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**Front cover:**
North Staircase, Chicago Museum of Contemporary Art
(Photo: Steve Hall © Hedrich Blessing)

**Back cover:**
Speech, Language & Hearing Centre, London NW1
(Photo: Alan Delaney)

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Arups' New York office prepared the structural concept for this new Museum, whilst in London the design of the internal environmental control systems and the lighting was carried out. Particular care was needed to protect the often delicate works of art from detrimental atmospheric and thermal effects.

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This fast-track temporary pavilion was built with translucent polycarbonate panels to reflect the plastic transparent aesthetic of the Swatch watch. Ove Arup & Partners California carried out the structural and building services design within six months from initial concept to opening.

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For over a century the scenery-handling equipment inside the fly-tower of the Opéra Garnier has been subject to various alterations and 'improvements'. This article describes the new, simpler, and more efficient internal structure designed by Arups as part of the complete refurbishment of the Paris Opera by 2001.

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This new school for hearing-impaired children under five is tucked into a tiny central London site near busy thoroughfares. Arups' building engineering design had to achieve very high levels of acoustic controls to fulfil the special needs of the teaching spaces.

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The University of Huddersfield relocated its School of Computing and Mathematics in a refurbished 19th century mill building. Ove Arup & Partners' structural design has created state-of-the-art working spaces, with raised floor computer access, while retaining and enhancing much of the original masonry and cast iron structure.

**The Heathrow Transfer Baggage Tunnel**
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To facilitate the growing transfer traffic at Heathrow Airport, a new 1.4km underground fixed link has been created between Terminals 1 and 4. As lead design consultant, Arups developed and implemented the design of the dedicated tunnel and the automated baggage handling installation.

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For this new facility, Arups carried out the environmental assessment and gave specialist environmental advice; specified the process plant and turbo-generator; designed the energy recovery and power generation system, the building, the building services, and service interfaces; and supervised construction, installation, commissioning, and testing.

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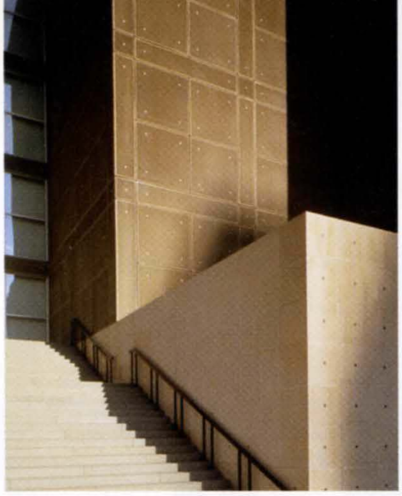
Arup Research & Development have, through their experience of preventing corrosion on metal structures such as offshore platforms and pipelines using cathodic protection, developed the method further and applied it in newer and more challenging situations such as bridge columns in tidal estuaries and steel piles founded in acidic contaminated ground.

# Chicago Museum of Contemporary Art

Nicola Martin
Andrew Sedgwick



2. Front façade detail.

1. Front entrance.

3. The permanent collection lobby on the fourth floor, with Richard Lang's 'Fire Rock Circle'.

### Introduction

In 1986, due to the demand for more exhibition space, the Board of Trustees of the Chicago Museum of Contemporary Art (MCA) decided that the time had come to expand. To accommodate the ever-increasing collection, a large and central site had to be found that would continue to draw the public - as had been the case since the MCA's founding in 1967 - to a mixture of permanent and temporary exhibitions displaying a wide range of contemporary art. After a two-year wait, the State of Illinois granted MCA a desirable site, flanked by two public parks and Lake Michigan to the east, and Chicago's Water Tower and Michigan Avenue on the west. In 1989 MCA's newly-appointed Director, Kevin Consey, began an international search for an architect to fulfil the museum's needs, and two years later, after painstaking selection, the German architect Josef Paul Kleihues was chosen. It was his first American project. Kleihues' previous achievements included the Berlin Neukölln Hospital, the Museum for History and Prehistory in Frankfurt, the Municipal Art Gallery and Henninger Museum in Kornwestheim, and the Municipal Art Gallery and Museum Lutze in Sindelfingen.

### The project

The aspirations of the MCA Trustees and Kevin Consey came to fruition in a $46M project. The design team - Kleihues as design architect, associate architects J Epstein & Sons International Inc, and engineers Ove Arup & Partners - had to work within a 2 acre (0.8ha), 219ft x 416ft (66.8m x 126.8m) rectangular site, the restriction of the gallery environment necessitating a controlled yet 'art friendly' space. The building was to have five storeys, and Arups designed a reinforced concrete structure on a 28ft (8.5m) grid, with a lightweight concrete roof on metal decking, spanning onto steel joists and beams.

The Board of Trustees had specific wishes for their building. They wanted a multi-functional facility with a shop for books and design objects, a café, a special events area, and a sculpture court ( which would be demolished at a later date for the extension of the museum should it become necessary), as well as the exhibition spaces. Also included was the Mayer Education Centre containing studio classrooms, an area suitable for symposia and special performances, a 15 000-volume art library and a 300-seat auditorium. These other aspects contribute to the museum's purpose, described by the Director as to 'exhibit, collect, interpret and preserve contemporary art in a manner akin to journalism'. The emphasis is to explain and share art history as it occurs, not only by exhibiting the works, but also by educating the public about art history. The Mayer Centre runs interactive classes where, for example, members of the public may tour the museum and then create something in one of the studio classrooms based on what they have seen. The educational possibilities extend further with lectures, symposia, films, etc. Realising all these facilities was the responsibility of the design team.

### Architectural concept

Being chosen for the MCA project was a great delight for Kleihues because of his admiration for Chicago's own architecture, which he describes as pragmatic and functional; to this underlying spirit he wished to make his own contribution. His clear approach resulted in a finely-honed simplicity, coupled with visually effective use of space and light - 'an interplay between transparency and containment', as he describes it. This was the foundation of his design.

Looking into the museum from the east (Lake Michigan) side of the building, one can see through its axis to the Water Tower and Michigan Avenue on the west side, and vice versa, but within this transparent envelope the exhibition galleries themselves are self-contained, and visually and aurally opaque. Isolated by two layers of enclosure, outside and within the museum's walls (inside masking the sound of voices, and the movement and noise of people walking up and down stairs and escalators), visitors are drawn into a personal environment with the art. Kleihues said that he 'would never build a museum that would interfere with the visitor's ability to concentrate on art'.

4. View facing east towards Lake Michigan across the atrium.

The galleries are connected by a common three-storey lobby through which Kleihues' showpiece 'Propyleic' North Staircase sweeps grandly upwards to the 'contained' galleries on the south and north sides. The staircase, an interpretation of the Propyleia of the Acropolis, is one of the most notable features of the museum's interior. As at the Schinkel Altes Museum, the stair forms a huge star-like motif in the centre of the building.The original concept was designed by one of the structural engineers in Arups' New York office to achieve the same bold effect.

Notwithstanding the museum's spatially creative interior, visitors are first struck by its exterior. Kleihues adopted a rigorous grid plan for both the museum building and the sculpture court, each measuring 184ft (56m) square. The base of the building is constructed in Indiana Limestone with a façade of square and rectangular aluminium panels, cast to create a texture of small pyramids on their surface. The use of cast metal and the strict and imposing structure are in keeping with the Chicagoan architectural influence. Kleihues looks upon it as a step back to the tradition of the Chicago school of architecture of Adler and Sullivan.

### Internal environment

As with all galleries and museums, one of the most important requirements is to create and maintain a carefully controlled environment in which paintings and other *objets d'art* can be safely exhibited without detrimental internal atmospheric fluctuations and temperature. At MCA the pieces on display vary widely in style, age, materials, and fragility/strength, all demanding rigorous attention to preservation.

The 'transparency and containment' nature of Kleihues' design means that designated zones in the building have a range of atmospheric conditions. From the east to the west, along the 'transparent' axis of the building, significant fluctuations occur due to the sun. In these transparent spaces all the visitor functions except the exhibiting areas are situated, ie the admission and membership desks, the restaurant and café, the elevators, and stairs. The far west side overlooking Michigan Avenue has high solar gains through its large glass wall, so careful planning was needed for a comfortable temperature here whilst maintaining equal comfort at the opposite, east, end of the transparent axial zone, which is subject to less solar gain due to the shading effect of surrounding buildings. Exposed thermal mass and variable air volume (VAV) systems are used in these areas.

In the gallery spaces even more care had to be taken, not only for human temperature comfort levels, but also to maintain a suitable environment for conserving the art on display.

Arups carried out extensive research to determine exactly the conditions needed for effective and efficient art conservation. Information from the Illinois Environmental Protection Agency (IEPA), which is responsible for finding, correcting, and controlling air pollution targets in support of the Clean Air Act Amendments for 1990, helped Arups with pollutant protection strategy. Chicago's pollutant levels are high, due mostly to the prevailing winds bringing gaseous and particulate pollutants from the west. Sulphur dioxide, nitrous oxides, ozone and chlorides were all potential sources of chemical attack on the art works, so the air circulation method employed had to remove these effectively.

The gallery spaces are served by an outside air handling unit (AHU), which contains a prefilter for coarse matter and a bag filter for finer particles. After this basic filtration, the air passes through two carbon filters, the first to remove the aggressive chemical substances, and the second, even finer, to catch any stray remaining carbon particles. When the pollutant concentrations have been reduced, the air is chilled or heated as appropriate. The AHU also has a heat recovery facility to reuse any useful energy in the expelled air.

5. The North Staircase from the third floor.

Within the gallery spaces, close control of air quality was required to prevent degradation of the art works. A high efficiency filtration system reduces gaseous contaminants as well as dust so that the art works need cleaning less frequently: cleaning inevitably causes wear and damage, however carefully it is carried out.

Rapid fluctuations in temperature and humidity cause damage to paintings, because paint expands and contracts due to water within its base materials being absorbed and evaporated. This is controlled via a network of sensors strategically located in the gallery spaces, so that changes in the state of the air can be quickly detected. They incorporate a triple redundancy back-up system and are regularly calibrated. The network of sensors forms part of the controls system for the air-conditioning system which maintain conditions within narrow ranges at a constant air temperature of 70°F with a relative humidity of 50%.

Such close control is not required in the office spaces, but to satisfy the variable occupancy loads and temperature requirements, a fan coil system with local control is used. Fresh air is introduced into the offices and the fan coil recirculates the room air. For areas like the restaurant and auditorium, 'economiser' AHUs vary the air volume supplied according to the occupancy loads.

## Lighting

The nature of the architecture and the purpose of the building not only dictated strict attention to environmental control but to the means of lighting as well. Natural lighting throughout the second floor galleries was proposed wherever possible. As well as being more energy-saving, natural light supplies a more complete spectrum of colours than common artificial sources.

The galleries for the permanent collection are top lit by a series of rooflights. The surrounding tall buildings cast a complex pattern of light and shadow onto these rooflights as the time of day and the seasons change. The variability of daylight on these rooflights is controlled by the galleries' natural lighting system so that these rhythms of the external environment are perceptible, but not so prominent that they cause excessive non-uniformity in the lighting of the suite of spaces.

A lux hours approach was adopted as a conservation strategy for the lighting system: illumination levels in the galleries are constantly monitored and target annual illumination exposures set for each type of art work within the collection.

Potentially damaging radiation in the ultra violet part of the spectrum is removed from the incident natural light by UV filtering laminate within the external glazing.

Arups took measurements to show the extremes of external light levels throughout the year. Although this proved that direct sunlight penetration would be far too bright for direct contact with art works, indirect or filtered sunlight should be allowed to give the full range of light spectra, thereby enhancing the colour appreciation potential of the works. The second floor galleries have barrel-vaulted glass ceilings beneath two systems of active light control louvres. Photocells monitor the amount of natural light reaching the galleries below, and occasional adjustments to the louvre settings are made automatically to ensure design illuminance targets are maintained.

## Conclusion

Kevin Consey has said that Josef Kleihues interpreted the brief for the Chicago Museum of Contemporary Art so faithfully that he could not perceive any other form for it; the team involved - the architect(s) and engineers - had collaborated successfully to construct a new jewel for the city and its citizens. The building is a robust monument to the preservation of, and education about, contemporary art.

Chicagoans have long awaited the opening of the new Museum, whose inauguration ran from 21-23 June 1996. The first official opening subject to public viewing hours took place on 2 July 1996.

6. Below: Permanent Collection Gallery.

7. At foot: The completed Museum with Lake Michigan in the background.

## Credits

*Client:*
Kevin Consey, Board of Trustees
of the Chicago Museum of
Contemporary Art (MCA)

*Design architect:*
Josef Paul Kleihues

*Associate architects:*
J Epstein & Sons International Inc

*Consulting engineers:*
Ove Arup & Partners Tom Barker,
Mike Beaven, Katherine Holden, Rob Lund
(mechanical),
Lidia Johnson (public health),
Andrew Sedgwick (lighting)
Nicola Martin (administrative), (London)

Dan Brodkin, Ray Crane, Mel Garber
(structural) (New York)

*Illustrations:*
Steve Hall; © Hedrich Blessing

# The Swatch Olympic Pavilion

## Larry Chambers

1. Swatch Pavilion in its Centennial Olympic Park context.

### Introduction

Located within Centennial Olympic Park in downtown Atlanta, Georgia, the Swatch Pavilion offered an exciting presence for sales, promotion and interactive exhibits during the 1996 Olympic Games. Centennial Olympic Park, covering about two square blocks, was a major focal point during the Games and provided a beautifully landscaped facility with various sales and exhibition structures, including the Swatch Pavilion.

### Concept

Design and construction was on an extremely fast track. Ove Arup & Partners California, who were invited to participate as structural and services engineers by architects Pfau Architects in mid-December 1995, had approximately six months from when design started in mid-January 1996 to completion for the opening of the Olympics in mid-July. Within this very tight time frame, a limited budget, and the temporary nature of the project, the objective was to design a visually exciting building from thoughtfully combined, ready-made systems.

