THE ARUP JOURNAL

2/1998

ARUP

THE ARUP JOURNAL

Vol. 33 No. 2
2/1998

Published by
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London W1P 6BQ

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Front cover:
Planar glazed wall and entrance canopy at the Scottish Exhibition and Conference Centre (Photo: Richard Davies)

Back cover:
'BP Solar Showcase', designed and engineered in six weeks by Arup teams for the G8 summit, Birmingham, May 1998 (Photo: Grant Smith)

Keith Hunter

The new Scottish Exhibition and Conference Centre was conceived in response to a desire to develop Scotland's capacity for hosting international conferences, and as a landmark building for Glasgow's role as UK City of Architecture and Design 1999. For the 'Armadillo', as the building has been nicknamed, Ove Arup & Partners carried out the full engineering design, including civil, structural, mechanical, electrical, public health, geotechnical, and transportation.

BP

In the search for alternative, non-polluting, and renewable sources of energy, the use of photovoltaic cells as building panels - converting sunlight directly into electricity - has been developed in recent years. This article describes a variety of such projects with which Arups has been involved, including the 'BP Solar Showcase' designed and engineered in six weeks for the May 1998 G8 Birmingham summit by teams from Arup Associates (architect and engineer) and Ove Arup & Partners (photovoltaics, façade, acoustics, and IT/telecommunications).

Sean McDermott

With a wing-span almost equalling that of a jumbo jet, Anthony Gormley's *Angel of the North* is the largest sculpture in Britain. Engineers from Ove Arup & Partners developed the structural design of *The Angel*'s body and wings, and designed the foundations and 20m deep piling to secure the 208 tonne steel sculpture to its hilltop site overlooking Gateshead.

Beyeler Foundation

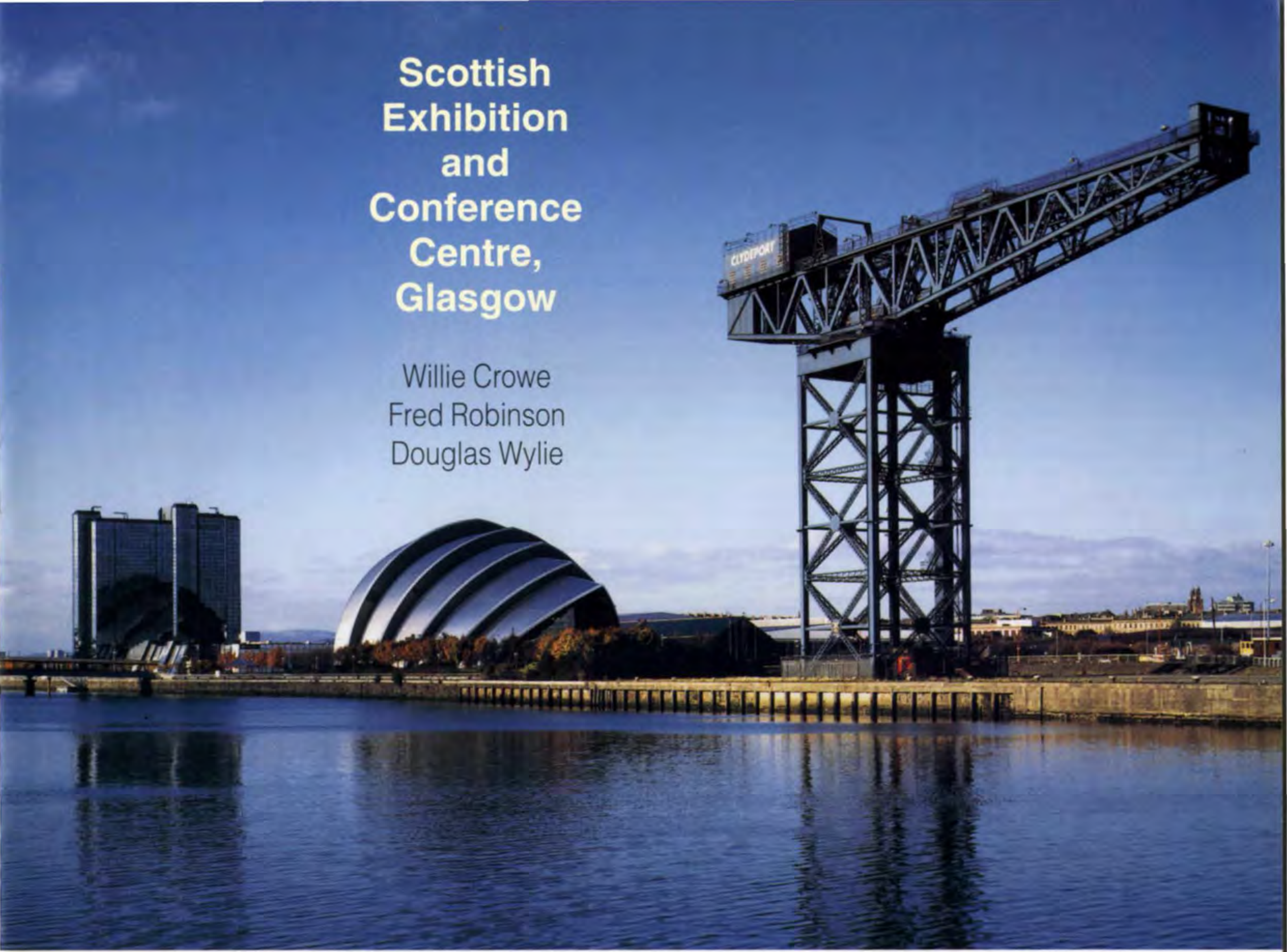
This new museum houses a large private collection of classical modern paintings, as well as some sculptures from Africa, Alaska, and Oceania. A feature of the design is the multi-layered roof, which allows natural light to illuminate the art on winter days as well as controlling sunlight levels on bright days. Ove Arup & Partners carried out the structural scheme design, the detailed roof design including the glazing, the services engineering with a detailed energy analysis, and the natural lighting design.

Peter Mackinven

Up to now, the time taken by road baggage transfer between Terminal 4 and Terminal 1 at Heathrow Airport has been a limiting factor on connecting times for transfer traffic. To facilitate baggage transfer, an automated system has been provided within a 1.4km tunnel. Ove Arup & Partners were lead designers for all disciplines, including civil and structural engineering, mechanical and electrical services, and baggage handling. A previous *Arup Journal* article described the design and construction of the civil engineering works. This present article outlines the methodology and design of the the baggage handling system, and the mechanical and electrical services.

Scottish Exhibition and Conference Centre, Glasgow

Willie Crowe
Fred Robinson
Douglas Wylie



Introduction

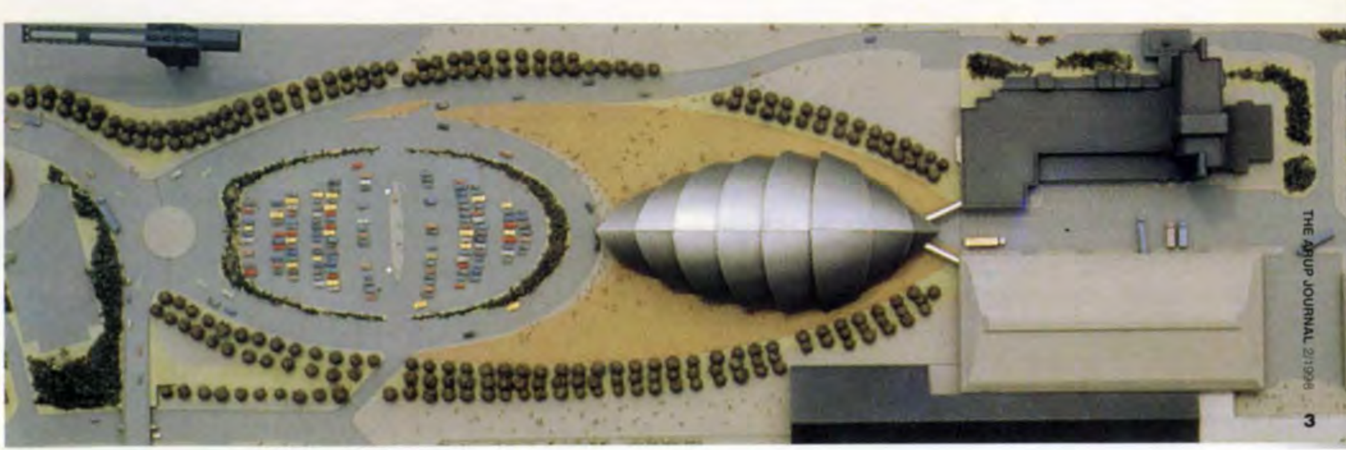
Early in the 1990s the conference centre market was identified as a potential source of growth for business in Scotland. Based on this, the board of SECC Ltd (Scottish Exhibition and Conference Centre) embarked on an ambitious plan to develop its existing facilities in Glasgow; this consisted of expanding the existing exhibition space and breakout facilities, and constructing a new flagship conference centre building. Ove Arup & Partners Scotland was interviewed for the project in March 1995 and subsequently commissioned to carry out the full engineering design, including civil, structural, mechanical, electrical, public health, geotechnical, and transportation.

During the interview Arups presented their design team for the Edinburgh International Conference Centre[1], the team being based in their office in South Queensferry. One of the conditions of the new brief was that key designers were to be on site, and to fulfil this requirement Arups agreed to locate a full design team at the site with back-up primarily from the South Queensferry office. The site office selected by the client was the original Victorian pumping house used to control the water level in the original dock; Arups joined the site design team of Foster and Partners, the architect, there and shared accommodation with them throughout the contract.

The initial design proposals and the scheme design were prepared in the pumphouse, sufficient to allow tendering of a design and management contract. Bovis were subsequently appointed as the DMC contractors at this stage, and both Fosters and Arups were novated to Bovis. Work was organised in a series of packages to allow Bovis to tender all elements of the building at an early stage and subsequently guarantee the maximum price to SECC Ltd. The City of Glasgow Council were the main funding agents for the project, but financial assistance was also forthcoming from the EC.

1. The new landmark conference centre in its former dockland setting: east elevation.

2. Queen's Dock under construction in the 1870s.



3. Architect's model of Scottish Exhibition and Conference Centre.

Background

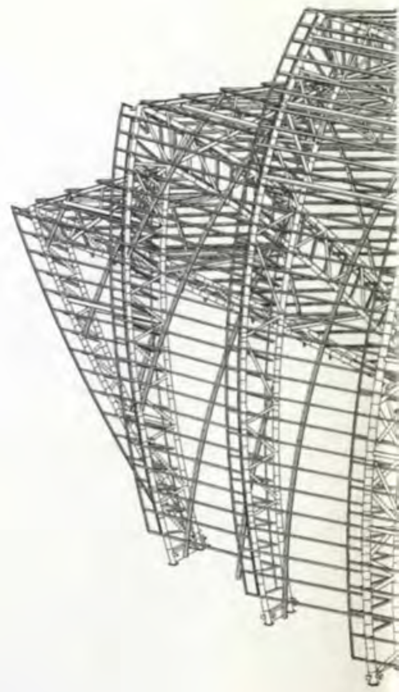
Despite its name, the SECC did not have a custom-designed conference centre, but used modified exhibition halls for that purpose. Research on behalf of the client pointed to the need for a large-capacity dedicated auditorium seating in excess of 3000 delegates, a size that ideally complemented the already extensive exhibition halls. The new conference centre is one of only five facilities in Europe with a capacity exceeding 3000, and enables Glasgow to compete with major conference and exhibition facilities around the world, thus attracting new business to the UK.

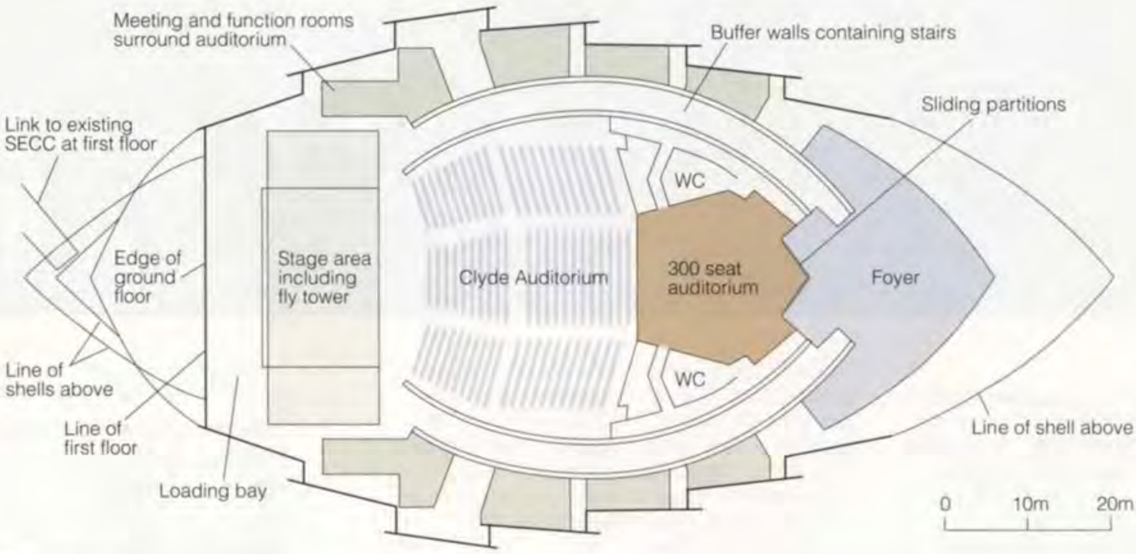
Besides the new landmark conference centre, the brief also included a new 5400m^2 clear span exhibition hall, and conversion of an existing exhibition hall into a multi-purpose breakout facility (including a flexible auditorium space with 600 seating capacity). Existing circulation routes were extended to provide covered access to the new facilities. The SECC complex is situated close to the heart of Glasgow on the banks of the Clyde, where the new conference centre and the Finnieston Crane together dominate the local skyline; the visually individual building was quickly christened 'The Armadillo'.

The site

The existing buildings in the complex were built over the infilled former Queen's Dock. This had been constructed between 1872 and 1877 and comprised two basins immediately adjacent to the Clyde with a canting basin at the entrance. The site operated as a dock until 1970 when it was closed; filling took place over the next decade, predominantly with demolition rubble, understood to come from the St Enoch Station, end-tipped into the water-filled basins. Although no records exist of the tipping, it was understood that the great majority of the degradable material in the fill, such as timber, was removed and burnt on site.

