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Summary This is the first of a series of four papers which describe a three-year research project into 'advanced fabric energy storage', which is defined to be the subgroup of fabric-energy-storage systems which pass ventilation air through a structural mass element for the purpose of heat exchange. The technique can reduce or eliminate a building's requirement for mechanical cooling and allow the heating requirement to be demand-shifted to the night-time cheap electricity tariff. The paper presents a literature survey of advanced fabric-energy-storage systems and describes the historical development of the 'FES-slab' – the leading commercial system. Subsequent papers describe the investigation of the slab with a computational-fluid-dynamics model, the theoretical analysis of the cfd results and the incorporation of a slab model into a full-building simulation and, finally, results from experimental monitoring of the first uk building to apply the FES-slab.

Advanced fabric energy storage I: Review

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1 Introduction

1.1 Traditional cooling techniques

The necessary conditions for human survival are often defined as food and shelter. Although shelter also implies some form of refuge, it may largely be taken to mean thermal comfort. Historically, thermal comfort has been attained through the evolution of traditional building styles which suit the local environment. In desert regions, where temperatures can be too hot during the day, yet too cold at night, the local architecture often features thick walls to mediate the daily temperature swing and night ventilation to cool the structure.

Figure 1 shows the application of these techniques as used in a traditional Iraqi house[1]. Ventilation is supplied via the roof-top air scoop and passed through a cavity wall before entering the occupied space. Hot daytime air is thus cooled by interaction with the walls and the heat transferred is later used to warm the cold night air. Additional cooling is sometimes provided by placing a jug of water in the air path to humidify the air.

This paper describes the use of these principles of passive thermal storage and night ventilation to provide low cost cooling in modern, energy-efficient offices.

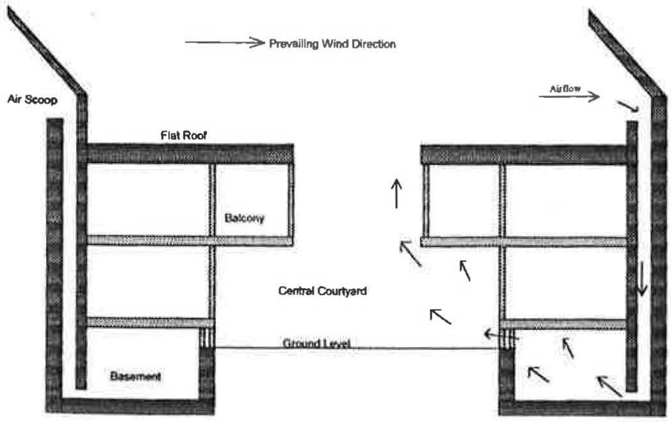

Figure 1 Traditional Iraqi dwelling featuring air scoops and integral ventilation pathways

1.2 Office development in recent decades

During the 1980s, continued improvement in insulation levels as well as an increase in fenestration levels and an almost universal acceptance of false ceilings, lightweight partitions and carpeted floors exacerbated summertime-overheating problems and led to a rapid expansion of mechanical cooling in regions such as Western Europe, where it had previously been largely unnecessary.

The 1990s, with growing concerns about environmental pollution, have seen increased interest in low energy buildings. Further momentum has been added by the ban on production of chlorofluorcarbon gases for air conditioning, the phase out of HCFC alternatives and the drive to return CO_2 emissions to 1990 levels by the end of the decade. Summertime overheating has focused attention on low-energy cooling and international research has been rationalised by the creation of an International Energy Agency annex (Annex 28), with the UK's chosen topic being fabric energy storage (FES). This research project was partly an outcome of that initiative.

2 Principles and benefits of fabric energy storage

Fabric energy storage (FES) is a technique whereby the thermal capacity of a building's structure is used to store a large amount of energy for only a small variation in temperature. This enables the building to buy electric heating during the night-time cheap tariff and store it until the following day or, alternatively, to absorb day-time heat gains and store them until they can be purged with free night cooling. In the most appropriate cases FES can eliminate the need for heating and mechanical cooling. As the technique is relatively simple to apply, often requiring little more than the avoidance of suspended ceilings, it has gained a good deal of acceptance e.g. References 2–7. The effectiveness of 'simple' FES is, however, limited by the following features: the heat transfer is restricted by the free surface area, heat-transfer coefficients are relatively poor and the control over the heat exchange is, at best, indefinite.