The original intention was to give the client a demountable pavilion that could be used again at other events. This idea was quickly rejected, however, as the client was unsure when or where they would use it again, and where to store it. The design team then focused on using materials which could be re-used, re-sold, or donated after the Olympics.

The fundamental conception of the pavilion was as a diaphanous 'magic box': borrowing from the plastic transparent aesthetic of the Swatch watch, the building was entirely clad in translucent polycarbonate panels, and revealed its inner parts - its internal workings, structure, and services - all in a manner analogous to the Swatch watch.

### The building

The pavilion consisted of 750m$^2$ (8070ft$^2$) of sales and exhibit space at the ground floor plus a 250m$^2$ (2700ft$^2$) mezzanine for Swatch employees and VIPs, all in an 'extruded' form varying in height from 5m (16ft) at the south end to 10m (33ft) at the north end where the mezzanine is located. The extruded shape is given two twists in the linear form in plan to impart a serpentine quality.

The extruded polycarbonate panels which form the skin of the building gave varying degrees of translucency, and offered a particularly good medium for colour and video projection at night.

2-4 Left to right. The pavilion reveals its chameleon quality in the transition from day to night.

5.
'The building was entirely clad in translucent polycarbonate panels, and revealed its inner parts - its internal workings, structure, and services - in a manner analogous to the Swatch watch.'

During each night of the Olympics the pavilion was transformed into a glowing lantern. By varying the colour of the light with filters, it became a chameleon - each night a different colour - and by projecting images from the previous day's sporting events onto the façade, it was also transformed into a giant video screen.

Using a polycarbonate cladding system during the summer months in Atlanta was a major concern because of solar gain, and the architect's original idea of having panels on the roof as well as the vertical surfaces was rejected because of this problem.

Instead the design team incorporated a built-up roof using rigid insulation over acoustic metal decking; a double-skin system wherever possible at the vertical surfaces limited the gains at the walls. There was a trade-off between the translucency which the architect desired and the solar performance needed to maintain a comfortable internal environment.

The building structure was a simple steel system of open web joists supported by UC column sections, and steel braced frames laterally. It was designed to be quick to erect, inexpensive, light in appearance, and expressing a simple clear logic.

The Swatch Pavilion was an interesting logistical challenge for the design team because of its fast track design and construction period. It also offered the opportunity of using some different types of building materials to give the unusual quality required.

**Postscript**

*In the early morning of 27 July, a bomb exploded at Centennial Olympic Park. Although it occurred only about 50ft (15m) from the north-east corner of the Swatch Pavilion, the building only suffered minor damage.*

**Credits**

*Client:*
Swatch AG

*Architects:*
Pfau Architecture
Eyecandy

*Consulting engineers:*
Ove Arup & Partners California
Peter Lassetter, Larry Chambers (structural), Alisdair McGregor, Tom Watson (mechanical), Peter Balint (electrical)

*Exhibit design:*
Eight Inc.

*Photos:*
Mark Darley

# Refurbishing the Paris Opera fly-tower

Colin Jackson
Sophie Le Bourva
Jane Wernick

1. Opéra Garnier, showing fly-tower on the right.

## Introduction

In April 1994 the Parisian theatre consultants Scène, with Ove Arup & Partners as structural engineers, won a limited competition to renovate the fly-tower at the Paris Opera, designed by Charles Garnier, opened in 1875 - and otherwise known as the Opéra Garnier. Since the new Opéra Bastille opened in 1989, the Opéra Garnier had been devoted exclusively to ballet. Renovating the fly-tower, which comprises about half in money terms of the FF145M first phase of a general refurbishment of the building, due to be complete by 2001, improves the production facilities to meet the demands of a modern opera company and allows opera to be staged once again. Arups' role as subconsultant to Scène was to appraise the existing wrought iron hangers and grid structures; design the new steelwork with tender drawings, specifications and calculations supplied in French; and check the contractor's detailed design and construction drawings.

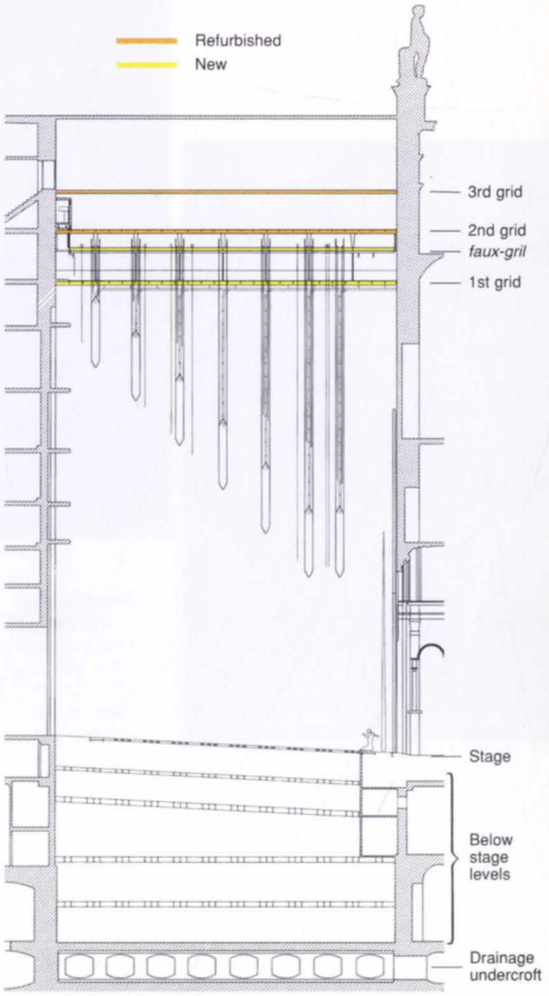
## The building

The design and construction of the original building is a fascinating story, having some interesting parallels with some of today's projects. Garnier's 1860 competition entry was one of 171; four elimination rounds reduced these to five who entered a second stage, from which the 36-year-old Garnier was chosen. The building is 173m long, 125m maximum width, rises 56m above street level, and has a 7m deep basement (beneath which is the drainage undercroft made famous by Gaston Leroux, Lon Chaney, and Andrew Lloyd Webber in *The Phantom of the Opera)*. The auditorium seats 2200. The original cost estimate of FF29M was reduced by government-imposed savings to FF18M, but the final bill reached FF35M. Construction began in 1862 and lasted 13 years, in which time over 30 000 drawings were issued. Basement construction alone consumed 165 000 man days of site work, and seven months were devoted to lowering the water table by 5m, which also dried up all wells within 1km of the site (much to the chagrin of the local inhabitants). An opening ceremony was planned to coincide with the Paris World Expo of 1867, but delays reduced this to unveiling the main façade. During the Franco-Prussian War of 1870-71, the partially completed building was used to store army supplies, and following the French defeat and the siege of Paris, it was occupied by the Paris Commune.

## The fly-tower

The stage is huge: 26m front to back and 32m side to side. The 53m wide fly-tower encloses the stage and wings, housing scenery not in use, above the stage during a production. The scenery hangs from cables that pass over pulleys supported by grids of small beams. The Opéra Garnier has three grids, allowing for raising and lowering a large number of backdrops that are fixed to flying bars, lighting bridges and other items of scenery. Originally counterweights were used to raise and lower the scenery manually; gradually, this system was replaced with a series of electric motors. The 1st, 2nd, and 3rd grids, respectively at 35m, 39m and 42m above the stage, are of wrought iron and consist of joists running side to side supporting the grid deck, and spanning 3m onto beams of riveted angles and plates suspended from 60mm diameter hangers on a 3m x 3m spacing. The hangers are supported by 1.65m deep beams made of riveted plate flanges and lattice webs. These span 26m front to back, and are supported on stone walls. Several walkway levels above the wings are supported by two rows of cast iron columns.

2 below: Section through fly-tower.



Originally, the grid deck was in timber, but during a major refurbishment in 1936 - ironically aimed at improving operating and fire safety as well as modernising the equipment - a fire destroyed part of the roof. Three of the original 26m-span wrought iron roof beams were replaced by reinforced concrete I-sections, and all timber grid decks were replaced by perforated, folded metal plates.

In 1980 a report on the fly-tower structure led to further works, the most significant being to strengthen the wrought iron roof beams with stressed tendons, and encasing half the cast iron columns in steel. The roof beams can be further strengthened in the future by increasing stress in those tendons.

## The competition brief

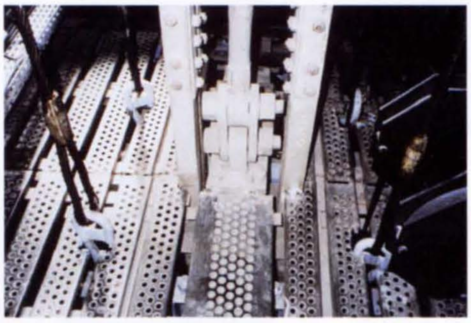
By 1994, as a result of the various refurbishments and constant tinkering with the arrangement of pulleys and motors, the appearance of the fly-tower was fairly chaotic (see Figs 4 and 5). As well as tidying up, the main objectives of the refurbishment were to:

- locate 84 flying bars and their 84 motors, spaced 200mm apart, each carrying a live load of 1 tonne
- create a system of travelling beams, able to carry suspended point hoists, supporting up to 2 tonnes over the entire stage area, and locate their motors
- carry the 18 existing lighting bridges - about 3 tonnes each - as well as some other existing items at the front of the stage like the safety curtain
- reduce the noise to the audience from scenery lifting equipment
- computerise the operation of all these devices.

## The competition scheme

The concept combined modernisation and restoration. Over the years many steel hangers had been added to enable the grids to support items of machinery which replace the original manual counterweight lifting systems. By locating the machinery outside the grids, above the wings which have cast iron column supports, and replacing the 1st grid by a much lighter steel structure, as well as utilising the additional capacity of the 1980 strengthening of the roof beams, it was possible to introduce an additional grid, the *faux-gril* or false grid, to support all the suspended items. This was placed between the 1st and 2nd grids, and supported from the original wrought iron hangers, thus allowing the removal of all later additions. This grid cannot be walked upon like the others, but is accessed from the 1st grid. The hangers themselves could support the additional load, but some stronger bolts were required where they passed through the 2nd and 3rd grids.

To progress the design, it was necessary to understand the lifting systems and how the flymen will use them, to derive the corresponding loads on the structures. The loads on the *faux-gril* from the flying bars and lighting bridges were straightforward to calculate, since the motor and pulley positions were fixed and maximum accelerations and decelerations - to be programmed into the controlling computer software - specified. For the point hoists, however, each motor could be used to lift an item at any position over the stage by passing a cable directly from the motor to a vertical pulley attached to a travelling beam, or via a horizontal pulley attached to another travelling beam. A visit to the Lyttleton fly-tower at London's Royal National Theatre showed the tortuous routes sometimes chosen by flymen. A set of possible configurations were worked out to cover all possible arrangements, as long as fairly simple rules, which still give great flexibility, are followed. The flying bars and lighting bridges produce net horizontal loads on the *faux-gril* because the motors are attached to one of the other grids, and the cable running from motor to *faux-gril* is not vertical.



4.
The 1st grid before renovation.

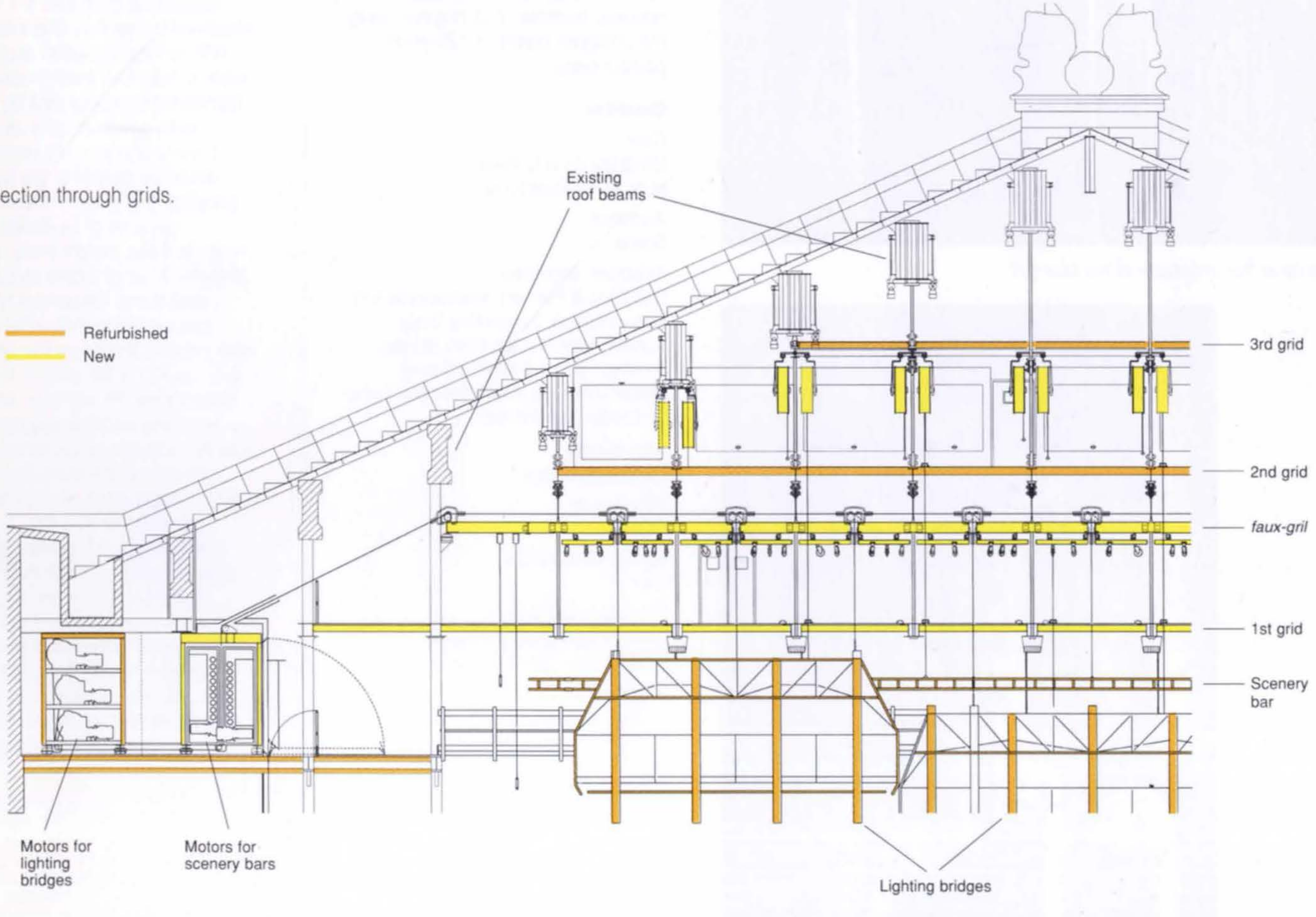
## The structures

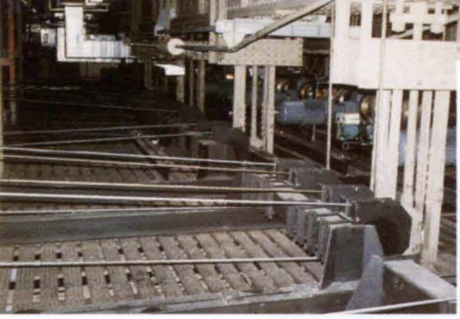
The new 1st grid has a similar structural layout to its predecessor but uses lighter rolled steel sections and open mesh flooring.