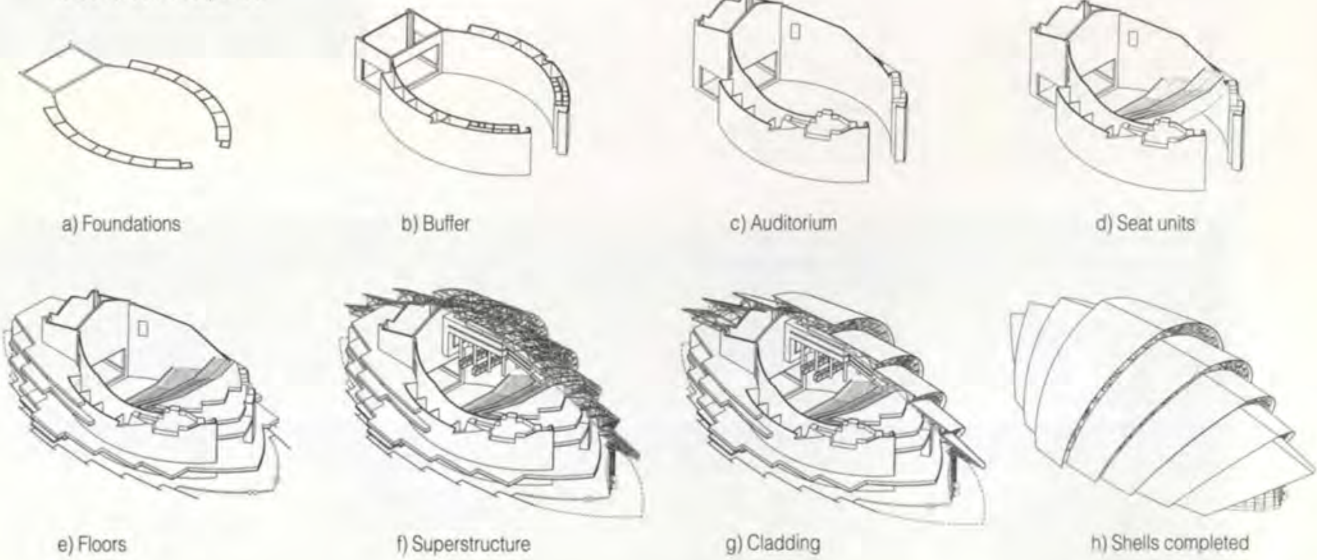
The new conference centre location straddled an internal quay wall, so two-thirds of the building lies over the infilled dock and the remainder on the old quayside. A full site investigation comprising trial pits, trial trenches, shell and auger boreholes, and rotary boreholes was undertaken in June 1995. The former quay wall and the associated dead man anchor blocks and ties were identified in trial trenches and surveyed into the site grid. Ground conditions in the docks comprised a 13m depth of cobble and boulder-sized blocks of masonry and reinforced concrete within a matrix of ash and brick.

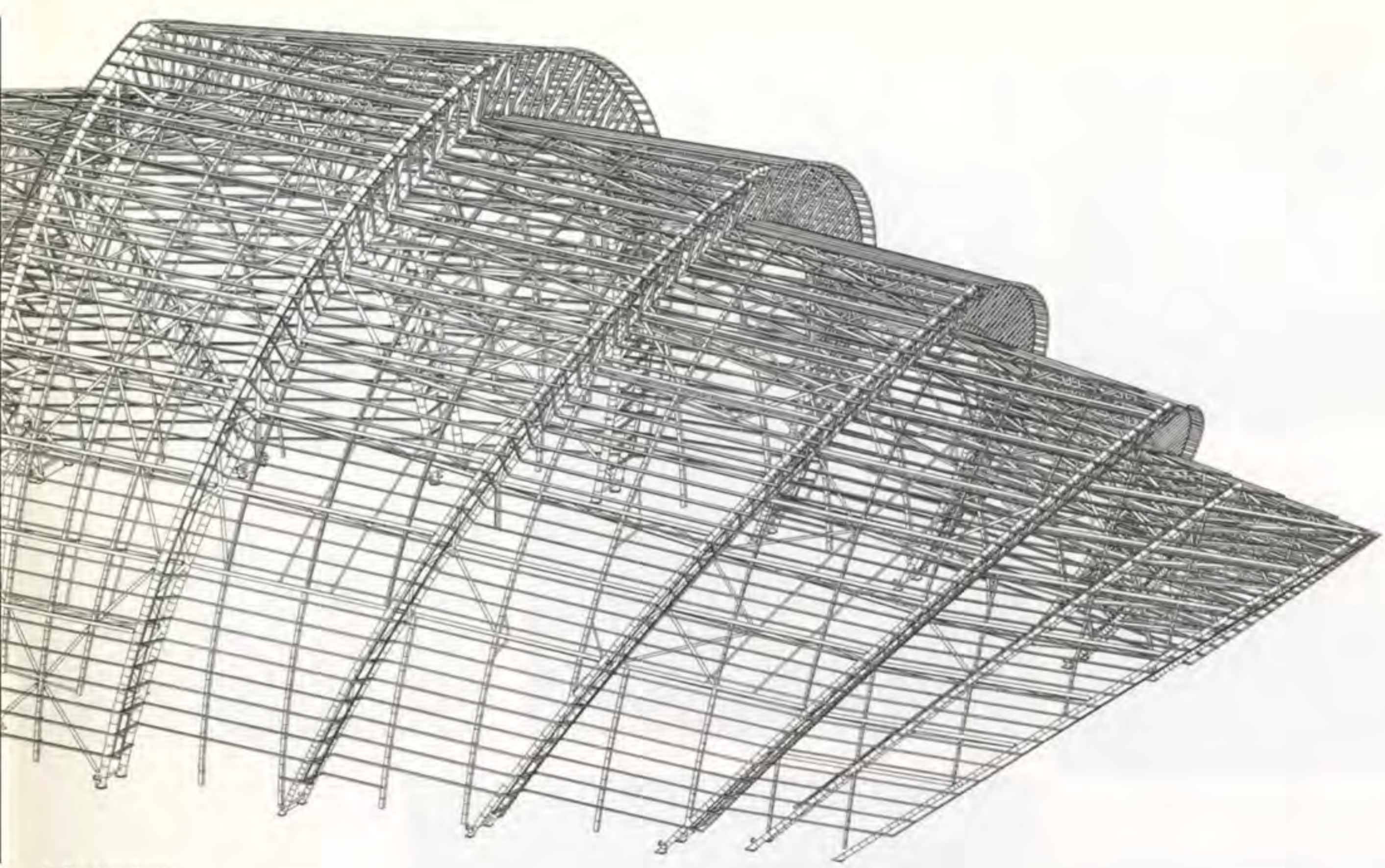




4. Ground floor plan.

5.Construction sequence.





6. Roof steelwork.

Underlying this was around 11m of loose to medium dense silty gravelly sand which in turn overlay bedrock - moderately weak to moderately strong sandstone - at around 24m below ground level. The ground conditions on the former quayside were similar, except that the depth of fill was only up to 5m or so, comprising mainly the loose granular alluvium dredged from basins during construction of the docks. Although the site investigation identified little organic material in the fill, monitoring of standpipes in the boreholes recorded elevated levels of soil gas, which meant that a gas membrane had to be installed below the slab with a system of venting pipes to avoid gas build-up.

Piling

The existing facilities comprised large-span, truss-framed buildings on shallow foundations supported by the fill, which had been improved by dynamic compaction. For the 3500kN - 4000kN column loads in the new conference hall structure, piled foundations socketed into the bedrock at depth were proposed. These were located on either side of the buried quay wall with ground beams to span this feature. A contractor-designed piling contract was let to Westpile in October 1995 and 172 900mm and 600mm diameter bored piles were placed over the three-month contract period. Initially, the piles were drilled and cased through the fill with the depth through the underlying alluvium being constructed under bentonite. Latterly, however, the contractor elected to case the piles over their full depth. Despite the nature of the fill in the docks, remarkably few piles hit major obstructions and only three had to be relocated.

Structural design

Design of the roof structure was initiated through a major geometrical analysis which defined the node points of the arches and served as a check of the architect's 3D modelling of the eight shells. These were derived from 38m radius cylinders, the minimum achievable without requiring pre-bending of the roof sheeting. This very simple concept of not pre-bending the sheeting therefore dictated the basic curvature of all the shells and led to an economical cladding envelope. Three-dimensional modelling played a major part in designing the conference centre, its shape being generated entirely by 3D computer modelling techniques. The roof structure was symmetrical about its centreline and each half shell was a symmetrical surface defined by inclined cut planes projected through the basic cylindrical form.

The most economical wrap of the shell roof was explored in detail to reduce to a minimum the enclosed volume of the building. Because of this very tight wrapping round the building the shells were found to be almost vertical where they met the ground and so horizontal thrusts had to be resisted at first floor level.

The roof steelwork is based on a series of trussed arches formed from structural hollow sections. The largest steel shell was used to balance and brace the structure and was tied to the flytower at two strong points. The braced shell was then used to hang the other arches from its leading and trailing edges. The braced shell is always under an imbalanced load because of the greater number of shells on the east side of the building than the west side.

7. Bored pile: casing required to rockhead.

In its response to thermal effects the Armadillo behaves like a large accordion, with significant movements at the extreme eastern tip above the glazed wall. These effects had to be carefully considered at all stages of the design.

Tendering the steelwork package

During tendering, the steelwork tenderers were asked to demonstrate their ability to carry forward the 3D modelling into fabrication drawings, and to prove the compatibility of their systems were asked to draw a series of simple truss members connecting the arches. Watson Steel of Bolton were selected to fabricate and erect this prestigious steelwork contract because of the confidence they gave the designers that their 3D fabrication drawing system was compatible and sufficiently advanced to interface with that of the team. Average steelwork rates were above £2000 / tonne but the roof structural steelwork, and in particular the curved arches, would be in excess of £3000 / tonne on average.

Watsons were initially appointed on a restricted contract to spend a six-week development period with the designers. This period was primarily to allow Watsons to guarantee their out-turn steelwork price to Bovis. This intensive six-week development period, undertaken jointly between Watson, Arups, and Fosters, was all carried out in the site design office. This allowed architect, engineers, and contractor to work together to produce the initial shop drawings and shortcut the conceptual approval process. The fabrication costs of the curved arches were identified, and by careful redesign and consideration the number of arches was reduced by two. The working together of designers and fabricator allowed them to guarantee the out-turn price of the steelwork and be fully appointed on this basis.

8. Concrete walls complete, floor plates wrapping around walls, and arches about to be erected.

11. Connection between braced shell and flytower walls

12. Braced shells 5 and 6 erected.

9. Plate girders supporting lower balcony.

10. Site welding primary arch.

13.
Roof steelwork over main entrance.

14 below:
Steelwork over main reception area.

Concrete works on site

While the design of the steelwork was being finalised, work on site consisted of constructing the ground beams and pile caps to prepare for building the concrete buffer walls around the auditorium. These walls had several functions, but were primarily to contain the main auditorium and support the main circulation stairs accessing the three levels of terraced seating in the main Clyde Auditorium.

A significant co-ordination exercise was carried out prior to constructing the concrete walls to ensure that all holes for steel beams, supporting floor plates, and services penetrations were fully dimensioned and detailed prior to the preparation of reinforcing drawings.

The concrete walls do not primarily support the arched steelwork roof but were very useful in resisting lateral forces, particularly at the head of the flytower. Two arches are propped from the concrete walls but, generally speaking, connection between the steel roof and concrete walls was resisted. Where connection had to be made between the roof and the concrete, carefully-designed movement brackets had to be installed because of differential movements between the concrete supporting structure and the more flexible steel roof.

Roof steelwork

The roof is supported by 900 tonnes of structural steelwork, mainly comprising 500 tonnes of structural hollow sections. The booms of the arches are bent to the elliptical form required by the shells and the complete arches (60m across by 45m high at their largest) were first bent and then welded together on the shop floor to the exact geometry, prior to being cut into sections and transported to site. The transportable sections of arch were then site-welded together in a series of jigs and very tight sight tolerances were achieved. On erection the worst out-of-position arch was little more than 20mm from the location predicted by the computer model - a remarkable achievement by the fabricator.

Between the main arches, secondary trusses spanning 20m at their longest were fabricated from column sections with circular hollow section diagonals. Open sections were selected for these members for cost reasons and also for the ease of fixing secondary steelwork to support services, etc, at a later stage. These secondary trusses tend to sag as they become progressively more horizontal and a series of significant sag rods and sag bracing systems hold them in position. This bracing system also restrains the secondary trusses under the action of wind suction.

After some study of how to clad the shells economically, purlins were positioned at 1.5m centres, spanning approximately 6m, and the *Kal-zip* cladding system was fixed directly to these members.

Floor plates and balconies

A further 900 tonnes of structural steelwork was used to support the floors and balconies. The latter cantilever up to 15.5m and were constructed from plate girders designed dynamically and to recommendations in the National Building Code of Canada. Because of the very large cantilevers, the natural frequency of the girders was very difficult to control and struts were introduced to utilise the in-plane stiffness of the floors to the rear of the auditorium; these in turn acted as horizontal beams spanning between the concrete walls round the auditorium. This simple adjustment significantly increased the natural frequency with minimal increase in steel weight.

Precast concrete seating units were designed to span between the plate girders and were cast with integral balustrades and fixings for in situ steps - all to speed construction and achieve the required finish.

Floor plates

The auditorium and flytower are surrounded in plan by approximately 6000m^2 of composite flooring. These areas support the flexible use spaces, distribution corridors, bar, and general circulation space round the auditorium. They also have a secondary function, transmitting the thrust forces of the main roof support structure into the Clyde Auditorium's concrete walls.

Mechanical installations

There can be no doubt that the Armadillo is exceptional value for money at a total cost of £26M. Value on this scale is never achieved by accident and the pursuit of high quality + low cost was particularly relentless for the building services elements. The challenge was always to be both highly inventive and use conventional and readily-available products and materials throughout.

From the outset, any floor space that did not form part of the client's usable area was a target for cost reduction and review. The architects responded well and kept circulation space to a minimum, also the same approach for services resulted in air-handling plantrooms for the major spaces wrapping round the flytower and Clyde Auditorium. The original size of these particular plantrooms was reduced to about one-third by the use of huge plasterboard plenums that allowed air ducts to be created in previously unusable space within and through the complex shapes produced by the structural steel.

As the design progressed, services were either designed out or allocated space. However, the one major exception to this was that there was no logical or affordable area for boiler plant and its attendant flue; given the building profile, this was a design headache for some time. Then the client, with characteristic pragmatism, solved both these problems at a stroke by allowing the team to house the boilers in an adjacent building. Pipework connections were hidden under a link bridge with his existing facility.

The cathedral-like void above the Clyde Auditorium was in sharp contrast to the confined spaces elsewhere in the building. The conventional wisdom was to reduce the volume with a partial ceiling to hide the lighting bridges and control the acoustic response of the space. In fairness, the architects were the driving force in rejecting this approach, but like it or hate it the resulting exposed ductwork and lighting booms have a strong visual impact and required a considerable effort from all team members. As with all parts of the project the team most certainly included the management contractor and the large array of sub-contractors.

15. Entrance foyer.

The Clyde Auditorium leaves visitors to the Armadillo with their most lasting impression but the first impact is created by the glass-fronted main foyer. Most of the time this tall space, stretching the full height of the overflying shell, is sparsely occupied but as the Clyde Auditorium empties, upwards of 3000 people discharge into the foyer and circulation spaces. The problems created by these sudden changes were solved relatively simply. The perimeter heating below the glazing was made more powerful to counter the tendency for misting to occur, the mechanical heating and ventilation operates as the normal background system, excessive and fast changes in temperature are dealt with by large and automatically opening vents at high and low levels. These vents add up to some 25m^2 of opening and work to good effect.

Mechanical cooling in the building is limited to the auditoria and control rooms. The concrete walls, flytower, and ground slab of the main auditorium add up to a massive amount of exposed concrete, and this has considerable and beneficial moderating effect on the internal environment. However, it also had to be recognised that the auditorium may be unused and unheated for significantly long periods, so a boost cycle and a system of nozzles were introduced above the proscenium arch to provide quick heat-up; thorough testing has shown this to work well.