2.1 Definition of advanced fabric energy storage

Advanced FES is defined here to mean FES systems which have ventilation air passed through them, allowing heat exchange at internal as well as external surfaces. This allows advanced FES systems to improve on the performance of 'simple' FES by increasing the area available for thermal interaction, producing enhanced heat transfer due to forced convection within the structure and providing improved control through variation of the period and rate of air flow.

Advanced FES formed the focus of this research project, which included a literature survey of advanced FES systems, computer simulation of a particular advanced FES system both in isolation and in a full building model and experimental monitoring of a UK advanced FES office. The remainder of this paper contains the literature survey, while three subsequent papers describe the remaining sections of the project.

3 Literature survey: General

The literature survey began with the identification of five advanced FES systems before selecting the FES-slab as the market leader and investigating its development and level of acceptance around the world. Finally, the survey reviews all the UK buildings which, at September 1995, have put advanced FES into practice.

4 Survey of advanced FES systems

4.1 The FES slab

The most successful advanced FES system is the patented FES-slab (known by the trade name 'Termodeck' in the UK), which was first used in the late 1970s, in Sweden. It uses a patented arrangement of interconnected hollow cores to form an air path within a precast concrete plank, as shown in Figure 2.

An optional extension known as switchflow allows the air-path to be diverted from three-core to one-core operation, as shown in Figure 3. This is intended to provide a 'short-circuit' airpath should the slab become exhausted of useful energy.

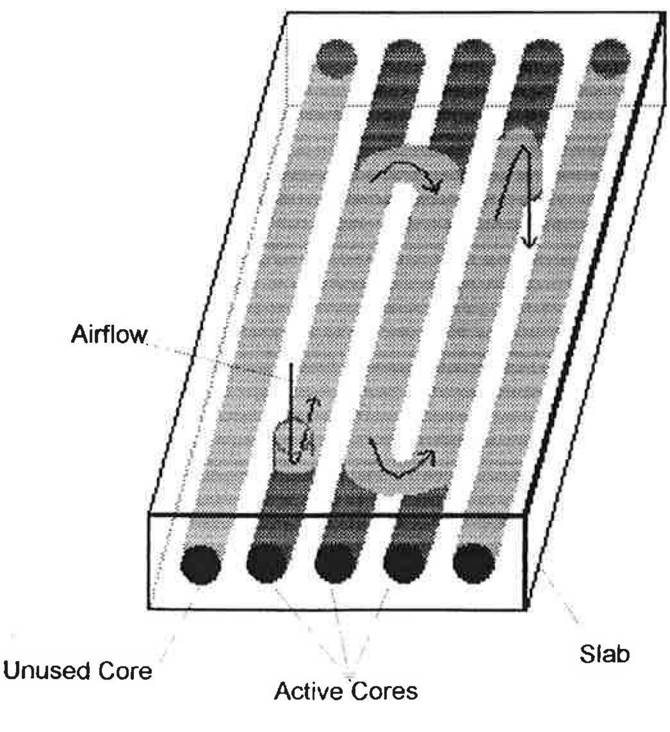

Figure 2 FES-slab

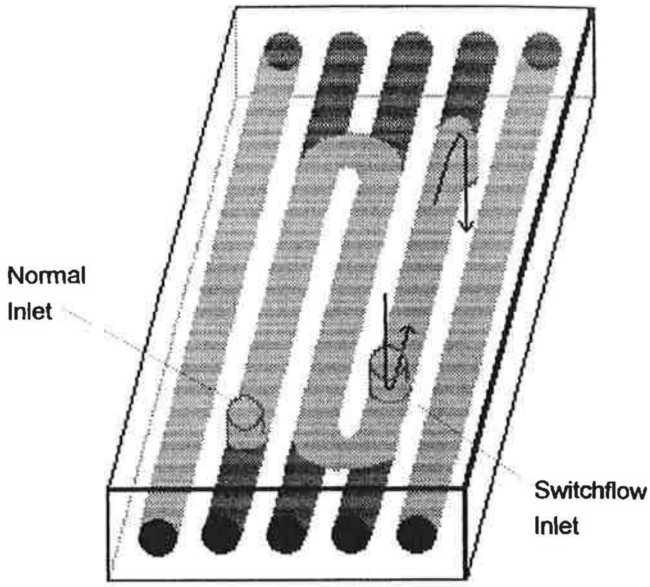

Figure 3 Switchflow refinement to the FES-slab

The Swedish practice is to arrange FES-slab buildings with a series of offices along each side of a central corridor, as shown in Figure 4. Air supply to the slabs is from ducts which run along the corridor, behind a suspended ceiling. Extract is along the same, central corridor, through the false-ceiling plenum. Typically, the air would leave the slabs via ceiling diffusers, although in some cases it is passed through a wall cavity to enter the room at low level. The slabs' undersides are normally exposed to improve thermal interaction with the occupied space.