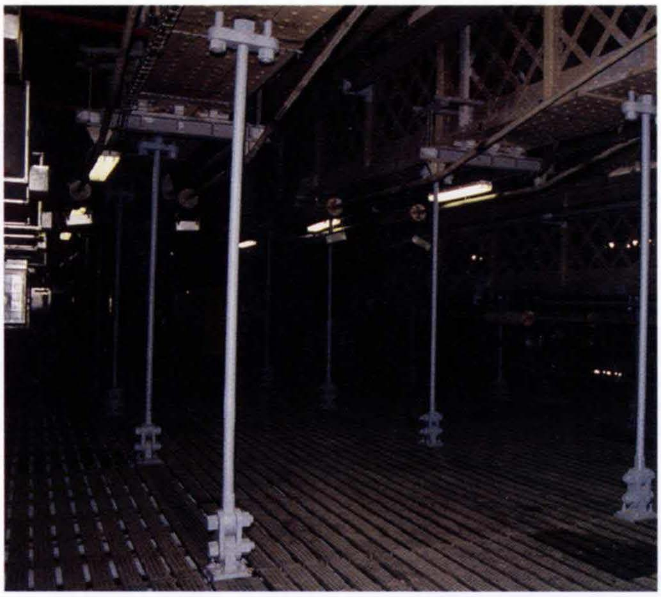
The *faux-gril* is a grillage of I and H-sections at right angles, suspended from the existing wrought iron hangers. Live load deflection is limited to 1/500th of the hanger spacing to ensure smooth operation of the flying bars. The *gril* is braced in plane in both directions, bringing the horizontal loads to the existing stone walls. The motors are supported in two locations:

- on the 1st grid, near the front and back stone walls for the point hoists
- on the level below the 1st grid, at each side of the fly-tower outside the width of the grid for the flying bars.

3. Section through grids.





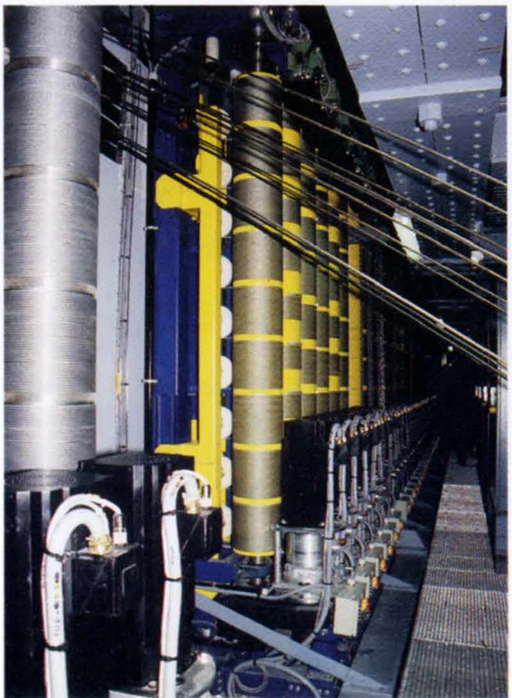


5 above: The 3rd grid, before renovation, and 6 right: after renovation. The underside of the roof beams is visible.

Horizontal forces are carried by trusses spanning 26m between walls, located above the floor in the motor rooms. Extra horizontal loads perpendicular to the stone walls could not be applied. Each motor is quite a piece of engineering in itself, around 3m high and weighing about a tonne. These had to be shoe-horned between new and existing structures into the motor rooms, which are now so full that only a very narrow access passage remains.

A late client relaxation of the very strict acoustic requirements from 15dB(A) to 25dB(A) at the conductor's rostrum allowed the motor room structures to be connected to the *faux-gril*, reducing the effect of horizontal loads.

7. Looking up at the underside of the *faux-gril*.



8. New motor room.

## Conclusion

The work went to tender in October 1994 in several packages for which separate contracts were let. Start on site was January 1995, and completion March 1996 - in time for the opening performance of Mozart's *Don Giovanni*.

All the lifting equipment was tested in situ for some critical combinations of loads and movements. Testing and snagging the new computer software was carried out at night, while rehearsals took place during the day.

The system of travelling beams for the point hoists was finished after the opening and the complete new system is now available to the opera flymen.The fly-tower has been restored to some of its original purity: the unsightly layers of 120 years peeled away.

## Credits:

*Client:*
Ministère de la Culture
et de la Francophonie

*Architect:*
Scène

*Structural engineers:*
Ove Arup & Partners International Ltd
Michael Bussell, Damian Eley, Craig Gibbons, Mark Graham, Colin Jackson, Jonathan Latham, Sophie Le Bourva, Eleanor O'Doherty, Adrian Robinson, Darren Sri-Tharan, Jane Wernick.

*Acoustician:*
Capri Acoustique

*Economiste:*
Algöe

*Bureau de contrôle:*
CEP

*Steelwork contractors:*
Charpentiers de Paris/Baudin
Chateauneuf/Spie-Fechoz

*Illustrations:*
1: Colin Jackson
2, 3: Scène/Lesley Graham
4, 5: Michael Bussell
6-8: Sophie Le Bourva

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Tucked into a tiny mews site in Christopher Place, London, NW1, between Euston Station and the new British Library, the Speech, Language & Hearing Centre is a new school for hearing-impaired children under the age of five. The site was originally earmarked for offices by a developer and the architects Troughton McAslan, but when this proved unfeasible it was donated for the proposed school, with Troughton McAslan leading the design team and Arups providing all engineering services, including acoustics advice. The brief was for a building to mirror the needs of nursery-age children and have a scale of spaces to match, but also provide a pleasant working environment for staff. Too often, children's needs are addressed solely by including primary colours whilst ignoring effects of scale and space, and this rather narrow view prejudices enjoyment of the space by adults who may spend much of their working lives there.

In the absence of similar buildings in the UK, design development was greatly assisted by Angela Harding, an experienced teacher of hearing-impaired children. Her knowledge of other schools around the world and of the acoustic requirements, as well as her clear architectural preferences, provided a strong direction to the design team; when some attended one of her classes to quantify acoustic requirements, the brief immediately became clearer, and the design improved. One of the biggest problems for the hearing-impaired is that they find it difficult to differentiate between sounds they want to hear and background noise, a problem compounded by hearing aids, which amplify all sounds. Clearly the acoustic environment would be crucial to the building's success and would influence many aspects of its design. A very restricted site, height limits, and the large number of rooms required, all meant that the school had to be planned extremely efficiently. At ground and first floors the architects split the 20m x 8m plan in two with a minimum width corridor, arranging teaching and therapy rooms with specific acoustic requirements along one side at the front. Staff rooms, toilets, kitchenettes, stairs and lift are opposite at the rear. As well as giving functional advantages, this arrangement also reflects the need for mechanical ventilation to the teaching spaces so that they can always be used with the windows closed to exclude external noise. The top floor is divided between a large multi-purpose room and an external playground.

# Speech, Language & Hearing Centre, London

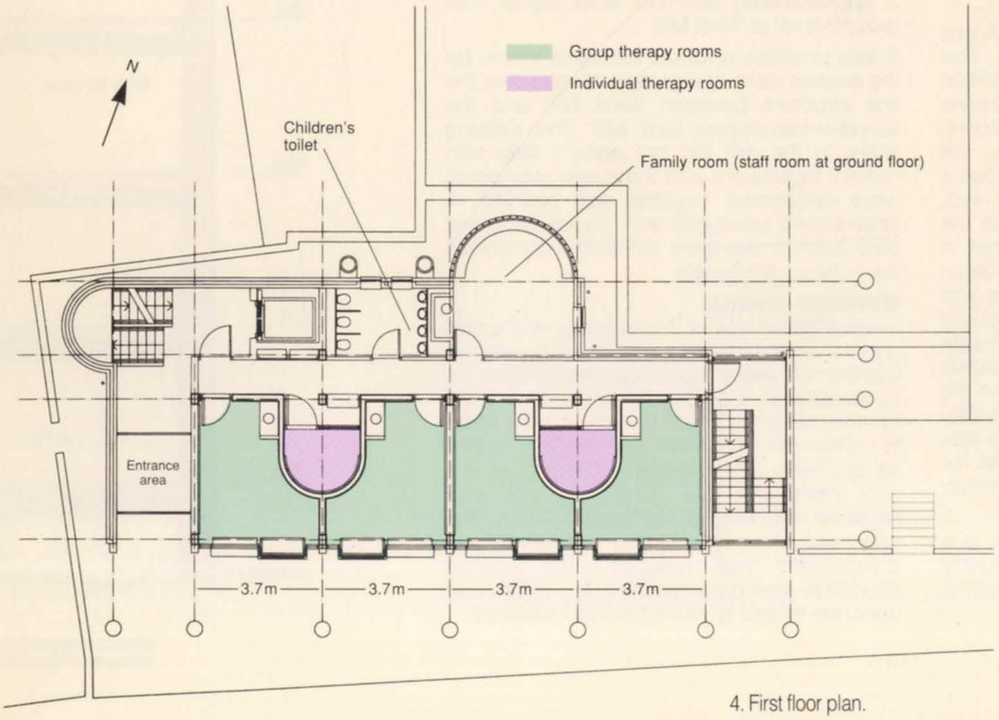
Fiona Cousins

Step Haiselden

1. Angela Harding working with pupils in a group therapy room.

2. Family room.

3. Front façade.



4. First floor plan.

The structural grid was set out to suit the room dimensions and an in situ reinforced concrete frame chosen: site access was very restricted and precast concrete would not have given the necessary acoustic separation between floors. A quiet mechanical ventilation system was designed to serve the teaching spaces and therapy rooms. Air is supplied via ducts in a false ceiling zone above corridors, which also acts as an air extract plenum. Every supply and extract branch duct is fitted with an attenuator to minimise noise transfer between rooms.

High performance partitions between adjacent rooms were essential as teaching hearing-impaired children involves many loud toys; this acoustic isolation necessitated fire alarms and lights in every room. Also the weight of the acoustic doors - too heavy for five-year-olds to open - meant that door closers had to be very slow operating, giving time for supervisors to avert danger to tiny fingers. Double walls of single-leaf dense blockwork allowed both sides to be fair-faced, as are the concrete columns and downstand beams.

Elsewhere, there are separated stud partitions with double thicknesses of plasterboard. Building the partitions required careful supervision to maintain their acoustic integrity despite the service penetrations required.

The Speech, Language & Hearing Centre has been open since September 1995. Despite a tight budget and the design constraints imposed by the building's acoustic requirements, the project has been viewed as a success by all members of the design and construction teams, as well as the end users. This was confirmed recently when the Centre was short-listed for a British Construction Industry Award, and received an RIBA Regional Award.

## Credits

*Client:*
The Speech, Language & Hearing Centre

*Architect:*
Troughton McAslan Ltd

*Consulting engineers:*
Ove Arup & Partners
Step Haiselden (structural),
Fiona Cousins (mechanical),
Nathan Ware (electrical),
Rod Green (public health),
Nigel Cogger (acoustics),
Derek Bedden (detailing)

*Quantity surveyor:*
Boyden & Company

*Main contractor:*
Overbury Southern

*Illustrations:*
1: Alan Delaney
2, 3: Peter Cooke
4: Troughton McAslan

# Canalside West, Huddersfield

Mike Robinson Andy Marsland

## Introduction

Canalside West Mill is the larger of two mills built for Benjamin Lockwood in 1865 on the south side of Huddersfield Narrow Canal. It was extended in 1886 and continued in production until the mid-1980s when the Lawton family, the last owners and operators of what was now Lawtons Mills, acquired more modern facilities elsewhere in Huddersfield.

In summer 1991 the then Huddersfield Polytechnic had a burgeoning student population and was beginning to expand towards realising its ambition to achieve University status. Lawtons Mills were purchased that year to give the necessary space on a natural southerly extension of the campus, and a design team including Ove Arup & Partners' Manchester Office was commissioned to investigate the feasibility of converting the West Mill building into a new home for the School of Computing and Mathematics. The conversion was to include the six-storey spinning building (West Mill itself), a weaving shed, a small office building, and a stone chimney, as well as the adjoining engine house and boiler room. Both financial constraints and heritage considerations (the Mill is listed Grade 2) required as much original structure as possible to be retained.