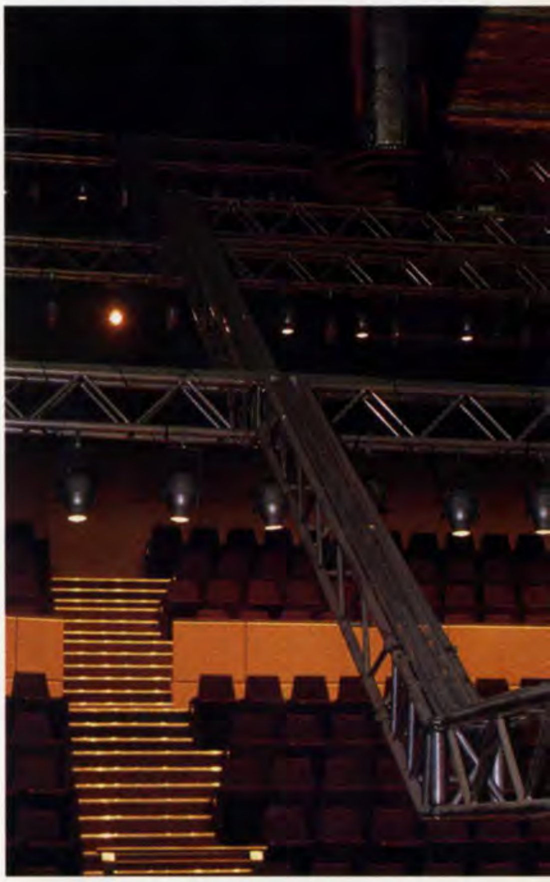
Electrical installations

The conference centre has an 11KV electrical supply direct into the 1500KVa cast resin transformers. These power an LV switchboard with full bus-bar coupler arrangements and a secondary essential supply fed direct from a standby generator. Sub-distribution boards throughout the building supply lighting and power requirements.

The building's profile meant that distribution space had to be carefully considered, and considerable co-ordination was needed to route all the cable trunking and trays. Lighting was another challenge. The Clyde Auditorium had no fixed ceiling, so the house lighting had to be suspended some 30m up in mid-air. To achieve a maintainable system, aluminium lighting trusses were suspended from the roof steelwork, motorised and synchronised to allow lowering and raising of the house lights; these were specially designed by Erco Lighting to accept a 250W tungsten halogen lamp within each theatre-type lantern. The end result gave a theatrical type suspension with a lighting level of 400 lux on the 3200 seats, complete with full dimming facilities.

The front entrance foyer and circulation spaces were of great importance to the architect, and the lighting team's brief was not only to highlight the steelwork, but create moods: shadowing of lighting around the public walkways.

16 below: Lighting trusses in the Clyde Auditorium.



17 below:
Ductwork and (behind)
lighting bridges above the Clyde Auditorium.

Scottish Exhibition and Conference Centre, 18 Top: Cladding in progress, and 19 above: The eight clad shells.

20. The Clyde Auditorium.

This was achieved by mounting directional floodlights on the buffer wall, directed outwards and reflected back from the shells' inner surface. This gave the correct lighting level on the walkway, highlighted the vast amount of steelwork and created shadows around the cladding.

The Clyde Auditorium's vast volume made fire protection a further major challenge, which was solved by installing seven beam transmitters and receivers. The transmitters were mounted on the lighting bridges to allow the client easy maintenance. The fire alarm system allowed for full integration with the stage smoke curtain, smoke extract fans, fire doors, and full voice evacuation system, interlinked with the existing six exhibition halls away from the conference centre. The security systems were required to be monitored and controlled from the existing security office some 200m from the conference centre. A network of containment and outstations allowed the CCTV and intruder alarm systems to function remotely.

During construction a late request for two escalators and two glass scenic lifts had to be incorporated as well as the original two 1000kg fire-fighting lifts and goods lift. This addition to the original programme was still met on time by the contractor.

Together with the normal electrical design elements, Arups was required to co-ordinate and assist in the installation procedures of the technical services - production lighting and sound, video, signage, data, and telecommunications.

At the time of writing the building has been operational for nine months and successfully hosted a number of major events with every seat full. Clearly this is a very successful project, a credit to the design team and contractors and a very valuable asset for the client.

Facts and figures for the new conference centre

Overall length: 120m

Width: 65m

Height: 40m

Area of flooring: 13 000m^2

Area of roof: 10 500m^2

Project cost: £26M

Key Information

- The Clyde Auditorium can accommodate 3200 people on three levels of tiered seating.
- 1800 tonnes of structural steelwork were used in the construction, consisting of circular hollow section and universal column and beam sections.
- Over 4000 drawings were prepared in the production of the steelwork element alone.
- The impressive glass-fronted arrival foyer has 810m^2 of planar glass supported on steel bow truss girders.
- Construction was completed in less than two years, on schedule and within budget.
- The Conference Centre had to be ready in time for the prestigious Society of American Travel Agents Conference, and it was. From this, Scotland received an important boost as an international destination for major conferences.
- The SECC is a landmark building and a new symbol for Glasgow, the UK City of Architecture and Design 1999.
- Having already fired the imaginations of conference organisers throughout the world, it is expected to generate an estimated 1000 new jobs in Glasgow and £26M per annum revenue for the City.

Reference

(1) BISSET, Alastair. Edinburgh International Conference Centre. *The Arup Journal, 31*(1), pp8-12, 1/1996.

Credits

Clients:
Glasgow City Council
SECC Ltd

Architect:
Foster & Partners

Consulting engineer:
Ove Arup & Partners Scotland Alastair Bisset, Willie Crowe, David Guild, Stuart Hunter, Gerry O'Brien, Sean Walsh (civil/structural)
Alan Garrard, Alan Richmond (geotechnical)
Gordon Carrie, Jim Hampson, Peter Kearns, Ian McGarrity, Harry Mulholland, Fred Robinson (mechanical)
Willie Stevenson Martin Surridge, Douglas Wylie (electrical)
Sam Cook, Annalisa Coutts, Alan Coventry, Alan Grant, Alan Keith (draughting)

Quantity surveyor:
Gardiner & Theobald

Project manager:
Turner & Townsend Project Management

Design and manager contractor:
Bovis Construction (Scotland Ltd)

Concrete works contractor:
Balfour Beatty Construction Ltd

Electrical contractor:
Balfour Kilpatrick

Mechanical contractor:
Crown House Engineering Ltd

Ground beam and pile cap contractors:
O'Rourke (Scotland)

Steel fabricator:
Watson Steel Ltd

Piling contractor:
Westpile Ltd

Acoustician:
Sandy Brown Associates

Illustrations:
1, 14-20: Keith Hunter Photography
2. Mitchell Library
3, 7-9, 11, 12: Ove Arup & Partners Scotland
5. Foster & Partners
10, 13: Woodward Staton Croft
4. Martin Hall
6. Watson Steel

From space technology to building skin

1.

2.

Ray Noble

Introduction

Photovoltaic devices - or solar cells - convert sunlight directly into electricity. They comprise layers of glass and, sandwiched between them, silicon cells reacting with sunlight to generate electricity.

Originally invented by the French scientist Bequerel in 1839, solar cells were developed by the space industry in the 1950s. Since then they have been used primarily where a low-maintenance, high-reliability energy source has been required, and conventional ones were unavailable or impractical. Subsequent to their earliest application on satellites, they have been used for remote terrestrial purposes including marine navigation and telecommunications equipment.

PV cells were first use to clad and roof buildings in the 1980s, when the need to find alternative, renewable, and non-polluting power sources became apparent. However, their use is currently hindered by factors like high cost, relatively low efficiency, problems with storing excess electricity, and the common misconception that they are only suitable for use in hot and sunny climates.

The PV building industry is still in its infancy: most solar cell building applications could be described as 'showcase' projects, demonstrating the potential of PVs.

However, as competition between manufacturers increases, and influential governing bodies begin to promote this seemingly infinitely renewable energy source, costs are falling and efficiency is rising, leading to more widespread use of solar cells in the building industry.

Research and early applications

In 1989 Arups' Newcastle office was approached by BP Solar and Newcastle Photovoltaics Applications Centre. As a result Arups became involved in a study examining the suitability of PV panels as a building material. A report was prepared in association with the Department of Trade & Industry, which concluded that commercial buildings, used primarily during the day, are an ideal location for PV, while domestic properties have a poor power match, as demand is greatest in the evenings and early morning when sunlight levels are low or non-existent.

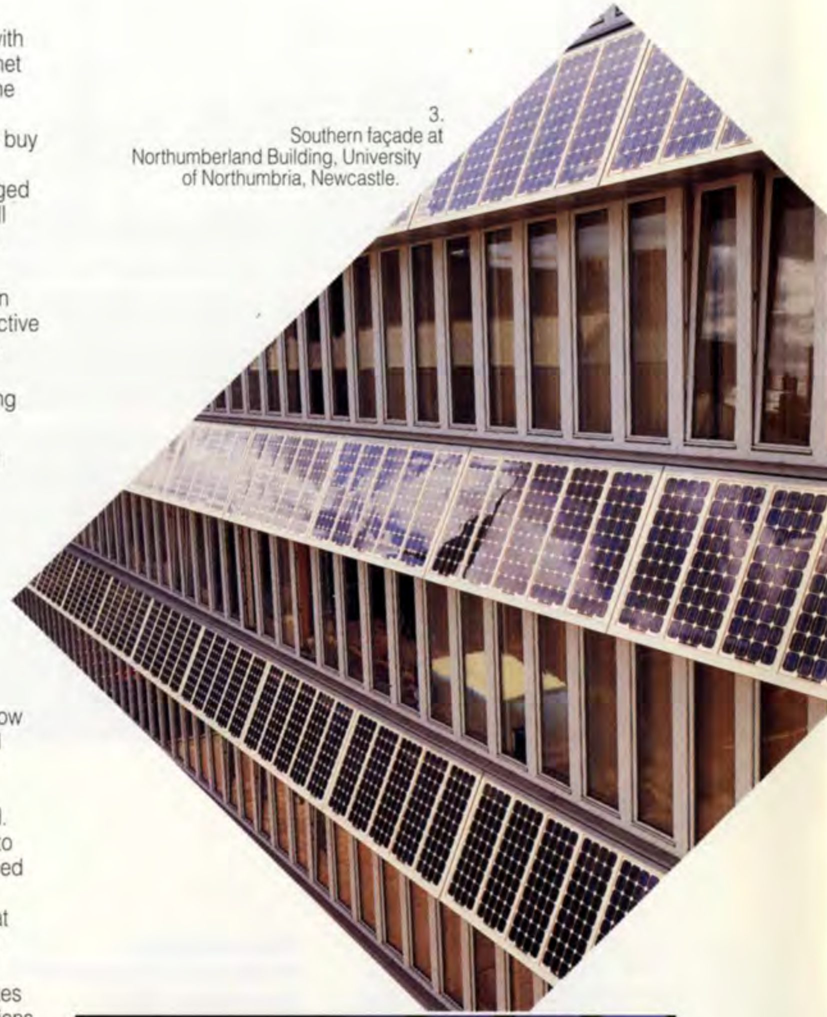
These domestic occupancy patterns highlight the problem of how to deal with excess power. Battery storage is inefficient and expensive, and while fuel cells may provide a future solution, currently the favoured method is to connect the system to the grid supply, thereby inputting electricity to the grid during the day, and importing it back at night.

This situation is ideal in countries where two-way metering is used with the consumer only paying for the net amount of electricity drawn from the grid. However, in other countries, including the UK, power suppliers buy the excess electricity at a cost of around one third of the price charged for grid-supplied electricity, as well as charging a connection fee and metering costs.

Although legislation may change in the future, presently it is more effective to provide PV power equating to a maximum of the daytime load or, better still, to equal the base running load of the building.

Taking this approach, and leading directly from the report, Arups became involved with over cladding the southern facade of the Northumberland Building, at the University of Northumbria in Newcastle (Fig 3). This was the largest PV façade in the Northern Hemisphere at the time, at approximately 300m².

The Northumberland Building is now over three years old. It has proved totally reliable, with no slippage in performance and achieving the energy figures originally predicted. From its opening in January 1995 to April 1998, the façade has produced 68 500kW hours of electricity and saved 66 tonnes of CO_2 gases that would have been produced using conventional fossil-fuelled power production. With continuing debates on global warming and CO_2 emissions, the environmentalists are lobbying hard for support for solar power, and it is this aspect that is raising the profile of PV.



3.
Southern façade at Northumberland Building, University of Northumbria, Newcastle.

4.
Colour range on a PV unit.

Ove Arup & Partners has engineered other PV projects since, including a programme of PV-powered filling stations with BP; 'Factories for the Future' for Ford; and most recently the 'BP Solar Showcase', designed by Arup Associates for the recent G8 summit in Birmingham (all described here). Additionally, in 1993 Arups engineered a new production facility in New Jersey, USA, for the manufacture of PV panels for Advanced Photovoltaic Systems, a production facility that has since been purchased and modified by BP Solar.

Maximising efficiency, minimising cost

PV production

PV arrays are expensive: at around £800/m^2 fully installed they are equivalent in price to high quality stone cladding like marble. However, this cost should be considered in relation to the pay back period, incorporating the money saved through power generated. PV prices have already fallen some 80% since the early 1980s, and this downward trend is set to continue as production and new processes develop. Equally, any national or international changes in policy will affect costs quickly, with major government-led initiatives already under way in Japan, Germany and the Netherlands.

The PV market is likely to increase significantly in the next few years. One of the world's leading manufacturers, BP Solar, has announced a commitment to develop its turnover from $60M in 1997 to over $1bn within 10 years, and other producers have similar expansion plans.

Manufacturers are also responding to the demands of the building industry, developing a range of products to make PV panels a more 'design-friendly' material. Three years ago, most manufacturers produced a standard module, sized to provide charge for a 12V battery, at around 1mm x 0.5mm with dark blue or black PV cells (the most efficient colour to convert light to electricity). Panels can now be specified in any size up to 2m x 2m. Backing sheet colours can vary, as can the cell colour (Fig 4) and the cell process, with monocrystalline and multi- or polycrystalline cells available. Glass PV modules have also been developed, where the cells are spaced to allow light to pass between them.

Text continued on page 12 overleaf ▶

BP Filling Station, Muhlenstraße, Berlin

In 1995 Ove Arup & Partners was commissioned by BP to investigate how PV modules could be used on its filling stations. Two main concepts were developed: one for existing stations, where modules would be bolted to the top of the canopy (Fig 5); and the other for new-build stations, with PV modules as an integrated component of the station (Fig 6).

The former of these methods was used when, in mid-August 1997, Arups was commissioned to install PV modules on a filling station in Berlin. This was to be completed by the end of September 1997, coinciding with a talk on climate change given in Berlin by BP Oil's Chief Executive, John Browne.

Three recently-completed filling stations were identified as possible sites, from which one in the Muhlenstraße in former East Berlin, by a remaining section of the Berlin Wall, was selected. The design comprises a series of PV cells situated around the canopy over the pumps, the roof edge of the car wash, and integrated into the pricing pillar. Solar cells can be added to building roofs and walls of buildings in Berlin without planning permission - thus notably speeding the construction process.

A major driving force behind this project was the ambitious schedule - just over one month from first commissioning to completion. BP Solar's standard 585 Saturn modules were chosen for their immediate availability. The support framework was developed with the installer, Facade Technology, using easily obtained materials.

The whole installation was prefabricated in the UK and delivered to site in a container truck, with full workshop facilities provided for any site adjustments required.

Each group of 10 modules was connected to an SMA Sunny Boy inverter to convert the DC electricity produced by the modules to AC. The AC wiring was then fed through to the switchboard in the shop through the existing cable ducts. The array installed is rated at 12kWp: around 10% of the overall electrical consumption of the site. Adjacent to the shop entrance, a display records the instantaneous power output and kW hours generated.

The full installation was completed in 10 days, and the facility commissioned and handed over on schedule.

Since completion, market research has indicated a favourable public response to the installation. A second new-build BP station recently opened at the Lisbon Expo, and a station in Bedford, UK, is due to open soon. 10-15 further stations will follow in locations throughout Europe in the next few months, with a potential rolling programme of 400 stations per year being planned.

