INNOVATION IN CONSTRUCTION - EXPERIENCES FROM A HYPOCAUST SYSTEM IN AUSTRALIA

Robert J. FULLER

Built Environment Research Group, School of Architecture and Building, Deakin University
Waterfront Campus, Geelong 3217, Victoria, Australia, Email: rfjull@deakin.edu.au

Abstract
Introducing new technologies poses a particular challenge to the players involved in a project. For a successful low energy building, a new design process is required and players must assume new and additional responsibilities. Hypocaust systems, where conditioned or non-conditioned air is passed through ducts within the concrete floor or ceiling of a building prior to its delivery to the rooms, are starting to appear in new buildings in Australia. This paper describes the lessons learned from the early experiences with a hypocaust system, installed in a new building in Melbourne. It concludes that a more cooperative process among all those involved in introducing and using a new 'technology' is essential if the problems described are to be avoided or at least minimized.

Keywords
Design process, hypocaust systems, innovation, low energy building, technology introduction

INTRODUCTION

We are living in the era of significant change with respect to the type of building now being designed and erected. Driven by environmental concerns, particularly the need to reduce greenhouse gas emissions, many of our new buildings are now being described as 'low energy', 'sustainable', 'green' and even 'deep green'. In Australia, to this point in time, the impetus for this change has come from clients, who for a variety of reasons are responding to increased levels of environmental awareness, but increasingly the driving force will be legislation.

The development of new materials and technologies, the “hardware”, becomes available as demand grows and manufacturers usually adapt to marketplace changes. The “software”, however, which includes the knowledge required to operate innovative systems, new design and commissioning processes, and cooperative working between the parties involved, tends to lag behind hardware development. This means problems, failures and less-than-optimum outcomes due to lack of experience and cooperation between the main players are possible.

This paper further develops ideas previously explored by Fuller and Luther (2003). It describes some of the pitfalls that exist and the problems that have been encountered when introducing a new technology into the construction industry. In this instance, the new technology is the hypocaust system. Since the case study described in this paper is almost certainly the first application of this technology in Australia, the experiences should be of value to other first-time users. The technical performance of the hypocaust, its design details and any performance are only reported where necessary to illustrate problems that have occurred and their possible causes.
The paper begins with some background information about hypocausts and a description of the building and its particular hypocaust system. This is followed by a general introduction to the ‘players’ in the construction industry together with some comments about the process required to achieve a successful low energy building. Examples of the shortcomings and problems that have occurred in the process of introducing the hypocaust system in the case study building are then described. Finally, some outcomes of the process are described and conclusions are drawn.

HYPOCAUST SYSTEMS

The term hypocaust derives from the Greek word hypocaustis, indicating a heating apparatus placed under the building it proposes to heat. The ancient Romans heated their buildings by passing the hot combustion gases from wood furnaces through the cavity walls and floors. In the modern application, conditioned or non-conditioned air is passed through the building element (floor or ceiling), thus using the thermal properties and behaviour of that building element more effectively than in a conventional building. The modern technology was developed in Sweden in the 1970s and has been installed by the Termodeck® companies in over 300 buildings, particularly in Scandinavia and the United Kingdom. Considerable industry experience has therefore been gained. In the UK, for example, “the product development stage involving advanced fabric energy storage systems (viz. Termodeck®-type systems) is complete” (Winwood 1997).

In brief, evaluations of some of the buildings fitted with hypocaust systems have been favourable from several perspectives. These are reduced energy use and CO₂ emissions (Probe Team 1998), reduced construction costs, increased comfort levels because of radiant cooling, more stable internal environments and reduced short-term peak demands for cooling, offering the potential to reduce equipment size and capital costs (Braham 1998).

BUILDING DESCRIPTION

Hypocaust systems are starting to appear in Australia. To date two buildings on a university campus have used the local version of the hollow concrete panel system. The first building to use this system in Australia is a three-storey multi-purpose structure on the Burwood Campus of Deakin University. Either side of a central atrium, each floor is divided into pods, which are then used as teaching spaces, laboratories or sub-divided into offices (Figure 1). Known as Building T, it incorporates a number of low-energy features designed to provide acceptable levels of thermal comfort, while at the same time significantly reducing the demand for energy. The concepts behind the building and the simulation process undertaken to assist in the choice of materials and systems have been described elsewhere (Luther and Fuller 2000 and Fuller and Luther 2002).
One of the innovations in the building is its hypocaust. In this system, air is forced through the hollow cores of the concrete ceiling/floors at each level in certain modes of operation. The hypocaust system in Building T has already received some publicity because it is the first application of this concept in Australia (Anon 2002a and 2002b). The arrangement of the hypocaust in Building T is shown schematically in Figure 2.

