The Roman Hypocaust Heating System

Calculations and thoughts about construction, performance and function

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A research project sponsored by the University of Innsbruck

Abstract: It is considered one of the Roman civilisation´s greatest achievements, a vast number have been excavated in thermal baths and residential houses throughout the territory of the Roman empire: hypocaust heating, the first underfloor heating in human history. Specialized literature praises comfort and the simple yet effective construction and operational mode of this heating system. Aside from the fact that there is no standard hypocaust heating but rather countless different varieties, experiments in reconstructed facilities have proven that running them is nowhere near as easy and trouble-free as assumed. Throughout this book, hypocaust heating is viewed from an archaeological and a technical angle in order to better understand the whole system as an interaction of its components. To add to this occupational technical knowledge of heating systems, the author employed-amongst other things-the help of three Austrian research and testing institutes as well as a prestigious boiler manufacturer´s R&D-department. Any experiences (as far as they were still documentable) the heating models operators already had also bolstered the project. Modern technical standards served as a basis for comparison, wherever that was possible.
Some of the results:

1. The heat demand of 11 structures heated by hypocaust heating in antiquity is-for the first time-calculated using modern standards and methods.
2. This serves as a basis to derive necessary room temperatures and resulting of this the necessary floor temperatures, needed to achieve the resident´s comfort. In order to objectify the results, they are compared with modern norms.
3. Multiple versions and varieties of individual components of hypocaust heating and their coaction within the overall system are portrayed for the first time.
4. Special consideration is bestowed upon the so-called wall heating system.
5. Suggestions are made with regard to any parts that have not yet been ascertained archaeologically. I don´t strive to show off my own competence in this particular field. I much rather want to provide my colleagues with a set of tools that will help them to see hypocaust heating from a different angle, because most of the time normally one mostly finds what he or she knows and is looking for.
6. Flow conditions within the hypocaust are depicted schematically as a computer simulation for the first time.
7. Heating itself, combustion and the suitability of different fuels are examined and various criteria of their assessment are established.
8. Difficulties that arose in the reconstructed buildings are addressed, potential causes are listed and-wherever possible-solutions are provided.
9. Advice for the proper running of a reconstructed hypocaust heating is given.
10. Facts that were considered ascertained are questioned critically and-in some cases-reinterpreted.

This thesis incorporates two and a half years of intensive research, about 10.000km by car and a plethora of heating related and constructional knowledge (based on more than 20 years of author´s experience of working in the heating sector before he started to study Classical- and Roman Provincial Archaeology). It is – at the point – probably the most extensive paper about this antique heating system.

Since the extent of this documentation of 800 pages (including a cd-rom) necessitates it:

A short overview of the content with some illustration examples:

(AP= archaeological park, the work consists of two parts)

Part 1

Main components of a hypocaust heating

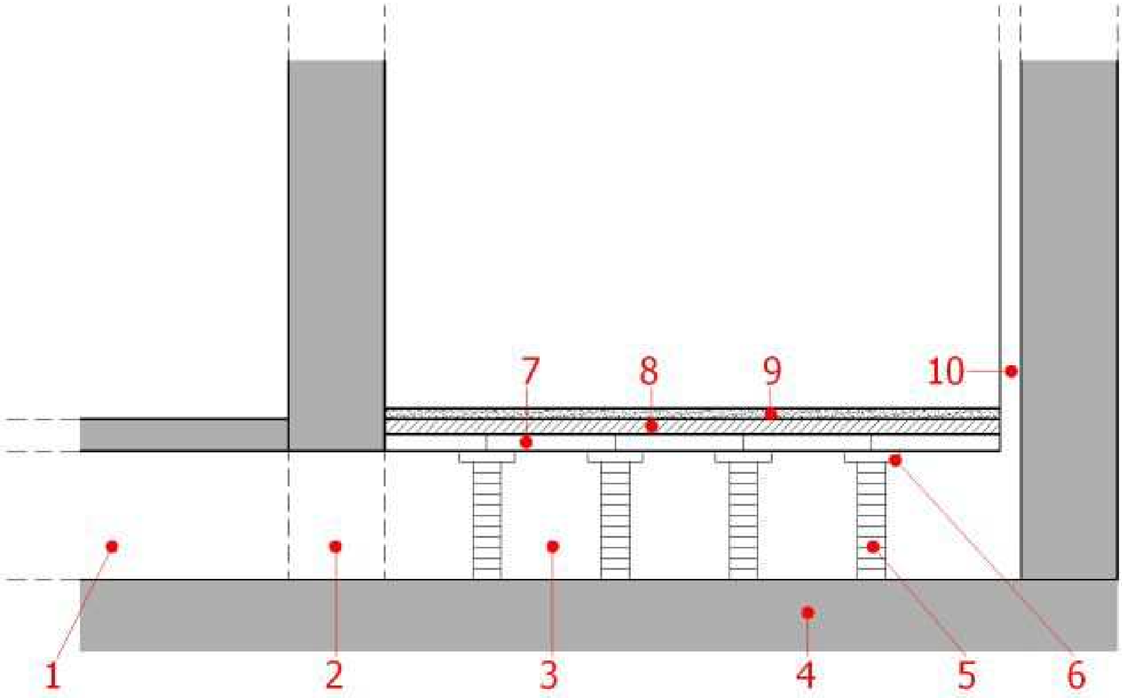

Fig. 1 – sectional view of a hypocaust heating, © H. Lehar 2010

1. praefurnium (furnace)
2. combustion channel
3. hypocaust
4. lower base
5. hypocaust pillar (pillae stack)
6. carrier/base plate; contact face; head plate
7. suspensura - plates
8. raw/rugged screed
9. fine screed
10. underfloor heating system with flue, box flue tiles inside the walls to heat them?

7.+8.+9. combined are called "suspensura" (= the floor construction as a whole)

The examined objects

Reconstructed building which where heated with a hypocaust during the antiquity, regardless of whether the have a functioning hypocaust heating now. Calculation of the heating load is only possible if a building exists three-dimensional, either in reality or virtual. A ground plan alone is insufficient.

- Römermuseum Homburg – Schwarzenacker, Haus 17
- Archäologischer Park Carnuntum, Haus II
- Römisches Freilichtmuseum Hechingen – Stein, Villa Rustica
- Archäologischer Park Carnuntum, Villa Urbana
- Archäologischer Park Magdalensberg, „Repräsentationshaus“
- Archäologischer Park Carnuntum, Thermen der Zivilstadt
- Römervilla von Möckenlohe
- Römermuseum Homburg – Schwarzenacker, „Haus des Augenarztes“
- Römerkastell Saalburg, Archäologischer Park, Versuchsraum in der Principia
- Archäologiepark Römische Villa Borg
- Archäologischer Park Xanten, Herbergsthermen

e.g.: Archäologiepark Römische Villa Borg

D-66706 Perl-Borg, Germany

Reconstruction with modern materials[1], no working hypocaust heating available

Fig. 2 – thermae AP Villa Borg, exterior view © H. Lehar 2009

[1] Birkenhagen 2009

The Praefurnium

Used building material, execution alternatives, their impact on combustion and the complete system.