Project partners:

BP Oil & Retail (client)

BP Solar (PV manufacturer)

Façade Technology (PV installer)

Ove Arup & Partners (PV engineering design)

5. PV modules installed on Muhlenstraße filling station in Berlin.

6. Concept for integrating PV panels on filling station canopy.

▼ *Continued from page 11*

Funding

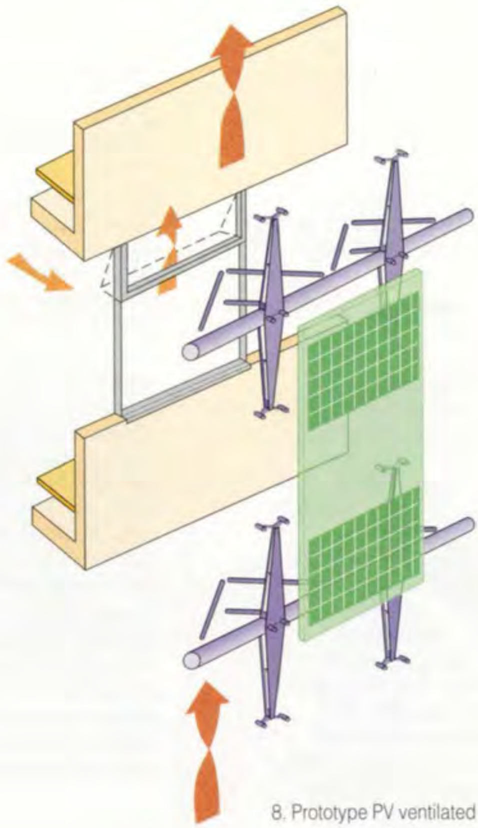
The cost of PV projects can be offset with grants from appropriate bodies such as the EU, and can also often attract private sponsorship. With some grant-assisted projects, the level of peak power production is required as part of the application. Often this power output specification is produced on the basis of manufacturer's cell data, with the PV tender occurring at a later stage. This method is inadvisable: cell efficiency varies significantly according to the product used - from 3-17% - and to produce a previously-specified power output can cause variations in the intended area of PV of up to 150%.
It is generally more economic to choose a manufacturer producing the most efficient cell, thereby reducing the amount of support framework and wiring: of the £800/m^2 cost quoted earlier, around £400/m^2 forms the cost of the PV modules, with the remainder covering the cladding framework, wiring, and AC/DC inverter. It is also worth considering that some cells offer improved energy production in low light levels, and therefore will produce more kW hours of electricity per year.

Location and design

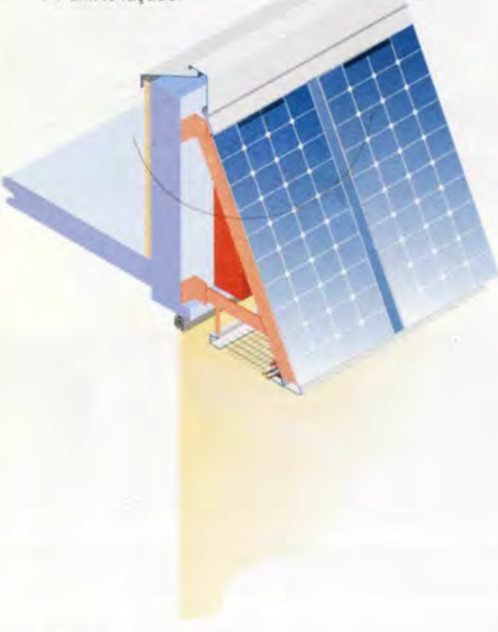
To maximise PV efficiency, the location and orientation of cells is important. In a northern latitude, the south face of a building produces more electricity, as the level of light available throughout the year is greater from a southerly direction. PV cells on a north face would only produce around 15% of the electricity equivalent cells would generate on a south face. (Conversely, in southern latitudes PV cells achieve optimal performance when facing north.) Depending on the latitude of the site, inclining the modules will allow greater light levels to fall on the cells. In the UK, angles up to 50° can produce around 20% more power than a vertical installation.

Also the wider site location should be considered, as shading effects of other buildings or trees can have a significant effect on power output. Modules are wired in series, called strings, until a suitable voltage is produced. Each string is then wired independently to the AC/DC inverter (either a number of small inverters, or one large inverter). If any area of a module in the string becomes shaded the power input of the entire string drops to the level of the shaded module. Design details should avoid this effect.

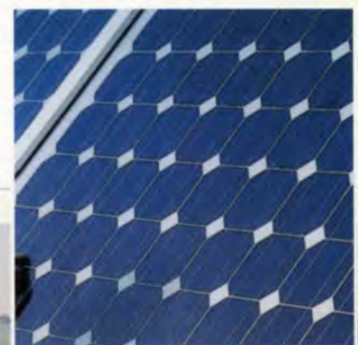
Rainscreen cladding is one of the most appropriate cladding systems for PV facades because it allows rear ventilation of the panels. PV panels produce a substantial amount of heat while converting light into electricity, and keeping the cell cool improves its efficiency. Ove Arup & Partners is researching a more holistic application of PV façades involving the use of this excess heat, either to redistribute through the building, or to assist in the buoyancy effects of naturally ventilated buildings.



8. Prototype PV ventilated façade.



7.
Principle of attaching PV unit to façade.



Ford's 'Factory for the Future', Bridgend

The Ford engine plant at Bridgend is the first completed project in Ford's 'Factory for the Future' initiative. 26 rooflights, each 9m long x 5m wide, have been inserted into the existing roof of the 24 300m^2 lightweight steel-framed plant.

On each rooflight, the north elevation is double-glazed, while the south elevation incorporates 10 opaque, 1.9m X 1.5m photovoltaic laminates. BP Solar high efficiency Saturn cells have been used in a glass/EVA/tedlar construction. The whole system achieves a total nominal peak power output of 97kWp. The AC current generated by the cells is fed to an inverter located on the rooflight gable, and onto an existing roof-mounted substation for use directly within the factory.

By using a combination of clear glazing and opaque PV modules, the rooflights also allow natural light into the plant, decreasing demand for artificial lighting and improving the working environment. Around 105MW of power will be saved every year as a result, equating to CO_2 emissions of more than 100 tonnes.The design recognises the limited capacity of the existing roof covering, and maintains its former U-value.

Due to the innovative nature of the project, and the potential for replicating it in the future on buildings of a similar type, funding was obtained from a number of sources including the EU 'Thermie' Programme, the Department of Trade & Industry, and Ford's own 'Factory of the Future' programme.

Project partners:

Ford Motor Company (client)

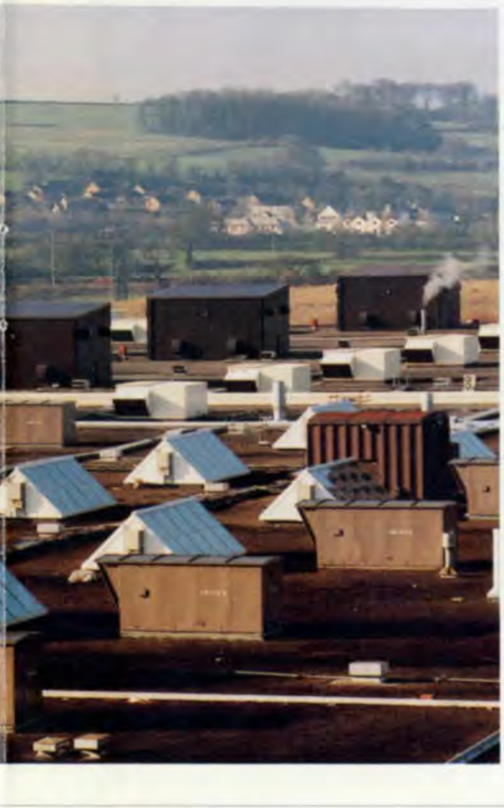
BP Solar (PV manufacturer)

Ove Arup & Partners (PV engineering design)

Façade Technology (PV installer)

9 left: Close-up of PV panel at Ford plant.

10 below: PV panels on rooflights at the Ford engine plant, Bridgend.



BP Solar Showcase

Mike Beaven
Tony Broomhead
James Burland

This year's annual G8 summit in Birmingham gave the BP Group the opportunity to demonstrate British innovation. BP Solar approached Ove Arup & Partners' photovoltaic team in Newcastle, asking for a detailed brief for a prototypical building, showing how photovoltaic cells could be incorporated into energy efficient domestic and commercial buildings.

Together, Arup Associates - architect and engineer - and Ove Arup & Partners - photovoltaic, façade, acoustic, and IT/telecommunications engineers - designed and engineered the pavilion in just six weeks, achieving the opening date of 14 May 1998.

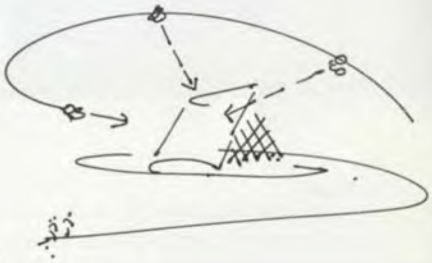
The photovoltaic installation is the driving force behind the 113m^2 pavilion. The south-facing solar wall is curved and angled to optimise absorption of solar energy and maintain a nearly constant electrical output, whilst also shading the east and west vertical walls to protect against excessive solar gain. A laminated plywood frame supports the curved solar wall, facilitating rapid fabrication and construction. Generating a peak of 15kW of electricity, the PV installation powers ventilation, lighting, and electrical equipment. It is connected to the National Grid, allowing excess electricity to be exported during the day and imported during the night.

Double-glazed units with Pilkington's 'K' low emissivity glass are used on the east and west walls, combined with plywood infill panels on the west wall. The level of glazing and the amount of opaque panelling in the walls has been designed to balance internal heat gains - incurred through lighting, equipment and people - with heat losses.

Two heat recovery systems are employed. One uses 'waste' heat from the electrical cupboard housing the photovoltaic inverters, and from the rear of the photovoltaic cells (applying the principles described on pp12). A fan blows this hot air down ducts in the building's fabric into a flap damper chamber adjacent to the entrance, from where it is directed into the interior or exhausted outside, according to internal heating requirements.

The second system employs the principles of a Roman Hypocaust: hot air is drawn from the top of the pavilion, and blown through a second integrated duct, again to a damper located next to the entrance. If the heat is not needed internally, the hot air is directed to an underfloor chamber comprising ducts of clay land-drain pipes that diffuse the air through the underfloor joist zone. A 'pebble bed' is used in this area, providing additional thermal mass to the structure, thus helping to minimise diurnal and seasonal temperature fluctuations. Air is supplied to the space through proprietary swirl floor diffusers.

This building is a prototype: its orientation and the level of glazing and insulation, can be adapted to suit its function and location. Other energy-saving features were considered, but not included because of the rapid construction period and temporary nature of the building. However devices such as rainwater collection to use in a recycled water system; increasing the structure's thermal mass; further sustainable technologies could be incorporated in future developments from the BP Showcase.



11 left:
Early architectural concept.

12,13:
above and below:
The completed BP Solar Showcase.

Project partners:

BP (client)

BP Solar (PV manufacturer)

Arup Associates (building designer)
Carolina Aivars, James Burland, Peter Llewellyn, David Spencer, Matthew Vaudin, Daniel Wong (Architecture/Interiors)
Tony Broomhead, Ben Lawlor (structure)
Mike Beaven, David Hymas, Pat Regan (services)

Ove Arup & Partners (PV engineering design)

Façade Technology (PV installer)

Future technologies

There is now a significant level of worldwide research into the technology of PV panels. The most expensive component of a PV module is the silicon, not because it is a scarce material - indeed it is one of the most common elements on earth - but because of the production process involved.

One method of addressing this problem is to use a less expensive sort of silicon. All silicon used in PV cells is a waste product of the microchip industry, but needs refining to extract the silicon either in its monocrystalline or poly (multi) crystalline form. Monocrystalline silicon has traditionally been used in PV cells: it is the more expensive of the two because of the more costly refinement process, but achieves the greatest efficiency. Polycrystalline cells are becoming an increasingly popular option: they are less efficient, but are cheaper and, when coloured, are a striking design tool.

A second method that has the potential to bring down costs significantly in the future will be to use thin film photovoltaics. This basically consists of applying a thin coating of semiconductor material (amorphous silicon, cadmium telluride) evenly onto glass up to a thickness of 30μ. This technique is more suited to mass production and uses less semiconductor material. Currently, however, they are hampered by being relatively inefficient (6-7%) compared with silicon cell modules (up to 17%). As this technology is developed further, efficiencies of 10-12% can be expected at costs of around one quarter of present silicon cell modules.

Reference

(1) McGREGOR, Alisdair *and* BRANDON EHART, Pamela. The APS project, Fairfield, California. *The Arup Journal, 28*(4), pp12-15, 4/1993.

Credits

PV engineering design:

Ove Arup & Partners Len Balbach, David Hillcox, Ray Noble, Malcolm Shaw, Barbara Young
Jennifer Gunn, Sean McDermott, Claire Noble (graphics assistance)

Illustrations:
1, 4, 7,8: Jennifer Gunn, Sean McDermott, Claire Noble
2, 9, 10: © copyright BP
3.Sally-Ann Norman
5, 6: BP Solar
11: James Burland
12, 13: Grant Smith

The Angel of the North

Mike Brown   Neil Carstairs   John Thornton

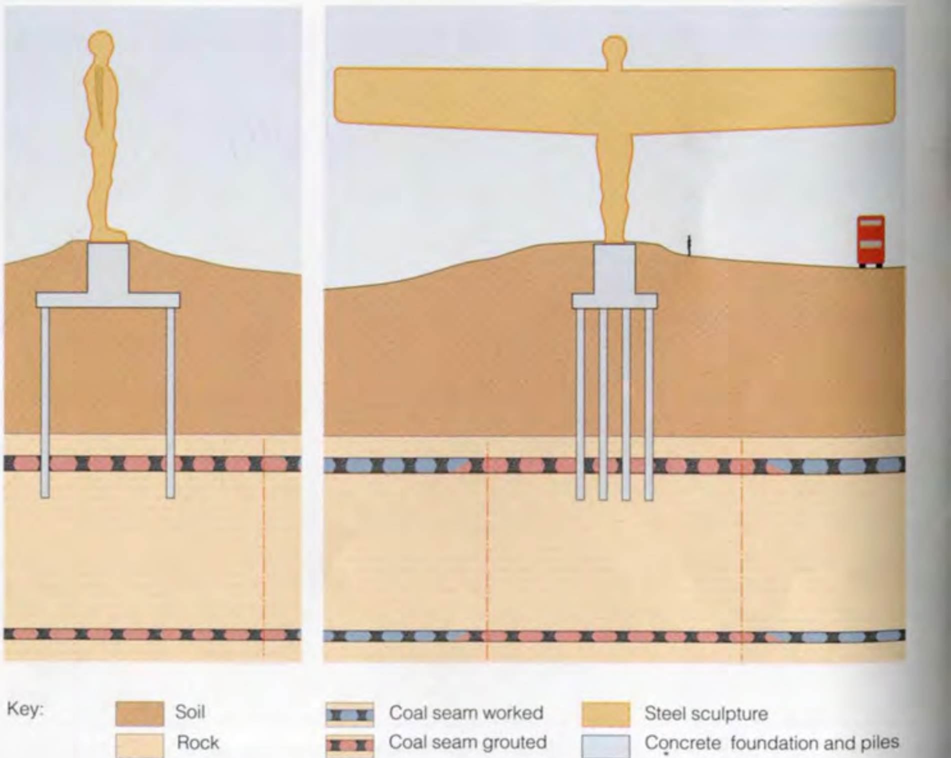
1.