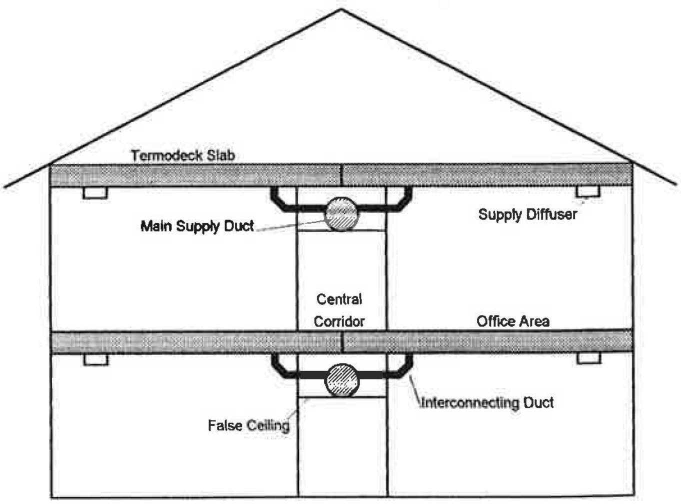

Figure 4 Layout of a typical FES-slab building

By September 1995 the FES-slab system had been successfully applied in over 1 000 000 m^2 of projects in climates as diverse as Sweden and Saudi Arabia.

4.2 The plenum-and-slab system

Figure 5 shows the 'plenum-and-slab' advanced FES system, which was the first system to find application within the UK, in 1978 at the South West Regional Headquarters of the Central Electricity Generating Board, which is described below. Air is supplied through a number of large plenums

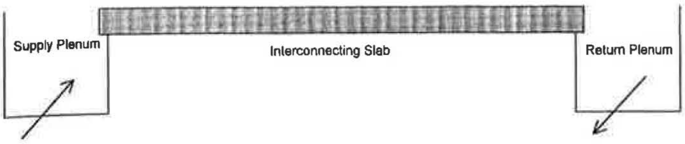

Figure 5 Plenum-and-slab advanced FES system

which are interconnected by the hollow cores of the building's floor slabs.

4.3 The generic slab

The generic slab, shown in Figure 6, provides a non-patented alternative to the FES-slab. The generic slab's parallel air paths permit a reduced flow velocity and hence provide improved heat transfer; however, this effect is counteracted by a relatively low level of turbulence. The system has been applied in several 'experimental' buildings in Finland[8] although, by September 1995, its only UK application is the Ionica building, described below.

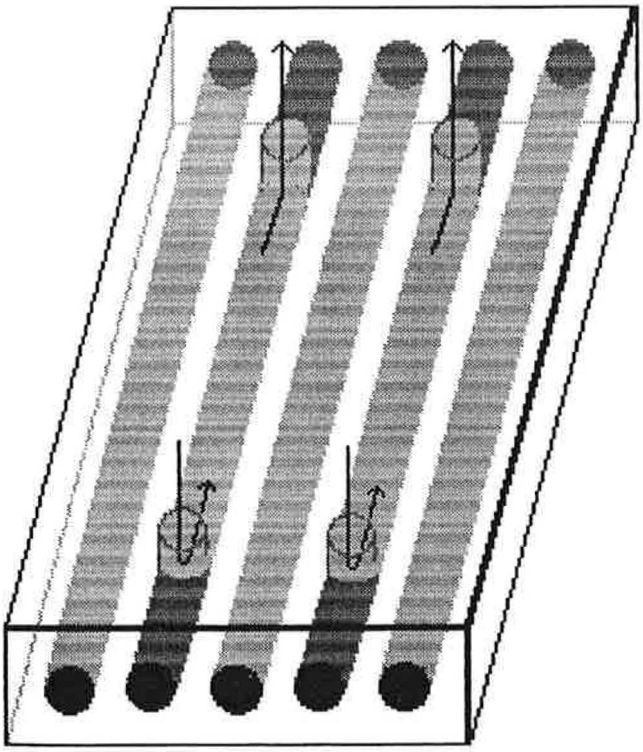

Figure 6 Generic advanced FES-slab

4.4 The 'double wall' system

The patented Norwegian 'double wall' building structure, shown in Figure 7, was proposed in 1993[9]. The system creates two independent air paths around a central core, which is shaped to create a high degree of turbulence. The first building to apply this technique is planned for Stavanger, Norway.

