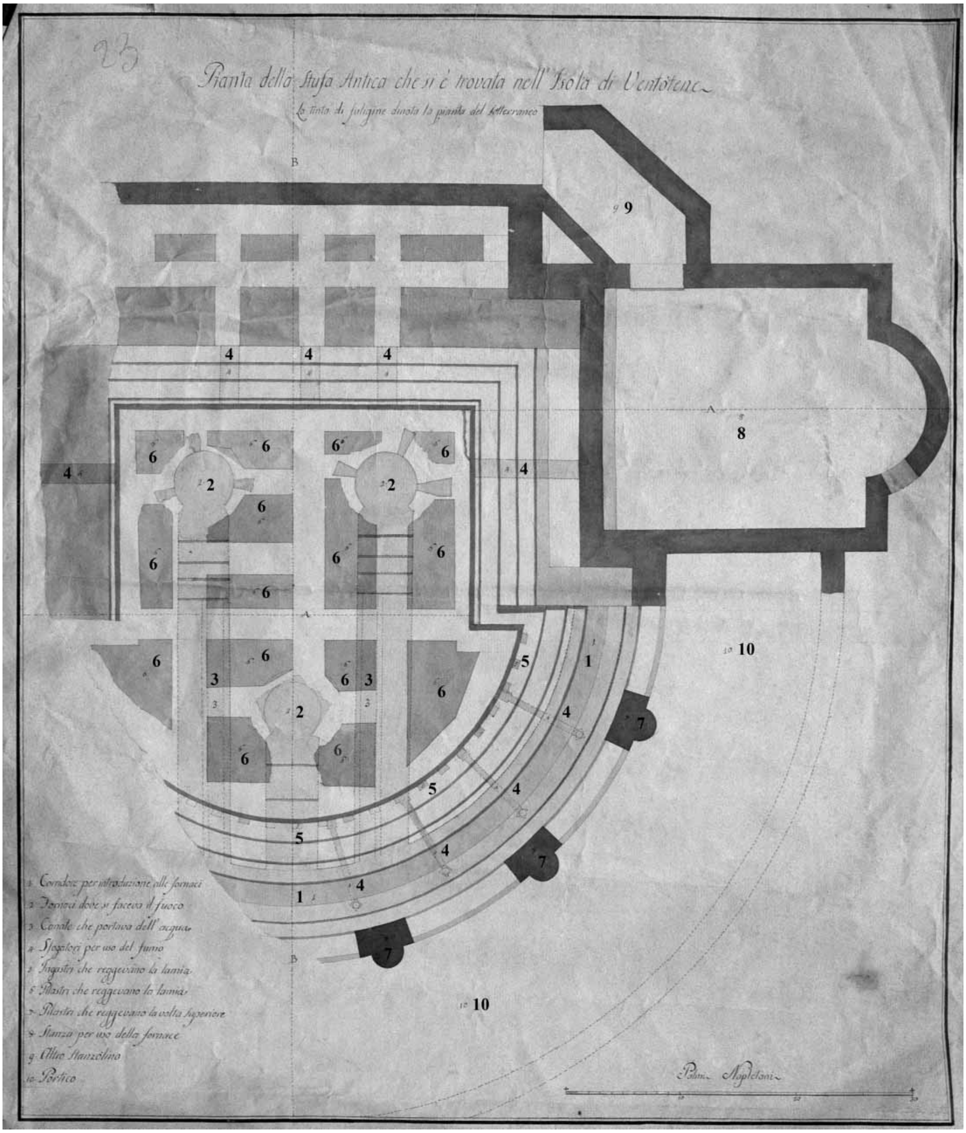

Figure 5. *Plan of the ancient furnace found on Ventotene island. 1: corridor leading to the kilns; 2: kilns where fire was produced; 3: channel bringing water; 4: pipes for the use of smoke; 5: joints supporting the* lamia *(covering); 6: pillars supporting the* lamia*; 7: pillars supporting the upper vault; 8: room for the use of the kiln; 9: other small room; 10: portico.* State Archive, Naples, from De Rossi (1993: fig. 18).

state of preservation than it is currently (Figures 5–9).[2] Under the Bourbon kings, part of the brickwork was removed in order to extract the stone from the volcanic bank against which it was built.

The *piscina calida* is organized over three superimposed levels, produced partly through excavation and partly by building the necessary retaining walls. The hypocaust under the

[2]The drawing, published by De Rossi (1986: figs. 240–242, 1993: fig. 21) is remarkable, showing a clear understanding and a noteworthy skill to represent such a complex structure, articulated on several levels. According to the annotations on the drawing, two (missing) transversal sections were to complete the document.

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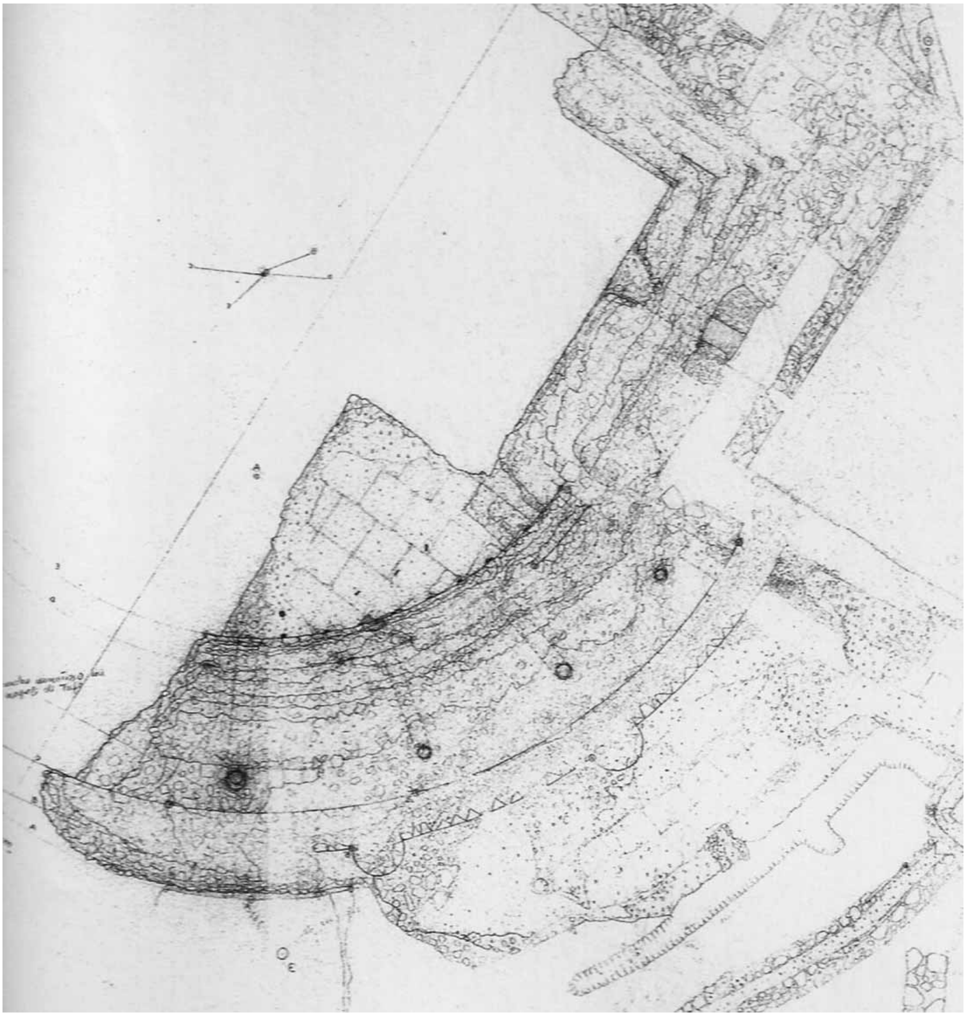