Background

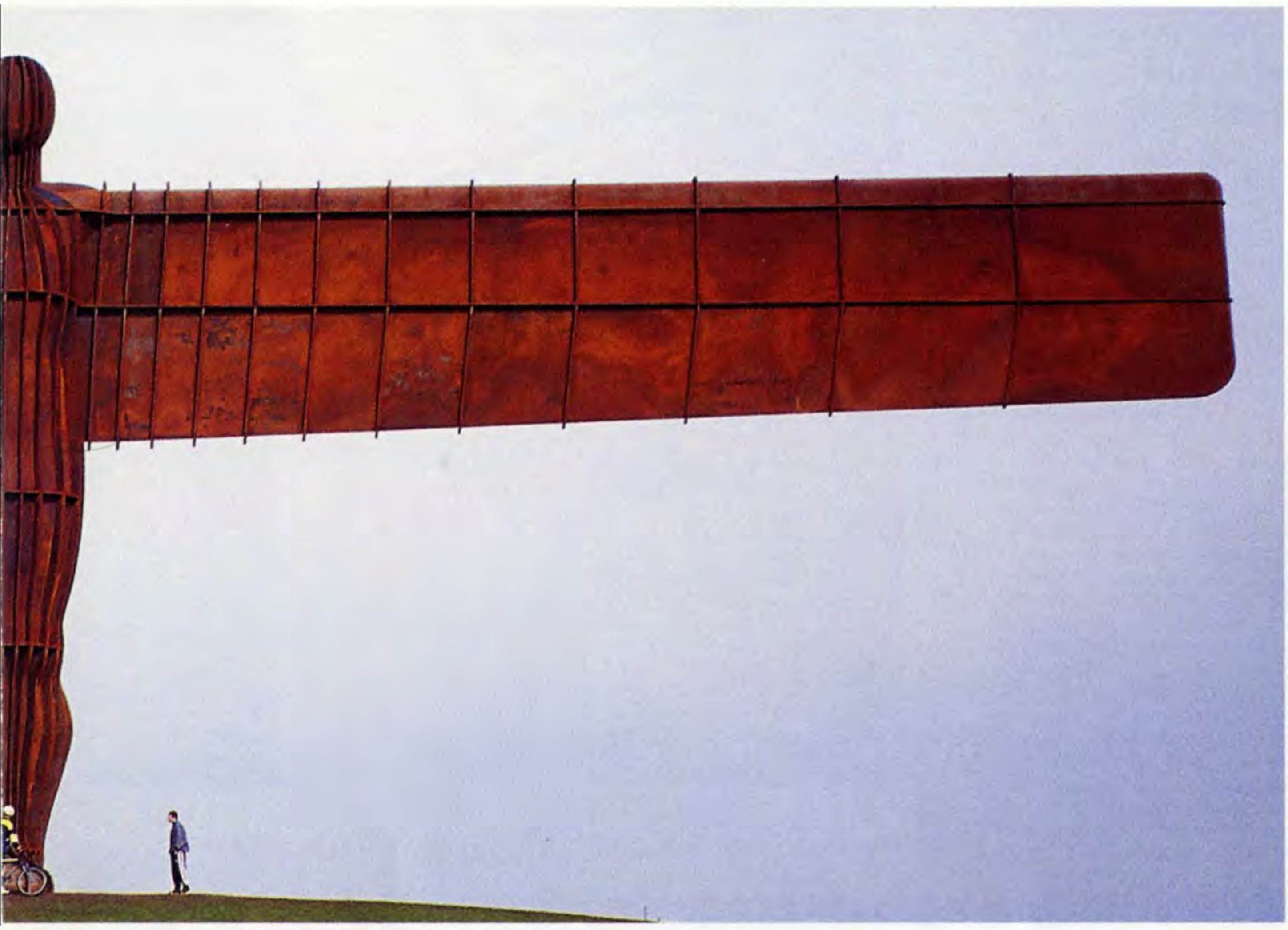
Gateshead, on the south bank of the River Tyne in Tyne & Wear, has always played second fiddle to metropolitan Newcastle. In 1986 the Council decided to try to create a better image of the town with a pioneering scheme called 'Art in Public Places' - over 20 sculptures and murals for streets, parks, metro stations, and hospitals. A highlight is *The Angel of the North* by sculptor Antony Gormley, winner of the 1994 Turner Prize. This vast and dominating steel statue, 20m high x 54m wide, now stands on a long, low hill where two dual carriage-ways meet, and signals to some 90 000 motorists daily their arrival at Gateshead's outskirts.

Realising the project took several years. In the early 1990s the Council inherited an old colliery site on the town's southern boundary and their thoughts turned to a landmark sculpture. Selected from a 1993 shortlist, Antony was invited to visit the site at the head of Team Valley overlooking a long sweep of the A1 motorway, and produce designs.

The commission was confirmed in 1994 but there was significant local opposition to *The Angel's* form and scale. In 1996, however, Northern Arts - the regional arts co-ordinator - staged 'Visual Arts UK', a year-long fantasia of exhibitions and events throughout the north, and as part of this Antony with local volunteers set up *The Field*, an arrangement of some 40 000 small terracotta figures, in an abandoned railway factory near the town centre. Some 25 000 people came to see The Field, making it by far the most-attended art exhibition in the north east. This led to a more positive view of *The Angel* and the Council pushed ahead with its plans for the £800 000 project, most of the funding coming from an Arts Lottery grant.



2. Elevations of *The Angel* showing anchorage.



Concept

Antony Gormley conceived *The Angel* as using heavy industrial and shipbuilding techniques to construct a material image of a spiritual subject. Aeronautics and anatomy combine in an exoskeleton of ribs and diaphragms, and an inner body of plate modelled on the sculptor's own.

The engineering challenge

As soon as the scale and form of *The Angel* became clear, Gateshead Council commissioned Arups' Newcastle office to advise on the structural design. John Thornton, from the London office, had worked closely with Antony Gormley on an earlier, unrealised, project for a large brick figure for Leeds, and they started to discuss the problems.

In designing any structure, the consulting engineer has to ensure it remains standing in all conditions. The fundamental problem of The *Angel* is resisting wind. Imagine you are on top of a hill. On a calm day you can stand upright with your feet together. In a stiff breeze you can still keep them together, but you need to lean into the wind to avoid falling over, using your weight to balance the horizontal force of the wind. In a strong wind you must lean further forward, and because it gusts you also need to move your feet apart to maintain balance. In a howling gale you retreat from the hilltop and take shelter. *The Angel* cannot lean into the wind, spread its feet, or shelter, and the wings offer enormous resistance to wind.

Developing the solution

The ideal overall dimensions of *The Angel* as a whole had been chosen by the sculptor, and Arups' first task was to establish if a structure with these proportions could be made to work. Antony wanted *The Angel* to be made of *Cor-ten*, a special weathering steel which does not need painting but is protected by a rusty patina that forms during the first few years.

The critical section was at the ankles where the forces to be resisted are large but the cross-section small. A wind blowing on *The Angel's* front is resisted by tension in the shins and compression in the heels. The distance between heel and shin must be as large as possible to minimise these forces (this is why electricity pylons get wider at the base). An internal skeleton, as in the Statue of Liberty in New York, would have been possible, but Antony was keen to use the visible parts of the structure to carry the load leaving the internal space empty, and anyway there was not enough space inside the ankle skin, or inside the wings, to accommodate a skeleton. Discussions between Antony and John Thornton led to a solution where these forces were carried by visible vertical ribs - a key feature of the sculpture. The skin of the body also helps carry the load, and in particular resists twisting of the body when a gust of wind hits one wing only. Horizontal plates at intervals up the body stabilise the ribs and skin.

The wings use the same concept of visible ribs carrying the load, but this time the ribs are horizontal. Another problem was the possibility that when the wind hit the wings obliquely the tips might flutter, leading to local damage or brittle failure under repeated cycles of loading - as a wire can be broken by bending it backwards and forwards. Arups' wind specialist, Andrew Allsop, was brought in early to consider this.

Estimating the cost

Once the concept was finalised, initial calculations were made to establish the number and thickness of plates needed to carry the various loads. A budget for the sculpture was estimated, but because of its unusual nature it was decided that the fabricators who would eventually build it should be asked to advise on feasibility and likely costs. Both sculptor and client were very keen that *The Angel* be made locally, and about 60 firms in the north east were contacted by Arups. Four expressed interest, and Arups took a 1/20th scale model Antony had produced to each of them so that they could see what the problems would be. Following these meetings the budget cost estimate for the steelwork was refined.

Another area to be investigated at this stage was what *The Angel* was to stand on. To stop it falling over, the feet had to be held down, with the foundations able to carry the weight without moving. The soil on the site was not strong enough for this, so reinforced concrete foundations needed to go 20m down to rock. The mound on which *The Angel* was to stand had to be removed temporarily to allow this foundation to be built. Also, old mine workings on the former colliery site had to be filled in. The cost of the foundations had to be estimated and added to that of the steelwork before the Council could pursue funding.

3.
Upper part of *The Angel's* body.

Completing the engineering design

Antony continued to develop the design, making a series of different scale models to establish what refinements were needed for the desired effect. One change affecting the detailed design was to make the visible section of the ribs longer while keeping the overall size the same. This meant that the skin cross-section got smaller and so thicker plate was needed to carry the twisting loads.

Forming complex shapes,such as those needed for the body skin, from flat plate is very difficult. Cylinders or cones can be formed easily by rolling flat plate like paper, but on much of the body the surface curves in two directions like that of a ball. Thin plate can be hammered into this shape, but the thicker plate needed for the skin near the ankle was very difficult to form in this way. This problem could have been avoided with an internal core of simple shapes, but there was felt to be too little room to connect all the ribs to it and, as already noted, Antony was keen to avoid an internal structure. Alternatively, the skin could be cast by pouring molten steel into a mould, and after consulting various foundries this solution was adopted for tender purposes for the body's lower sections. Casting such complicated shapes is expensive, and the budget for *The Angel* was now fixed, so it was expected that only the lower body, where the skin needed to be thickest, would be cast.

Arups developed the final design for the body and wings, refining the earlier calculations on plate thickness and working out how the whole shape should be defined for fabrication, with data on the body being scanned into a computer while the wings were defined geometrically on the drawings. The foundation design was also refined at this stage.

The lowest tenderer for the fabrication proposed to use an internal structural skin formed from conical and flat sections, and then to form the external skin from thin plate. He demonstrated that making the rib connections in the confined space available near the ankle was possible and, as the only solution which could be made within the overall budget, this alternative was adopted.

Steelwork fabrication

To ensure that the shape of the body was an exact enlargement of Antony's model, the contractor arranged for a plaster cast of the skin to be scanned into a computer by stereo photography (as in mapmaking). A 3D computer model of the body was developed from this scan. Instructions from this were passed directly to the cutting machine which produced the pieces of plate from which *The Angel* was made.

These then had to be welded together into the final form. The wings were fabricated first, followed by the feet, starting with the inner core to which the vertical ribs were fitted. Fabrication of the body then continued upwards to the chest, while the head was made separately. More than 2000 pieces of internal horizontal rib were welded between the vertical ribs to form the template over which the final skin was fitted. Skin panels were generally formed over these ribs using local heating and brute force.

Antony Gormley maintained a close interest in the fabrication process, encouraging the welders and platers to achieve an exceptionally high standard of finish.

Foundations

The reclaimed colliery pit head site has up to 15m of fill over rockhead. Site investigation identified two coal seams beneath the site. Grouting of the workings was included in the foundation contract, 100 holes being drilled 33m though soil and rock to inject a sand/cement mixture. A foundation of 750mm bored piles end-bearing on the rock was chosen, and eight holes drilled 20m and filled with reinforced concrete. A concrete pilecap 12m long, 8m wide, and 1.5m thick was placed on top, ensuring that all piles remain in compression even under extreme wind loads. Above this, *The Angel* stands on a concrete pedestal 4m high, which on completion was buried so that the sculpture appears to be standing on the hill. 52 holding-down bolts 50mm in diameter and 3m long were cast into the pedestal, using a template match drilled with the base plate of *The Angel*.

Erecting *The Angel*

The Angel had to be delivered to Gateshead in three pieces (the body and two wings), and a temporary bolted connection between these pieces made up in the air on site, so that the cranes could be removed before permanent welding. This temporary connection was designed by Arups to take the full weight of the wing, plus a substantial wind loading. The connection was originally conceived using splice plates and bolts in shear, but concerns about handling the large splice plates, and problems with fit during trial erection, led to a late change to an end plate connection using bolts in tension.

The three parts left Hartlepool at 6.00pm, Saturday 14 February 1998, on three multi-axle low loaders. Never travelling at more than 15mph, and watched by crowds lining the route, the convoy with its large police escort travelled across to the A1, drove through Durham to avoid an understrength bridge, and arrived on site at midnight. Starting at first light on Sunday (an astonishingly calm day), the body was raised off its trailer in a tandem lift by 500 tonne and 300 tonne cranes, turned to the vertical, and lowered over the 52 holding-down bolts, fitting first time. These were then tightened. Watched by half a dozen TV crews, over 100 journalists and photographers, and more than 1000 local people, the first wing was in position by lunchtime and by dusk the second wing was fully bolted up. The wind rose overnight, delaying the scaffolding needed for in situ welding, but within a fortnight the permanent welded connection and infill skin panels were added, and the steelwork of *The Angel* was completed. Landscaping to return the site to its original form was carried out in March.

The Angel of the North vital statistics

Steelwork

- Height: 20m
- Wingspan: 54m
- Average wing depth: 5.7m
- Weight: 208T
- Ankle cross-section: 780mm x 1.4m
- 3000 pieces of steel assembled
- 136 bolts each 48mm diameter attach wings to body
- 22 000 man-hours on fabrication
- 10km of welding.

Design

- 70T horizontal wind force to be resisted
- 450T force in wing diaphragms
- 1200T force in ankle ribs
- 50T force in each 50mm bolt
- 2500 man-hours on engineering design and drawing.

Foundations

- 5000m^3 soil excavated and replaced to reform mound
- 100T grout pumped into mineworkings up to 33m below ground
- 700T concrete and 32T reinforcing steel in foundations to 20m below ground
- 52 bolts each 50mm diameter and 3m long hold *The Angel* upright in wind.

Conclusion

The Angel was a unique and fascinating project to work on, and has transformed the southern approach to Tyneside. Working closely with the fabricator and the Council, Ove Arup & Partners helped the sculptor to realise his concept without having to compromise on appearance to achieve a safe structure.

Postscript

The Council's commitment to this project was a contributory factor in attracting Lottery funding for a major new contemporary art gallery and concert hall complex to be built on the bank of the Tyne, and a footbridge to link this complex to Newcastle Quayside.