There are at least two differences between the hypocaust system used in Building T and those used in Europe - at least those described in the literature. These differences have possibly impacted on the performance of the system. Firstly, three uniformly spaced outlet holes per concrete panel have been used to deliver air in contrast to a single outlet used overseas. Secondly, except in a night purging mode, outside air is not introduced directly into the hypocaust and so the concrete panels do not temper fresh ventilation air, which is the practice in European hypocaust systems.
THE PLAYERS

From concept to occupancy, there is a myriad of players in the process of achieving a successful building. Winch and Carr (2001) listed the principal actor groupings, a modified version of which is shown in Table 1. Interestingly, those authors did not cite the user as a significant player in the process. In the era of low energy buildings, where adaptative responses by the occupants are often required, the user will play an important, if not crucial, role to make the building work. Likewise Winch and Carr (2001) did not include academics or researchers as an important player in the modern construction process. At a time when innovative and novel ideas are more likely to appear in new buildings, this grouping should play a significant role.

Table 1: Principal actor groupings in construction projects

<table>
<thead>
<tr>
<th>Grouping</th>
<th>Typical Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client</td>
<td>Building owner</td>
</tr>
<tr>
<td>Academics</td>
<td>Researchers</td>
</tr>
<tr>
<td>Consultants</td>
<td>Architects, engineers, principal quantity surveyors</td>
</tr>
<tr>
<td>Regulatory</td>
<td>Building control; development control authorities</td>
</tr>
<tr>
<td>Contractor</td>
<td>Principal contractor</td>
</tr>
<tr>
<td>Trade Contractor</td>
<td>Trade contractors</td>
</tr>
<tr>
<td>Users*</td>
<td>Occupants - various</td>
</tr>
</tbody>
</table>

(added from Winch and Carr 2001)

Usually for any successful new or innovative technology, one of the above players must adopt the role of the champion. Mogavero and Shane (1982) describe this person as the never-say-die person, who "keeps the project moving and, most importantly, makes the necessary adjustments to make certain the project keeps heading in the right direction." Writing specifically about the construction industry, Dulaami (1995) also highlighted the role of the innovation champion and described what type of individual this is likely to be and the conditions required to allow him or her to thrive.

THE PROCESS

The principal actor groupings likely to be involved in any construction project, however, do not act alone. An effective process should link their contributions. Reports of successful low energy buildings stress the importance of using a whole-building integrated approach resulting from "conscious choices and unusual collaboration among .... staff, the owners, the engineers, ..... architects and ..... consultants" (Miller 1999). A report on the well-publicised British Research Establishment building in the U.K. speaks of visible and invisible innovation. While co-incidentally one of the visible innovative components of this building is a hypocaust system, it is the invisible innovation of "up front investment in teamwork and collaboration, which mark it as an experimental building" (Cook 1998).

The importance of the integrated design process (IDP) in sustainable building design has been recognized internationally and guidelines are now available (IEA 2002). According to these, one of the key features of the IDP is "inter-disciplinary work between architects, engineers, costing specialists, operations people and others right from the beginning of the process".
IMPLICATIONS

Having described the players in an ideal process, some examples from the case study building described earlier are now used to illustrate how shortcomings in the traditional process and roles or responsibilities of the players can impede the successful introduction of a new technology.

Adopting an Iterative Process
The need for a different kind of design process has been discussed and this was attempted particularly in the early stages of the project (Luther and Fuller 2000). At a certain point, however, from the author's perspective, the process became somewhat traditional and linear, rather than continuing to be iterative and consultative. The reasons for this reversion are not clear and can only be speculative. The time and difficulties in organising multi-disciplinary meetings can be considerable, but a more likely reason is that the importance of the collaborative process and consultative decision-making was under-estimated. In Building T, for example, changes in the hypocaust control strategies were adopted without consultation with those responsible for the original design simulations. The effectiveness of these changes could easily have been tested by further simulation and subsequent problems avoided. The need to work closely together on innovative projects such as a hypocaust building is demonstrated by the experiences in the first UK hypocaust system. In this case, it was found that "from the client right down to the product suppliers, the project ... forced a rethink of established construction methods, whereby concept designers had to work much more closely with the construction team during the building's design development phase" (Bunn 1994).