Figure 6. *Original drawing of the currently preserved part of the* piscina calida *at Villa Giulia, the remains representing roughly equivalent to one-third of the original. The Bourbons heavily damaged and modified the remaining structures. The plan is drawn on the ground level of the portico.* M.L. Tarabochia

tub floor was built by employing brick walls combined with an iron grid supported by vertical posts, which have left imprints with rust marks on the subfloor, originally consisting of a layer of trimmed tiles. The capacity of the *piscina calida*, reconstructed with certainty from the evidence of the preserved remains and from the eighteenth-century drawing, is about 150,000 litres.[3] This equates to a weight of about 2000 kg/m^2 in addition to the bathers' weight: a considerable load, but one which does not fully explain the use of such a complex and expensive device as the metal grids, especially considering their application in the two small tubs previously analyzed. Certainly, this system improved the air circulation within the hypocaust by eliminating obstacles to airflow. Moreover, some reliance on the heat retention capacity of the iron can be presumed to have provided a certain amount of conducted heat.

[3]Assuming the level of the water to have been 15 cm under the highest step gives a maximum height of about 1.6 m from the bottom of the tub, for a volume of 145.9 m^3 of water.

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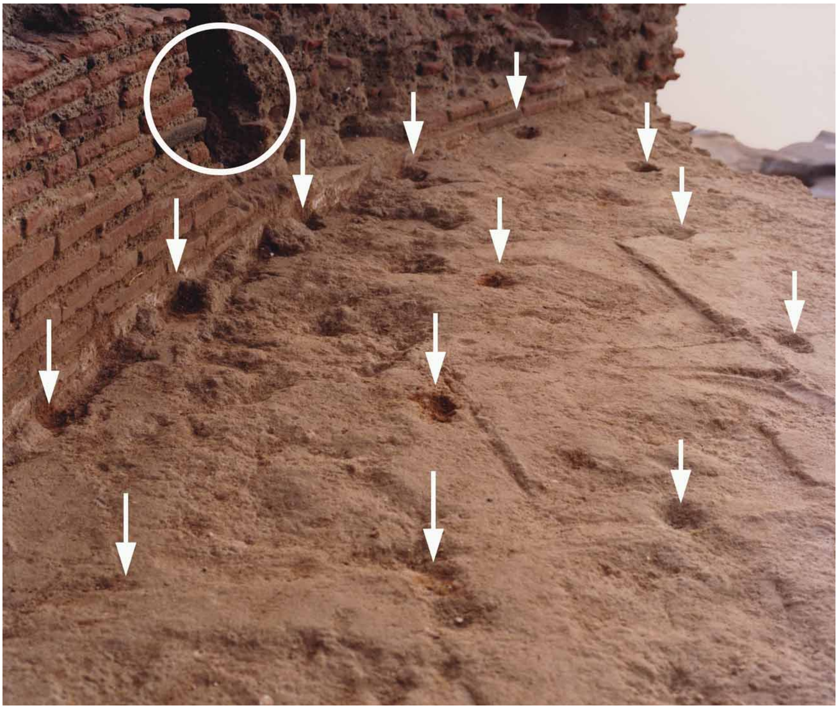

Figure 7. *Subfloor of the hypocaust. The imprints of the posts supporting the iron grid are clearly evident; those regularly fixed along the perimeter wall are at a distance of about 50–60 cm from one another. The white circle shows the hole of one of the oblique ducts conveying hot air to the upper room.* Photo: De Rossi (1993).

The metal grids may have also been employed elsewhere: among the materials found and documented on the largest of the two ships found in Lake Nemi, there are some large trimmed tiles with iron bars, tentatively interpreted as remains of a fireplace (Ucelli, 1950: 163). I suggest that they are actually the remains of the metal grid supporting the edge-trimmed tiles (Figure 10), which was used to construct an elevated floor connected with heated walls made with *tegulae mammatae* (very large square bricks with conical projections or flanges at each corner), also found *in situ*. In this case, the choice to use an iron grid was probably motivated by the need to lighten the load of the ship by using a technology that would have still been quite new in the middle of the first century AD.

Curvilinear Metal Grids

By the first century BC, builders were aware that by heating the perimeter walls, as well as the floor, it was possible to increase the temperature of a room without proportionally increasing the consumption of fuel. This is shown by the creation of heated walls using *tegulae mammatae* and, later, *tubuli* (hollow clay boxes) or *tegulae hamatae* (very large bricks with four nail holes to fix them to the wall); the ceiling could also be heated, as clearly documented by Vitruvius.[4] From the Hadrianic period

[4]Vitruvius (1997, 5, 10, 3). Actually Vitruvius records two kinds of devices, both in relation to a wooden roof structure: it was possible to hang a single or a double shell, thus obtaining simply a false vault, or a real interspace. In the first case, the primary function was explicitly to protect the wooden beams of the covering from humidity; in the second case, to properly