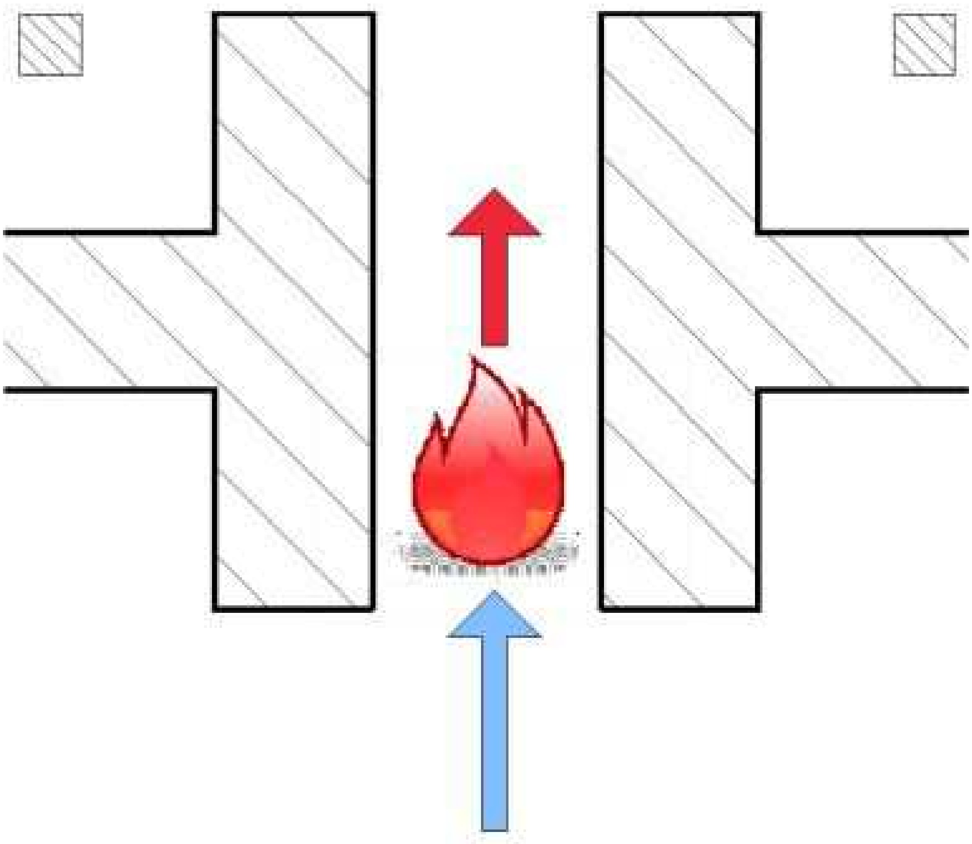

Fig. 3 – praefurnium with lateral walls that are drawn out of and into the hypocaustum (view from above) © H. Lehar 2010

The Hypocaust

Building material, measurements, proportions, impact of the suspensura's thickness on the heat transfer to the heated room, problems with strain and crack formation, emission of smoke gas into the room, attachment of the suspensura to the walls.

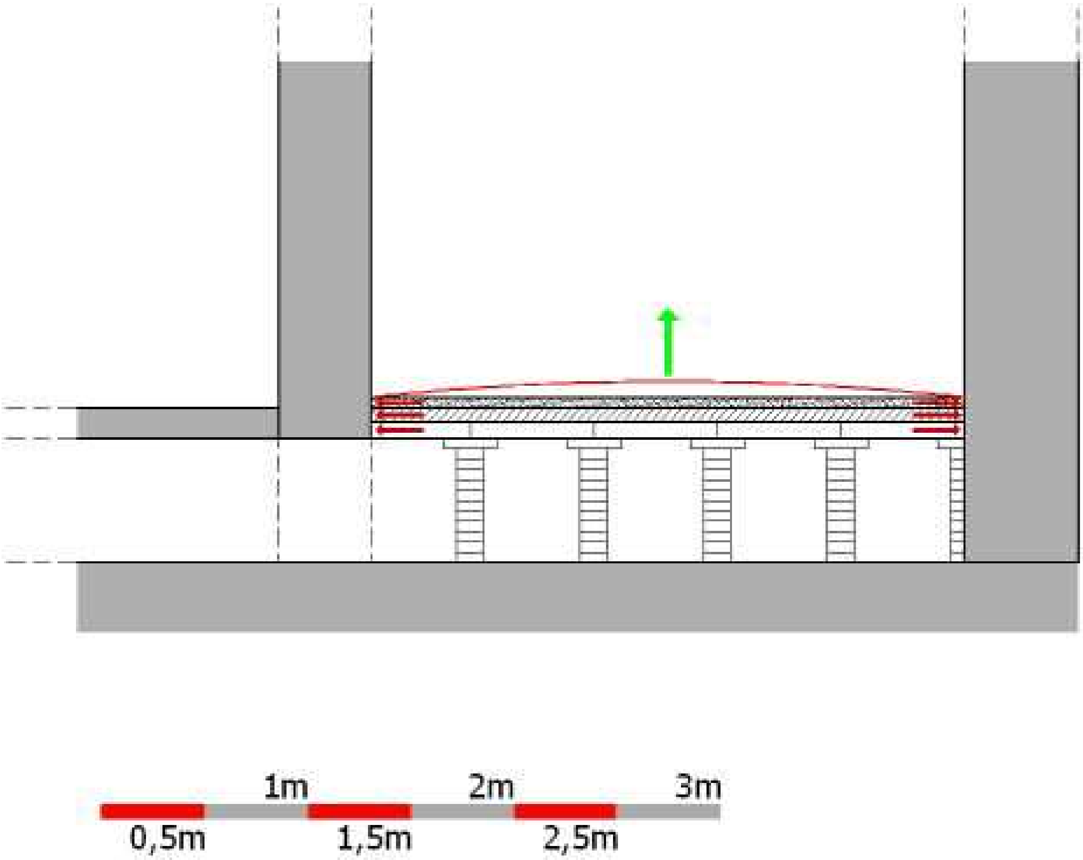

Fig. 4 – screed bulging upwards, as a result of too little space to expand sideways © H. Lehar 2010

Fig. 5 – the wall has been pressed outwards due to the heat – related dilation of the suspensura and has partially torn. Due to this, soot and flue gas were able to escape from the hypocaust; AP Carnuntum, Villa Urbana © H. Lehar 2010

The smoke vents

Building material, types of vents, tubuli and their fixation, assessment of sense and function of sidewise “connection openings”, new projections to their function. Since the vent’s course on the upper area isn’t known through findings, some technically possible alternatives for their configuration and course are shown.

