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Front cover: Ravenspurn oil platform (Photo: John Salter)
Back cover: View through pod windows at Rank Xerox, Welwyn Garden City (Photo: Jo Reid & John Peck)

Ravenspurn North concrete gravity substructure

John Roberts

Significance
Two concrete gravity substructures (CGSs) supporting production decks have been installed in the North Sea this summer.

In June the Gullfaks 'C' platform was installed in the Norwegian sector. At towout the structure weighed 850 000 tonnes — reputedly the largest object ever moved by man. At the beginning of August the Ravenspurn North concrete gravity substructure, weighing some 28 000 tonnes, was installed 80km off Flamborough Head in block 43/26 of the UK sector.

It is perhaps surprising that, of the two platforms, the Ravenspurn North CGS is of greater significance to the oil industry. In the UK over the last decade conventional wisdom has held that a steel jacket is the most economic substructure for a fixed platform. In Norway, on the other hand, where there is a more limited indigenous steel-making industry, the use of concrete gravity substructures has been encouraged.

As a result, CGSs have been installed in the Norwegian sector at the rate of about one per year over the last decade. Most of these are the well-known *Condeep* design developed by Norwegian Contractors.

A CGS was selected for Ravenspurn North because the operator, our client, Hamilton Brothers Oil and Gas Ltd., was convinced that the design developed was cheaper than the steel alternative. That decision has stimulated considerable interest among other operators, many of whom are now reviewing the technical and economic merits of alternative substructures.

1. Impression of Ravenspurn North central processing platform after installation of both decks.

The main reasons why concrete gravity substructures are now comparatively cheaper than steel jackets stem from design.

In the case of the Ravenspurn North CGS, the principal factors were as follows:

(1) The decks can be installed offshore in a single lift using a semi-submersible crane vessel after emplacement of the CGS on the seabed. Previous CGSs have been mated with their decks inshore prior to towout, or the topside equipment has been installed offshore in comparatively small lifts.

(2) The Ravenspurn North CGS will support two separate decks, of which only one will be installed initially, whereas all previous designs supported only a single deck. Thus the cost of a second separate support structure has been avoided.

(3) The CGS has been built entirely in a dry dock rather than partly as a floating structure — which has been Norwegian practice.

Ravenspurn North CGS

Environmental conditions

Depth of water at field (LAT – lowest astronomical tide):	41.6m
Height of design wave (100-year return period):	18.7m
Associated period:	12.3-15.3 secs.
Surface current (100-year return period):	2.41m/sec.

Dimensions

Caisson size:	62 × 54.5m
Caisson height:	16m
Shaft height above caisson:	37.5m
Shaft diameter — base	11m
— top	6m

Materials

Volume of concrete (grade C50):	9750m^3
Weight of reinforcement:	2750 tonnes
Weight of prestressing (27km):	450 tonnes
Weight of steel skirts:	350 tonnes
Weight of steel deck connections:	410 tonnes

Weights and draughts

Final weight of CGS in air:	27 850 tonnes
Floatout draught (on 1.5m deep air cushion):	9m
Towout draught:	13.5m
Main deck	
Operating weight:	8500 tonnes
Lift weight:	6000 tonnes
Compression deck	
Operating weight:	4000 tonnes
Lift weight:	3250 tonnes

Schedule

Start of concept design:	March 1987
Completion of detailed design:	March 1988
Start of site construction:	May 1988
Ready for floatout:	mid-July 1989
Installation at field:	August 1989

Gullfaks 'C' Platform

Environmental design conditions

Depth of water at field:	217m
Height of design wave (100-year return period):	30m

Dimensions

Caisson size (base area):	16 000m^2
Caisson height:	87m
Shaft diameter — base	28m
— top	14m
Shaft height above caisson:	162m
Skirts — concrete: length	23m

Materials

Volume of concrete (grade C65):	246 000m^3
Weight of solid ballast at towout:	165 000 tonnes
Weight of reinforcement:	80 000 tonnes
Weight of prestressing:	3550 tonnes

Weights and draughts

Final weight of CGS in air:	850 000 tonnes
Floatout draught (skirts and base slab only):	13m
Towout draught:	208m
Deck weight: — operating	55 000 tonnes
— at mating	48 000 tonnes