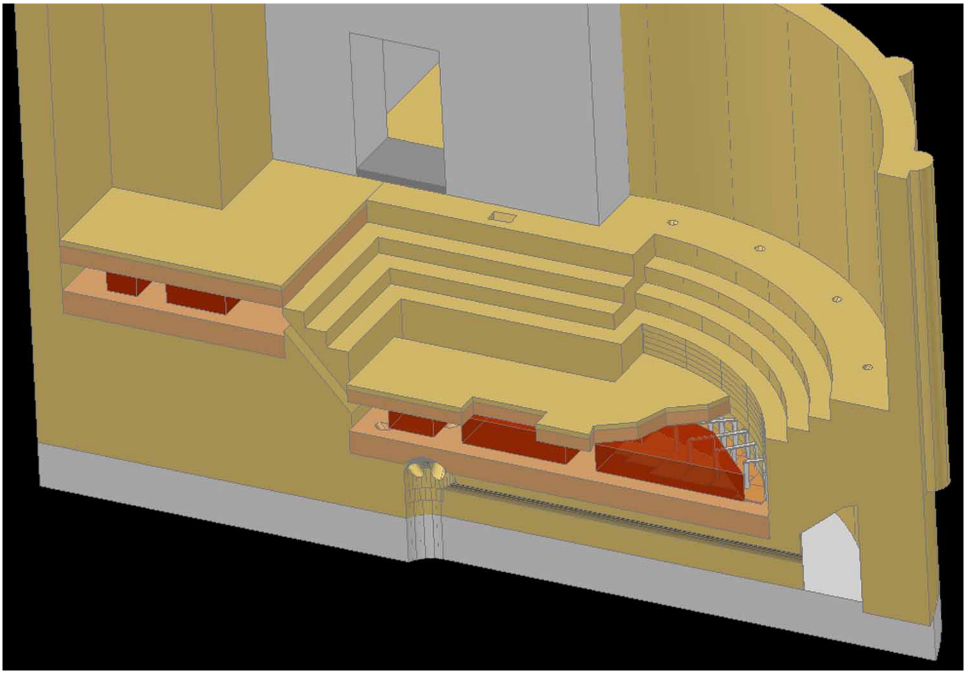

Figure 8. *Reconstruction of the iron grid with vertical posts and the brick walls supporting the floor of the tub at the Villa Giulia. The iron device is applied only in the tub. The heated floor of the upper area is supported only by brick walls.*

(AD 117–138), but probably even from the Trajanic period (AD 98–117),[5] hanging ceilings made of metal grids, usually of iron, were used to create heated air spaces along vaults. The hanging ceiling consisted of hooked bars provided with a transverse bar at one end, which was then embedded into the *opus caementicium* (Roman concrete) of the vaulted roofing system. These supported a metal grid made by arched and linear elements supporting large bricks that were arranged on the grid and then plastered along the *intrados* (the inner surface of a vault).[6] The process of setting up such a system was extremely demanding; it is similar to the far simpler horizontal hypocaust grids, suggesting that both devices come from a shared technological knowledge. The study of a number of well-preserved examples in Hadrian's Villa[7]

direct the hot air outside. See also Faventinus (2001, 17), and, Palladius (2003–2010, I, 40). For archaeological documentation, see Shepherd (1989: 419–31).

[5]I assume that the example found in the Domus Aurea, in the apse of room 51 (Fabbrini, 1983: 169–186, pl. I), has to refer to the insertion of projecting, heavy (bronze?) elements relating to the decoration of the *intrados*. The same interpretation can be suggested for the *frigidarium* of the Baths of Caracalla in Rome, where the holes are still visible in the vaults with remains of a decoration in stucco or mosaic (cold rooms 1 and 14 west, nn. 4,5,6 east; the numbering follows DeLaine, 1997). A clear example of the application of this kind of device can be seen in the barrel vault covering the *cella* of the temple of Hadrian in Rome. At the Baths of Trajan in Rome, there are scarce preserved parts of the heated rooms, but the use of iron devices and the introduction of brick-lined vaulting in the Trajanic period strongly suggest the use of hanging ceilings (see Amici, 2011: 224–28).

[6]The system has been skillfully identified by Giuliani (1975: 113–18), but without proposing a reconstruction that is both consistent with the archeological documentation and also technically possible.

[7]Tivoli, Hadrian's Villa: Heliocaminus Baths, *piscina calida* (1) dome; *tepidarium* (2) barrel vault; *tepidarium* (5) cross vault; *calidarium* (3) barrel vault; *calidarium* (4) barrel vault?; Small Baths, *piscina calida* (1), cross vault; *tepidarium* (2), barrel vaul; *calidarium* (3), cross vault; *caldarium* (4), cross vault; *caldarium* (5). Large Baths, *tepidarium* (1) barrel vault; *calidarium* (2) barrel vault; *calidarium* (3), cross vault and two barrel vaults; *calidarium* (5) cross vault; *tepidarium* (6) cross vault; *calidarium* (7) barrel vault. The numbering follows Giuliani (1975).

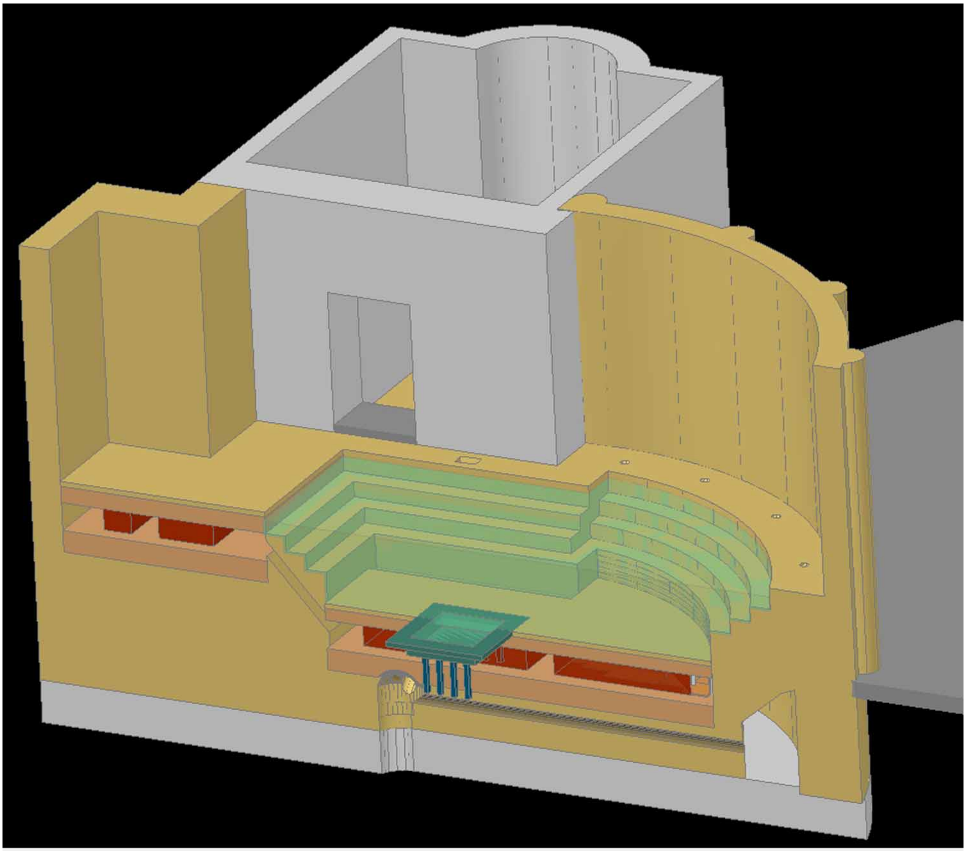

Figure 9. *Main section of the virtual reconstruction of the* piscina calida *at Villa Giulia.*