Fig. 6 – box flue tile with lateral openings. Remains of mortar show where it encroached the hourglass-shaped openings. This indicates possible use as a flue. AP Römische Villa Borg, museum © H. Lehar 2009

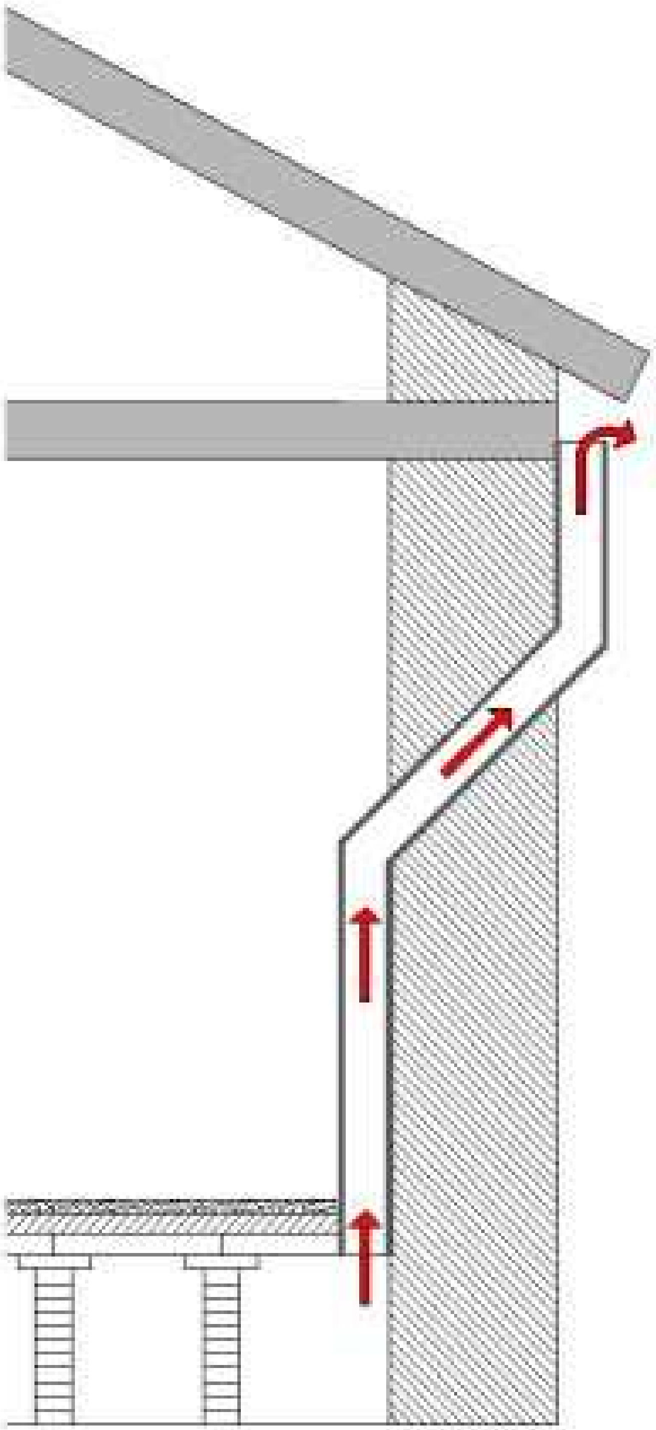

Fig. 7 – possible pathway of a flue © H. Lehar 2010

Heat Distribution on a heated floor

With the help of flow patterns it is shown how quantity and position of vents influences the heat distribution:

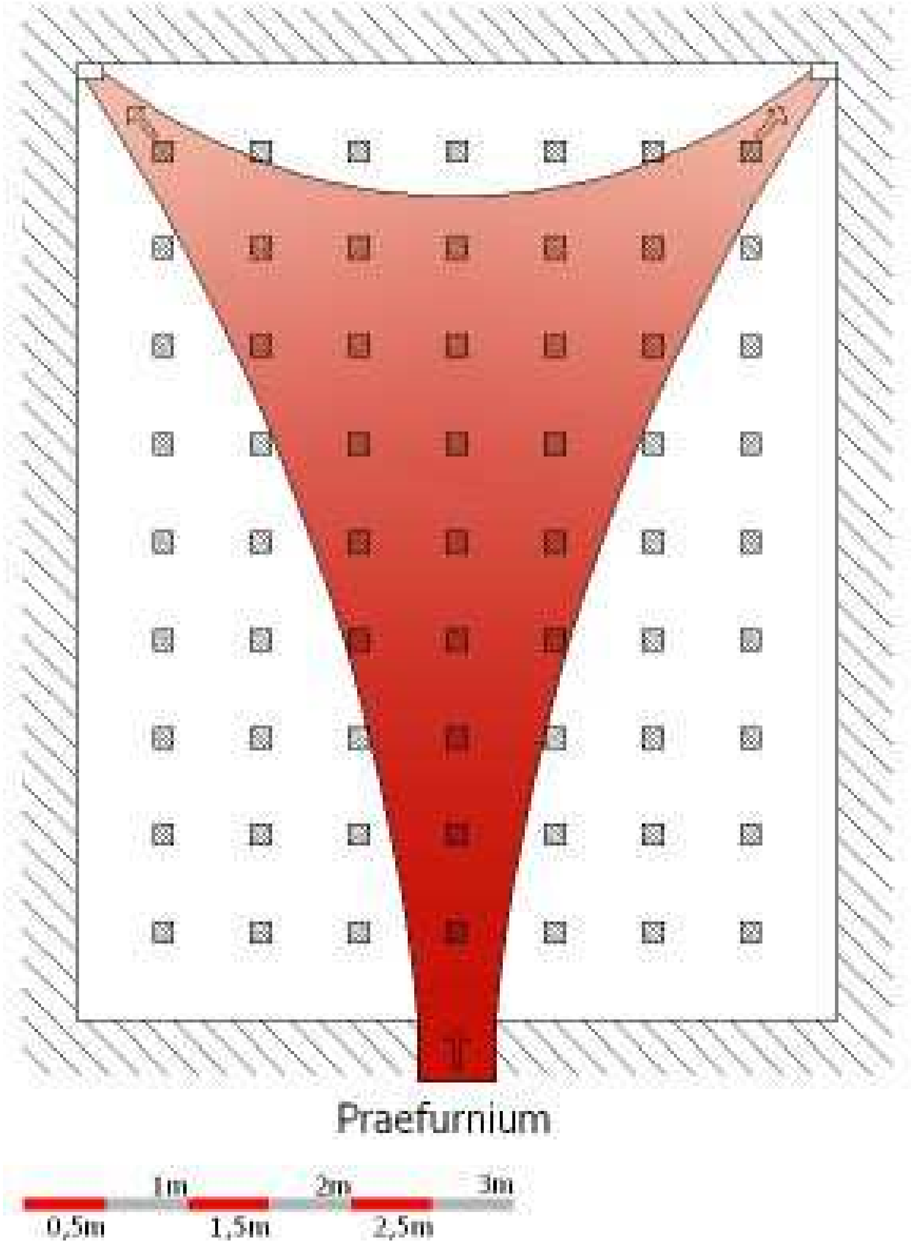

Fig. 8 – schematic path of currents using two flues; examples of this particular flue gas evacuation: villa urbana and (partially) thermae of the civilian part of the city of Carnuntum © H. Lehar 2010

It is demonstrated how the execution of the firing conduit and the suspensura can influence the evenness of heat output.