## Existing buildings

The spinning building has solid masonry walls with cast iron beams and circular hollow columns supporting brickwork jack-arch floors - a form of construction often called 'fire-proof', with mass brickwork protecting vulnerable cast iron beams. A single basement lies under approximately two-thirds of the building, whilst the roof is slate carried on very light wrought iron trusses. Next to it is the single-storey weaving shed, again with solid brick walls, and a timber truss roof carried on cast iron columns. The engines were housed in a lofty space as high as the third floor of the main building. The stonework remaining in the engine house is massive, giving some idea of the scale of the original spinning power plant - regrettably long since removed. At the front of the group of buildings is the 24.5m tall octagonal stone chimney.

## Surveys

As part of the feasibility study, Arups undertook a structural survey in 1991. This concentrated on the capacity and condition of the external masonry, the cast iron columns and beams, and the brick jack-arch floors, but also looked at the stone chimney, the foundations, and the drainage. The floors were found to be in good condition and, subject to the final design, retainable in the refurbishment. Samples of the cast iron in both beams and columns were also taken and tested to assess their compressive and tensile properties. Assistance was sought from Arup R&D in London to assess the safe stresses to be used. Column wall thicknesses were measured at one-third points around the perimeter - a simple check on concentricity. (Arup R&D with University College London have since used West Mill as a model for design exercises in the College's MSc structural design course.)

The stone chimney, though not in use, is a listed structure. It was found structurally adequate and now forms the focal point of the entrance to the buildings.

1.
Location
and site plan

Key

| | |
|---|---|
| ▨ | Existing University Campus |
| ■ | Restored Mill buildings |

## Refurbishment proposals

Planning and space requirements identified West Mill itself, the engine house, the weaving shed, and the chimney as the main part of the refurbished scheme; the other, ancillary, buildings were felt to constrain the development. Fortunately they did not have the same heritage or aesthetic qualities, and consent was given to demolish them. This gave the scheme a very open front aspect with good access. The internal refurbishment was a challenge: to retain the building's heritage qualities and provide modern computer facilities, without any incongruities. These two fundamental needs were resolved by creating an access floor raised off the existing brick arch/cast iron beam structure.

The scheme also included two lecture theatres, teaching rooms, and catering facilities. Access from the main campus required a new footbridge over the canal, meeting the building at first floor level as the main campus is approximately one floor level higher than ground level at West Mill.

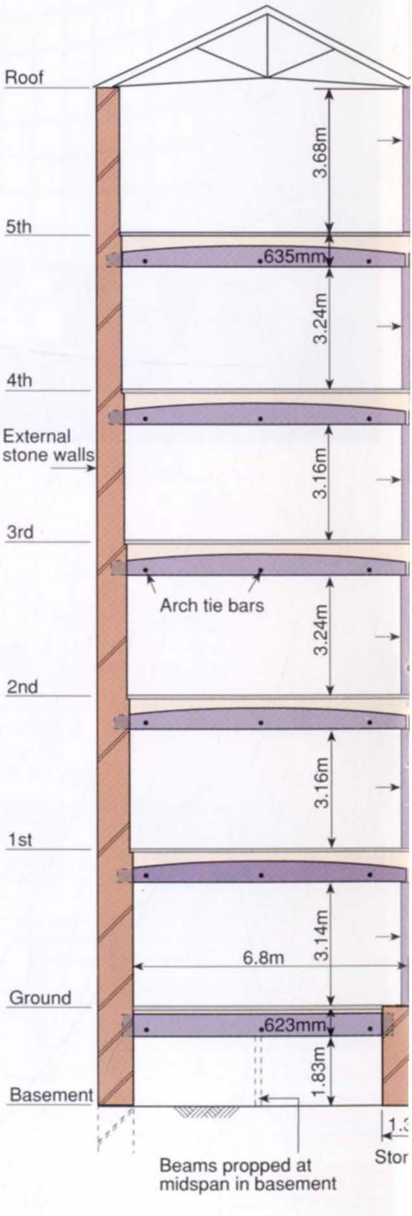
It also provides a robust industrial theme for the access stairs and glazed canopy over the link structure between West Mill and the as-yet-undeveloped East Mill. The existing stairs to the mill did not comply fully with current regulations and three new stair cores were introduced, together with two lifts. A landscaped courtyard and glazed canopies over each of the main entrances completes the scheme proposals.

## Heritage issues

Lawton Mills is one of the last of its kind in this part of Huddersfield, and having seen a number of similar buildings demolished for development, English Heritage and local amenity and historical societies were keen to retain as much of the original fabric as possible. After scheme design, advice and information was both given to and received from English Heritage regarding the proposals. An eventual and mutually happy compromise was reached, with original structural members retained but reinforced concrete added to strengthen the structure.

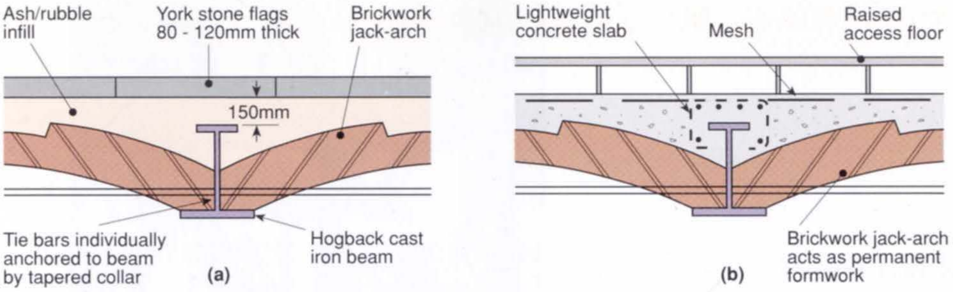
2. Rear elevation

3. Section through m



from new bridge.

ain milling building.



4. Floor sections: **(a)** before and **(b)** after conversion.

The external aspects were of key importance to English Heritage and the old windows were replaced with new aluminium ones to match the original window pattern. A requirement of planning approval was that the original slopes and material for the roof should be maintained, which resulted in constraints to the design process. Original stone pavings were also used in common parts to give a very real 'old' feel to the building.

The adjoining canal was seen as a readily available source of cooling water for the building and, as the University already had an agreement with British Waterways for cooling water for other buildings in the campus, this was the logical solution to designing the cooling systems. In parallel with the building refurbishment, the Huddersfield Canal Society also carried out a major clean-up and restoration of this redundant waterway as part of an ongoing programme to re-establish the link over the Pennines with Manchester.

## Design

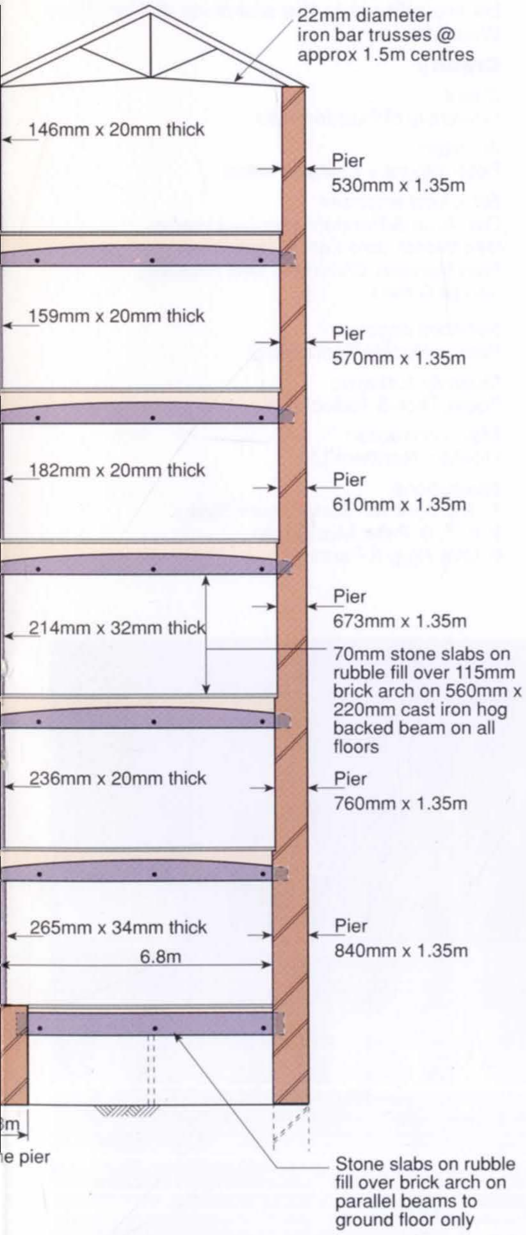
A common misconception when assessing 'fire-proof' cast iron and brickwork in a textile mill is that the original loadings were more onerous than current requirements. In fact, though mill machinery is heavy, it also occupies a large area and the equivalent unit loading can be as low as domestic and not up to teaching accommodation standards. Calculations showed the existing cast-in floor beams to be incapable on their own of carrying the chosen design load requirement of $4kN/m^2$.

The solution - which also took into account computer cabling access requirements and heritage considerations - was to remove the original stone slab flooring and ash/brick rubble and replace with a lightweight in situ concrete slab, stitched into the external walls. This gave a suitably flat surface for the raised access floor and also enhanced the beams' capacity by effectively creating composite T-beams. The brick jack-arches were able to support the self-weight of the concrete during construction and the concrete slab provided for overall stability tying into the external walls. Interestingly, the beams are hog-backed. They also become narrower at the support and the flags are thinner, testament to typical Victorian thoughtfulness in design.

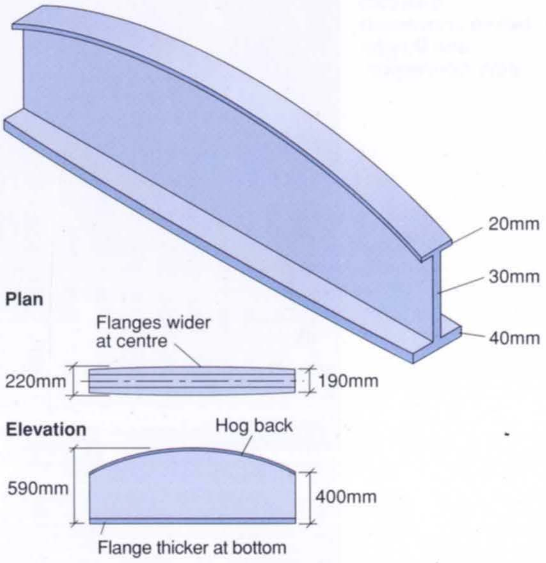
The engine house provided the shell for the new plantroom, and the basement allowed horizontal distribution of services at low level with new risers throughout for vertical distribution. This servicing system maintained a historical link by keeping the power source in the engine house. The massive stonework in the wall between the latter and the mill allowed large ducts to pass through without any significant underpinning, by using a stool system of construction.

The main 280-seat lecture theatre was to be housed in the north-lit, multi-bayed, pitched roof weaving shed. It needed significantly greater headroom than the existing 3m from floor to valley gutters, and column-free space, so a large concrete box was sunk into the ground to create the required volume. Steel columns were supported on its perimeter to carry new steel support trusses designed to fit in the depth between valley and ridge. These are now hidden by the ceiling and have replaced the original cast iron column support structure, an approach which allowed the external roofscape to be maintained. A smaller lecture theatre was also built inside the mill's ground floor. Here, the more generous floor-to-ceiling height obviated any modification to the beam/column structure.

The new footbridge needed an industrial technology 'feel' in keeping with the building's history, and its design comprises two load-bearing trusses which double as balustrades with the deck spanning between. As it enters the West Mill end at first floor level, new steps lead down to the landscaped courtyard at the front of the building.



5. Beam profile (not to scale).



6. Entrance lobby.

7. Typical upper floor corridor.

## Construction

During design development it was thought that the brick jack-arches could support the wet concrete after the stone slabs and ash fill were removed, and this proved correct. Concrete to all of the floors was placed without any formwork, falsework or propping, giving significant time and cost savings. During construction, however, the brick arches were found to be so dry that any contact between them and the new wet concrete resulted in the water being drawn out of the concrete, making it quite unworkable. This may be one of the few occasions on which hosepipes were used to thoroughly soak brickwork before and during concrete placement!

Despite the generally good condition there were two areas where, due to prior modifications, the brick arches were unstable and had to be taken down and rebuilt. The way they were replaced, using reclaimed bricks with curved timber formers, must have been a throwback to the 1860s, and the care taken in reconstruction has made the rebuilt arches indistinguishable from the original.

Generally there were few problems throughout construction. The whole project was completed in 18 months and handed over to the University early in 1995 for fitting-out.

## The building in use

September 1995 saw the official opening of Huddersfield University's new School for Computing and Mathematics at Canalside West Mill. The opening ceremony was performed by Lord Lewisham and attended by Fred Lawton, current chairman of the Lawton company. His presence was fitting testament to the quality of the original building and its conversion from a state-of-the-art 1860s textile mill into an equally state-of-the-art 1990s computer facility.

The success of the Mill's conversion was acknowledged by a Commendation in the 1996 Civic Trust Awards. The reaction from the building users is universally of great affection. The working environment of a fully air-conditioned modern building with raised floor computer access, coupled with the warm feel of natural stone walls and exposed brick arched ceilings, is probably unique. An added throwback to the original use of the building is the faint aroma of the original oils from the spinning process, engrained into the building fabric.

The only problem is that the quality of the space provided has made other schools in the University require their accommodation to be brought up to the standard of Canalside West Mill.