provides an overview of the system as well as much accurate and useful data. Accordingly, it is possible to make a reliable reconstruction and to determine the characteristics and the layout of every element along with the procedure for putting them into place.

The analysis of known examples clearly shows that the layout of the supporting bars of the grid can be divided into two groups based on the form of the vaulting system: one refers to barrel vaults and cross vaults, and the other refers to domes and semi-domes. For barrel vaults, the hooks provided with transverse bars were arranged in rows, both along the axis of the vault and perpendicular to it. In the case of cross vaults, the arrangement was similar but with hooks also along the diagonals. In domes and semi-domes, they were only arranged in horizontal rows. The hooks are oriented vertically in the barrel and cross vaults, whereas in the domes and semi-domes they are oriented radially, except for the first lower row which is vertical.

Grids for Hanging Ceilings Applied to Barrel Vaults and Cross Vaults

From the analysis of the remains of the vault of the *tepidarium* (warm room) in the Large Baths in Hadrian's Villa, Tivoli

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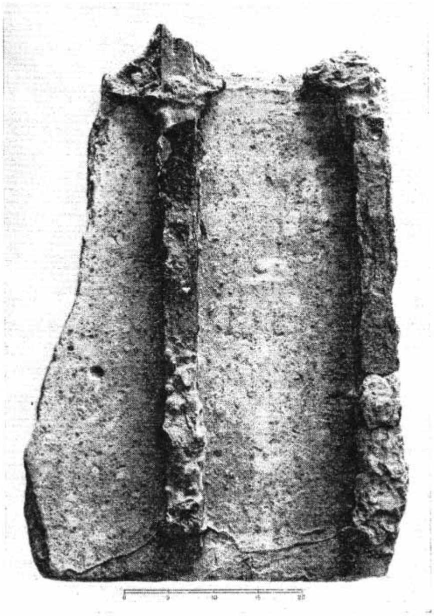

Figure 10. *Iron bars on a trimmed tile, set at a distance of 21 cm from each other at Villa Giulia; dimensions: 4 × 3 cm; maximum preserved length: 64 cm.* Ucelli (1950: fig. 163).

(Figures 11 and 12), and of the collapsed fragment, it is clear that the first row of bars was inserted at about 2 m from the springing of the vault, and the second at about 1.4 m from the previous one, and from the third onwards at about every 0.8 m. The interaxial distance is also regular, between 0.8 and 1 m. On the whole, it is possible to reconstruct a system of supporting bars composed of eighteen elements supporting each of the eleven arched rods along each row; furthermore, as can be seen from the imprints left in the concrete, the bars had a nearly vertical inclination (Figure 12).

The first row was level with the marble or plaster molding surrounding the top of the wall, which was composed of layers of plaster, *tubuli,* finishing plaster or marble slabs. It supported the ends of the arched elements of the metal grid, which were firmly kept in place by the successive rows of vertical bars. Horizontal rods were then placed on the curvilinear rods, fixed with rivets, and arranged about every 60 cm one from the other, in order to create the support grid for *bipedales*. The *intrados* of the grid, which was concentric with the *intrados* of the barrel vault covering the room, was then plastered and decorated (Figures 13, 14a, b, and 15). An air space about 40–45 cm wide was thus obtained and was directly connected to the system of *tubuli* arranged on the wall. It would have been wide enough for the suitable management of hot air and for the discharge of smoke.

A similar system can be reconstructed for cross vaults. The first row of bars supported the four curvilinear arched rods, while the four bars at the corners and those along the diagonals supported the arched rods following the diagonals of the vault. Horizontal bars were fixed upon them, at about 60 cm apart, and the resulting network supported a series of whole or partial *bipedales* (Figures 16 and 17a, b).

The information gathered from the analysis of the remains of the *tepidarium* in the Large Baths and of the *calidarium* in the Small Baths is reflected in sixteen other heated rooms with barrel or cross vaults that had hanging ceilings in the thermal buildings of Hadrian's Villa (see note 7) – a broad enough sample to ensure the reliability of the data. A strong homogeneity in the application of the system is evident; this technique was clearly the result of a very standardized and well-tested process.

Grids for Hanging Ceilings Applied to Domes

The analysis of the dome of the *piscina calida* in the Heliocaminus Baths at Hadrian's Villa, which is almost half-

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Figure 11. *The* tepidarium *in the Large Baths in Hadrian's Villa, Tivoli. Remains of the barrel vault, laid on formwork boards supported by a centering structure. The room has a square plan, measuring 11.48 × 11.48 m; the vault springs at over 7.2 m from the floor level. A large fragment of collapsed vaulting lies in the room. Clearly evident is the damage caused by the removal of the metal bars supporting the grid for the hanging ceilings. In this case, the first 45 cm from the spring of the vault has been chiseled away to extend the vertical wall upward for approximately 45 cm so that* tubuli *could be attached, as shown by the holes left by the T nails.*

preserved, allows for a reliable reconstruction of the grid supporting the hanging ceiling (Figures 18–20). As shown by the arrangement of the holes, the supporting bars were arranged in rows in concentric circles; only in a few cases do they align along the meridian axis. The first row from below, at +1.75 m from the level of the springing of the vault, has left vertical imprints in the concrete. The other bars, at a distance of about 80 cm one from the other, had a radial orientation.