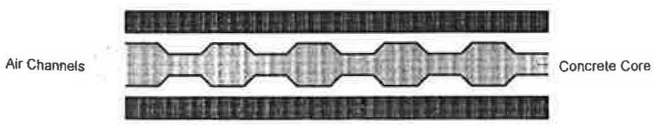

Figure 7 'Double-wall' building structure

4.5 The hollow-core screed

A third, patented advanced FES system was announced in December 1993[10]. It uses a 'hollow-core screed', as shown in Figure 8, and is the only advanced FES system which may be retrofitted into an existing building. The complicated air path and small core height are designed to produce highly turbulent airflow and good heat transfer; however, there are unresolved concerns about the inspection and cleaning such a narrow air path. As of September 1995 there are no buildings which have put this system into practice.

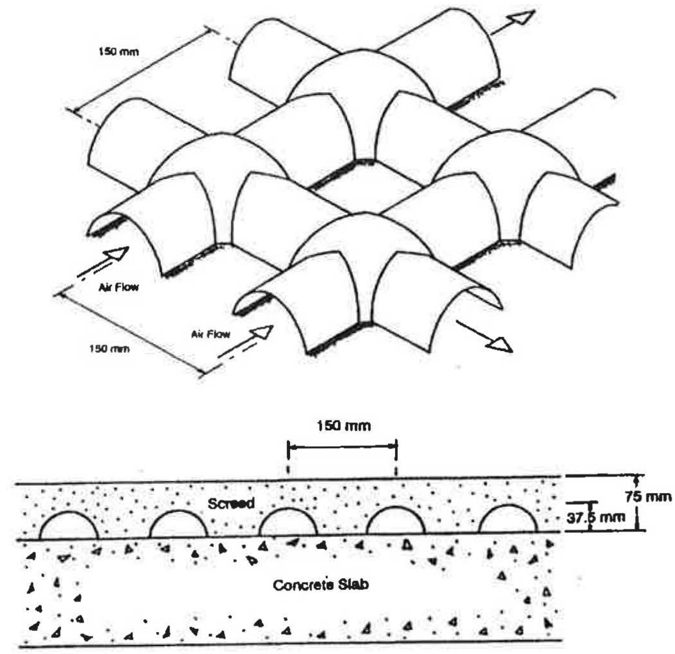

Figure 8 Hollow-core-screed advanced FES system

5 Survey of FES-slab development

Once the available advanced FES systems had been reviewed it was felt that the FES-slab was the clear market leader so the next section of the literature survey concentrated on the development of this system. This revealed that previous studies had taken place in several countries, often simultaneously and usually independently of each other.

5.1 Sweden

The first published mention of the FES-slab was a brief description in a technology update, in 1978[11]. The following year saw the 'official' launch with a publication by the slab's designer, Loa Andersson[12], and the construction of 12 projects covering 46 000 m^2. Interest also spread to the USA, where Andersson *et al.* presented a paper at the Second International Conference on Energy Use Management[13].

There were no more Swedish publications in the English language until 1989, when the FES-slab patent holders produced a publicity brochure[14]. By this time there were more than 200 FES-slab projects in Sweden, covering more than 800 000 m^2. The vast majority of installations were in office buildings, although the system had also been applied to health centres, schools and hotels. Monitoring of two of these projects produced annual energy-consumption figures for heating and ventilation of around 50 kWh m^{-2}.

5.2 The USA

The years following Andersson's 1979 paper[13] saw the promotion of the FES-slab system in several publications by the Energy Efficient Buildings Group at Lawrence Berkeley Laboratories[15–17]. All these papers accurately describe the FES-slab; however, none of them refer to any American buildings which have adopted the technique or to any American research. The absence of FES-slab buildings in the USA has been verified by correspondence with a major American concrete-slab manufacturer†. It is, perhaps, due to the low cost of energy in the USA.