## Credits

*Client:*
University of Huddersfield

*Architect:*
Peter Wright + Martyn Phelps

*Structural engineer:*
Ove Arup & Partners Mike Buckingham, Mike Bussell, Jane Collins, Mark Green, Andy Marsland, Chris Pynn, Mike Robinson, George Suthers

*Services engineer:*
Pearce Buckle Partnership

*Quantity surveyor:*
Poole, Dick & Associates

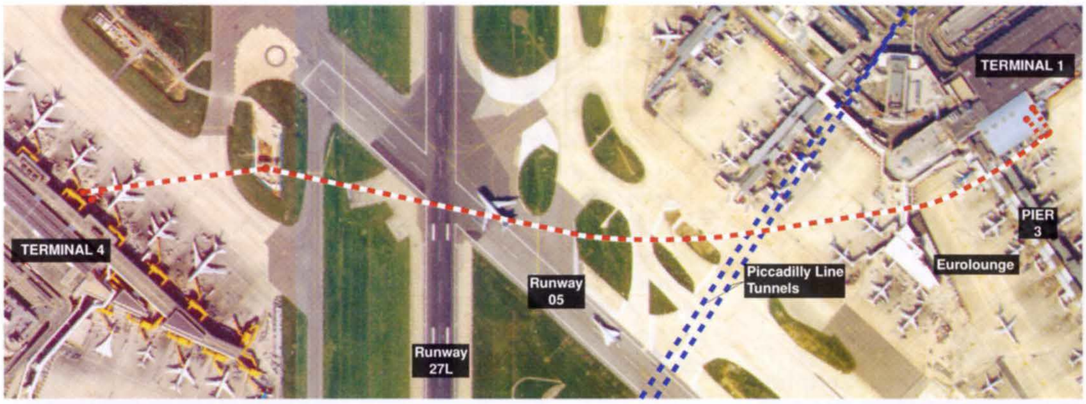
*Main contractor:*
Mowlem Northern Ltd.

*Illustrations:*
1, 3-5: Jennifer Gunn/Trevor Slydel
2, 6, 7, 9: Peter Mackinven
8: Ove Arup & Partners

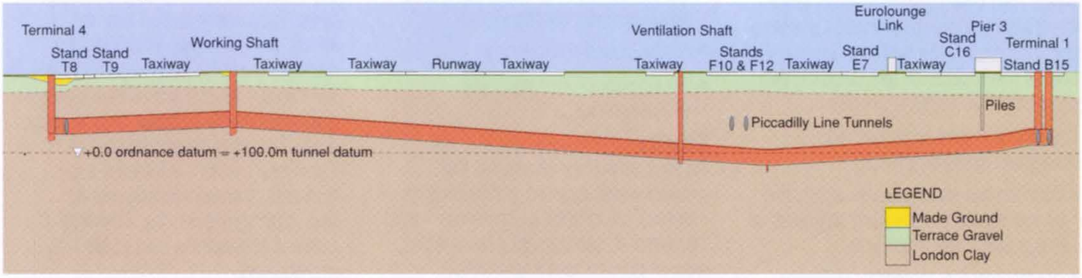
8 above:
Front elevation before conversion
and 9 right:
after conversion.

# The Heathrow Transfer Baggage Tunnel

Bill Grose
David Kaye



1. Horizontal alignment.



2. Geological long-section.

## Introduction

In recent years, transfer traffic has become one of the most important growth areas at Heathrow Airport, London. Transfer passengers use Heathrow as a hub to change from one flight onto another, and now some 30% of all passengers there do so. This has put great pressure on existing facilities and procedures, and connection times and reliability of the baggage transfer process have fallen behind acceptable international standards. To maintain market position Heathrow Airport Ltd have to invest to offer their customers the best possible facilities; an integral part of improving these facilities is to minimise connecting times between flights, and this means that baggage transfers must be as quick as possible. A further problem has been that the existing manual transfer baggage system led to too many bags being 'short-shipped', ie passengers achieved their connection but their bags did not.

In a feasibility study, Heathrow Airport Ltd established the commercial viability of constructing an automated, underground fixed link to convey transfer baggage between Terminals 1 and 4 (the route of the largest proportion of transferring passengers). Subsequently, Ove Arup & Partners were appointed as lead design consultant in May 1993 after competitive tendering. The appointment was for two stages of work: development and implementation.

## Design development

A multi-disciplinary Arup team, together with the project manager (Bovis Construction Ltd) and the client (BAA plc), examined alternatives for the baggage transfer systems, control systems, route alignment, and new buildings to house the additional equipment at each of the terminals. A key consideration at this busy and congested airport was finding sufficient space, not only from which to build the new underground works and associated buildings, but also to house the electricity substations, transformer rooms, and ventilation equipment needed. During this phase, design of the civil engineering works was accelerated such that a design and construct tender could be let shortly after approval of the Project Scheme Design Report.

The contract for the design and installation of the baggage handling system itself was also let during the development stage.

## The scheme

The system finally selected was based on destination-coded vehicles: bogey-mounted hoppers containing one item of baggage each, travelling on a narrow-gauge railway. The system is fully automated and has tracks on two levels, north-bound (from Terminal 4 to Terminal 1) on one, and south-bound on the other.

The horizontal and vertical alignments are shown in Figs 1 and 2, and the general arrangement of the baggage system and associated services inside the tunnel on Fig 3.

The baggage system links into Terminal 4 via an extension to the side of the terminal building, which also houses additional passenger seating, more retail space and baggage search facilities.

At apron level two shafts emerge, within which the twin tracks of the baggage system spiral up and down. Baggage cart loading and unloading at each end are via conveyor belt. The link into Terminal 1 is again via two shafts from which the baggage is transferred to a mezzanine floor, constructed as part of an extension to the existing terminal building.

## The tunnel and other underground work

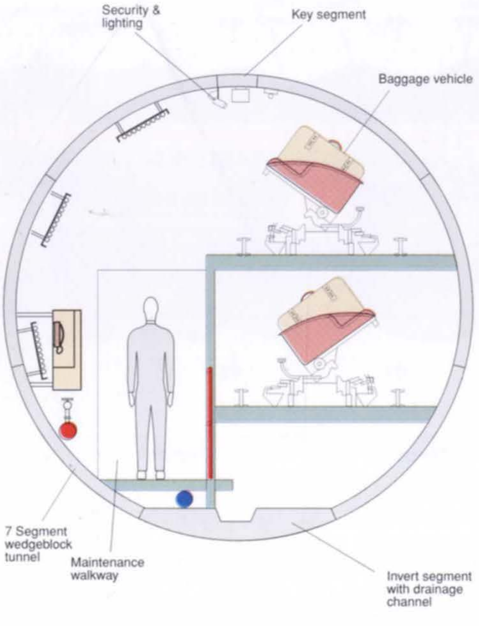
The route alignment was subject to a number of changes and value engineering exercises during the development stage. The horizontal alignment was chosen to avoid, where feasible, passing beneath surface structures, whilst endeavouring to keep the tunnel as short as possible to minimise both construction costs and the operational costs of the baggage system. Surface sites required along the route for construction access, electricity supply and ventilation further constrained the alignment. Vertically, the tunnel was kept entirely within London Clay for ease of construction, with at least one diameter's clay cover for safety, but as shallow as possible at shaft positions to minimise operational and construction costs.

Construction was entirely 'airside' of Customs control, placing additional demands on the project logistics. These included security clearance of all personnel, and controlled and limited access by the contractor to the worksites.

The latter were close to operational aircraft and therefore subject to additional specific restrictions like height limitations and strict control of site-generated debris.

The underground works, with a final construction cost of approximately £13M, were built between 1994 and March 1996 and included:

- a 4.5m diameter bored tunnel, 1.4km long, lined with a 7-segment wedgeblock precast concrete lining
- five 10.3m diameter shafts, between 18m and 28m deep, two at each of the two terminal buildings and one as a working shaft part-way along the route
- a further shaft, 6.25m diameter and over 30m deep, about half way along the tunnel for ventilation
- two complex junctions, one at each terminal, where the tunnel divides to meet with two shafts at each end. The junctions were formed using the New Austrian Tunnelling Method (NATM).



3. Cross-section through main tunnel.

### Ground conditions

Various site investigations had previously been carried out at the airport, and their reports were assimilated during the desk study stage to enable careful planning of the site-specific ground investigation.

The stratigraphy shown by the geological maps and confirmed by previous borings was 3-7m of Taplow Terrace Gravel, overlying London Clay.

During Heathrow's development, gravel had been extracted from pits randomly located across the airport; these had been subsequently backfilled with various materials. One was known to coincide with the location of one of the shafts for this project, but did not prove to be a problem.

The ground investigation was designed specifically to:

- confirm the stratigraphy along the tunnel route, particularly the level of the gravel/clay interface
- determine the strength, stiffness and permeability of the clay, these data not having been measured previously to modern standards
- take continuous rotary core samples of the clay for examination by tendering contractors, and
- confirm the groundwater regime in the gravel.

The Taplow Terrace Gravel was generally medium dense to dense, and highly permeable. The standing groundwater level was about 2.5m below ground level. The London Clay, unweathered for most of its depth, was generally very stiff, and similar to that found across most of Central London (where much tunnelling has been carried out), although at Heathrow it was a little stronger.

### Specification

Arups' performance specification in the Design and Construct contract for the tunnels and shafts covered the following key items:

- the division of design responsibility between the employer and the contractor
- the maximum permissible movements and damage criteria for each of the structures
- the employer's requirements for the execution and presentation of the contractor's design
- the durability and watertightness requirements for the works
- construction tolerances
- the employer's monitoring requirements.

### Shafts

As four of the six shafts on the project were located within metres of existing structures at Terminal 1 and Terminal 4, settlement prevention was of paramount importance. The water-bearing gravels were penetrated by a jacked segmental caisson, with pumped bentonite injected directly above the steel cutting edge. Once safely into unweathered London Clay, the segmental shaft was grouted and the cutting edge removed. Shaft sinking continued using permanent, steel fibre-reinforced, wet sprayed concrete down to formation.

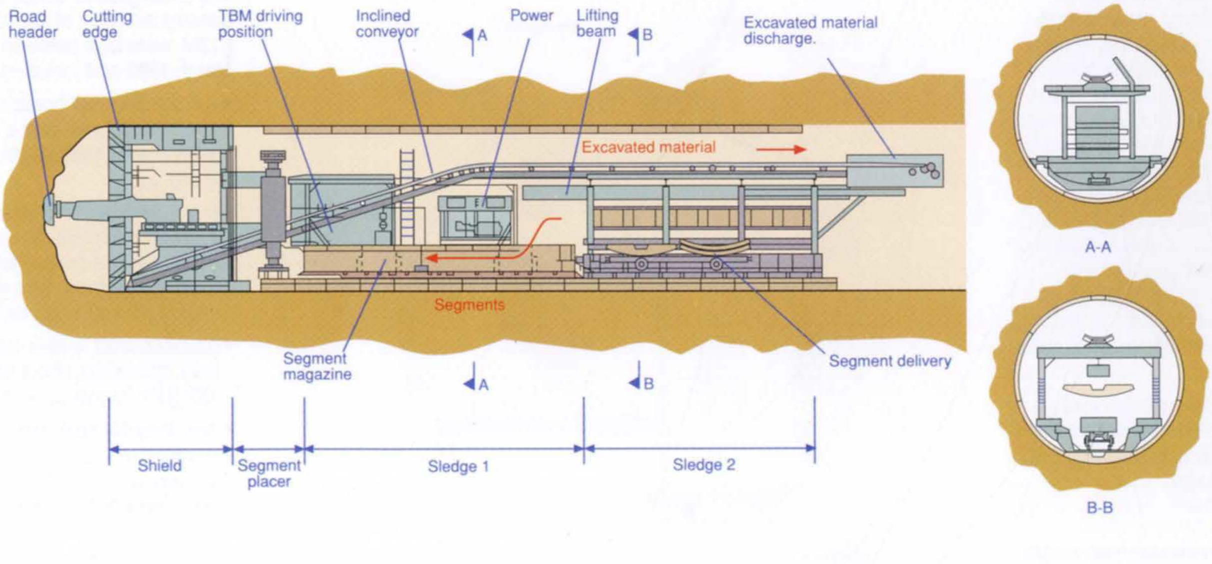
Excavation was at night and the 300mm thick lining sprayed during the days; the daily advance was limited to 1.2m on safety grounds and to limit movement. Thickened portal rings (for connection of the tunnel to the shaft) were incorporated as part of the shaft lining, thereby obviating the need for temporary works during breakout.

Surface settlement monitoring using precise levelling techniques showed that shaft construction resulted in vertical surface movements not exceeding 10mm, similar to that predicted from an axisymmetric finite element analysis.

As the extension to Terminal 1 - constructed under a different contract - was needed early, it was necessary to build the underlying shafts early as well. This was before the baggage interface design had been resolved, and later proved to be a constraint on the solution. Shaft construction work took place in one of the most congested airside areas at Heathrow, amongst the existing transfer baggage systems in Terminal 1 which are all manual and geographically spread over a wide area. Transfer bags arriving at Terminal 1 from Terminal 4 are currently transported by vans, and during the works, Terminal 1's current operations had to be fully maintained.

### Main tunnel

To meet the technical requirements and programme targets (a long average rate of 100m per week was required) at the lowest cost, the tunnel was constructed using an expanded precast concrete lining, with excavation and ring-building performed by a shielded Dosco roadheader. Spoil removal and ring delivery was by self-powered shuttle car (Fig 4 shows the tunnelling machine in diagrammatic form). In the event, the programme target construction rate was met, 16m being the best advance achieved in a single 10-hour shift.



4. Tunnel-boring machine.

The tunnel rings for the main drive comprised seven plates plus key (Fig.3), were 1m long and 150mm thick with convex radial joints, and were reinforced with 30kg/m$^3$ of steel fibre. Believed to be the first commercial use of steel fibres in tunnel segments in the UK, these rings proved cheaper than traditional segments using reinforcement cages. By minimising the number of segments in the ring and maximising ring length, erection time in the production cycle was reduced, resulting in further savings. Large segments attract higher stresses during handling and erection, but the fibre-reinforced concrete proved extremely resilient to damage, even though the segments were only 150mm thick.