As in the case of the suspended ceilings supported by barrel vaults, the first row of bars was level with the marble or plaster molding surrounding the top of the perimeter wall. It supported a horizontal circular rod and, judging from the position of the remaining holes, probably only three semi-circle arched rods, which were arranged vertically at regular intervals. These were then firmly fixed by radial bars coinciding with the holes still visible in the *intrados*. The remaining eight rows of bars assured the position and stability of concentric circular rods, which doubled when necessary to create modular spaces of 60 cm along the meridians. They were fixed with rivets to the three semi-circular vertical rods, in order to obtain a grid reproducing the shape of the concrete

Figure 12. Tepidarium *vault, detail, in the Large Baths in Hadrian's Villa. Evident in the concrete of the vault are the imprints left by the bars, which are nearly vertical. The holes are cut about 1 m deep.*

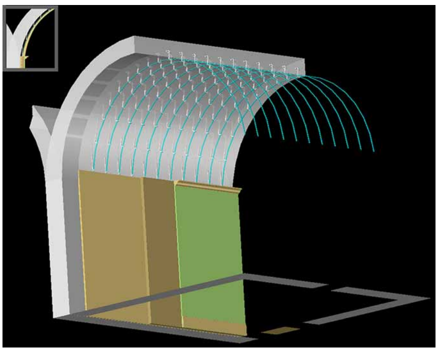

Figure 13. Tepidarium *in the Large Baths in Hadrian's Villa: reconstruction of the pattern of iron bars embedded in the concrete in relation to the arched elements of the grid. As shown in the detail section, the irregular distance between the first three rows of the bars assured a stable support for the curvilinear rods considering the vertical inclination of the springing of the vault.*

dome. The grid provided the support for the *bipedales*, which were cut in relation to the curvature of grid, creating a continuous surface to be plastered and decorated (Figure 21a–c).

Technically, the building process for achieving this kind of hanging ceiling was very similar for all three forms of vaults. It can be further defined in detail by comparing it to the remains of some heated rooms in the imperial baths of Caracalla and Diocletian in Rome, as well as to the Great Baths on the Lechaion road in Corinth, built around 200 AD (Biers, 1985: 47–49; Biers, 2003: 313–19).

From the analysis of the holes still visible in the concrete of all the vaults and from the few remains of the iron bars still preserved, or at least well-documented, it seems that bars of different lengths were embedded into the *opus caementicium* when it was laid on the centering (a temporary structure used to support an arch or vault during construction). A greater length, at least in the first (lowest) row, was necessary to assure the support of the main elements of the grids in relation to the spring of the vault. The number of examples are limited, but they seem to

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(a)

(b)

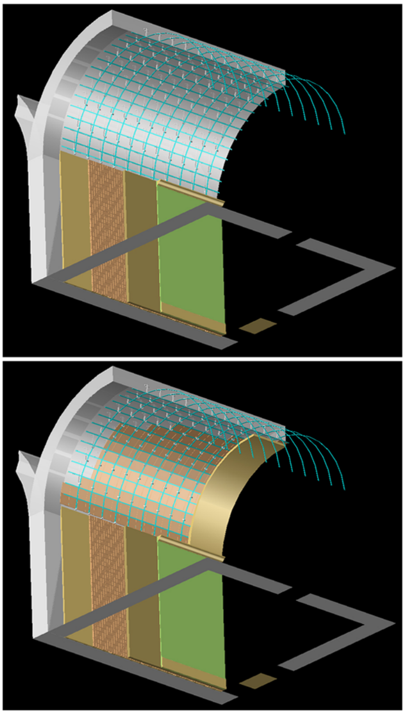

Figure 14. *(a, b)* Tepidarium *in the Large Baths in Hadrian's Villa: reconstruction of the pattern of the horizontal and the curvilinear rods. The resulting grid, properly supported and kept in place by the vertical bars, was divided into modular spaces of about 60 × 90 cm, which allowed for the insertion of* bipedales *from below. At the end of the process, the plastering of the curvilinear surface removed imperfections and irregularities.*

indicate also a variation in length according to the size of the room and, consequently, to the entire load that the bars would have supported. According to the latter parameter, the sizes of the bars themselves could change, as well as the size of the cross bars to be embedded into the concrete (Figure 22).

The bars would have had to project down through the formwork; after dismantling the centering, but keeping up the scaffolding, the curvilinear or rectilinear rods were arranged to the shape of the vault on the lower end of the first row of bars, fastening them to the hooked upper bars. Other rods arranged horizontally, straight in the case of a barrel vault and curvilinear in the case of a cross vault or a dome were fixed on them completing the grid.

It is possible that the bars, which supported most of the load, were separately forged, while the rods, sometimes of a remarkable length, were assembled by several forged pieces welded together and re-forged to obtain the desired size and shape before actually putting them in place. A riveted connection seems to be the most practical solution, even if not

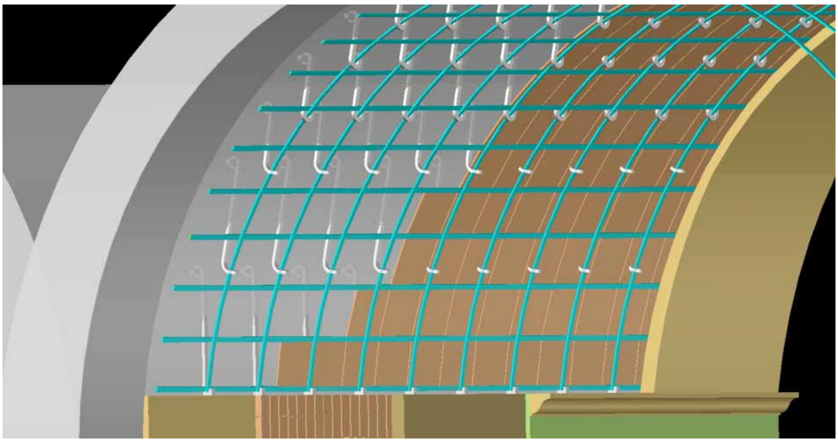

Figure 15. *Large Baths in Hadrian's Villa: axonometric sketch in detail. The structural vault is portrayed in semi-transparency, allowing an overview of the arrangement of transverse bars at the end of the iron hooks.* Bipedales, *whole or partial, were inserted onto the grid from below to obtain a continuous surface.*

Figure 16. *Small Baths in Hadrian's Villa, view from below of the vault of the* calidarium *number 3, heavily restored. The holes left by the removal of the metal bars are clear. The vertical pipe in the middle of the vault allowed for the discharge of fumes.*

unequivocal.[8] The pattern of the grid depended on the need to ensure the necessary support for the *bipedales* on at least three sides, while also providing enough room vertically to insert the bricks through the frame. The builders would have worked by horizontal rows, from bottom to top, simply laying the *bipedales* one after the other. Certain bricks would have been shaped by hand to fit the irregular spaces at the crowns and edges of the vaults. The hanging ceiling thus obtained was then plastered and decorated according to the furnishing of the room, removing imperfections, protrusions, or indentations. The complexity and the difficulty of this building process, clearly shown by the virtual reconstruction, is amazing: it required perfect planning, great accuracy in execution, and impeccable team coordination.