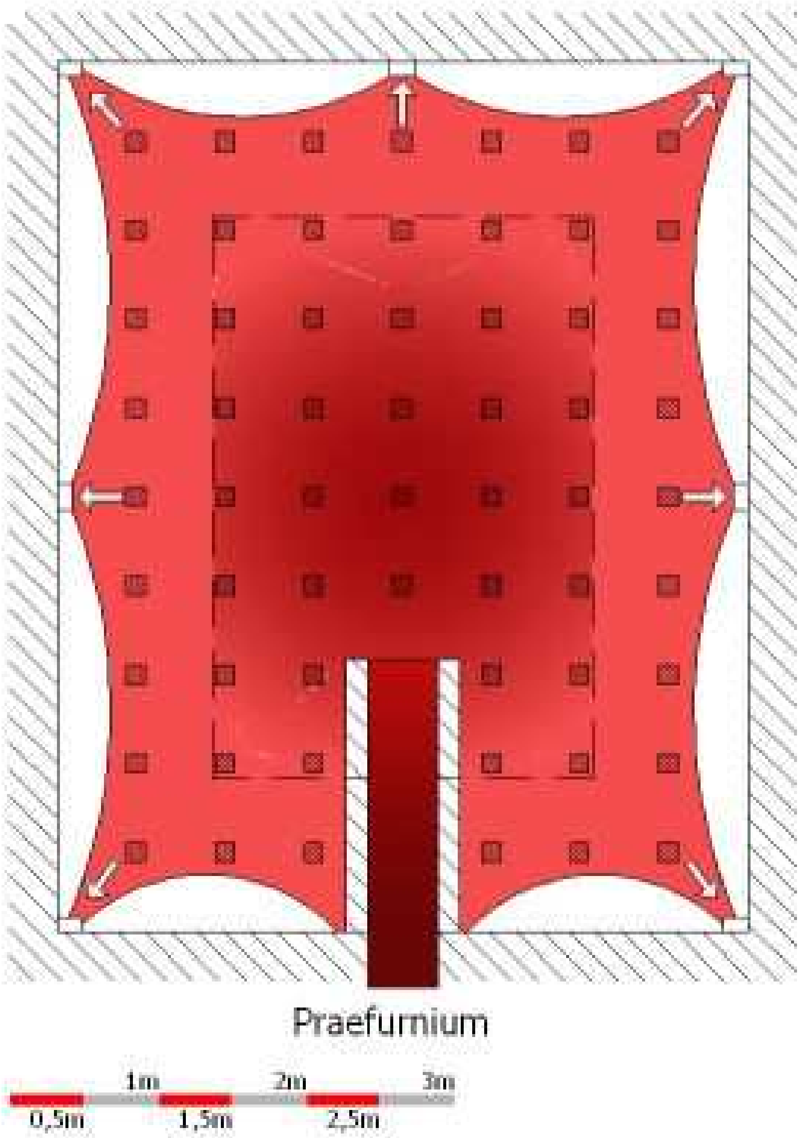

Fig. 9 – schematic path of currents using a conduit (reaching into the hypocaustum) and six flues (numbers vary in the field) AFTER equalisation of varying draughts. Possible examples for this flue gas evacuation (in these examples, flues have yet to be ascertained in the field, though): Castell Collen [2] (Llandorindod Wells, Wales, GB), Saalburg - Kastell[3], Kastell Stockstadt[4] (Stockstadt/Main, Landkreis Aschaffenburg, D) © H. Lehar 2010

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[2] Philipp1999, Br.12

[3] Philipp 1999, GeSup.27.1

[4] Philipp 1999, GeSup.30

The heating process

Since none of the reconstructed facilities work flawlessly and considerable damage has occurred, the combustion processes of wood and charcoal are examined n the basis of the problem of sooting (unwanted condensation of smoke gases).

Fig. 10 – AP Carnuntum, condensate stains (sooting) at the easternmost side of the "Apsisraum" of the villa urbana © H. Lehar 2010

Fig. 11 – AP Xanten; walls of the tepidarium in the lodging house thermae show strong sooting. These steins make it easy to trace the route of the vents towards the vaulted ceiling © H. Lehar 2010

The combustion is depicted schematically, pros and cons of the fuel types are presented and detailed recommendations for correct firing are made.