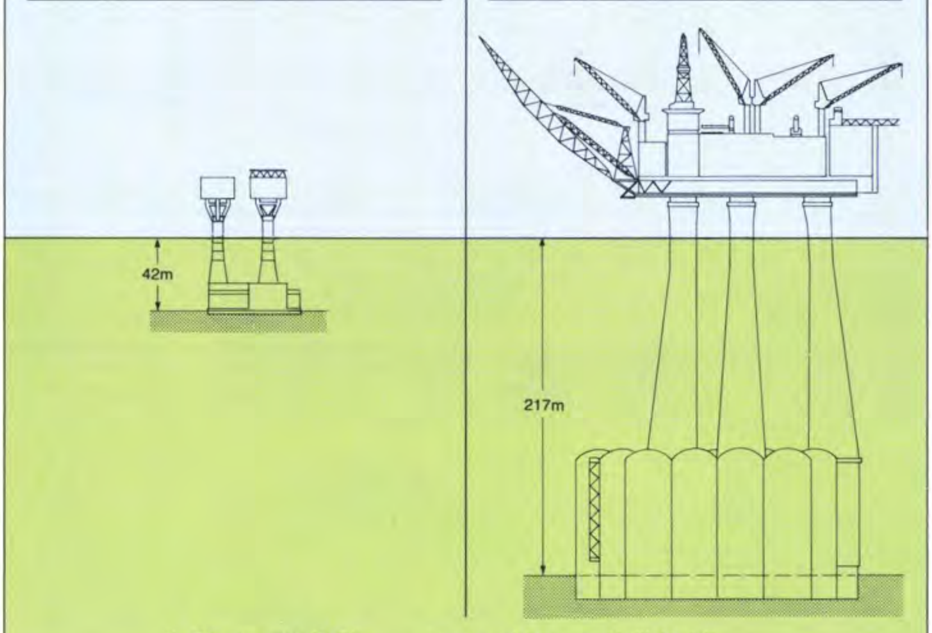
Schedule (design and build contract)

Contract award:	December 1985
Start of concept design:	December 1985
Completion of detailed design:	October 1988
Start of site construction:	January 1986
Ready for towout:	April 1989
Installation at field:	May 1989

Project team

Client:	Statoil
Partners:	Norsk Hydro Saga Petroleum
Engineering and construction:	Norwegian Contractors

(Source: Norwegian Contractors)



2. Ravenspurn North ..... compared to ..... Gullfaks 'C'.

(4) The structure was designed to be simple, highly repetitive and aimed to disassociate the concrete from the more ephemeral process pipework which it supports.

It comes as a surprise to the majority of civil engineers that the oil industry does not readily appreciate the advantages of adopting concrete as a structural material in a marine environment. In fact concrete is seen as a radical change which therefore involves greater financial and programme risk. Since the cost of the substructure supporting the production equipment on a platform typically represents less than 5% of the total field development cost, any 'innovative' design has to show substantial savings compared with the alternatives, before operators can accept the risks.

Potentially, the Ravenspurn design offered substantial savings but would not have been adopted except for the determination of Hamilton Brothers to prove the case.

FORMS OF SUBSTRUCTURE

Jackets

Piled steel jackets are by far the most common form of support structure for offshore platforms throughout the world. They consist of a tubular steel spaceframe supported on tubular steel piles driven after the jacket is located on a seabed. The word jacket was originally adopted as the name for the steel template placed in the shallow water swamps of Louisiana as a guide for the piled foundations which supported drilling equipment. Today virtually all jackets are transported offshore on purpose-built flat barges and installed either by launching from the end of the barge or by lift installation using a semi-submersible crane vessel.

In operation, hydrodynamic forces generated on the structure are transmitted to the seabed soils through the piles. The tendency for a jacket to overturn is resisted by tension in the piles on the upstream side and this load condition normally governs the design of the piles.

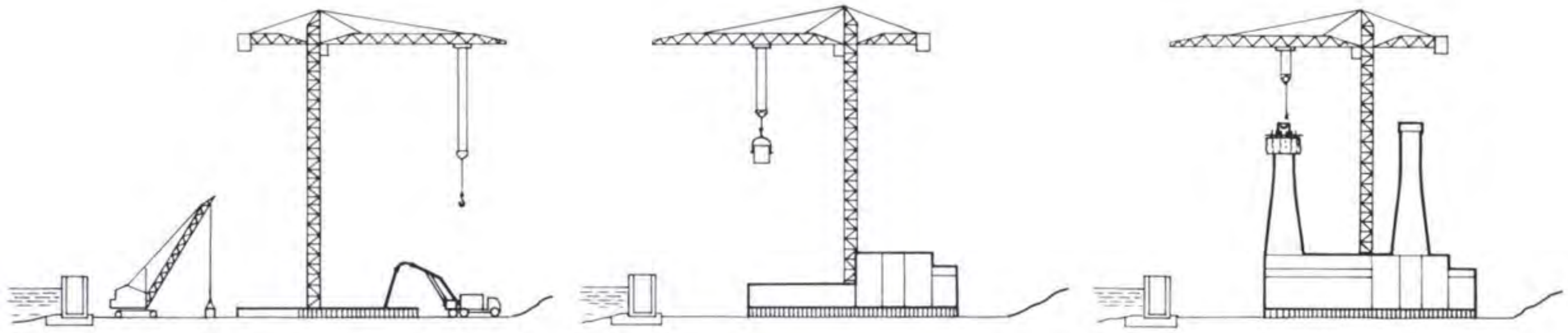
The popularity of piled steel jackets can be traced to the first offshore developments in the Gulf of Mexico. Steel rather than concrete was the material most familiar to the American engineers involved in developing offshore technology. The influence of American oil companies throughout the world is probably the main reason why steel jackets remain predominant.