The segments underwent full-scale load testing at the Building Research Establishment's Heavy Structures Laboratory at Watford, including tests on the radial joint (between adjacent segments in the same ring). The two convex surfaces forming this joint create very high contact stresses. Test results showed that reinforcing with fibres greatly improved the load capacity of the joints, both up to first crack and to failure, when compared to conventional reinforced, or unreinforced, concrete.

Because the tunnel passed beneath runways, buildings and other tunnels, settlement control was fundamental to its success and was monitored at regular intervals along the route. Surface measurements of points on and below the concrete apron were taken at night when aircraft movements had ceased, and involved precise levelling together with the surveying of borehole inclinometers and extensometers.

Using an expanded lining and a short shield, the ground was effectively supported within hours of being cut, thus limiting the face loss (to about 1%) and surface settlements. Actual settlement data showed good correlation with predictions, with a maximum surface settlement of 16mm when driving on the tightest (300m) radius curve, and an average less than 10mm recorded when driving on the straight. As movement criteria were based on 1.5% face loss, these settlements were well within limits.

## NATM junctions

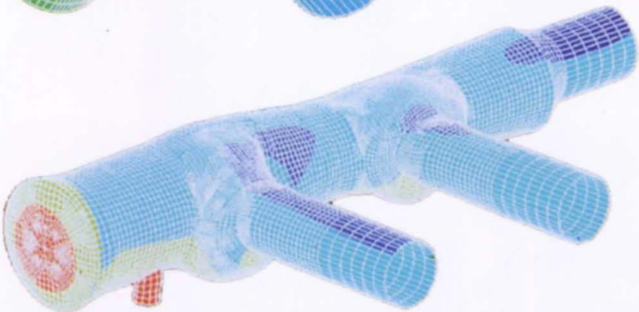
Each end of the main running tunnel needed to be enlarged, with spur connections to the shafts. The minimum sizes and shapes of these chambers were determined by the requirements of the baggage handling system itself and access to it. The junctions were to be built using what is now widely termed the New Austrian Tunnelling Method (NATM), or sprayed concrete lining (SCL), whereby the tunnel lining is formed in situ using shotcrete applied directly to the excavated soil face, incorporating steel reinforcement as bars or mesh. With the great flexibility in constructed space offered by NATM, chamber geometries at Terminal 1 and Terminal 4 were developed which neatly enveloped the complex paths of the baggage handling system and access ways, whilst minimising overall excavation volumes (Figs 5 & 6). Both chambers being directly below operational aircraft stands, settlement considerations and construction safety were again of paramount importance.

## Effect of the Heathrow Express collapse

Construction of the Terminal 4 junction, due to start in October 1994, was delayed several months by the collapse of the Heathrow Express NATM tunnels and the subsequent Health and Safety Executive investigation into the NATM method. Following detailed submissions to the HSE, methods and designs were given a clean bill of health and work at Terminal 4 finally began in February 1995, with Terminal 1 following that August.

BAA wanted additional assurance on the design of the NATM works, so they asked Arups to make a completely independent check of the contractor's design. This covered both the Terminal 1 and 4 chambers, and entailed extensive 3D finite element analyses using the GSA, SAFE and NASTRAN programs. In order for BAA to satisfy the HSE that the check was comprehensive, Arups first had to satisfy themselves, and then confirm to the client that the various construction stages had been fully considered.

5 & 6. Left and below: Finite element meshes for Terminal 4 and Terminal 1 chambers. (not to the same scale).



What soon became clear was that there is no single UK Code of Practice completely relevant to this construction method. Whilst there are some relevant other national standards such as the Austrian Code and the German *DIN 1045*, the nearest UK code is *BS8110*. Which clauses were most appropriate was the subject of much debate, both within Arups and with the Austrian specialist designers helping the contractor. Arups completed their independent check basing the concrete design on BS8110, although recommending some changes to the contractor's design. The client accepted the recommendations, and the changes were implemented. The process for obtaining HSE approval was extensive, involving several technical meetings with them and their advisors. The exercise culminated in the submission of two volumes - totalling some 1500 pages - describing the works at the Terminal 4 junction (and later a similar submission for the Terminal 1 junction). The report set out every aspect of the planning, design and construction process, describing the risk assessments and analyses, and explaining the control processes whereby such risks were minimised. In addition, it explained the management and audit systems, including clear definitions of responsibilities and accountability of both individuals and organisations.

7. The tunnelling shield prior to delivery.

8. The roadheader inside the tunnelling machine, ready for excavation.

The over-riding purpose was to demonstrate a pre-planned seamless process enabling the NATM works to be built in a safe and controlled manner, minimising and managing risks at all times.

The HSE called for additional submissions for the Terminal 1 works. As this chamber was considerably bigger than that at Terminal 4, it required a different sequence of construction, and brought with it several significant problems for consideration. Both methods are described below.

In all of this the team had to take account of the key lessons learned from the Heathrow Express collapse relating to design, construction and information management. Fortunately Arups had first-hand knowledge of these things, having been appointed by the Heathrow Express project Insurers to investigate the cause of the collapse. The submissions for the transfer baggage tunnels - scrutinised by the HSE and their technical advisors - were the first NATM proposals to be approved after the collapse, and the first to commence construction.

## Sprayed concrete linings

The system utilised sprayed concrete for both primary and secondary linings, forming a permanent composite structure. Using high quality, wet sprayed concrete, this method enabled a significant proportion of the primary lining to be considered as part of the long-term permanent structure, thereby substantially reducing the combined thickness of the temporary and permanent lining. After completion of the primary lining, the inner surface was cleaned and a thinner secondary layer applied and finished by hand to give a smooth finish. For the complex geometries required, where a traditional cast-in-place lining would have been expensive and time-consuming, this method offered significant economies.

## Construction at Terminal 4

The Terminal 4 chamber was built as a 6m diameter enlargement to the main tunnel, and included a 45° skew junction with a short 4.5m diameter connecting tunnel.

All works were in London Clay, with a minimum cover of 6m to the overlying gravel. The junction was serviced through the main tunnel, via the working shaft, some 250m away. Construction was in three stages: a top heading, to form the crown of the tunnel; bench excavation to construct the sides; followed by invert excavation to construct the bottom part of the lining.

9. 8.3m diameter NATM chamber at Terminal 1, during excavation and primary lining of side wall drift.

10.The completed chamber at Terminal 1, ready for fitting-out.

These excavations were staggered by 1m or 2m, with the top heading in advance of the bench, and the bench ahead of the invert. Ring closure was within one diameter of the face. Primary construction of the complex elliptical portal needed to form the skew junction was undertaken as work proceeded. An intermediate construction stage was required for placing tension reinforcement above and below the opening into preformed pockets. Great emphasis was placed on the quality of the construction and site management team, as high standards of workmanship were required to meet overall design targets.

11 Below: The completed main tunnel at an early stage of fitting-out, showing the walkway, both baggage tracks, and one of the 400 destination-coded vehicles.

### Construction at Terminal 1

The much bigger junction chamber at Terminal 1, also in London Clay, was formed starting with a full-face crown, bench, and invert advance (like the Terminal 4 chamber) to enlarge the tunnel to 6.5m diameter. To keep the size of the open face manageable where the diameter increased to 8.3m, this then changed to the 'side wall drift' method, where the tunnel is divided longitudinally into two halves by a near-vertical curved wall, and one side of the tunnel built (using the crown, bench, and invert sequence) before the other. Side entry portals were included for two inclined 4.5m diameter adit tunnels. As with Terminal 4, the works were serviced through the main tunnel, with access this time via a shaft some 500m away.

A specially developed three-dimensional optical system enabled in-tunnel convergence and settlement readings to be recorded quickly and accurately. Simple graphical plots, correlating movement trends with tunnel progress, were then produced, enabling the NATM engineer to assess quickly deformation trends and warn early of potential problems. The optical survey, together with a multiple laser system, was also used to control alignment of the works.

### Conclusion

At the time of writing, the tunnelling and other underground works are complete, and fitting out is well under way. The new structures at the terminal buildings are also complete and being fitted out. Speedy construction of the tunnels with good standards of workmanship resulted in less settlement than predicted,and no damage was caused to overlying structures, including fuel pipelines and the London Underground Piccadilly Line tunnels.

The baggage system starts commissioning trials in autumn 1996 in readiness for handing over in March 1997.

### Credits

*Client:*
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British Airways

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Miller Civil Engineering Ltd with
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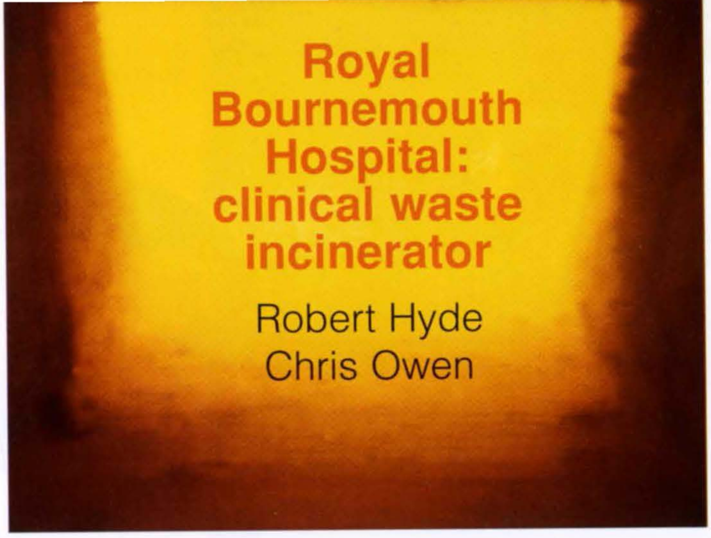
1: Aerofilms/Jon Shillibeer
2-6: Jon Shillibeer
7, 8: Bill Grose
9 © Lilleys
10, 11: Peter Mackinven

# Royal Bournemouth Hospital: clinical waste incinerator

Robert Hyde
Chris Owen



1 Above:
View into the
primary combustion chamber.

### Background

Incineration is regarded in the UK as the most appropriate way to dispose of medical waste materials. European legislation, leading to the UK's Environmental Protection Act 1990, forced the upgrade and/or replacement of many hospital incinerators; to comply with increasingly stringent waste handling, combustion and emissions requirements, they became far more complex and costly. Economies of scale rapidly became apparent, prompting professional, specialist companies to set up commercial plants for processing waste from several premises.

The requirement for flue gas treatment made prior cooling of combustion products necessary, and thus rendered waste heat boilers an integral part of the process rather than an energy-saving opportunity as on the previous generation of hospital incinerators. Large incinerators at hospitals became an attractive proposition, combining on-site requirement for waste disposal with a substantial heat demand and often existing planning permission for an incinerator. Studies by Dyvell Holdings Ltd, with Arup input, showed incinerators within the 1 tonne/hour limit - above which control passes from the local authority to the Environmental Agency - to be economically viable. (The catchment area for waste contracts and the base thermal demand of a large general hospital were crucial determining factors in this calculation.)

### The first incinerator

In autumn 1990, Arups were approached by Dyvell to help develop a commercial incineration facility at Queen Mary's Hospital, Sidcup, and in 1991 Dyvell contracted with the hospital to build it alongside the existing boilerhouse. Arups assisted with all engineering aspects including selecting the process plant, the contract for which was awarded to a UK company under licence from Basic Environmental Inc. of Chicago. Basic had recently entered the UK market via the Elm Energy project in Wolverhampton, a major waste-to-energy facility based on burning scrap tyres and the first of its type outside the USA.

Arups' Industrial Projects Group (IPG) designed the building, services, and interfaces with the hospital systems, prepared specifications and tender documentation, and administered a turnkey contract. The 1 tonne/hour plant incorporated a boiler recovering 3.5MW as high pressure hot water to the hospital system. Excess heat production in summer necessitated a substantial heat dump.

The plant was commissioned in August 1992 and rapidly showed that it met its design intent, disposal of the specified quantity of waste within the emissions limit set by the Secretary of State's Guidance Note *PG5/1(91)*. As 'Basic' incinerators were new to the UK market in the early 1990s, unsurprisingly teething troubles arose. Throughout the first year's operation, Arups gave technical and contractual advice, and detail design input in areas including refractory and insulation, heat recovery boiler specification, lime handling, acoustic treatment, and boiler fouling.

### The next stage

The technical and commercial success at Sidcup led Dyvell to bid, with technical input from Arups, for incineration contracts on nine more sites. Negotiations proceeded favourably at four, and Arups were asked to prepare environmental statements and planning applications. Despite increasing public hostility to incineration, planning consents were granted at Ashford, Ipswich and Bournemouth, and with a year's operational experience from Sidcup, selection of the next generation of plant ensued. IPG developed a generic specification as the basis for a two-stage tendering process. Rotary kiln and multiple hearth designs were considered, but for the next scheme the eventual choice was again the unique 'Basic' pulse-hearth design, supplied this time by Basic Shannon Combustion Ltd of Limerick.