Valuing Simulations
Not all architects and contractors are comfortable with or appreciate the value of building performance simulations, particularly those using complex programs. Larger organisations have embraced the technology, but still find it costly and time consuming. Increasingly there will be the need for even medium and small-sized firms to embrace computer simulation, if only to prove that their new buildings meet legislative energy and carbon emission performance criteria. Simulation models, however, can be particularly helpful in evaluating the performance of unfamiliar technologies or established technologies used in different climates or configurations. Balcomb (1999) also made the point that "building simulation should not stop with the completion of the design process. The tool that provides insight during design can continue to be useful during commissioning, operation and renovation".

Unfortunately, this has not occurred in this project. In addition, some important decisions made at the time of design simulations were not implemented in practice, undermining the value of the computer modelling and increasing the perception that the simulations were of secondary importance. The simulations assumed that ambient air would flow through the hypocaust and that control of hypocaust would be based on room temperatures, rather than the ambient conditions, which occurred in practice. Furthermore, in the original design brief, the partitions used to create individual offices in each pod were to be three-quarter height to allow good mixing of the air within the pod. Due apparently to concerns from staff about privacy, this has not occurred and some small totally enclosed offices have been created with full-height solid partitions. This change from the original specification will significantly change the thermal environment within each space. Experimental measurements taken in one pod over the summer in 2003 showed that the air temperature in the open and larger space was cooler than that in the adjacent three small offices. In another pod, similarly sub-divided, the
larger open space has been consistently 2-4°C warmer than two adjacent small enclosed perimeter offices during the winter of 2003.

**Importing Innovations**

Much has been written in the development literature about the dangers of introducing a technology to new users without fully considering their setting in its broadest terms e.g. Marjoram (1994). The existing infrastructure, culture, environment, legislation and expertise are all factors that should be considered. Transferring an air conditioning technology developed in one climate to another is likely to be problematic if it is not modified to suit the new conditions. The hypocaust or Termodeck® system was developed in Sweden, where the climate is obviously quite different to that in southeast Australia. One of the Swedish practices is to heat the concrete panels at night using off-peak electricity, so that a store of heat is created for use on the next day. Heat recovery systems are also commonly used in the Swedish and UK installations (e.g. Bunn 1994 and 1995). In most parts of Australia, heating is unlikely to be the main priority, especially in commercial buildings.

The extent to which a technology is modified when introducing it to a new setting poses a challenge. Moving too far away from the original concept runs the risk of diminishing the benefits that the technology has proved capable of providing. Hypocaust systems in Europe appear to have been universally used to temper incoming fresh air to be used for ventilation. This is in contrast to the system in Building T, where the existing air in the building is circulated through the concrete panels in all modes except a night purging mode. The one air outlet hole per panel used in European installations allows three passes of the air through the slab to maximise energy transfer. Some variation from this is sometimes used, depending on the thermal load of the room. Recent research suggests that five passes, instead of the normal three, would improve performance further (Barton et al. 2002). As noted earlier, this is in contrast to the three holes per panel and short pass length used in Building T, which results in the storage capacity of its hypocaust being under-utilised. In overseas installations, the slab core temperature is used as the basis for control, whereas in Building T, outside ambient temperature is the key parameter, and thus the thermal capacitance of the building is underestimated.

**Commissioning Innovative Technologies**

Commissioning is an established procedure in new building construction. But when innovative technologies are used, there is a danger that unfamiliarity will lead to imperfect solutions and short cuts in order to sign off the building. The uneven air flow distribution measured in four sections of the building provides an example of this problem. Each concrete panel has three 100 mm diameter supply outlet holes through which air is forced into the room below (Figure 2). Since the cores in the concrete are a constant diameter and the supply outlet holes are large in comparison to the size of the cores, uneven air distribution is inherent. This became evident to the mechanical services contractor at commissioning and their solution was to insert small baffles in some of the outlet supply holes to add resistance and hopefully balance the air distribution. In spite of this modification, however, the measurements in one area indicated that there was a large difference in air flow rates across the 15 outlet supply holes, ranging from zero to 250% of the average outlet velocity.