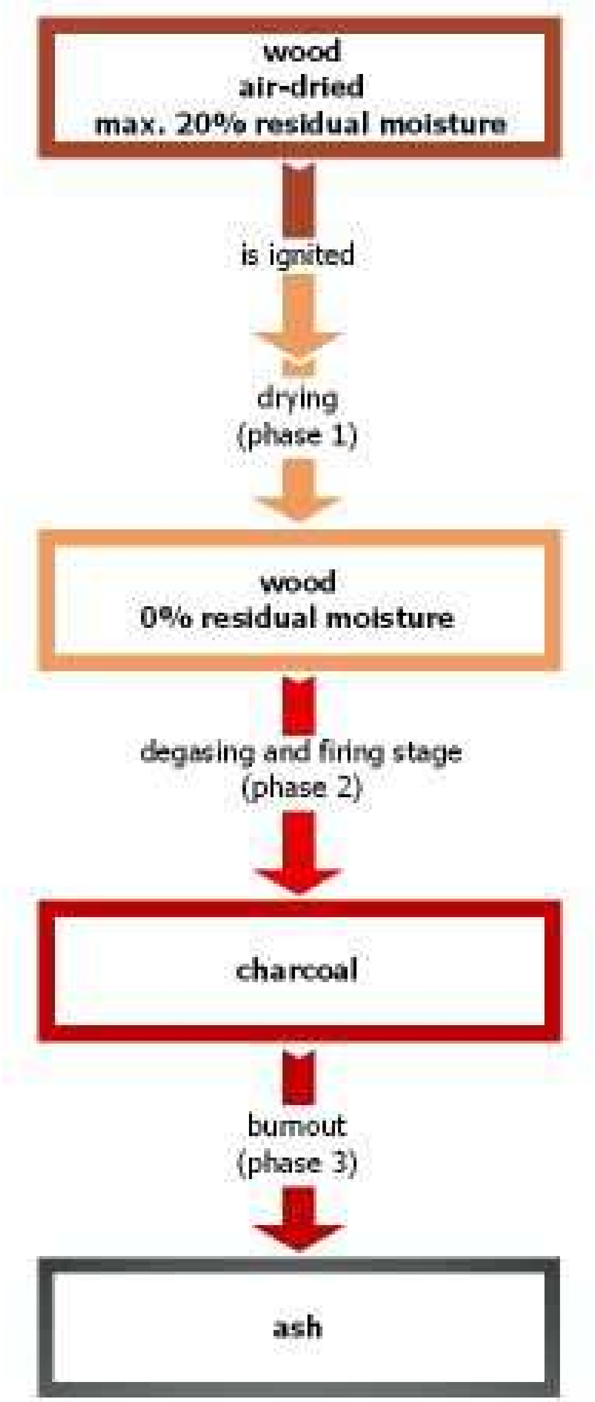

Fig. 12 – simplified depiction and description of the combustion of wood with upper burn-off (referring to L. Lasselsberger and R. Marutzky)[5]) © H. Lehar 2010

[5] Marutzky 2002, 43-47

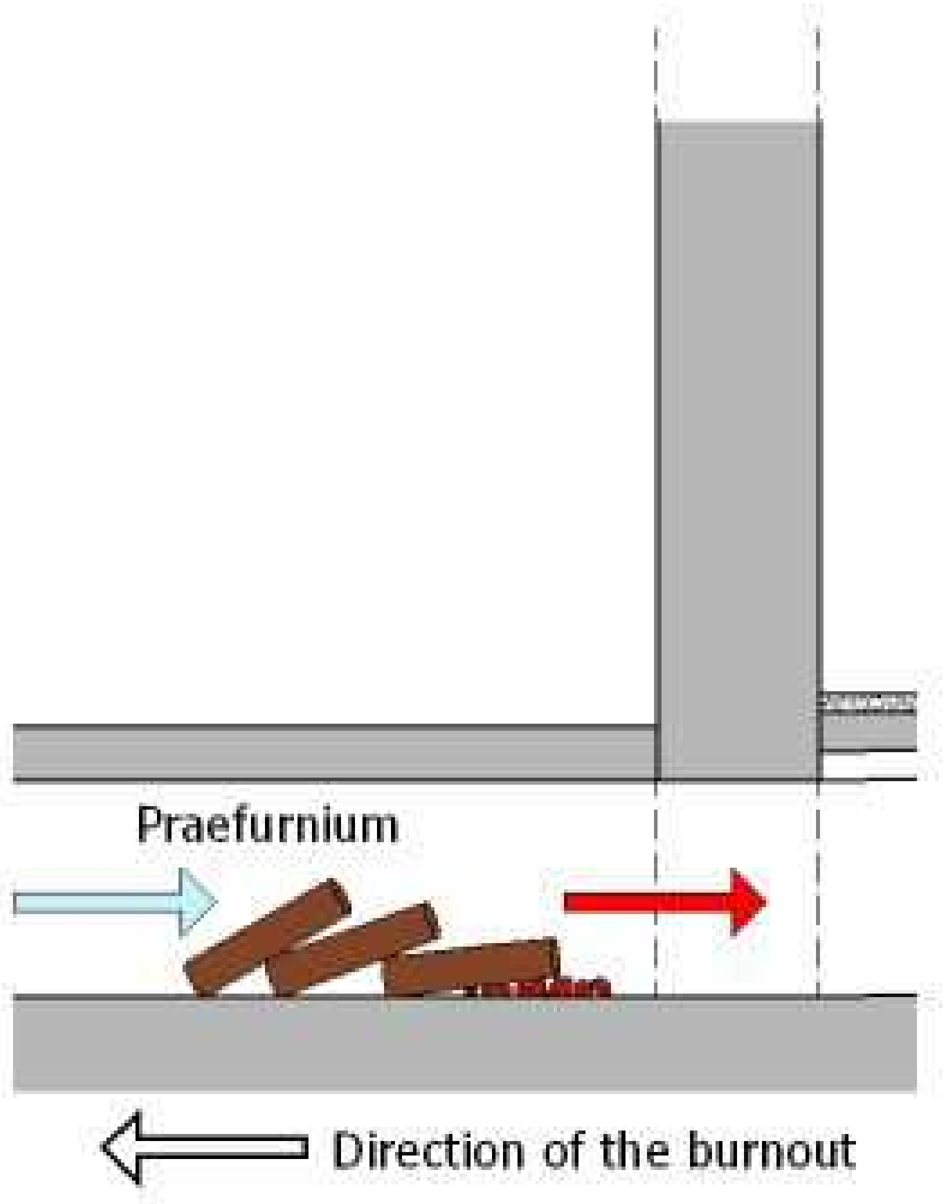

Fig. 13 – feeding at the rear of the embers/blaze © H. Lehar 2010

Since the smoke vents have a big impact on this area, their effect on the drift behaviour of the facilities is remarked upon and the necessary height of the vents is mathematically determined.