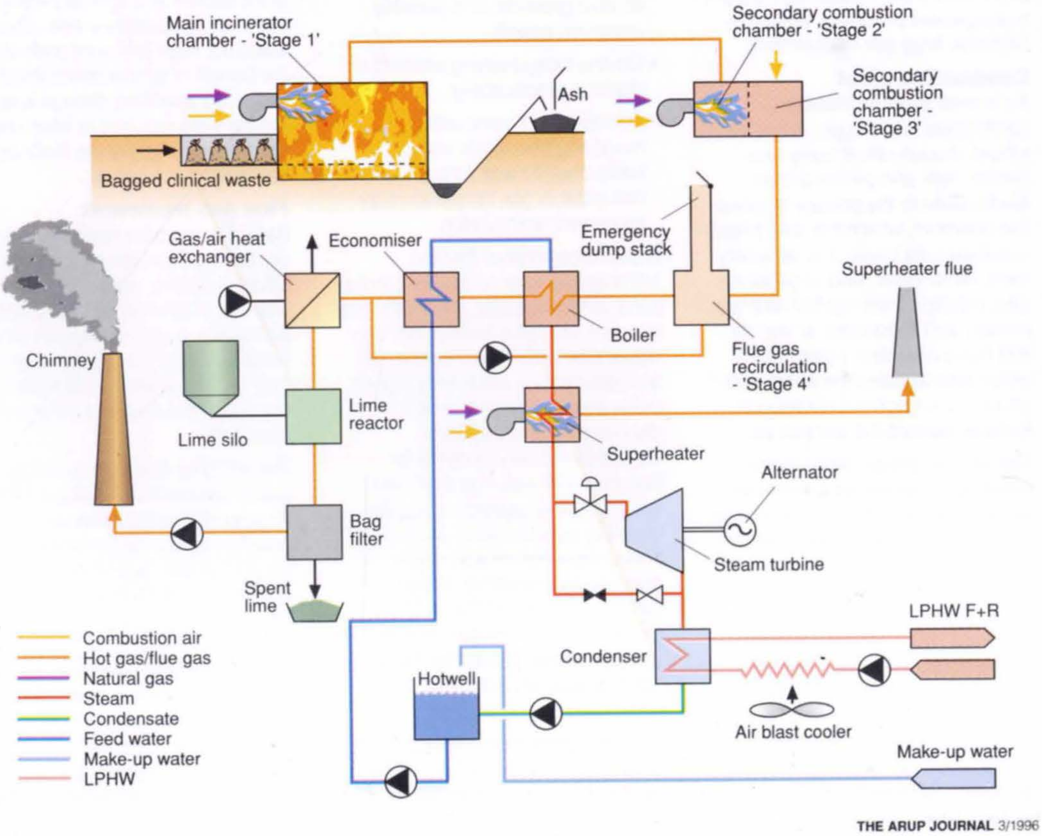
With Sidcup working, a contract in place for the Royal Bournemouth Hospital, planning permission for Ipswich and Ashford obtained, and a highly professional workforce, Dyvell had clearly become a force to be reckoned with and a very attractive business proposition. The company was purchased in 1994 by White Rose Environmental, the clinical waste division of Yorkshire Water Enterprises, who retained Arups as architects, engineers, and project managers for the Bournemouth project.

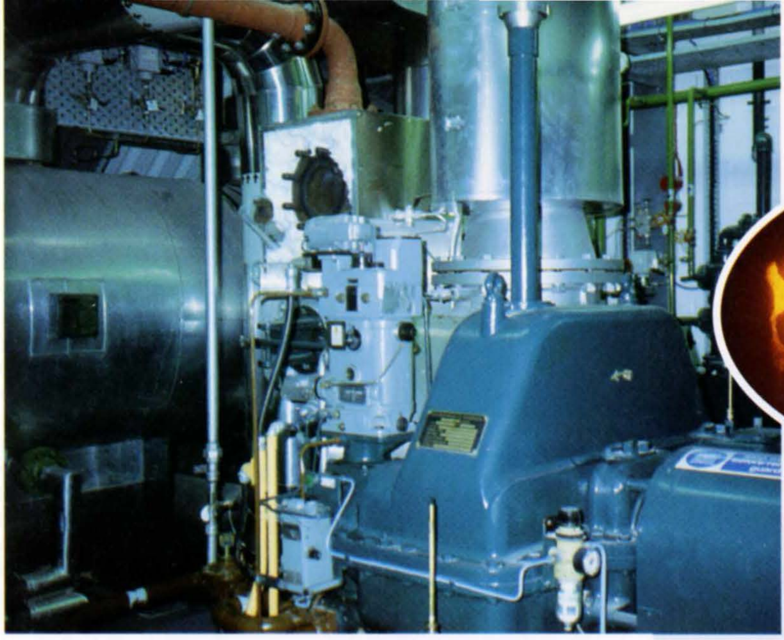
### Bournemouth

The hospital, being recently constructed, was served by a central boilerhouse supplying mostly low pressure hot water (LPHW), and also had a small batch incinerator that would have required replacement by 1995. Dyvell's economic model again indicated a 1 tonne/hour unit as optimum; various site-specific factors allowed Arups to develop a concept design which helped Dyvell win the contract against severe competition. Features included:

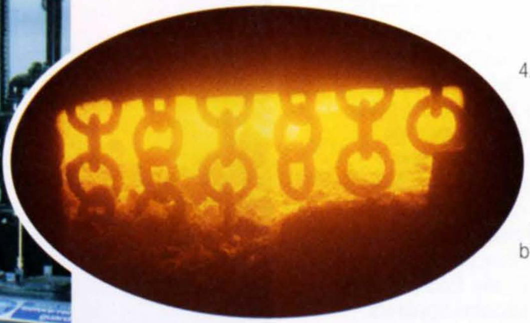
- co-generation of heat and electrical power, reducing the hospital's energy bills
- sensitive design of the building envelope to blend with surrounding structures
- efficient use of a very restricted site.

2 Below:
Simplified process flow diagram
for the Royal Bournemouth Hospital
clinical waste incinerator.





3.
Steam turbine.



4.
In the primary combustion chamber, heavy chains retain waste for improved burnout.

5.
Installation of (left to right) flue gas diverter, waste heat boiler, and fabric filter (baghouse).

Services ultimately provided by Arups included environmental assessment; model making; process plant and turbo-generator specification; detail design of the energy recovery and power generation (CHP) system, the building, building services, and service interfaces; contract administration; site supervision of construction, installation, commissioning, and testing; and specialist environmental advice.

### Contract structure

Three Dyvell contracts were taken over by White Rose: a modified JCT80 contract for the building and services, a modified MF/1 contract for the incineration process plant, and a conventional MF/2 contract for the turbo-generator.

The short building programme, and the development's complexity, meant that at times all three contractors were on site simultaneously. This presented some interesting contract management problems, solved by intensive Arup site involvement.

### Combustion plant

As in most small incinerators, combustion is in stages. A simple, robust, though rather bulky ram feeder, rack-and-pinion-driven, feeds waste to the primary combustion chamber, where the solid phase reactions take place. It is refractory lined, rectangular, and of generous size, equipped with ignition burners, primary and secondary air supply, and has a patented 'pulse hearth' which both agitates the waste and propels it through the continuous furnace towards the wet ash pit.

The second phase, designed to maintain the gases for a minimum two seconds at 1000°C, is in a large cylindrical refractory lined chamber equipped with supporting burners and tertiary air supply. The gases leave here to be cooled from a minimum 1000°C to about 760°C before entering the heat recovery boiler system. This 'Basic' design feature is intended to minimise potential damage to the boiler from contaminants in the hot gases, and is achieved, for energy efficiency, by recirculating some of the cooled flue gas. An emergency dump stack is also provided to discharge the hot combustion gases directly to atmosphere under certain failure conditions.

Obtaining an operating licence for this from the local authority caused the client problems, which were ultimately resolved with the help of Arups' environmental specialists.

### Heat recovery

Operating experience at Sidcup, confirmed more recently and somewhat reluctantly by others in the business, identified tube fouling of the waste heat boiler as the primary constraint on plant availability. Dyvell achieved their planned availability of 85% only by much management and staff effort, and finding a solution to this problem much exercised the design team.

- Water tube boilers were rejected on cost grounds, and possibly uncertain benefit.
- On-line tube cleaning seemed of dubious practicability.
- Additives and combustion-modifying chemicals were ineffective, as was further reduction in gas temperature by increased recirculation.

Experience showed that the 'combustion tube' of Sidcup's three-pass wet back boiler was ineffective in countering tube fouling. Not only did its elimination save space, but also allowed a substantially higher boiler pressure than normal for shell-and-tube construction.
The solution finally adopted for Bournemouth was to provide twin boiler streams, permitting regular cleaning without loss of availability. This unique feature was made possible by innovative design, jointly by Arups and Basic Shannon Combustion, for hot gas dampers. Its value has been proved by the near 100% availability achieved since commissioning of the plant.

In power generation, the higher the steam pressure the better - within reason. Municipal waste incinerators are generally designed for a steam condition of 40 bar/400°C to avoid tube problems. Although Beel Industrial Boilers have constructed shell-and-tube heat recovery boilers up to 35 bar, an optimisation study by IPG showed that anything above 27 bar would be uneconomic, due to the steeply increasing capital cost of the boilers and ancillary equipment, so this pressure was ultimately selected. High pressure underlined the benefit of economisers which were duly specified, though special means were required to keep metal temperatures above the likely acid dewpoint of the gases.

### Flue gas treatment

Basic Energy pioneered small-scale dry acid gas scrubbing systems for UK incinerators: again, Sidcup was one of the first. In 1991 most incinerator suppliers insisted on wet scrubbing and it is satisfying to see that, under current regulations, the dry option has become the industry standard.

The first step was to reduce the gases' temperature to about 140°C. A conservative approach to the question of acid dewpoint determined that this duty would not entirely be met by the economiser, so a non-corrodible air/gas heat exchanger was included. Injecting powdered hydrated lime to a reactor vessel at this temperature effectively reduces HCl emissions to well within required levels. Surplus lime, reacted material, and particulates from the furnace are then collected in a bag filter prior to exhaust. Provision was also made at Bournemouth for injecting powdered activated carbon to control further the emissions of dioxins and other toxic species. After exit from the baghouse the gases pass through the induced draught fan, past various monitoring and sampling points, and thence via a long horizontal duct to a flue within the existing lattice chimney structure.

### Power generation

Various factors, including the following, ensured that Bournemouth became the first clinical waste-to-energy plant in the UK to generate electricity successfully:

- Heat rejection at high temperature is an essential feature of the process to minimise corrosion. Generation of steam at high pressure is thus both possible and desirable.
- The marginal cost of rating a shell-and-tube heat recovery boiler for high pressure operation is not great.
- The hospital demand is for low pressure hot water, allowing the turbine exhaust condenser, which also serves as the LPHW calorifier, to run at a vacuum. These factors ensure a high heat drop across the turbine, giving enhanced power output.
- The hospital was particularly keen to reduce its dependence on electricity purchased from the public supply.

6.
Bags of waste being tipped into the incinerator hopper.

Thermo-economic modelling rapidly showed power generation to be attractive and its inclusion gave Dyvell's bid a strong technical and commercial edge. From the earliest stages of the feasibility assessment it was clear that an isentropic heat drop well in excess of 500 kJ/kg would be available. Although a heat drop of this magnitude would normally dictate a multi-stage steam turbine, considerations of availability, capital cost and space made a single-stage turbine the most appropriate prime mover. It seemed possible nevertheless that something approaching $500kW_e$ could be obtained, still leaving about $3MW_{th}$ available in the form of LPHW for hospital heating.

Tenders based on industry-wide standards were sought from four turbo-machinery suppliers for a skid-mounted turbine and alternator, a vacuum condenser, and all controls. To work effectively, the turbo-machinery needs various ancillary services, which were designed by Arups.

Included in the M&E package for the building contractor were:

- a cooling system, to remove heat from the lubricating oil, alternator stator, and other heat exchangers
- a non-condensibles extraction system, to remove any air accumulating in the exhaust condenser
- controls interfaces, to integrate the turbo-alternator into the overall incinerator complex
- a turbine bypass pressure reduction valve, to allow the incinerator to operate independently of the turbo-alternator.

The performance and indeed life of steam turbines is enhanced by superheating the steam. Various superheater design options were considered, the final choice being a separate gas-fired unit on grounds of capital cost and freedom from cleaning and maintenance. After considering alternatives, a synchronous generator was selected, rated to accept the power resulting from the incinerator's highest anticipated thermal output. Electrical control systems to G59 Recommendations were specified but 'island mode' operation (ie independent of the public supply) was not considered economically worthwhile. Safe shutdown of the combustion plant was assured by installing a small standby diesel generator.

Return water from the hospital heating system passes through a bank of air blast heat exchangers, then through the tube bundle of the vacuum condenser, before rejoining the flow header in the hospital's boilerhouse. The air blast coolers are controlled to ensure the maximum flow temperature to the hospital is not exceeded whilst simultaneously meeting the incinerator's heat rejection demand.

## Buildings and services

The architectural design of the building was dictated by the constraints of the site:

- a very limited area, surrounded by buildings in use throughout construction
- stringent noise limits, necessitating minimum penetrations of the building envelope
- the need to blend with surrounding structures, particularly the existing boilerhouse
- the need to allow for manoeuvring lorries up to 18m long.

Arups' specialist services were used to analyse noise emissions from the equipment on site, and to model road traffic movement. Both analyses were vital to gaining planning consent in the face of public hostility to the project.

Severe space constraints necessitated two storeys, the upper for the turbine hall and for most of the 24-hour waste storage required under waste regulatory guidelines. The efficient use of space eventually achieved in the building allowed the overall visual impact to be remarkably low. The two-bay, portal-framed structure has a semi-pitched roof profile in keeping with the adjacent hospital boilerhouse, and is clad in insulated profiled metal sheeting. Particular attention was given to noise control. Nearby housing forced stringent targets, which required careful design and specification of building fabric, air intake louvres, ventilation system, and air blast coolers.

Civil works included substantial excavations for the pits required by the Basic incinerator and ducts for piped services from the boilerhouse. A supporting structure was designed to carry the flue horizontally to the existing boilerhouse chimney cluster. Modifications were required to the gas intake and metering point, to provide a supply of firm gas sufficiently large for start-up of the incinerator.

## Conclusion

The incinerator plant was commissioned towards the end of 1995, and the turbogenerator passed acceptance tests in March 1996, when a consistent steam supply became available. State-of-the-art capacity now exists to meet both the waste disposal requirements of hospitals and medical practices in the South of England and the commercial aspirations of the owners and operators of the facility.