The most imposing example of the grid system ever realized is probably the one built over the *calidarium* in the Baths of Caracalla, where the holes left by the removal of the bars at the springing of the two remaining pillars of the dome are still visible.[9] I believe this is what is described with great admiration in the *Historia Augusta*:[10] '*thermos nominis sui esimias,*

[8]Bronze and copper rivets have been documented to have fixed slabs or metallic parts of tubs (for example, Talamo, 1993: 288–90).

[9]These holes were filled in during restoration, but are visible in photographs by E. Van Deman (Fototeca Unione, fondo Van Deman, 246–47).

[10]SHA, Vita Ant. Cara, IX, 4–5: translated as '...he left the magnificent baths which bear his name, of which architects say that the construction of their *cella solearis* cannot be imitated.

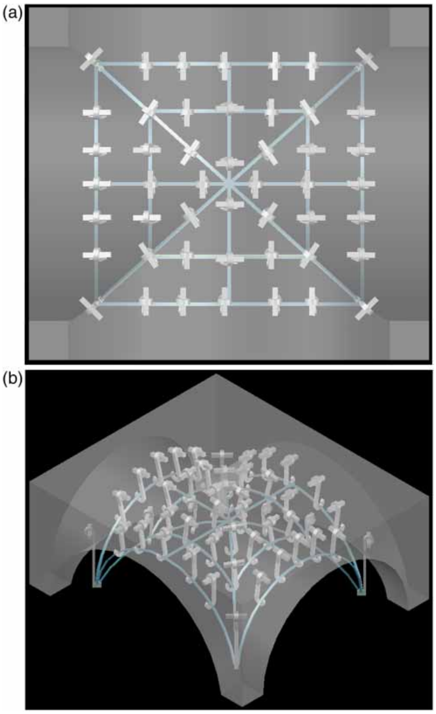

Figure 17. *(a, b) Reconstruction of the supporting grid of the* calidarium. *In this case, the small size of the room, 4.51 × 4.92 m, makes unnecessary a further partition of the grid.*

quarum cella solearem architecti negant posse ulla imitatione, qua[lis] facta est, fieri. Nam ex aere vel cupro cancelli sup[er]positi esset dicuntur, quibus cameratio tota concredita est, et tantum est spatii ut id ipsum fieri negent potuisse[nt] docti mechani'. Clearly, after nearly a century of experimentation, the technical difficulties in constructing a grid of this kind were surmounted so that this one of over 30 m was possible. Even if the information provided by the *Historia Augusta* may not be well-founded, the use of bronze and/or copper for the rods of the grid, in this case all curvilinear, could have been chosen for the ductility that iron could not provide; however, the use of bronze or copper for the vertical support bars is unlikely given the weight and the level of tensile stress they had to bear.[11]

Finally, the use of metal grids, in particular those for the hanging ceilings, required the drawing up of a separate project that had to be integrated into the structural one. Managing the complex installation of the grid would have had a significant effect on the logistics, organization, and timing of the building process; the installation of such devices involved the supporting structure[12] as well as the decoration of the rooms. Moreover, use of metals in this way required both skilled metal workers and significant financial backing to afford the cost of the material. Thus, it is probably not by chance that the metal grids appear during the Augustan period when there was an intensive exploitation of Spanish iron mines in the south-east and in Sierra Morena. Also, the reduction of Noricum to a *provincia* under Claudius made it possible to secure large quantities of iron, which was of the best quality, even in the opinion of ancient authors.

For it is said that lattices either of bronze or of copper were placed [over] under it to which the whole vault is entrusted and the span is so great that experienced engineers say it could not have been done'. For a detailed analysis of the text, see DeLaine (1987: 154–55), who proposes, however, even if tentatively, an exposed suspended ceiling in bronze and copper, without providing any detail for the construction.

[11]Bronze elements are documented in the vaults of the Corinth Baths, although, in this specific case, among the hooks supporting the bars of the grid. I do not think that the choice could have been influenced by the specific weight of the metals, as the difference favours iron, c. 7.85 kg/dm^3, as compared to copper, c. 8.93 kg/dm^3, and bronze, between 7.4 and 8.9 kg/dm^3 according to the percentage of tin in the alloy.

[12]It is possible to provide the approximate weight of the hanging shell proposed. Hadrian's Villa, Large Baths, room 1 (barrel vault): total weight of the shell = 13 tons, of which 5.6 tons for the iron grid, and 7.4 tons for the brick covering. For the hemispheric dome of Room 1 in the Heliocaminus Baths, the total weight of the shell: 16.6 tons, of which, 8.8 tons for the iron grid and 7.8 tons for the brick covering. The weight of the *intrados* decoration should also be added.

Figure 18. *The remains of the dome of the* piscina calida *at the Heliocaminus Baths. Fragments of the brickwork covering of the* intrados *are still in place. The hemispheric dome has a diameter of about 12 m at the spring of the vault.*

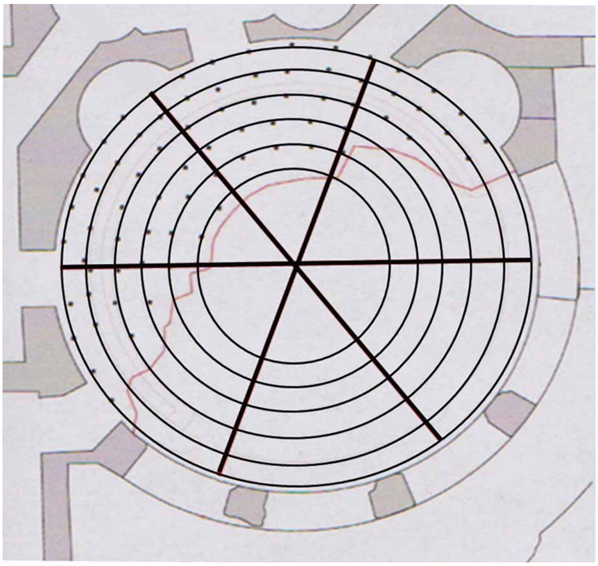

Figure 19. Piscine calida *from the Heliocaminus Baths. Planimetric projection of the dome with the holes left from the removal of the supporting bars. A certain degree of inaccuracy should be allowed, considering the rough removal of the metal elements.* A. Blanco; the pattern of the grid bars are by the author