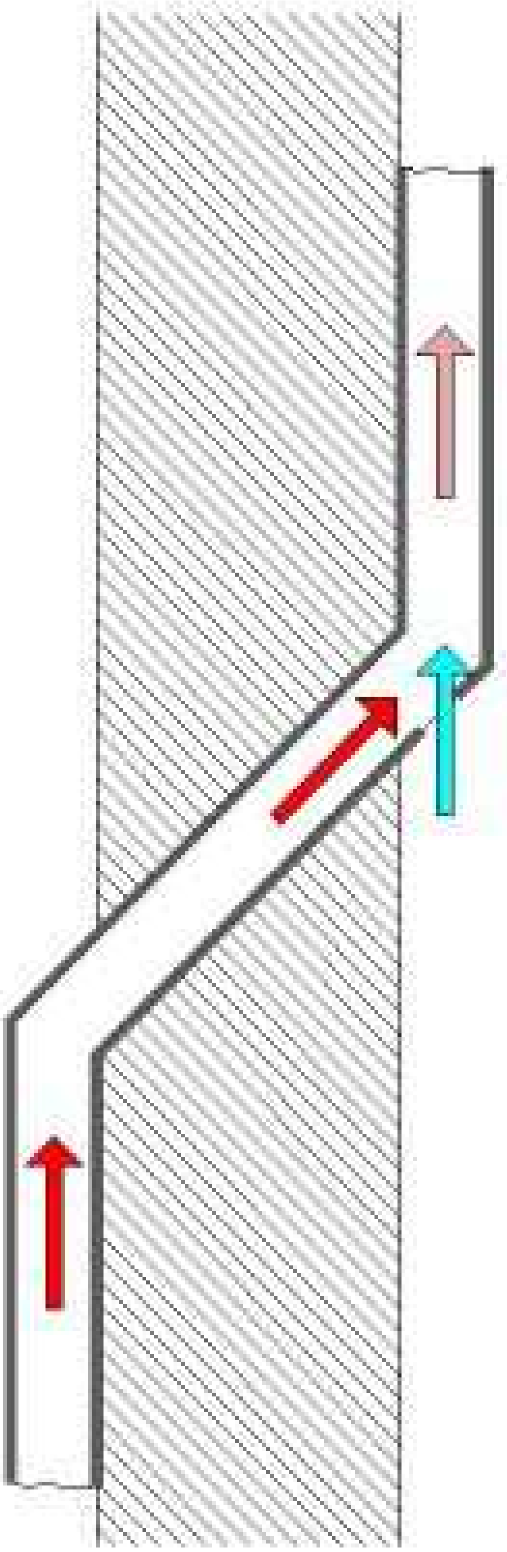

Fig. 14 – possible way of addition in the region of the outlet. Additional advantage of this method: the opening could be used to remove condensate formed in the outer portion of the flue without damaging brickwork or plaster. © H. Lehar 2010

The Tubulation

The so-called "wall heating" is examined in-depth, the flow conditions are presented elaborately and a new calculation-based application of the tabulation in contrast to the so far (with few exceptions) generally believed doctrine is shown.

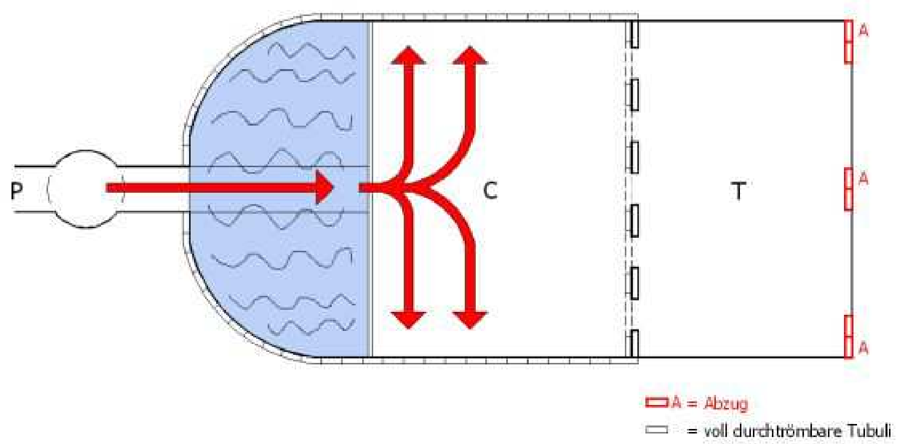

Fig. 14 – heating gases now don't drift - in the "standard" arrangement - from the caldarium (full of box flue tiles with openings to the top) directly to the tepidarium - they utilize the shortest way via the nearest strand of box flue tiles into the open (top view). Due to this fact, the caldarium is only partially heated, the tepidarium not at all[6]. © H. Lehar 2010

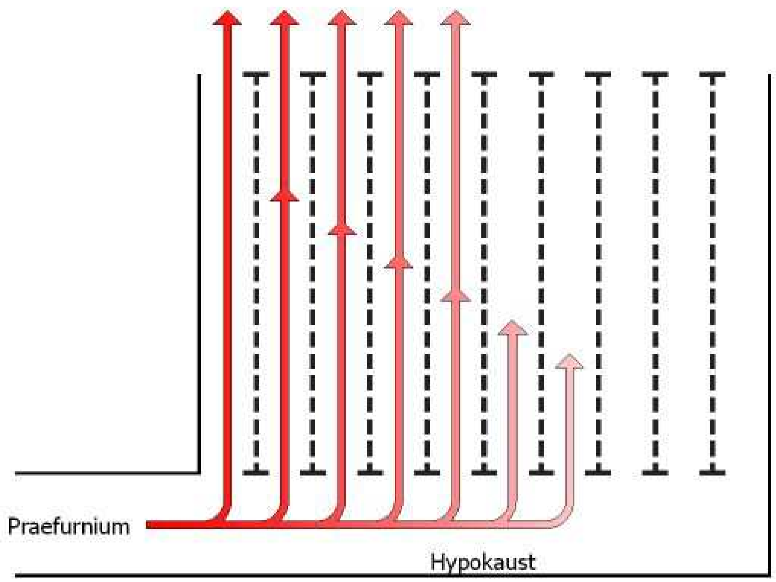

Fig. 15 – heating gases could have escaped outside through the nearest strands of box flue tiles (if lateral connections between the strands existed of not might have been irrelevant)© H. Lehar 2010

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[6] comp. Timmer 2007, 89f

Comfort

On the basis of modern criteria all 11 objects are tested on the fulfilment of contemporary comfort demands.

Requirements for comfort in heated rooms[7]:

These can be divided in two main categories: those who can be influenced through heating and those who cannot.

Influenceable through heating:

1. The room should be pleasantly warm.
2. The floor's temperature should be even and not at all too high.
3. The room air's temperature should be as even as possible through the entire room.
4. The temperature of the room's border planes (wall, floor, ceiling) should be as even as possible.
5. There should be no air draft emergences in the room
6. Each room's temperature should be adjustable independently.
7. The air quality in the room is important: no toxic elements, no bad smells, pleasing air humidity, no dust swirling, no dust devolatilization.
8. The temperature differences between individual rooms should not be too high.

The floor temperatures necessary to cover the heat demand are important and show the use of hypocaust heating, particularly in the living area, in a new light.

Connection Floor temperature – Sensation[8]

surface temperature of the heated floor	transfer of heat from ground to heated floor	sensation to user
18°C	2,7 Watt	unpleasant
20°C	2,3 Watt	pleasant
24°C	1,7 Watt	pleasant
25°C	1,5 Watt	pleasant
27°C	1,2 Watt	pleasant
30°C	0,6 Watt	unpleasant