Despite the plant being of substantially greater capacity than that which it replaced, pollutant emission from incineration on the site has been dramatically reduced and an overall reduction in $CO_2$ emissions achieved. Furthermore, combustion of fossil fuel for hospital heating has been reduced to a fraction of previous levels and a significant contribution made, with otherwise unusable sources of energy, to the hospital's electricity demand. All this has been achieved within tight site area and noise performance constraints, and the minimised visual impact that the location demanded.

### Credits

*Client:*
White Rose Environmental
(initially Dyvell Holdings Ltd)

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*Incineration plant supplier:*
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*Turbogenerator supplier:*
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*Buildings & services contractor:*
Wiltshier Construction (Wessex) Ltd with Drake & Scull Ltd

*Illustrations:*
1, 3, 4, 6: Chris Owen
2: Trevor Slydel
5: Trevor Hodgson

# Cathodic protection in civil engineering

Graham Gedge

## Introduction

Cathodic protection (CP) prevents corrosion of metals by altering their electrical potential to the immediate environment. This change removes all areas that are anodic - where metal dissolution occurs - and changes them to cathodes (hence 'cathodic protection '). Using CP to prevent corrosion of engineering structures and components is long proven: originally devised in the 1820s by Davy, the technique was well established from the 1930s. It can be applied to structures or components permanently immersed in an electrolyte such as soil or water, either by using an external power source (impressed current), or by connecting dissimilar metals (sacrificial anodes). Both methods have been used in widely varying industries, most notably for buried pipelines, and from the late 1960s CP also became an established way to protect coated and uncoated steel jackets, and coated pipelines, in the offshore oil and gas industries.

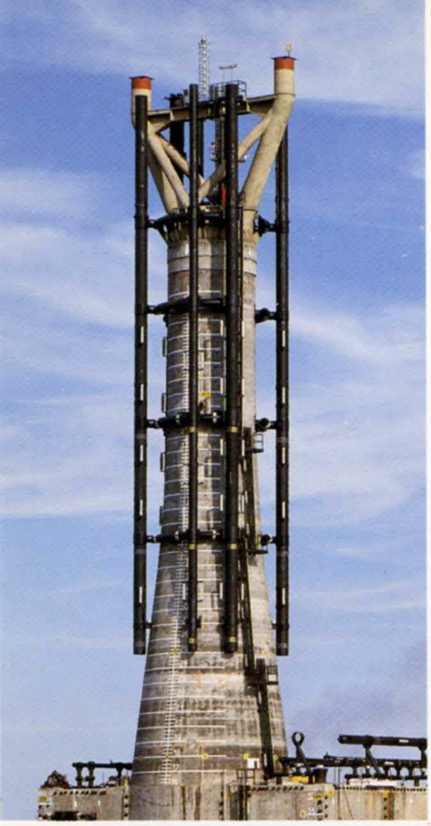
During the late 1970s and early 1980s, it became apparent that many reinforced concrete structures built in the previous 10-20 years were proving less durable than expected, for several reasons: one was the intentional addition of chlorides to the original mix; another, the exposure of structures to high chloride environments in service. CP became a favoured remedial solution, particularly for bridge structures, and in the 1980s this sector of the construction industry was a developing market.

Unfortunately, the technique suffered from overselling as the 'cure-all'. It is not. CP is only one of several mitigation techniques to combat corrosion, and must be technically and economically justified.

## Conventional systems

### *Offshore structures*

Until very recently, Arup Research & Development's experience of CP - perhaps not surprisingly - was on industrial engineering projects, the first being the Ravenspurn North CGS[1]. Although a concrete structure, it incorporated a large area of steel in the product riser pipes, (see Fig.1 overleaf) the service pipes, and the associated support structure of ring beams. As most of these were to be permanently immersed in seawater, the design codes required them to be provided with CP in the same way as for a steel jacket. ▶



1. Detail of Ravenspurn North CGS, showing cathodically protected steel riser pipes and supports.

All the exposed steel was coated (most steel jackets in the North Sea are not). All the steel was deemed to be electrically continuous with the reinforcement: the former reduces current, and therefore sacrificial weight requirements, while the latter increases it. It is important to understand that there was no intention or need to protect the reinforcement per se, only to take account of its effect in drawing a proportion of the supplied current from the system.

After Ravenspurn the next commission was to examine remedial options for the Brent field. This differed in that CP was to be applied to the piping systems within flooded shafts - a more defined, and benign, environment than open seawater. Here, design current densities could be reduced and hence the anode weight, desirable given the difficulties of handling and installing anodes in the shaft's restricted space. More recently, Arup R&D designed a CP system for the UNOCAL gas facility in the southern North Sea. Again, it was of concrete, and treated similarly to Ravenspurn, but the certifying authorities had to be convinced that the CP system would not cause hydrogen embrittlement of prestressing tendons, which are effectively isolated from the system.

The latest such project is the CP system design for the Wandoo development in Western Australia (Fig. 2). In essence, this is very similar to Ravenspurn, with some modifications to account for local conditions. The waters of the north-west coast of Australia are somewhat warmer than the North Sea: for anode design, 25° has been assumed rather than 10°C.

### *Pipelines*

Again, Arup R&D's experience of pipeline CP has been via industrial engineering projects. Primarily these relate to providing gas lines to power stations, with the CP design controlled by British Gas standards. CP systems have also been designed for a gas line crossing the Moray Firth and for a small onshore oilfield at Palmers Wood development in Surrey. These systems have all been reasonably straightforward and designed in accordance with well-established procedures and standards, the differences from offshore being in particular methods. For shorter pipelines, sacrificial anodes are still favoured, but impressed current has been preferred on longer lines, or where more than one line has been used. Cost has usually dictated this, allied to the greater operational flexibility it allows.

## Newer applications

The work on conventional CP design, using well-established systems and design standards, gave Arup R&D an understanding of the technology.

Allied to a general understanding of corrosion, this provided a sound basis for developing the use of CP in other areas where well-established design procedures do not exist. Two recent projects demonstrate how Arup R&D have exploited this to achieve solutions to challenging corrosion problems.

### *North Seaton Bridge*

This bridge was designed in the early 1970s to carry the A189 over the River Wansbeck estuary in Northumberland. It was of reinforced concrete, with columns based on a slender 'tapered super ellipse' geometry. In 1990, inspection revealed that, although it was generally in good condition, five of the six central columns were cracked and sounded hollow in the area of the high tide level. In 1991, Arup R&D were commissioned to determine the cause of these problems and propose remedial works if necessary.

Investigations and tests revealed the cracking to be caused by reinforcement corrosion, attributed in turn to chloride ingress to the bars. The preferred remedy was to install an impressed current CP system. At the same time, the client decided to structurally upgrade with an additional layer of bars and concrete. The work was eventually commissioned in winter 1995.

In the UK, most applications of CP to reinforced concrete have been on motorway bridge structures, which are exposed to a more clearly defined and constant environment - in essence that of atmospheric exposure. Previously these applications have not involved placement of additional concrete and reinforcement over the anode mesh. At North Seaton the condition was very different. Not only was there additional concrete but also the environment varied with height up the column. The effect of these features, allied to the good quality of the original concrete, has a significant effect on the operation of a CP system. This was recognised in the design and the columns were split into upper and lower zones.

When steel is cathodically protected, the anodic (metal dissolution) reaction is stopped. The cathodic reduction reaction (usually oxygen reduction), however, continues at a rate controlled by the current supplied. For constant current devices, this rate is fixed. As the rate at which oxygen is reduced is constant over the whole structure (assuming a common current density), oxygen concentrations at different locations may vary with exposure. The oxygen concentration at the steel will determine its potential, as measured by an embedded reference electrode at the surface. These differences will arise because of both macro and micro changes in the concrete's permeability.

In the present context, macro variations are particularly important. In the atmospheric zones, permeability will be relatively high with oxygen freely available at the steel surface. In the submerged and tidal zones, the concrete is permanently saturated with water, so oxygen availability at the steel will be restricted; saturated concrete is

2. The Wandoo platform.

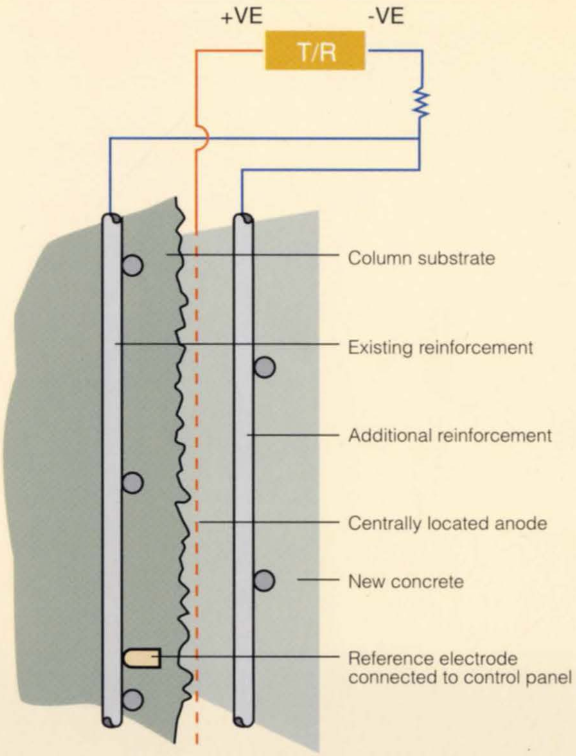
very much less permeable than non-saturated. The oxygen concentration at the steel will also be affected by the concrete cover to the bars, which in this case was increased from about 50mm at corroding bars to 125mm, thus significantly increasing the diffusion distance.

These differences would be expected to affect both the natural and protection potentials. In areas of higher oxygen availability, potential would be less negative; in areas of low oxygen it would be more negative. This was found to be the case on all the columns. Prior to energising, the natural potentials on the upper zones were all between +200 and +500mV compared to the lower (saturated) zones.

Once the CP system was energised, the potentials of all zones changed only very slowly with time - away from the natural values. After about one month, none of the zones could meet the established acceptance criteria, developed for bridge decks, of a 100mV shift four hours after switching off the system.

Most of the upper zones, however, were showing a four-hour shift of 60-80mV, so it was decided to increase the permitted decay time to around 24 hours and to record potential continuously. This decision was based on recognising the role of oxygen in the corrosion process: the potential of the steel will change positively as the oxygen concentration increases at the steel surface. It was concluded, in this instance, that both the concrete cover and quality were restricting oxygen access to the steel. Increasing decay time would, therefore, negate this problem by increasing the time for oxygen to reach the steel. It was found that the 100mV shift criteria could be met if the decay period was set at 10 hours.

A similar exercise on the lower zones was less successful. Even when left to decay for 70 hours, the 100mV shift was not achieved. Again, this can be accounted for by oxygen availability at the steel. In the lower zones, this would be even more restricted than in the upper, because of the reduced permeability of saturated concrete.



3. Schematic of CP system for North Seaton Bridge.

### *Contaminated land foundations*

Increasingly, construction projects involve re-use of contaminated land. This can present many, considerable, difficulties for the design team, one being the durability of foundation piles if the ground is acidic. If this is the case then the usual approach to dealing with corrosion, based on a small corrosion allowance, cannot be used as there are usually no reliable data for such conditions. With Ove Arup & Partners Ireland, Arup R&D recently undertook a feasibility study of using steel piles in acidic, contaminated ground in conjunction with CP.

In this particular case the ground had become contaminated with very high levels of sulfate, the pH was less than 4, and the water table only a few metres below the surface. The ground was thus likely to be corrosive, and rates could not be predicted with confidence. This problem could be overcome by using impressed current CP in conjunction with a coating. The design required approximately 600 piles on about a 2.75m square grid.

These features caused a problem for the CP design: where to put the anodes? In normal CP design, the anodes - or groundbed - are placed in a few locations remote from the structure. Here, this would have resulted in massive groundbeds, significant volt drops (caused by high currents in the cables), and no guarantee that the central piles would have received sufficient current to achieve protection.

It was therefore decided to place individual anodes centrally between groups of four piles and to group a number of rows together from a common power source. Whilst this ensures protection, it is not the most economic either to install or to operate. To reduce both such costs, a specialist electrical consultant was employed to model the as-designed system. In particular, the effects on current distribution of removing anodes and varying coating quality (in terms of its electrical resistance) were investigated. It was found that the former had only a marginal effect, but coating quality was a significant factor.

The current flowing in a CP system is greatly influenced by the insulating properties of the coating. Arup R&D showed that, provided the coating had a resistivity of >1010Ωcm, current demand would be negligible. The model then investigated the effect of coating damage at various areas on the pile; again, adequate protection could be achieved. Perhaps more importantly, the output of the modelling provided data that could be included in the specification and checked on site. In this case Arups were able to specify a minimum coating resistivity and an acceptable range of pile-to-earth resistance. This can be correlated with the area of damage to the coating that might occur during driving and, as this can be measured on site, would allow the design assumptions to be verified. With this approach, operating costs could be cut by 50-75% pa.

### Conclusions

Using CP to prevent corrosion is well established and commonly used in certain sectors of industry. Arups' experience and understanding of the technology in these areas has allowed the techniques to be adopted and modified for use in newer, more challenging environments. The designs discussed in this article are, it is believed, unique: at North Seaton the understanding of corrosion was used to adopt appropriate acceptance criteria to assess the system, whilst in Ireland a system was designed that would prevent corrosion, and a specification for coating quality developed that optimises the CP performance.

### Reference

(1) ROBERTS, J. Ravenspurn North concrete gravity superstructure. *The Arup Journal, 24*(3), pp.2-11, Autumn 1989.

### Credits

*Illustrations:*
1. Peter Mackinven
2. Kim Vivian
3. Denis Kirtley
4. Neville Long

4.
North Seaton Bridge, with temporary coffer dams for remedial works

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