Credits

Client:
Gateshead City Council

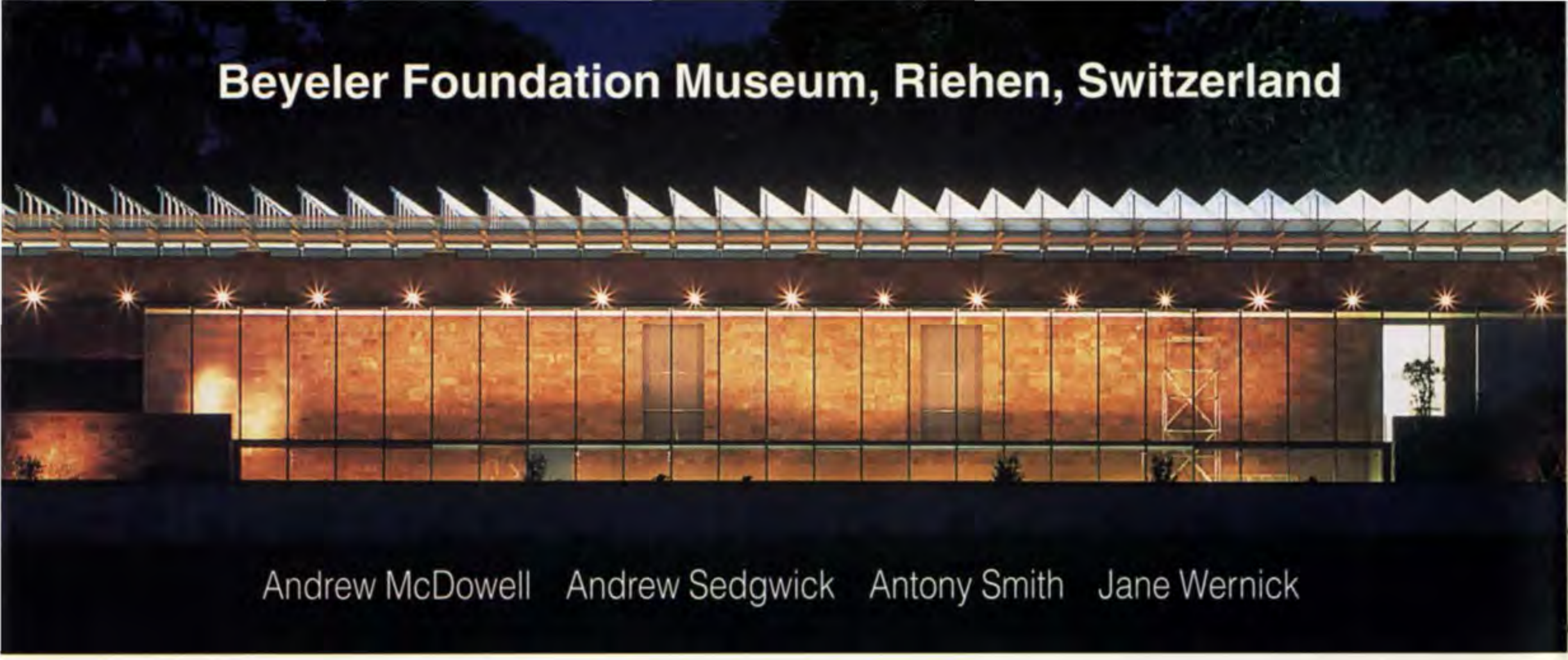
Sculptor:
Antony Gormley

Structural engineers:
Ove Arup & Partners Yasmeen Al-Boutie, Mike Brown, Neil Carstairs, Andy Christie, John Gregory, Simon Harris, David Hilcox, Neville Long, Sean McDermott, Graeme Mellor, Deirdre O'Neill, Colin Peart, Steve Shaw, Tamsin Silvester, David Swainson (Newcastle) Jim Johnson (Sheffield) Andrew Allsop, John Blanchard, Bob Cather, Ian Feltham, Graham Gedge, Simon Maisey, Chris Murgatroyd, Caroline Ray, Martin Self, Tony Sheehan, John Thornton, Jane Wernick (London)

Steelwork fabrication contractor:
Hartlepool Steel Fabrications Ltd

Foundation contractor:
Thomas Armstrong Ltd.

Illustrations:
Sean McDermott



Beyeler Foundation Museum, Riehen, Switzerland

Andrew McDowell Andrew Sedgwick Antony Smith Jane Wernick

Introduction

The Beyeler Foundation was set up to provide a permanent home for Hildy and Ernst Beyeler's modern art collection, which ranges widely from van Gogh and Monet to Picasso and Rothko, as well as including sculptures from Africa, Alaska, and Oceania. Its new museum stands in a park donated by the commune of Riehen, near Basle, and was designed by Renzo Piano, whose restrained, tranquil design was specifically intended 'to serve art, and not the other way round'.

The building is clad in red porphyry and comprises four monumental parallel walls, with glazed end walls and a glazed winter garden down the long west side giving views of the surrounding rural landscape. A single-storey basement houses plant, storage, and a small parking area, as well as temporary exhibition space accessed from the winter garden. The roof is multi-layered, consisting of (from the top down) inclined opaque white glass brises soleil; a flat, clear, double-glazed roof; operable louvres; a glass ceiling which defines a 1.5m loft space; and a perforated metal ceiling (Fig 2). These allow daylight to illuminate the art on average winter days and yet provide control of the sunlight levels on bright days.

Renzo Piano was appointed architect in 1990 and Ove Arup & Partners as consulting engineers in 1992; over a considerable period the design went through several concept changes. Arups carried out the structural scheme design, the detailed roof design including the glazing, the services engineering with a detailed energy analysis, and the natural lighting design. Swiss consultants did the detailed design for the services and the concrete structure, and provided construction supervision.

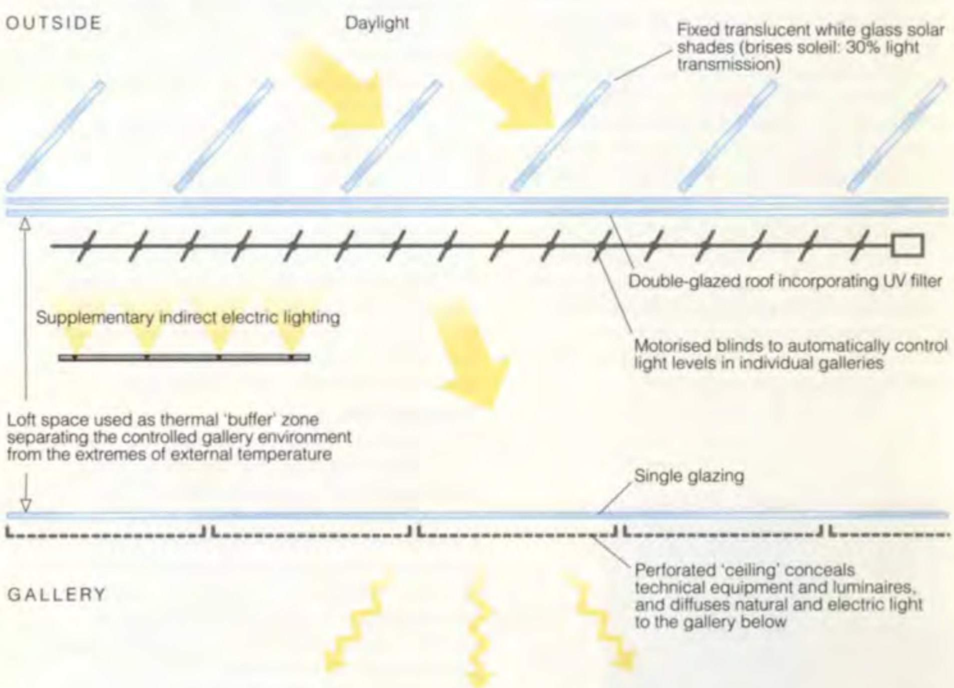
Structural engineering

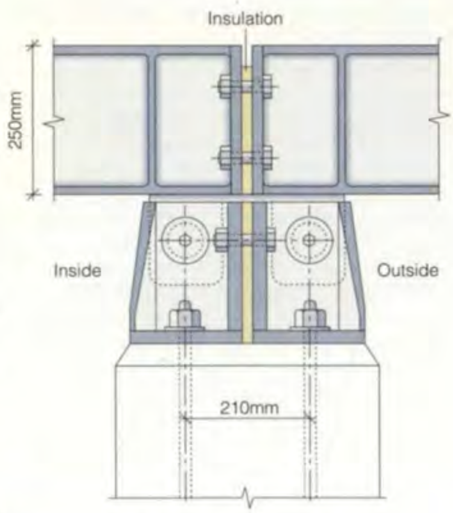
The structure reflects the architect's desire for spaces between four long, massive walls with a light, crystalline roof structure - 28.3m by 127m on plan so that it overhangs all round - controlling the amount of natural light entering and also modifying the internal environment. The walls are 108m long, at 7.8m centres, and 6.05m high. The galleries are typically 6m x 7.8m, with larger exhibition spaces 7.8m x 12m, 7.8m x 18m and 15.6m x 18m.

The basement, at level -4.3m, and the ground floor structure are in reinforced concrete. Reinforced concrete columns stand at 6m centres within the long walls, and support the roof steelwork. Services run within the walls up to the loft space. The overhangs at the north and south ends are supported by stone-clad steel columns, while at the south end the ground slab extends to form a lily pond stretching into the landscape.

1. The west wall at night.

2 below: Section through roof build-up.





3. Detail of column/beam fixing.

The steel roof structure gives continuous support for the various roof layers in all situations: at the 2.5m cantilevered edges along the long sides, in the normal internal condition, and where parts of the long inner walls and their columns are removed to allow for the larger spaces. The roof supports the glass ceiling and internal louvres, the double-glazing, and the posts that carry the glass shading panels. Primary beams span continuously east/west, while secondary beams are arranged in pairs on either side of the columns spanning 6m typically north/south. In the larger exhibition spaces additional beams span 12m or 18m parallel to the secondaries, on the column lines.

To maintain a crisp appearance the 250mm deep beams, all lying in the same plane, are all fabricated using plates. The primaries have a box section with the flanges projecting outside the webs, so that their appearance is similar to that of the fabricated I-sections used for the secondaries. The beam/column connections were all made using steel castings and bolts. Joints, which can carry forces and moments, are provided where the steelwork passes from inside to outside the building, to minimise the effects of cold bridging (Fig 3).

The white glass brises-soleil are supported by numerous vertical posts composed of steel tubes and castings and bolted to the tops of the beams on site. The fixings for the glass were also made from steel castings, with adjustment for site tolerances provided by bolts. The top bolted connections allow glass to slide parallel to the glass, but take wind loads perpendicular to the glass so that differential deflections of the beams supporting the top and bottom of one plane of glass do not induce high stresses into it.

The structure was designed to Swiss codes. As well as accommodating reasonably high snow loading, the building also lies within a seismic zone and was designed for horizontal forces of c7% of the total vertical loads.

Natural lighting design

An early design discussion between Ernst Beyeler and Renzo Piano centred on the issue of natural light. Beyeler had seen the Menil Foundation building in Houston[1,2] by Piano and Arups, and was keen to have the same quality of colour and generosity of daylight in his own museum. It was agreed that natural light be admitted across the whole ground floor roof and that construction should maximise the opening hours when the collection can be seen under daylight alone. At the same time, it was recognised that the Beyeler Collection is of international importance and that its long-term conservation was a top priority. The current best practise standards for exposure of works of art to light in terms of illumination level and spectral content had therefore to be observed.

After studying natural light data for Basle, Arups recommended a target daylight factor of 4% - around twice that in most European museums - with an active shading system to control internal light levels within predetermined limits, particularly on bright summer days.

This brief is met by the all-covering multi-layer glass roof. Outermost are the fritted glass brises-soleil, positioned to prevent direct sun penetration during all museum opening times but otherwise maximising the admittance of diffuse light from the rest of the sky vault. Beneath this, the weather-proof double-glazed skin incorporates a high performance ultraviolet filter to remove the most damaging parts of the electromagnetic spectrum. The system of motorised aluminium louvre blades immediately below are computer-controlled to create the desired light levels in each ground floor room. Different light levels can be selected for each as necessary for conservation or viewing considerations. Outside museum opening hours, the louvres are closed to prevent unnecessary exposure of the artworks to light. The louvre system is in the loft thermal buffer zone - in summer the external brises-soleil and the active louvres combine to prevent 98% of incident solar radiation from reaching the gallery climatic zones beneath.

The lower boundary of the loft is formed by a laminated glass ceiling to the galleries, which can be walked on to access and maintain the louvre motors and supplementary electric lights in the loft. As daylight fades, triphosphor linear fluorescent fittings are gradually energised to maintain the desired light levels.

Perforated metal panels carrying a diffusing paper insert form the visible ceiling in the ground floor galleries. This final layer partially hides the complexity of the roof construction above and gives a calm and uniform light to each room. Additional small low-voltage spotlights on stems at the junctions of each ceiling panel allow for the occasional highlighting, particularly of sculpture which benefits from more strongly directional illumination.

4. The west gallery looking north: the glazed wall on the left overlooks fields; the main gallery is behind the wall on the right. At the far end, access to the temporary exhibition space in the basement is via a glass lift.

5. Looking south out to the lily pond.

6. The west wall, looking north.

Mechanical and electrical engineering

Air-conditioning is strongly discouraged in Switzerland. The Swiss voted some years ago to abandon the development of nuclear power on environmental grounds and to reduce their reliance on electricity bought from France, much of which is nuclear-generated. The government therefore legislated to reduce the national demand, one of their first targets being energy used in buildings.

But what then for priceless works of art which, according to current wisdom, require strict control of their environment, particularly humidity?

Fortunately special exceptions are made, subject to certain conditions:

- A 'statement of need' must be submitted to the local authority justifying mechanical cooling and ventilation. Arups prepared this for the client, based on the use of the building for the display of valuable works owned or borrowed by him, and current guide-lines and recommendations for viewing and storing works of art.
- A dynamic analysis of annual energy use must be carried out and submitted to demonstrate that the building is as energy-efficient as possible. The local authority examines this in detail and may request further energy-saving measures.

7.
Typical large gallery space.

8. Brises soleil, looking west.

Energy analysis

The required analysis was carried out using the AR&D program ENERGY2, which makes use of the thermal and radiation algorithm of ROOM to dynamically model a representative part (c50%) of the museum. A detailed model for the AHU plant and heating and cooling systems was designed, including control narratives which required ENERGY2 to be modified. After calculating the power required by the building for every hour of the year - real weather data for Basle was used - the data was presented as a histogram of energy consumption itemised by heating, cooling, lighting, etc. Annual energy cost and global warming effect (CO_2 production) were derived depending on the energy source: gas or electricity.

ENERGY2 analysis was used to evaluate the cost/energy benefit of features like displacement ventilation, thermal wheels, and heat recovery from the chiller. Interestingly, energy saving by creating thermally massive internal walls was shown to be negligible due to the 24-hour environmental control.

An ice store was installed on the Swiss consultant's recommendation, although it does not reduce overall energy consumption. The Swiss strongly advocate ice stores and using off-peak electricity (with tariff incentives), as they can thus reduce their peak daytime demand and the corresponding in-flow of nuclear electricity from France.

Building form and fabric

Arups' involvement from the outset meant they could control creating an energy-efficient building. The galleries are protected from climatic extremes (-11°C winter; 33°C summer) by thermal 'buffer' spaces on the roof and the east and west sides. In the roof the heated and ventilated 'loft' means that despite the 100% glazed roof, perimeter heating is only needed in the galleries with windows directly to the outside. To the east is a stone clad concrete wall and ancillary rooms; to the west the semi-conditioned 'winter garden' with countryside views - a place to rest and to circulate to the temporary exhibition gallery on the lower floor. The galleries are hence suitable for displacement ventilation - appropriate for a museum due to the low air velocities and low noise.

The roof shading scheme developed during the design period from factory-type northlights to external fins or shades in white diffusing glass with only 30% transmission, the elegant form and material of which became a major architectural feature. Further shading is provided by motorised blinds in the 'loft' and a light diffusing perforated suspended ceiling in the galleries.

HVAC systems

A true displacement system was designed to reduce air velocities near the artwork to a minimum. The air is emitted at barely perceptible velocities from purpose-made wooden linear floor grilles which, with one floorboard either side, can be removed for cleaning the ductwork plenum below or access to electrical sockets (for portable display cabinets with a power/lighting requirement). Below the full-height windows perimeter heating is by trench convectors concealed below the same wooden grilles.