[7] Lehar 1989, 1-19

Recknagel 1990, 40-70, 337f

[8] Kollmar 1980, 23

Lehar 1985, 7

comp. Peschak 1983-2, 8

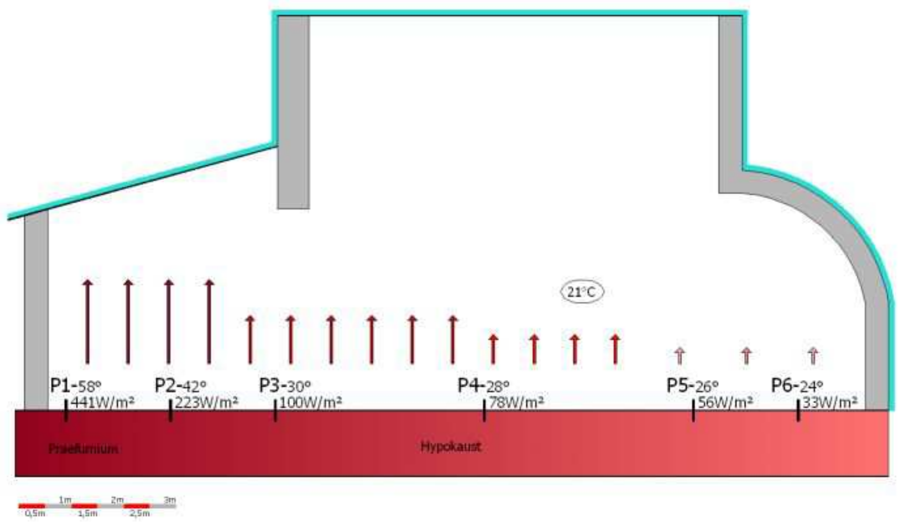

Fig. 16 – possible appearance of a temperature and performance gradient. Metering in the "Apsisraum" of the villa urbana in AP Carnuntum. 27-12-2008, outside temperature between 0°C and -3°C [9] © H. Lehar 2010

e.g. Römermuseum Homburg – Schwarzenacker, House 17

One room (26,4m^2, ti=20°C) was heated with a holohedral hypocaust heating and it's own praefurnium.

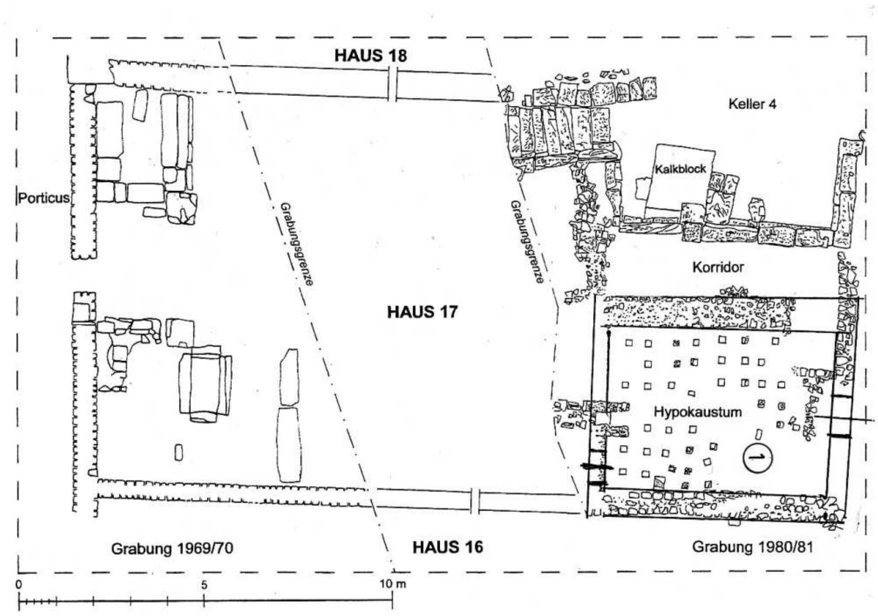

Fig. 17 – AP Homburg - Schwarzenacker, house 17, layout © Ermer GmbH.& Co.KG 2002

[9] Reithofer 2009

Pleasant Heat

Expressed through the covering of the norm heating load and the amount of necessary, even floor temperature needed for that.

The calculations showed among other things:

Norm heating load (outside temperature *ta* = -12°C, temperature in the room *ti* = 20°C): 4390W (is consistent with the heating load of a modern heat-insulated flat of 80 m^2)

Floor temperature (*tfb*) necessary for covering heat demand:35°C

It is not possible to cover the head demand with the today according to ÖNORM max. permissible floor temperature (*tfb*) of 29°C for living areas.

If one wanted to keep within the *tfb*=29°C, one could only reach an inside temperature

ti = 16°C with a norm according *ta* = -12°C.

ti = 20°C in connection with *tfb* = 29°C would only be possible if *ta* = 0°C.

Heat demand and Consumption

For the first time the heat demand according to ÖNORM was calculated for 11 objects. The results provide the basis for determining the floor temperatures necessary for heating and the starting point for roughly calculating the fuel usage for one winter.

For the aforementioned **House 17 in AP Homburg – Schwarzenacker** (45,5m^2 heated) this results in:

Heat demand = 4,39kW (is consistent with the heating load of a modern heat-insulated flat of 80 m^2)

Usage beech wood (facility efficiency factor 30%):

7,7 m^3 = 5544 kg (5,5t) beech wood = 188 m^2 forest area

Usage charcoal (facility efficiency factor 35%):

1678kg (1,7t) charcoal = 6712kg (6,7t) beech wood = 228 m^2 forest area

Hot on the trail of ignis languidus

With electronic data processing the drift course of smoke gases in the hypocaust could be simulated and it could be shown that “a creeping fire with smoke which lazily writhes through the hypocaust” (Statius, Silvae) is possible, and what conditions (construction and type of heating) need to be met for this drifts to develop.