5.3 The Netherlands

In the Netherlands and Belgium the FES-slab has a different trade name ('Energon'), a fact which has caused the majority of work performed within these countries to be overlooked.

Five FES-slab buildings were constructed in the Netherlands between 1982 and 1989. It seems that an unsuitable control strategy made the system initially unsuccessful and interest waned, despite the subsequent rectification of this problem.

Between 1983 and 1993, the Delft University of Technology undertook probably the largest single study of the FES-slab. However, as it was mostly published internally, in Dutch and using the Dutch trade name, the work has remained largely undiscovered. The study involved computer modelling, experimental monitoring and the development of an improved control strategy using multi-speed fans[18–20].

5.4 Belgium

The first Belgian FES-slab building was completed in 1984, with a further seven buildings constructed in the following decade[20]. For most of these buildings it has apparently been necessary to compensate for the Belgian climate with a small chiller.

5.5 Norway

The patent holder's publicity brochure[14] mentions that some FES-slab buildings have been constructed in Norway; however, no references have been found to any Norwegian publications.

5.6 The United Kingdom

UK experience with the FES-slab began with several years of unsuccessful marketing by the UK licensees in the mid 1980s. The first UK publication to mention the system was presented at the 1987 CIBSE Conference[21]; however there seems to have been little interest until the patent holder's brochure was followed, in 1991, by a journal publication[22] and a conference paper[23], both of which described Swedish FES-slab experience.

In 1992 the Building Services Research and Information Association (BSRIA) started a two-year research project looking at the UK application of FES and advanced FES systems including the FES-slab[24]. At the same time, the Building Research Establishment (BRE) conducted some experimental studies with the FES-slab, investigating its thermal performance and its susceptibility to particulate and micro biological contamination. 1992 also saw the commencement of this research project.

†Private correspondence with David Hanson, Chairman, fabcon Inc, 6111 West Highway 13, Savage, Minnesota, USA, 9 June 1995.

The BRE studies concluded in 1993 with the production of two papers[25,26]. The first paper is largely qualitative; however, the contamination study produced the following conclusions:

(*a*) As concrete does not support microbiological growth, the air pathways of the FES-slab present no more risk than normal metal ducting.

(b) Particulate contamination of the air supply was found to be significant for a few weeks after commissioning; however it soon died away.

(*c*) Standard cleaning methods (brush and air lance) produced satisfactory results along the straight sections of the air path. However, the connections between cores were found to be difficult to reach. It was therefore suggested that extra access points should be provided.

1993 also saw the start of construction of the first two UK buildings to use the FES-slab; at West Malling in Kent and the University of East Anglia (UEA) at Norwich. Finally, 1993 saw the publication of a journal article[27] and an MSc thesis[28] which detailed the early progress of this study towards a computational fluid dynamics (CFD) model of the slab.

1994 saw the completion of the West Malling building, with client occupation during the autumn and monitoring commencing as part of this project, in December. Preliminary results from this research were presented in several publications[29–35] throughout the year, while the autumn brought the conclusion of the study that the BSRIA had begun in 1992. The results were published at the CIBSE Conference[36], in a technical note[37], a journal publication[38] and at a seminar[39]

1995 has brought the completion of the uea FES-slab building and the commencement of energy monitoring at that site. Further orders have been placed for FES-slab buildings at De Montfort University (4000 m^2), Peel Park in Blackpool (8000 m^2) and Nottingham Trent University (9000 m^2). The year also saw the completion of this programme of research, part of which was accepted for presentation at the 1995 CIBSE conference[41].

5.7 Saudi Arabia

In 1991, the UK licensee of the FES-slab converted its Riyadh factory to demonstrate the application of the FES-slab in Saudi Arabia. The first commercial project there was the Sultana Centre, which was completed in 1993[42]. Subsequent contracts included a 'small palace' near Riyadh and a 32 000 m^2 commercial centre, which will probably be the world's largest FES-slab installation[43]. The specification of the FES-slab for the commercial centre allowed the developer to reduce the air conditioning requirement by two-thirds and thus undercut the construction costs of its closest competitor by 23%.

6 Survey of UK advanced-FES buildings

This final section of the literature survey reviews all of the UK buildings which, at September 1995, have put advanced FES into practice. Many more buildings use simple FES and several more advanced-FES buildings are in design.