Air supply to each gallery module (typically 90m²) is controlled by VAV boxes mounted vertically in a 1.8m wide services 'corridor' on the basement level below, running most of the length of the building and containing 20 VAV boxes and associated supply and extract ducts - one at high level and one in a trench below a metal walkway. The VAV boxes are fed by two AHUs sized to give reasonable redundancy.

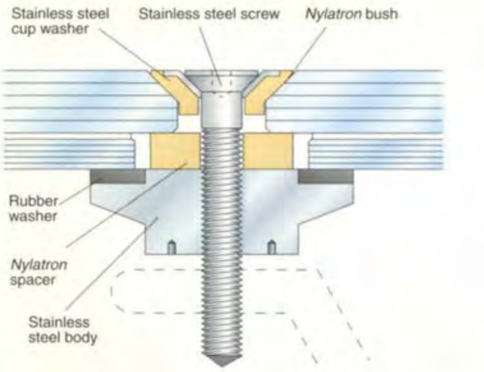
A fresh air and exhaust air AHU can provide up to 50% fresh air should external conditions be favourable. Rotary regenerators (thermal wheels) are utilised in two locations in the air system:

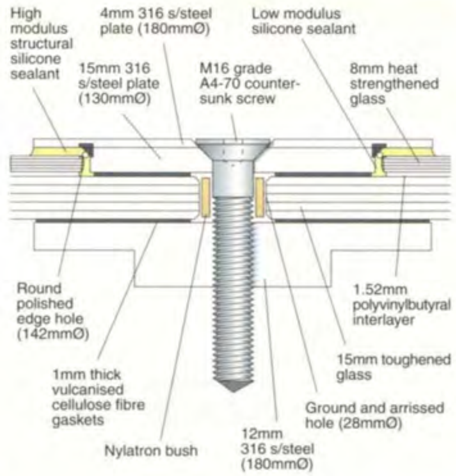
- the primary AHU to recover heat from the exhaust air in winter
- the main AHUs to obtain reheat following dehumidification by transferring heat from the extract air (cooling it in the process and thus reducing the cooling coil requirements when recirculating).

Bolted glass roof panels

The 4000m² flat glass roof consists primarily of conventionally supported, double-glazed insulating units, but the cantilevered glass overhangs provided a particular challenge. As glass roof panels have become more popular, guidelines and codes of practice have developed for determining their composition and thickness. But whilst these codes were applicable to the conventional double-glazed panels, the roof incorporated other unusual glass elements not covered by such codes.

9. The lily pond and the south overhang.





10.
(a) above:conventional bolted glass fixing;
(b) right: roof panel fixing detail designed for Beyeler Gallery

The overhangs did not need to be insulating, double-glazed units, instead they comprise laminated, single-glazed panels. The design of the four cantilevering corner panels warrants particular discussion since, due to their unique, asymmetric configuration and the differences in behaviour of laminated glass under various loading conditions, their design is not covered by any codes.

Unlike steel or reinforced concrete, glass has very low tensile strength which cannot be appreciably increased by variations in chemical composition.

However, heat treating basic annealed glass can produce different levels of residual compressive stress in its surfaces. This acts like a prestress which must be overcome before tensile failure can occur, effectively strengthening the glass.

The corner panels are 3.2m x 2.39m, with the primary support 900mm in from the shorter edge and 1.23m from the longer edge, creating a 1.5m cantilever to the free corner. The panel composition selected was a pane of heat-strengthened glass, 8mm thick, laminated on top of a 12mm toughened glass pane using four 0.38mm layers of polyvinyl butyral interlayer.

Although contrary to the conventional practice of placing the toughened layer on top, this design ensures that should the lower, toughened glass break, the upper layer works compositely with the broken layer, preventing instantaneous collapse and complying with the safety plan.

The panel was analysed in four stages by hand calculations, a linear model in Oasys' General Structural Analysis (GSA) program, a large deflection theory model in Nastran, and finally more hand calculations to justify the 'central' clamping detail. This detail supports 64% of the total weight of the panel, so to keep stresses within permissible limits, the diameter of the clamping plate at the primary support was increased to 180mm. This was governed by the need to rigidly clamp the thicker, bottom layer of glass to eliminate bending stresses across the bolt hole and prevent failure of the roof panel.

A test programme written by Arup Façade Engineering simulated the effects of maintenance personnel, snow, and windloads, and confirmed the panel's behaviour if accidental damage caused the top, toughened layer to fail. This prototype panel was successfully tested in Germany in September 1996.

Conclusion

Work began on site in the summer of 1994 and was completed in1997. The new Beyeler Foundation Museum was opened during a series of festivities between 14-19 October 1997, to great acclaim.

References

(1) BARKER, Tom, *et al.* The Menil Collection, Houston, Texas. *The Arup Journal, 18*(1), pp2-7, April 1983.

(2) RICE, Peter. Menil Collection Museum roof: evolving the form. *The Arup Journal, 22*(2), pp2-5, Summer 1987.

11. Monet's *Water Lilies* triptych at the south end.

Credits

Client:
Beyeler Foundation

Architect:
Renzo Piano Building Workshop

Consulting engineers:
Ove Arup and Partners Betsy Almond, Duccia Farnetani, John Jo Hammill, Richard Matthews, Sarah Kaethner, Eleanor O'Doherty, Stuart Smith, Barney Wainwright, Jane Wernick, Richard White (structural)
Tom Barker, Andy Sedgwick, Andrew McDowell, Lidia Johnson, Jonathan Ward, Emmanuelle Danisi, Hilary Caton, Mike Holmes, Neil Beverley,Alex Wilson (building services)
Graham Dodd, Antony Smith (façade)
Darren Sri-Tharan, Derek Woodcraft (draughtsman)

Consultants to Mr Beyeler:
Florian Vischer; Urs Albrecht

Local consultants :
Cyrill Burger & Partner AG (structural)
Ing. Bureau Jakob Forrer (mechanical)
EAG (electrical); Bogenshutz AG (plumbing)

Main contractor:
Zublin & Wenk AG

Steelwork contractors:
Jakem AG (roof)
Nyfeler Otto AG + Preiswerk & Esse AG (winter garden and walls)

Sub-contractors:
Sulzer (mechanical);
EAG (electrical)
Vegla/Lanz (glazing)

Illustrations:
1, 4: Michael Denance
2, 3, 10: Martin Hall
5 -7, 11: Beyeler Foundation
9: Antony Smith
8: Jane Wernick

Heathrow Transfer Baggage System

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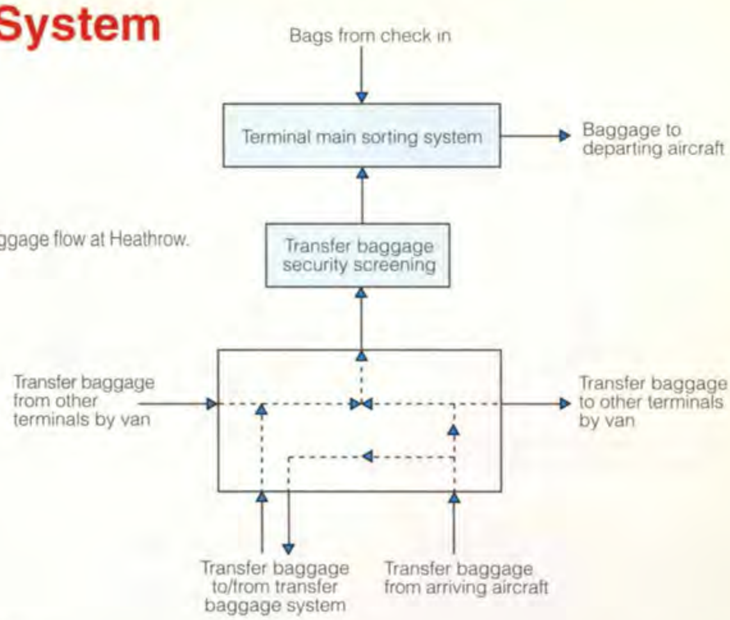
Andrea Blackie
Davar Abi-Zadeh



1. Principles of transfer baggage flow at Heathrow.

Introduction

Being able to attract transfer traffic is an important part of an international airport's business. London's Heathrow currently acts as a major hub for international travellers *en route* elsewhere, and as a gateway for passengers transferring between domestic and international flights. Of the 50M a year currently using Heathrow, about 30% are transfer passengers.

With stiff competition between leading airports to attract transfer traffic, success as a hub or gateway relies on the facilities for transfer passengers and minimum connection time between flights.

At Heathrow, transferring baggage by road between Terminal 4 (T4) and Terminals 1, 2, and 3 in the central area has been a limiting factor on connection times, with many bags missing their connections. To improve the level of service, and reinforce Heathrow's position as a European hub, an automated high speed baggage transfer system linking T1 and T4 was proposed.

Ove Arup & Partners was appointed by BAA as lead design consultant in May 1993, responsible for architecture, civil and structural engineering, mechanical and electrical services, and baggage handling. With the introduction of CDM regulations, a separate appointment as planning supervisor followed.

Transfer operations at Heathrow

The principles of transfer baggage flow at Heathrow are shown in Fig 1. Bags are delivered from aircraft to a dedicated area in the arrival Terminal, from which they can be routed to the correct Terminal for the onward flight and introduced into the main baggage handling system (BHS). All transfer baggage is security screened at the departure Terminal before being introduced into the main system, minimising dependence on security measures at the originating airport.

The HTBS project incorporates three major elements:

- a new underground link between T1 and T4
- a new transfer baggage sorting facility in an extension to T4
- security screening for all transfer baggage at T4.

A new transfer baggage sorting and screening facility has been developed in parallel at T1 as part of the upgrade of its handling system.

Developing the scheme

A performance specification was developed, based on projected transfer figures for Heathrow and target connection times.

Key parameters for the system included:

- a capacity of 2500 bags/hr (42 bags/min) between T1 and T4
- 18 minutes' transit time from T4's loading docks to T1's baggage system
- an ability to handle 75% of the normal throughput (ie 32 bags/min) in the event of component or subsystem failure.

Competitive tenders were sought for design and installation of the system from several international suppliers, based on Arups' performance specification. A range of solutions were proposed, most employing a form of destination-coded vehicle (DCV) using small carts on rail tracks. The chosen supplier was BAE, an American supplier then installing a DCV system at the new Denver Airport.

The chosen solution

DCV transfer system

The configuration of the HTBS is shown in Fig 2. The DCV system includes:

- single track running in each direction in the main tunnel
- a parallel 'empty cart storage' (ECS) track in the section of tunnel nearest the Terminal buildings, providing a buffer before release of carts out of the tunnel, and parking spaces for carts.
- spiral sections of track in the two vertical shafts at each end of the tunnel, providing the entry and exit to the tunnel section.
- a 'racetrack' within the above-ground baggage handling areas at each end of the system, enabling the transfer of bags from the DCV system onto conventional conveyors.

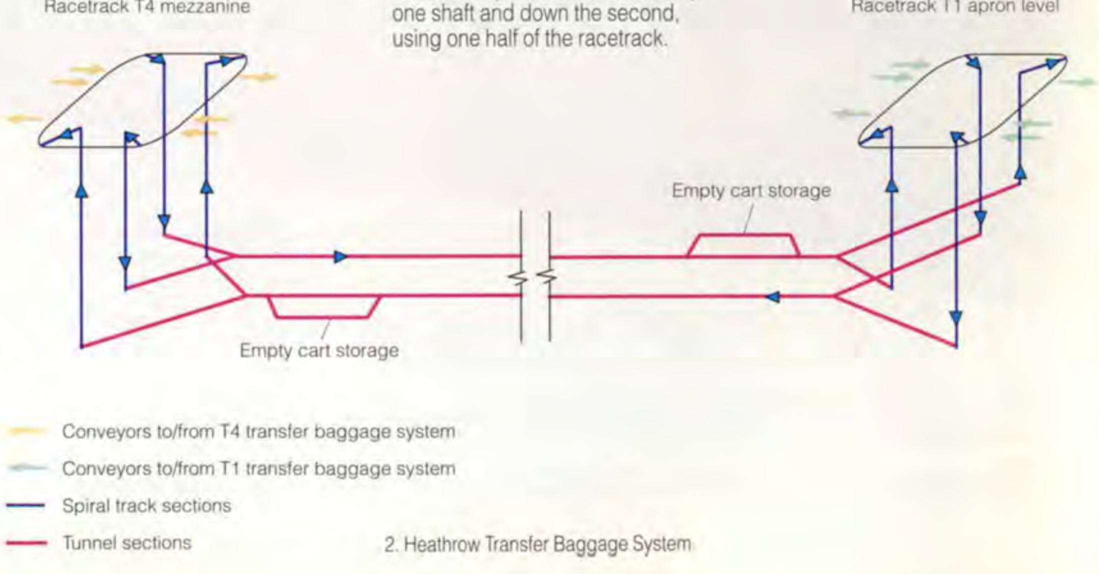
The combination of the above-ground racetrack with two access shafts allows the system to operate in a number of different modes, as follows:

- normal operation carts travel up and down spiral tracks in the same shaft, and use the whole racetrack, giving two opportunities to offload and load bags.
- 'fall back' operation carts travel up one shaft and down the second, using one half of the racetrack.

By switching between the four normal modes and 16 fallback modes, it is possible for system operation to be maintained under most possible failure scenarios.

The DCVs are propelled by motors mounted on the track, driving metal plates on the undersides of the vehicles. Three principal drive mechanisms are used:

- linear induction motors (LIMs) in the high speed sections of track in the tunnel. These use the metal plates under the carts as motor armatures, and provide the impulse to maintain cart velocity without requiring physical contact.
- synchronous drives, located in empty cart storage, up spirals and racetracks, using drive wheels acting on the metal plates to propel the carts in a controlled manner
- rotating permanent magnets, located in the down spirals to decelerate the carts.



2. Heathrow Transfer Baggage System

T4 transfer sort

The T4 facility uses conventional conveyor technology to sort and screen baggage. Bags enter from the DCV system and from loading docks at apron level, and are sorted by automatic reading of the unique bar code references on the baggage tags, which allows a sort allocation computer (SAC) to identify bags and their destinations. Provision is allowed for manual reading of damaged or badly printed tags.

In line with ICAO (International Civil Aviation Organisation) recommendations and the requirements of the UK Department of Transport, all hold baggage is subject to security checks, and the T4 sort facility incorporates a multi-stage X-ray screening process for all transfer bags introduced into the main baggage system.

Civil engineering

The development of the underground link between T1 and T4 involved major civil engineering works, including:

- a 1.4km tunnel under one of Heathrow's main runways and the Piccadilly Line Tube tunnels
- complex underground junctions by the two Terminals
- vertical shafts adjacent to the Terminal buildings at each end of the system, for transporting baggage into and out of the tunnel
- a working shaft and a ventilation shaft located part way between the terminals.

The design and construction of the underground works were described in a previous Arup Journal[1].