In the Elizabeth Fry building in the UK, one of the key design lessons listed by the Probe Team (1998) was "careful and persistent commissioning and handover during the first two years of occupation ... which proves the value of 'sea trials' for buildings of any originality or complexity." In other words, commissioning for a building with an innovative feature such as
a hypocaust requires a different approach to that normally perceived by contractors to be their obligation. This has not occurred in the case of Building T and problems in control and general operation when they have surfaced have been viewed as new problems.

**Monitoring Innovative Technologies**

Traditionally, there has been little interest shown by the building owners in the thermal performance of their buildings. Unless energy consumption was obviously excessive and energy costs were high, little monitoring was conducted. The detailed monitoring and evaluation of the thermal performance of low energy buildings is, however, essential to meet environmental and legislative standards. Not only will monitoring allow target performance to be verified, but it will also allow problems to be identified and fixed.

Fortunately, modern buildings almost always include a building management system (BMS), which monitors and controls the conditioning equipment in response to internal and external environmental variables. While the installation and commissioning of the BMS is carried out by a specialist contractor, it is usually not clear whose job it is to analyse the large amounts of data recorded daily. Unless there is a specific on-going contract with another specialist contractor e.g. an energy audit company, then in-house staff must be allocated and trained to do this work. If this is not done explicitly, there is a real possibility that the tedious task of on-going data evaluation will fall through the cracks.

In the case of the hypocaust, precisely this appears to have happened and as a result the malfunctioning in both of the cooling modes in the operation of the hypocaust went unnoticed for nearly six months. It only came to light as a result of some independent research work on the system that had not been originally scheduled. This example bears out the point made by Balcomb (1999) that "failures in building systems often go undetected for years, resulting in inefficient performance". Control problems appear to be commonplace with hypocaust systems, at least in the early UK installations. In the first building, the Weidmuller Interface offices, three control systems were tried between first occupancy in 1994 and 1997 (Winwood 1997).

**Redefining Academics**

The old idea that academics and researchers are the source of new knowledge, which is disseminated down to industry, is under revision. Gann (2001) contrasts the traditional mode of knowledge production with an emerging mode of new knowledge generation. In this, universities are increasingly undertaking consultancy work, while industry has become more involved in research and training. In this project, this latter mode was very much in evidence. The Built Environment Research Group acted as paid consultants to the Buildings and Grounds Department of the university to provide general conceptual advice in the design stage as well as the thermal and lighting simulation results for the proposed building. To all intents and purposes, the official involvement of the researchers ceased at the completion of this phase of the work. This is not a desirable or effective process because a checking procedure in the phase from concept and simulation to reality is no longer available to the project.

Despite the pressures in today's universities, academics probably still have more time to follow up innovative ideas, have greater access to published work and because of their chosen career path, should have a greater curiosity to understand the intricacies of new technologies. However, academics are certainly not always as knowledgeable about new technologies as they may sound or as realistic about the on-site demands of building construction. In this
project, for example, the knowledge of how best to control the hypocaust was certainly not adequate at the time of the simulation stage of the design process.

**Manufacturing an Innovation**

Some of the less obvious aspects of the software that must be part of any successful technology have already been described in the introductory section of this paper. More obvious examples of software are the operating and installation instructions, which should accompany the purchase of any hardware. This is clearly the responsibility of the manufacturer of the technology. In this project, this information has not been provided, although the panel manufacturer claims that they were not invited to meetings to review hypocaust design issues. They also believed that the academics involved in the project were familiar with all aspects of the system, which exemplifies the point made earlier in this paper about academics.

Difficulty has also been experienced in sourcing a local supply of air diffusers or adjusters to insert into the outlet holes of the concrete panels. It would be reasonable to assume that diffusers are an integral part of the hypocaust and are required to make it function in the way intended. In marketing their concrete panels as part of a natural conditioning system, rather than just as a static building element, it would also be reasonable to expect the technology to be supplied with all the components required to allow this to happen effectively. This would appear to be particularly important in a market where the manufacturer is the sole supplier of the system. Some imported diffusers were offered but these were apparently too expensive and a local product is now being sought.