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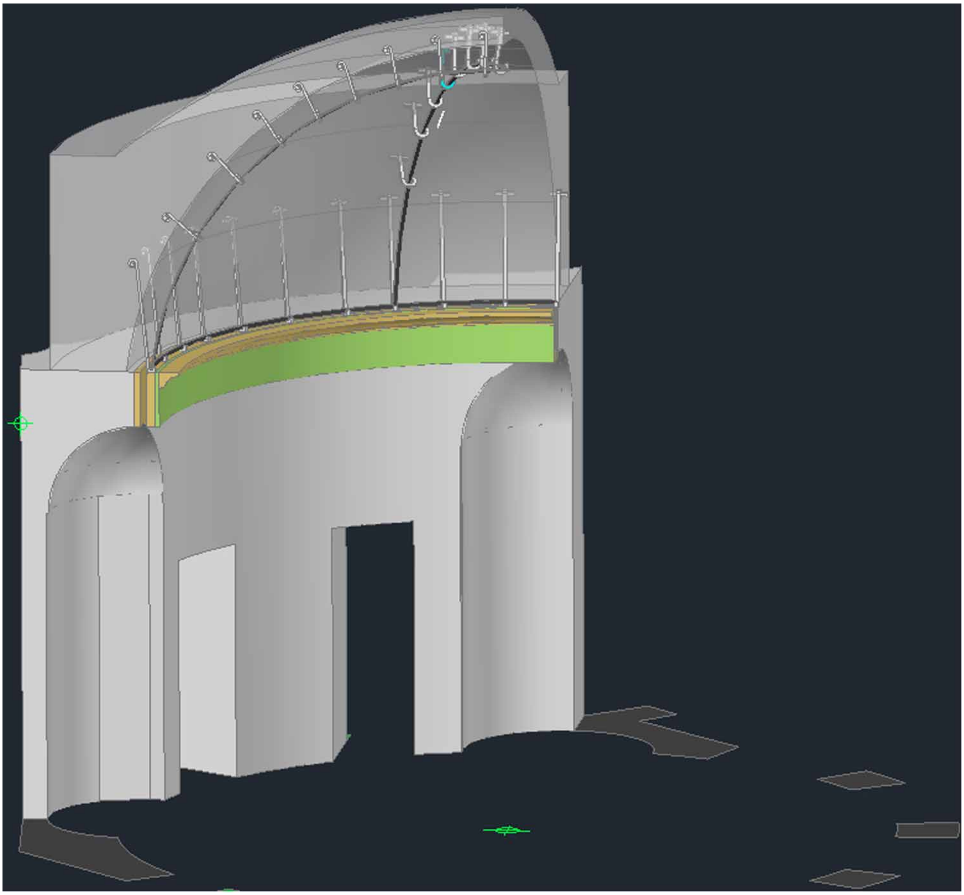

Figure 20. *Dome of the* piscina calida *from the Heliocaminus Baths, reconstruction of a section of the support system of the metal grid. The dome is shown in transparency, in order to emphasize the shape and position of the transverse bars at the heads of the iron hooks.*

Conclusion

On the whole, specific conditions were required for planning and using metal grids. These devices seem to have been reserved exclusively for prestigious buildings, and they were used during particular historical periods characterized by political stability, at first under Augustus, then from the beginning of the second century to Diocletian. They appear only in projects that are characterized by sophisticated planning, high levels of technical expertise, and considerable economic assets, all of which allowed the creation of innovative, demanding, and enduring projects.

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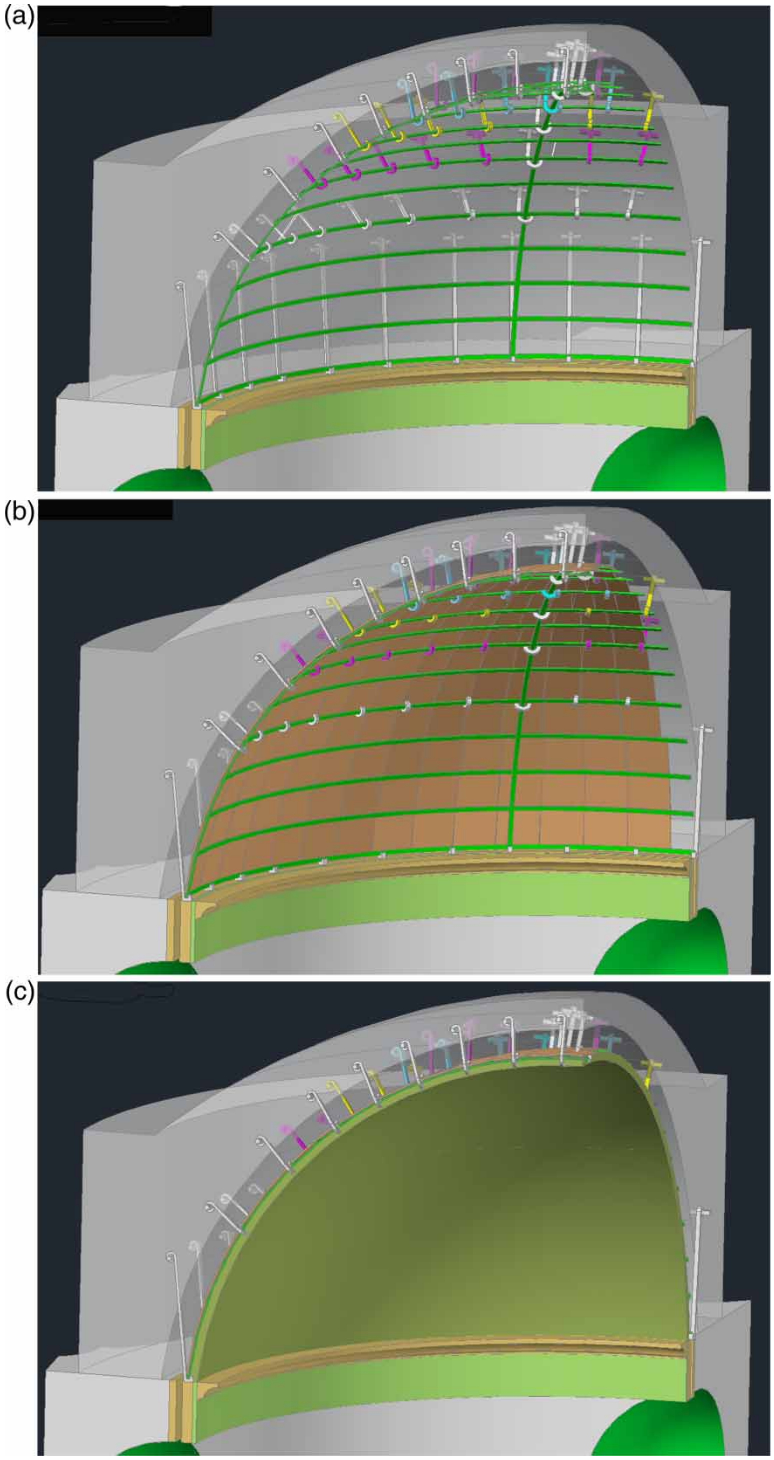