Integrating the design

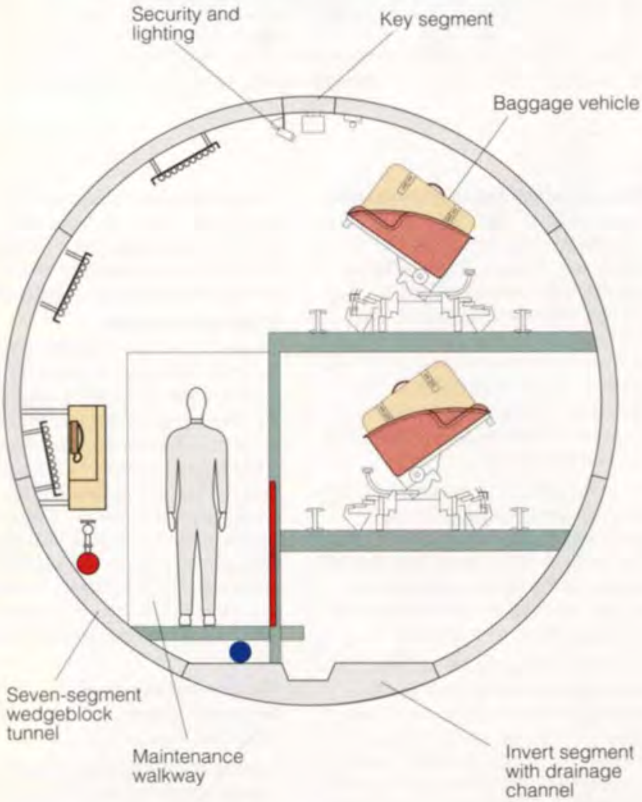
As lead designer for the project, the Arup team were responsible for the overall integration of all elements of the design. Key factors included:

Programme implications

To satisfy the intended programme it was necessary to begin design and construction of the civil and building works before the specialist systems had been fully defined and suppliers appointed. The spatial and service requirements were defined on the basis of concept solutions, and refined where appropriate as the systems design and operational requirements were clarified. The impact of changes and developments in both had to be accommodated in the building and services design.

3. The top of the spiral at Terminal 1, showing automated control panels.

4. Cross-section through main tunnel showing co-ordination.



Spatial constraints

The development of most new facilities at Heathrow is constrained by competing demands for space in and around the existing Terminal buildings. Expansion outwards is constrained by the landside and airside operations, whilst the height of above-ground construction is limited by factors such as line of sight from the control tower. In developing the HTBS design, various options including below-ground construction had to be considered for the new baggage handling areas.

The ultimate solution developed for T4 combined the baggage hall with development of a new gate lounge and retail space, whilst that at T1 resulted in expansion over an aircraft parking stand and rearrangement of departure gates.

Main text concludes on page 25 ▶

5. Loading docks at Terminal 4.

Mechanical and electrical services

Overview

The M&E installation within the HTBS combines various specialist tunnel systems with more traditional building services, covering safety, operational and environmental control requirements.The design had to be developed in close liaison with regulatory bodies, including the airport authorities (BAA fire officer, Heathrow Airport ltd Fire Safety Department, and BAA Health and Safety Manager) and external bodies (London Fire and Civil Defence Authority and the local authority Health and Safety Officer).

The M&E design and its integration in the whole project were closely linked to the fire strategy and other life safety issues. The nature of the project meant that many elements were not covered by Building Regulations or the usual UK codes of practice, and that fire safety engineering techniques had to be employed, as well as some NFPA (National Fire Protection Association) standards.

Electrical services

System power

This is supplied mainly from two dedicated 1.6MVA substations along the route of the tunnel, one at the working shaft and the other at the ventilation shaft. The shafts carry LV cables from the substations to distribution boards and motor control centres at tunnel level. Power for the areas above ground at T1 and T4 is taken from substations in the Terminals themselves.

No standby power generation is provided for the HTBS, and to increase the resilience of the electrical system, supplies from LV switchboards to motor control centres are interleaved, as are supplies from motor control centres to individual motors. This allows the system to continue running, though at reduced capacity, even if a fault occurs on a switchboard or transformer.

Programming constraints meant that the substation transformer sizes had to be fixed fairly early in the project, well before the BHS design was complete. As its details were clarified, in particular the operation of the linear motors which drive the baggage carts through the tunnel, the electrical load crept steadily upwards to the point where a new substation had eventually to be installed at T1 to cater for the increased load.

Linear induction motors (LIMs)

A LIM consists of two plates, made of metal laminations, placed opposite each other with an air-gap between them. Each plate carries windings, like the stator windings on a rotary induction machine. Underneath each baggage car a metal sheet or 'slider' is attached, which passes though the LIM's air-gap. The magnetic field created by the LIM stator windings generates an opposing magnetic field in the slide, which provides the driving force to propel the cart though each LIM and along the tunnel.

The way LIMs operate results in a very uneven load characteristic. When they are idle a steady and relatively low current is drawn, but as the cart's slider passes through the motor it increases rapidly to approximately eight times the idle level, decreasing again when the slider leaves the LIM. The peak current is drawn for a maximum of two seconds, while the idle period varies depending on how many carts are running at the time. Because of this, much time and effort was spent in conjunction with the BHS designers in confirming the running load of the system. A series of tests on a LIM were carried out by ERA in their laboratories. While helping to confirm the currents drawn by them, these highlighted a potential problem of low-level harmonics on the electrical network being amplified by LIMs to damaging levels. Extensive site testing was needed to confirm that any harmonics present were within acceptable limits.

6. Smoke vent strategy.

Fire detection and alarm systems

The fire detection system has to respond to two types of fire: firstly in an item of baggage on its way through the tunnel; and secondly in the tunnel itself, for example at an electrical switchboard. The first, 'burning bag', scenario is worse from a detection point of view, as the item could be moving at up to 20mph in the main section of the tunnel. The system must respond fast enough to 'track' bags as they pass through.

The airflow rates in the tunnel ruled out the use of conventional heat or smoke detectors. At tender stage, the design was fixed using an optical linear heat detection system, but the system manufacturers stopped making it shortly afterwards and the design had to be changed.

The final solution uses the VESDA air sampling system, which operates by drawing air from the tunnel into a series of tubes and thus over detector heads to check for smoke. The fire alarm system is controlled and monitored from the HTBS control room at T4 and interfaces with the existing systems in both T1 and T4.

Other fire-related services include a leaky feeder along the length of the tunnel to allow radio communications between apron level and the tunnel. Whilst primarily for the emergency services, it is also available for use by maintenance staff during normal operation. As a back-up communications system, a three-hour rated fire telephone system is also provided, with phones at 100m intervals along the tunnel.

Lighting

Lighting throughout the system is generally from surface-mounted twin fluorescent luminaires, with floodlights in the shafts at each end of the tunnel, and is controlled by the tunnel management and monitoring system (TMMS). In the Terminal areas, emergency lighting is fed from dedicated central battery systems. In the tunnel, the distances involved and the difficulty of providing suitable battery rooms led to fittings with self-contained batteries being used. At the client's request, automatic monitoring was provided to reduce the time required for routine testing of the emergency lighting systems.

CCTV and security

Initially, CCTV was provided in the tunnel to monitor personnel as part of the safety procedures for the system's operation. As the client's requirements evolved during the project, this was extended to monitor possible trouble-spots on the baggage system. The CCTV system is linked to the access control system - swipe-card readers linked to cameras on all doors leading into the HTBS. The access control system is primarily for safety, not security, and is intended to allow only authorised (and therefore trained) personnel access to the tunnel.

Mechanical services

Ventilation system

This was needed to control:

- the maximum temperature of air in the tunnel and shafts at 35°C by removing the heat generated by the BHS
- environmental conditions during manned operation
- spread of smoke and unburned fuel fumes, and
- to provide safe passage for evacuation of personnel and fire-fighting access.

During normal operation - defined as the continuous operation of the baggage handling system from 04:00 - 24:00 hours, the ambient air is drawn into the tunnel via a 'penthouse' at the top of the ventilation chamber, Fig 6(DR52). The vitiated warm air from the tunnel discharges to the baggage handling halls in T1 and T4 via the two shafts, and is then directed to the outside via exhaust louvres located strategically to provide heating for drivers who occasionally transfer bags manually. The ventilation fans are fully reversible, to draw air from Terminals and discharge at the penthouse. This can ventilate the baggage handling halls during hot weather.

In emergencies like fire or fume detection (from fuel leaks or spills on the apron drawn into the tunnel), fans supply air at maximum duty in normal or reverse directions. The maximum air volume for the system is 110m^3, which is designed to satisfy the design fire size. The maximum air volume achieves a minimum velocity of 1.5m/s at the most remote tunnel, which is the velocity to remove smoke and prevent back layering of smoke during an emergency.

The minimum air volume is based on achieving the 0.5m/s air velocity in the most remote tunnel required for manned conditions; this is acceptable to the Health and Safety Officer, the Fire Officer, and LFCDA. It corresponds to a velocity of 1.5-2m/s in the tunnels to T4 and T1.

The normal air volume for controlling tunnel temperature varies, and was established from a heat transfer model developed for the heat sink effect of the tunnel. It depends on the deep ground temperature of 14°C, the outside ambient temperature (assumed to be a sinusoidal profile), and the amount of heat dissipated from the LIMs and other electrical devices. A value engineering exercise supported a variable volume concept, and three variable speed fans were selected, each at 50% duty, to satisfy the most stringent conditions.

Fan selection required detailed calculation of the aerodynamics of the tunnel, of the supporting structures for the BHS, and the dynamics of the BHS. Further constraints were the fully reversible nature of the system and the unequal length of tunnels between the ventilation chamber and the Terminals.

8. Carts in completed tunnel.

7.
Conveyor systems at mezzanine in Terminal 4, showing co-ordination of building, services, and automation, and X-ray screening equipment.

An aerodynamic model was necessary to iterate the calculations for the boundary conditions imposed on the terminal shafts.

The fan chosen was the axial flow type selected for 55m^3/s, 1450rpm at 1450Pa to compensate for pressure drops in the inlet and outlet mesh guards, with shut off dampers and noise attenuators. Fans were tested for full performance at the design pitch angle of 15° at various frequencies and at 12° and 17° in accordance with BS848. The maximum time for a fan to reach full-forward or full-reverse speed from stationary was 45 seconds and the time for a fan to reverse from full speed in one direction to full speed in the other was 120 seconds. Each motor is 132kW and manufactured for two reversals during 15 minutes in any hour with 250°C. The fan assembly is constructed for 10 years' design life at normal operating conditions and for a minimum of two hours' operating at 250°C.

Control and monitoring systems
The control system for the ventilation system is direct digital controllers interfaced and monitored with the TMMS. The ventilation system can operate at normal, manned and emergency modes selected from the control room. During normal operation, the fan speed is controlled by temperature sensors located in the tunnels adjacent to T1, T4 and the ventilation chamber. At each location two space temperature sensors are provided operating as a control and monitor pair.

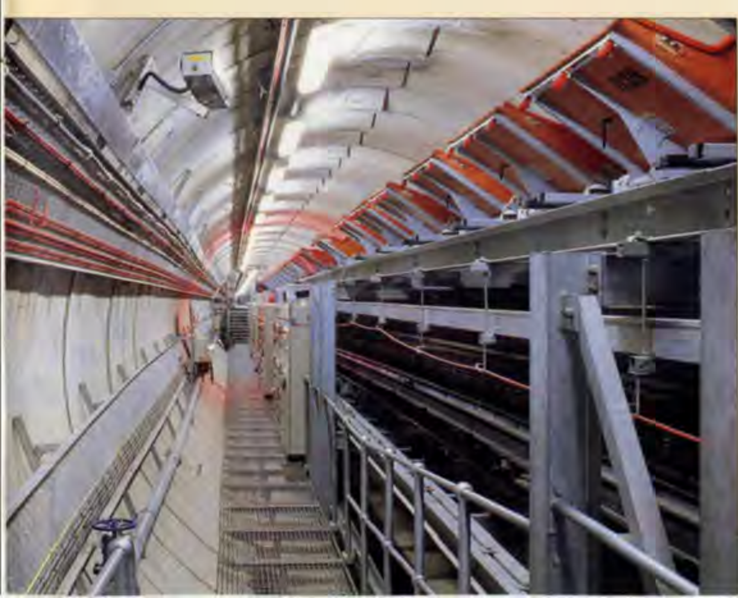
An alarm is raised when the difference between two readings is more than 2 C to prompt calibration checks of the sensors.

When people are in the tunnels, the fans are controlled by air velocity sensors in the tunnels near T1, T4 and the ventilation chamber. At each location two velocity transducers, each with its own multi-point flow grid, measure air velocity in both directions (normal and reverse). During an emergency condition or fire the fans operate at maximum speed.

Fume detection
A fume gas detection system monitors the level of aviation fuel fumes in the tunnels at four stations, at each of which three detectors determine the value of gases. The control system calculates the differences for three readings in pairs. The pair with lowest difference is selected and averaged to indicate the measured value for the station.

Should the absolute difference between the non-selected detectors and the determined reading be more than 5% of low explosion level (LEL) over a 24-hour period, a recalibration alarm is raised for the non-selected detector. The current and averaged gas level for each location are displayed at the TMMS. Also, each fume detector incorporates its own first stage (25% of the LEL for jet fuel A1) and second stage (50% of the LEL for jet fuel A1) high level alarms, which are monitored on the fireman's switch panel as well as on the TMMS. At the first stage high fume alarm from any of the monitored stations, the duty ventilation fans are switched on at high speed to ensure safe passage for evacuation.

Carbon dioxide and oxygen deficiency
In addition to the above, at each monitoring station carbon dioxide and oxygen detectors are provided. If low oxygen or high carbon dioxide levels are shown at any of the stations, an alarm is raised on the TMMS and illuminated on the local gas detection panels.



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Space limitations in the baggage hall were a key consideration in developing an integrated design solution. In co-ordinating the structure, building services and handling equipment, the team had to ensure that adequate baggage clearances, safe maintenance access, and required means of escape were provided. To prove the design and achieve sign-off from the client, users, and statutory bodies, detailed co-ordination drawings were required in conjunction with colour presentation drawings and physical models. Colour diagrams, developed from the engineering drawings, proved effective in communicating the key elements of a complicated design to all project participants.

System interfaces
Integrating the new transfer system with the existing Terminals required a wide range of interface issues to be resolved, affecting the design, construction, and commissioning stages. Building interface issues ranged from managing the impact of tunnelling work on new above-ground structures at T1, to developing a fire strategy that integrated the tunnel with areas in both Terminals.

The BHS interfaces involved co-ordination between two suppliers within the project itself and a third equipment supplier working at T1. Interface issues needing to be addressed included the physical (spatial) co-ordination between systems, the interfaces between control and IT systems, and the operational links between the different systems. By introducing an automated link between two previously independent baggage systems, the TBS will have an impact on baggage operational procedures across the entire Airport.

Testing and commissioning
The reliable operation of the new baggage system is critical to the transfer operation at Heathrow. Non-performance, resulting in damage or delays to baggage, has significant commercial implications for airlines, and could give the Airport adverse publicity.

Given the complexity and critical nature of the system, a rigorous testing and commissioning programme was needed to prove the performance both of individual elements and of the whole. Working with individual suppliers and the commissioning manager, Dome, Arups developed a comprehensive testing plan to validate the performance of the system. Seven series of tests allowed the performance of individual sub-systems to be validated in normal and simulated failure modes before linking them together to test interfaces and overall performance. Later stages of the testing programme were heavily constrained by the need to link into existing baggage systems, which typically operate for 18 hours a day. Interface tests had to be carried out during a 4-6 hour night-time window, without disrupting planned maintenance activities in the Terminals.

Conclusion
The transfer sort facilities at T1 and T4, including security screening, were operational in summer 1996, with road transfer of baggage continuing between the Terminals. Installation of the main transfer system was completed in 1997, with most of the test programme completed by the end of that year. The system then underwent final commissioning tests before handover to the users for a phased start-up early in 1998.

Reference
(1) GROSE, B, and KAYE, D. The Heathrow Transfer Baggage Tunnel. *The Arup Journal*, *31*(3), pp15-18, 3/1996.

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Printed in England by Reedprint Limited, Windsor, Berkshire