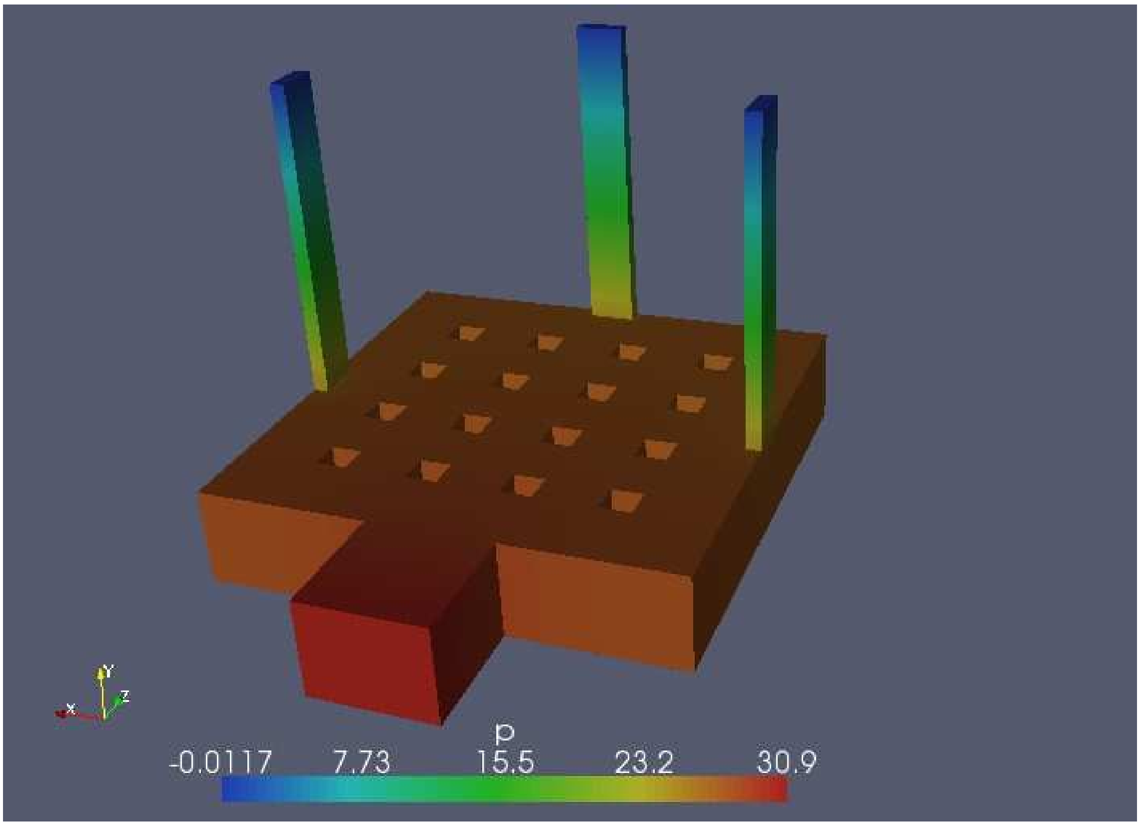

Fig. 18 – depiction of the specific pressure distribution in the model-hypocaust. © tgm Wien, P. Herzog 2011/H. Lehar 2011

Part 2

(contains all plans, profiles, views and calculations for part 1)

Preliminary Notes:

For technically experienced readers Part 2 contains all calculations whose results were mentioned in part 1; as well as the building plans which were used. Existing building plans were incurred, if there weren't any the buildings got measured and the plans drawn.

Furthermore it contains calculations whose content is interesting but weren't included in part 1 to limit the scope of this work. On the other hand not all calculations were done for every object because it didn't seem meaningful or significant, or because there doesn't exist a modern norm (thermae).

The calculations carried out with a computer were done with ÖNORM appropriate programs. The results don't differ significantly from calculations done according to other norms (e.g. DIN).

The used climate data for Austria originate from ÖNORM M7500 and for Germany from DIN EN 12831 and DIN 4701.

For other calculations I used generally known formulas from heating technique, though in many cases I "switched" them, which means that I used them to calculate values which are normally known, but searched for in our cases.

Calculations which where kindly provided to me by heating specialists are depicted unchanged.

Most calculations were done by myself, so for example:

reach the measured surface temperatures (measurement R. Reithofer) **on 27.12.2008 in rooms 2 and 3 in Villa Urbana**

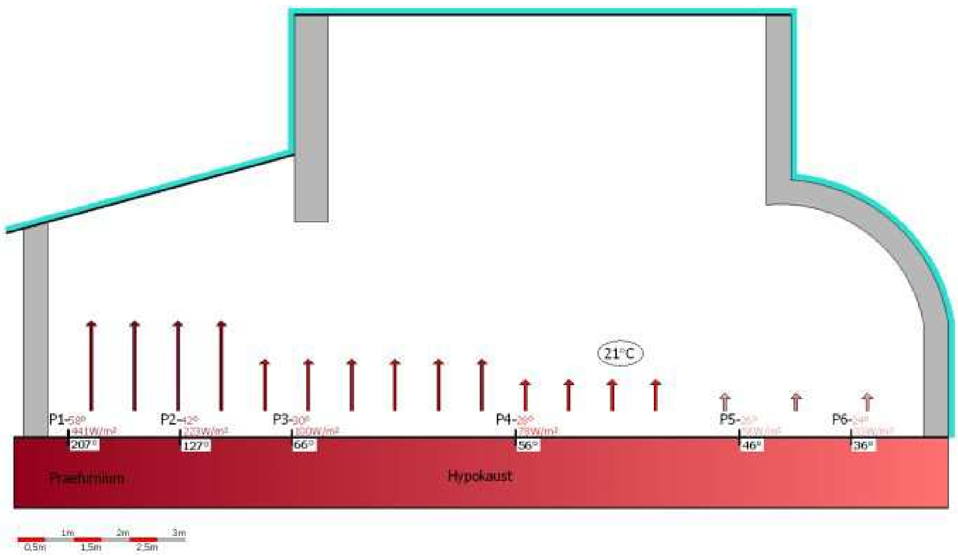

Fig. 19 – calculation of the necessary temperatures of the suspensura-underside in order to reach the earlier (Messung R. Reithofer) measured surface temperatures. © H. Lehar 2010

The k-number of the suspensura was calculated with 2,75 (according to data from K.F. Gollmann)
Basis for this was the formula for calculating heat loss via a building element:

$P = f \cdot k \cdot \Delta t$ at which applies: $\Delta t = tfb.u - tfb$

For our means f can be assumed to be 1m^2, which simplifies calculations.
Therefore the formula is uses as follows:

***tfb.u* = *tfb* + (*P*:*k*)**

point of measurement	calculation step 1	is further	calculation step 2	***tfb.u***
P	***tfb* + (*P* : *k*)**		***tfb* + (*P* : *k*)**	
P 1	*tfb.u* = 58 + (411 : 2,75)		58 + 149 =	207° C
P 2	*tfb.u* = 42 + (233 : 2,75)		42 + 85 =	127° C
P 3	*tfb.u* = 30 + (100 : 2,75)		30 + 36 =	66° C
P 4	*tfb.u* = 28 + (78 : 2,75)		28 + 28 =	56° C
P 5	*tfb.u* = 26 + (56 : 2,75)		26 + 20 =	46° C
P 6	*tfb.u* = 24 + (33 : 2,75)		24 + 12 =	36° C

Summarisation

Though many questions can be answered better based on this research, the fact remains that some of it is – though justifiable- speculation and combination.

Therefore it isn't possible – even though desirable- to provide a patent medicine for the construction of a flawless hypocaust heating. The facilities are too different and each one has to be considered individually.

But some useful tips are possible:

1. rather build a simple heating system and don't plan to include too many specialities (e.g. Tubulation).
2. allot a own praefurnium or each room.
3. preferably a praefurnium of the type according to illustration 37.
4. execute the hypocaust either with an even under-floor or an execution with only a very slightly rising under-floor and a parallel to this rising suspensura as shown in illustration 149.
5. vents in sufficient numbers, not too high and arranged to ensure good heat distribution.
6. fuel with charcoal.
7. absolutely avoid short time usage
8. don't use building material or construction techniques which weren't available to the Romans. The results would be incorrect and only of limited use for research of the heating system.

But – as stated – these tips don't replace planning and calculating with experts who should have read this book. In addition the in the course of this work developed calculation methods for optimum height of the vents and the presentation of the drifts should be used. An element of risk remains nonetheless since hypocaust heating is an extremely complex structure of which we still don't have enough secured knowledge.

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