Figure 21. *(a–c) Dome of the* piscina calida *at the Heliocaminus Baths, reconstruction of a segment of the overall support system of the elements of the metal grid. The horizontal circular elements have been hypothetically arranged at about 60 cm apart, but a shorter distance could have been possible.*

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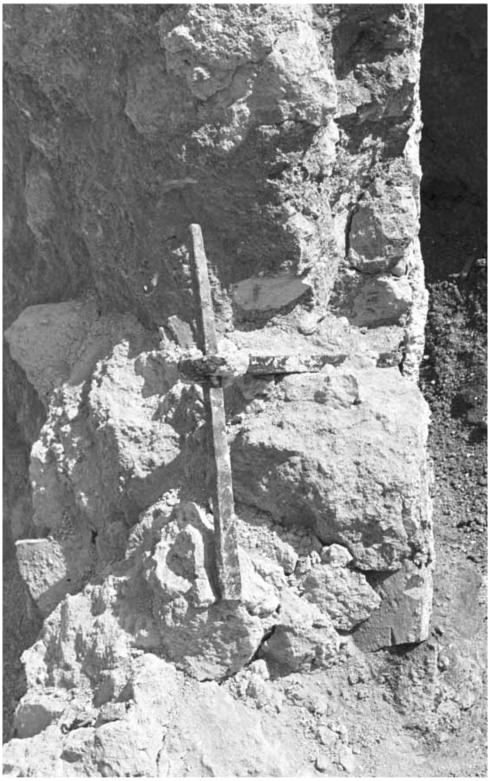

Figure 22. *Corinth, Great Baths on the Lechaion road. Bronze bar found in a segment of the collapsed vault. The bar had already been cut in antiquity, so that it would not protrude from the* intrados *of the vault, probably as a result of the remodeling of the building; the hanging ceiling was removed, and the vault plastered* (courtesy of the American School of Classical Studies at Athens, Corinth Excavations, inv. BW 1968 020 31).

The remains of the bar after restoration (P. Vitti). The transverse bar, usually 20–25 cm long, is here 34 cm long and was inserted in the hole fashioned at the end of the bar. In other examples, the end of the bar was bent around the cross bar.

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Technologie sophistiquée du fer dans les systèmes de chauffage des thermes impériaux romains: Exemples atypiques

Durant l'époque impériale romaine, la métallurgie avait atteint un haut degré de spécialisation et de complexité. Le fer était utilisé même jusque dans la construction, ce qui conduisait à quelques résultats très particuliers. On avait atteint une maîtrise avancée de la technologie avec une compréhension totale des propriétés du métal; ceci dans un contexte social et économique caractérisé par des ressources financières abondantes et un niveau élevé de créativité appliqué aux projets architecturaux. Un dispositif encore jamais publié fût découvert dans la construction de plusieurs sols de la villa de Giulia, la fille d'Auguste, à Ventotene (Italie). Dans la zone thermale, les sols en béton des baignoires sont soutenus par une grille en fer maintenue en place par des barres verticaux en fer bien ancrées sous le plancher, autorisant ainsi la large diffusion d'air chaud et fournissant en même temps le support pour les charges superposées. Une grille métallique curvilinéaire soutenue par des crochets en métal était utilisée afin d'obtenir une voûte carrelée, créant un espace pour la circulation d'air chaud dans les calidaria*. L'analyse approfondie des restes de deux systèmes voûtés dans la villa Adriana à Tivoli (Italie) permettent une reconstruction précise de ce dispositif. Le processus de construction était difficile et complexe, exigeant une planification minutieuse et une exécution d'une grande précision. Toutefois, après presqu'un siècle d'expérimentation, nous pouvons soumettre le plafond suspendu construit au-dessus du* calidarium *des Bains de Caracalla à Rome comme le plus impressionant exemple de la méthode à grilles jamais réalisé.*

Mots-clés: archéologie du bâti, travaux de construction, technologie des métaux, contexte économique

Ungewöhnliche Beispiele hochentwickelter Eisentechnologie in den Heizsystemen römischer kaiserlicher Bäder

Während der römischen Kaiserzeit erreichte die Metallurgie ein hohes Maß an Spezialisierung und Komplexität. Die Nutzung von Eisen dehnte sich sogar bis in die Bautechnik aus, was zu einigen sehr bemerkenswerten Ergebnissen führte, die eine fortgeschrittene Meisterschaft der Technologie mit einem umfassenden Verständnis der metallischen Eigenschaften erreichten und in sozialem und ökonomischen Kontext durch umfassende finanzielle Ressourcen und ein hohes Maß an Kreativität bei architektonischen Projekten geprägt waren. Eine bislang unpublizierte technische Einrichtung wurde in verschiedenen Böden der Villa von Iulia, der Tochter des Augustus, in Ventotene (Italien) entdeckt. Im Bereich der Thermen waren die Kalkbetonböden der Badebecken mit einem eisernen Gitter unterzogen, das Eisenstangen, die fest mit dem Boden verankert wurden fixiert wurde und eine umfassende Heißluftzirkulation wie auch eine Stützung darüber befindlicher Lasten erlaubte. Ein von Metallhaken gehaltenes gebogenes Metallgitter wurde genutzt, um unter den Bodenplatten einen überwölbten Kanal für die Zirkulation von heißer Luft in den calidaria *zu bilden. Eine sorgfältige Analyse der Überreste zweier überwölbter Systeme in der Villa Adriana in Tivoli (Italien) erlaubt eine eindeutige Rekonstruktion dieser Anlage. Der Bauprozess war schwierig und komplex und erforderte eine sorgfältige*

Planung und äußerst akkurate Ausführung. Jedoch war es – nach einem Jahrhundert des Experimentierens – die hängende Decke über dem calidarium *der Caracalla-Thermen in Rom, die als das beeindruckendste jemals ausgeführte Beispiel eines solchen Gittersystems bezeichnet werden kann.*

Stichworte: Bauarchäologie, Konstruktion, Metalltechnologie, ökonomischer Kontext