The most probable cause for this less-than-optimum transfer of knowledge is the lack of the local manufacturer's familiarity in using their product as a hypocaust. This shortcoming will hopefully disappear as local experience grows. In fairness it should also be added that in this particular project, an additional and significant factor was the appointment of an administrator for the project builder in the early stages of construction. The principal contractor obviously plays a vital role in driving a project and coordinating the input of sub-contractors such as the hypocaust supplier. In the difficult and complex situation created by the failure of the project builder, there were limitations on the ability of a sub-contractor to influence project outcomes.

**Being an Active Building User**

In traditional air-conditioned buildings, little has been demanded of the building occupants in terms of their responsibilities for building performance. The low energy buildings of the new era will require a more informed, adaptable and cooperative user. Initially, the most significant reductions in energy consumption will be achieved by relaxing the conditioning requirements from the previous (almost) steady-state conditions possible with conventional mechanical systems. In Building T, for example, an early design decision was made that the temperature in the building be allowed to drift between a minimum of $18^\circ C$ and a maximum of $28^\circ C$. Compared to a constant $24^\circ C$, this change in conditioning philosophy was predicted to reduce the heating and cooling energy requirements by 85% and 50% respectively (Fuller and Luther 2002).

For this strategy to be successful means that the users must be more proactive to achieve personal thermal comfort levels. The users in Building T are therefore encouraged to open and close windows, raise and lower blinds, and turn ceiling fans on and off. With respect to window opening, they need to become informed of the conditions when this strategy is effective. For fresh air and natural ventilation, this is recommended if the outside air
temperature is below 26°C and blue lights in the atrium inform the building occupants whether to open or close their windows. However, many staff claim they do not know about this system.

For the users to willingly become involved in 'conditioning' the building and adapt to a more varied internal environment means that they must become knowledgeable and supportive of the different design philosophy behind their building. Most Australians are concerned about the decline in the quality of their environment and can be convinced to take small personal actions like recycling office paper. Now we must convince the new generation of office dwellers to become involved, knowledgeable and supportive of reducing energy use and greenhouse gas emissions at their workplace. However, the current perceptions of users of what may be involved to work in a low energy building and their willingness to adapt will vary considerably. It has already been noted above that some staff could not be convinced to give up the idea of a totally enclosed office.

Getting and keeping the users on-side, informing them about their building and any changes, achievements and problems is an on-going process, but one that is essential if significant numbers of resentful and unhappy staff are to be avoided. Unfortunately, the author has experienced varied levels of this, indicating that work in this area is still needed. Extreme examples of this include the blocking of air outlet holes with plastic bags by some staff because they experienced a draught from an outlet hole above their desk.

**Finding a Champion**

With established and conventional technology, no project player has to adopt the role of a champion and fulfilling traditional roles is adequate, but the need for someone to assume this responsibility in a successful innovative project was noted earlier. To date, however, this person has not naturally emerged from the current project players. Whether this is because they are "being stifled by modern management practices designed to maximise production and individual work output", as a study cited by Dulaimi (1995) suggested or for some other reason(s) is not clear. In Australia, it is evident that such an individual will be necessary to ensure successful outcomes in early demonstrations of the hypocaust technology. This is particularly important if the technology is to become accepted here as a possible component of low energy buildings, as it has overseas.

**OUTCOMES**

The prime objective of today's low energy buildings is to reduce energy consumption while maintaining occupant comfort. Problems caused by trying to use a traditional linear and compartmentalised process, rather than an iterative and inclusive one are likely to lead to unfavourable outcomes. Likewise a failure by project players to pick up new responsibilities associated with innovation can also lead to problems. In terms of the two key criteria of occupant comfort and energy consumption, the outcomes in this project have so far been mixed. These two aspects of the performance of Building T, together with some positive outcomes from the project are discussed briefly below.

**Occupant Comfort**

An internal survey covering a limited range of factors related to lighting, ventilation and comfort was conducted amongst the occupants of Building T at the end of summer in 2003.
Survey forms were returned by 29 of the building's occupants. Nineteen comments, none favourable, were received about air quality. Complaints about stuffiness and smells were common. It seems likely that the reliance on natural ventilation, rather than forced ventilation air, whose temperature is tempered by the hypocaust, could be the reason for this. Eighteen comments were received about ventilation, windows and the blue light indicator referred to earlier. The users' comments clearly indicated that they were not responding to this form of information and an alternative strategy is required and/or greater user education.