6.1 The ex-CEGB Regional Headquarters, Bedminster Down, Bristol

The ex-Central Electricity Generating Board South West Regional Headquarters is a three-storey prestige office covering 25 500 m^2 at Bedminster Down, Bristol. It was the first

UK building to apply an advanced FES system, using the plenum-and-slab technique described above.

The building has operated fairly successfully over the past decade, although it was necessary to install supplementary cooling, which the building manager estimates to be used on around 10 to 15 nights each year. Local active cooling is also provided in areas with particularly high heat loads.

Operational experience has highlighted the following weak points in this system of advanced FES:

(*a*) The large plenums mean that the system is only suitable for the ground floor.

(*b*) The use of floor slabs, rather than ceiling slabs, means that the controlled thermal mass is isolated from the occupied spaces by the carpets. This problem is compounded by the presence of uncontrolled thermal mass, which can make it difficult to provide sufficient space cooling without overcooling the slabs.

6.2 *The Weidmuller Klippon Products Office, West Malling*

The Weidmuller Klippon Products office at West Malling, Kent, was the first UK application of the FES-slab system. It is a 2400 m^2, two-storey office with supplementary heating and cooling from electric heater batteries and an indirect evaporative cooler. The building was monitored as part of this study; results are presented along with a detailed description of the building in a later publication(44).

6.3 *The Elizabeth Fry Building, UEA*

The University of East Anglia's Elizabeth Fry Building is the UK'S second FES-slab project(45–48).The 3250 m^2 four-storey building contains lecture halls, meeting rooms and a restaurant. It is laid out along traditional FES-slab lines, with ventilation ducts along the central corridor and air supply to the rooms via ceiling diffusers. The building is super-insulated and airtight, with wall U-values of 0.2 W $m^{-2}K^{-1}$ and a measured infiltration rate of 0.97 ac h^{-1} at 50 Pa. There is no local heating, although openable windows provide a degree of locally controlled cooling.

The building is equipped with multispeed and variable-speed fans, providing the potential for improved control over the flow rate, power consumption and energy efficiency of the system.

6.4 *The Ionica Building, Cambridge*

The Ionica building is a 4000 m^2, three-storey building on the St. John's College innovation park at Cambridge(49,50). The building is mostly open plan, with a large central atrium. Heat loads of up to 22 W m^{-2} are predicted for some areas, whilst parts of the building will be in use for 24 hours per day.

The building is designed to maintain comfortable conditions with a complicated mixture of passive stack, wind-driven and mechanical ventilation along with openable windows, external shading and evaporative cooling. The control system uses a 'learning' algorithm which is intended to become accustomed to the building's characteristics and present the most appropriate response to changing weather conditions.

Advanced FES is provided by passing ventilation air through the second and fourth cores of generic slabs. The slabs are said to provide a cooling potential of between 10 and 15 W m^{-2}, although the associated air-flow rate and temperature differential are not stated(49).

The BSRIA will be monitoring the building to see whether its annual energy consumption matches the predicted 103 W m^{-2}.

6.5 *The BRE's 'Office of the Future'*

The Building Research Establishment is planning an updated version of its original 'low energy office'(51). It will be a three-storey, 2000 m^2 building using natural ventilation driven by passive stacks and wind pressure. Although the details are still uncertain, the office looks set to use sinusoidal floor slabs, as illustrated in Figure 10. The slabs will support under-floor air ways and raised floors as well as increasing the surface area for heat transfer. In case passive measures alone are incapable of providing comfortable conditions, an under-floor heating and cooling system will be embedded in the 100 mm screed.

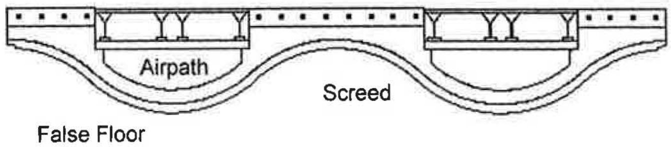

Figure 9 Sinusoidal advanced FES ceiling planned for the BRE's 'office of the future'

7 Conclusions

The technique of advanced fabric energy storage has been widely used outside the UK to reduce the energy consumed by heating and cooling commercial buildings. The range of advanced fabric-energy-storage systems has been reviewed and the FES-slab identified as the most widely used system.

A literature survey, reviewing the history of the FES-slab has shown that it has been adopted in climates varying from virtually tropical to Arctic. The system is starting to find favour within the UK; the first two UK FES-slab buildings have been identified and described.

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