A similar number of responses (18) were received about excess temperatures in the user's workspace. Once again, very unfavourable comments were received. The overheating was almost certainly due to the failure of the control system to operate correctly in both cooling modes and hopefully the rectification of this will reduce office temperatures in subsequent summers. The results of this survey contrast strongly with those conducted in hypocaust buildings overseas. The occupant survey taken from the Elizabeth Fry Building, for example, was described as "excellent, one of the best seen by BUS [Building Use Studies] in over ten years of similar studies. EFry [Elizabeth Fry Building] is thus likely to become a role model for future building design and management."

**Thermal Performance**

In terms of energy use, analysis of early data indicates that Building T is encouraging. The building is consuming approximately 133 kWh/m², which is 27% lower than the Victorian Government benchmark figure. Changes to these figures are almost certainly due to the changes in control strategies, particularly with respect to cooling, the inclusion of gas consumption for heating and reductions in lighting energy use.

Despite the control problems described earlier in the paper, the hypocaust has been forgiving. Over the summer of 2002-3, when outside temperatures were in the high 30s, air temperatures in a suite of rooms monitored on the North side of the building were 2-3 degrees below the design target - even when one of the chillers broke down for an extended period of several days. This experience bears out the point made by Shaw et al. (1994) following early experimental work with unventilated hollow core concrete panels at the Building Research Establishment in the UK. These authors commented that the ability of the technology to smooth out temperature fluctuations went "some way to compensating for improper design and control."

**Learning Experience**

One of the stated objectives of the client at the outset of this building project was that they wanted the design to demonstrate innovative technologies (Fuller and Luther, 2002). The client therefore deserves credit for being bold enough to be the first user of hypocaust technology in Australia. Adopting a new technology in a setting where there is little or no expertise is always likely to be challenging and have problems. Both the client and those involved in the design of the building and its hypocaust system have undoubtedly learned much, particularly the importance of the iterative design process. In practice, all of the problems encountered in this project can and are being addressed. The accumulation of a knowledge base in the design and use of this technology in Australia has begun and will be drawn on for subsequent projects. A number of new buildings using hypocaust systems are currently in the design stage.
CONCLUSIONS

Low energy buildings using innovative technologies pose challenges to the players in the construction project. Failure to adopt an iterative and consultative process, rather than using one that is linear and isolated, can mean that the knowledge and capabilities in the project team are not fully used. The lesson from other successful innovative low energy buildings is that an integrated design process is essential.

The traditional roles and responsibilities of construction project players are also often inadequate when new technologies are introduced. Traditional roles have developed around conventional technologies and processes and the new technologies demand extra responsibilities. For example, the hardware and software package must be complete because the source of supply and experience is limited. In the case of low energy buildings, on-going monitoring is essential if performance criteria are to be met and maintained. Users of low energy buildings face particular challenges and must be brought on-side through a good and continuous information flow.

The introduction of hypocaust systems to the Australian building sector, described in this paper, illustrates some of the challenges that can be encountered when introducing a new building technology. Although there have been some technical shortcomings in the hypocaust hardware, it is deficiencies in the software that has been the main cause of the problems described. In Australia, there is currently little or no experience in installing and using a hypocaust. This fact should have been acknowledged and more attention given to the hypocaust at relevant stages in the project. A more cooperative approach, driven by the client or their representative, among the parties involved would have avoided many of the difficulties encountered.

ACKNOWLEDGMENTS

The helpful comments on an early draft of this paper from Sean McArdle, Senior Project Architect, Buildings and Grounds at Deakin University, Peter Healy, Managing Director of Hollow Core Concrete Pty Ltd and Jonathon Wood of Umow Lai and Associates Pty Ltd are much appreciated. The permission to include data from client's commissioned internal reports on occupant comfort and energy use is also gratefully acknowledged.

REFERENCES


Mogavero, L.N. and Shane, R.S. (1982). What every engineer should know about technology transfer and innovation, Marcel Dekker, New York and Basel.