Gravity-based structures

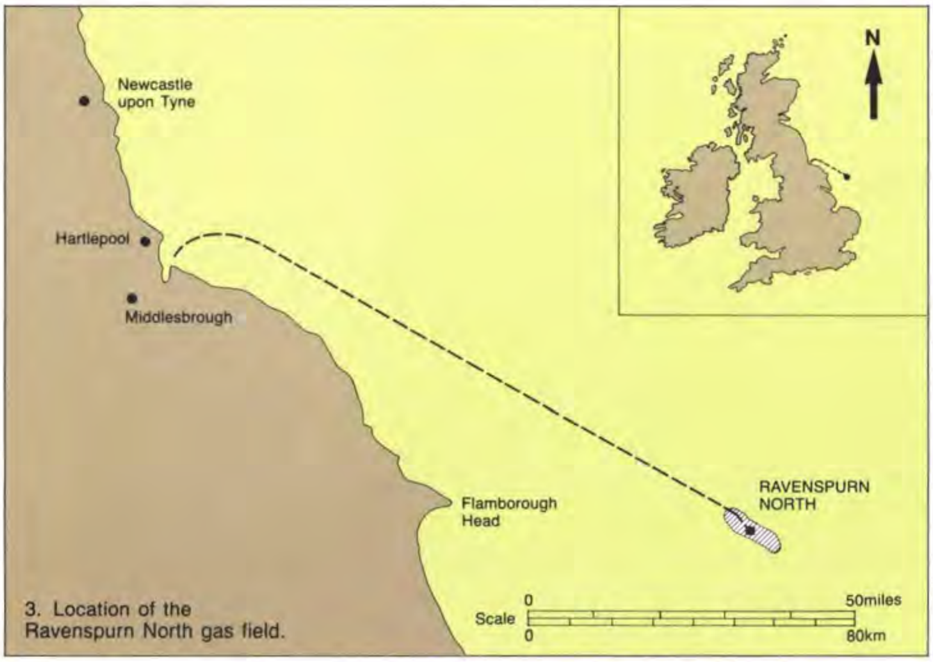
Gravity-based structures (either steel or concrete) resist overturning in the same manner as a simple pad foundation. To prevent uplift the width of the CGS base must be such as to ensure the resulting force from horizontal hydrodynamic loading, and vertical loads lie within the middle third of the base width. Apart from isolated examples such as the Royal Sovereign Lighthouse, concrete gravity substructures had not been used offshore until the early 1970s when a combination of factors created the need for a new design solution. At that time developments in the North Sea were at the forefront of offshore technology, requiring platforms in a deeper and more hostile environment than had been attempted previously anywhere in the world. In addition the platforms required very heavy topsides. At that time the largest offshore crane vessel could only lift about 1000 tonnes and therefore a large number of relatively small lifts were required to install the topsides on a conventional steel jacket. Concrete gravity substructures were designed to reduce the cost of offshore hookup by mating the CGS with a single-piece deck inshore prior to towout. The CGS and decks were constructed separately and the CGS ballasted down in deep water so that only the tops of the shafts were above the water. The deck was floated over the CGS on barges and the CGS deballasted to achieve the mating. In this way decks of up to about 50 000 tonnes have been installed.

Since the early 1970s concrete gravity substructures have been automatically associated with this sequence of construction and installation which has been adopted for all subsequent CGS designs installed in the Norwegian sector.

The Ravenspurn North CGS is the first concrete structure in the North Sea to break with this tradition.



4a. Casting the base slab to float out.



3. Location of the Ravenspurn North gas field.

Development of the design concept

Although Arups had previously designed a number of CGSs, none had been built. We were approached by Hamilton Brothers in October 1986 and were surprised to find out that they had already commissioned a number of design studies for the CGS option.

Arups were asked to undertake a technical feasibility study and prepare a cost estimate.

The CGS was required to support the central gas processing platform of the Ravenspurn North field. It will eventually process gas from four remote wellhead platforms imported via 324mm and 356mm diameter infield risers. Processed gas is exported to shore via a 600mm diameter line.

The main production deck will be installed in the spring of 1990 but the second deck, which contains gas compression equipment, will not be needed for several years, until the time when the gas reservoir pressure has dropped below contract pressure and the export pressure requires boosting. The maximum operating weights of the main deck and compression deck are 8500 tonnes and 4000 tonnes respectively.

During the course of the feasibility study a number of conclusions were reached about the design features required to realise the most cost-effective CGS:

(1) By installing the decks offshore using a semi-submersible crane vessel, the size of the base caisson could be significantly reduced compared to a design with the decks installed inshore. One of the chief determinants of the base caisson size is floating stability. For every tonne of structure at the top of the shafts, between 5 and 6 tonnes are required low down in the structure to maintain the same stability characteristics (metacentric height).

(2) Installing the decks offshore reduced the size of the CGS to the point where the entire CGS could be fabricated in any of the existing UK construction docks. Thus the cost premium associated with completion of the CGS while floating at an inshore location was avoided.

(3) By providing a design which could be constructed entirely within the dry dock, the problem was reduced to one of conventional prestressed concrete construction. The inherent economy of the structure therefore depended upon providing a design which was simple and highly repetitive and could be constructed from readily available materials.

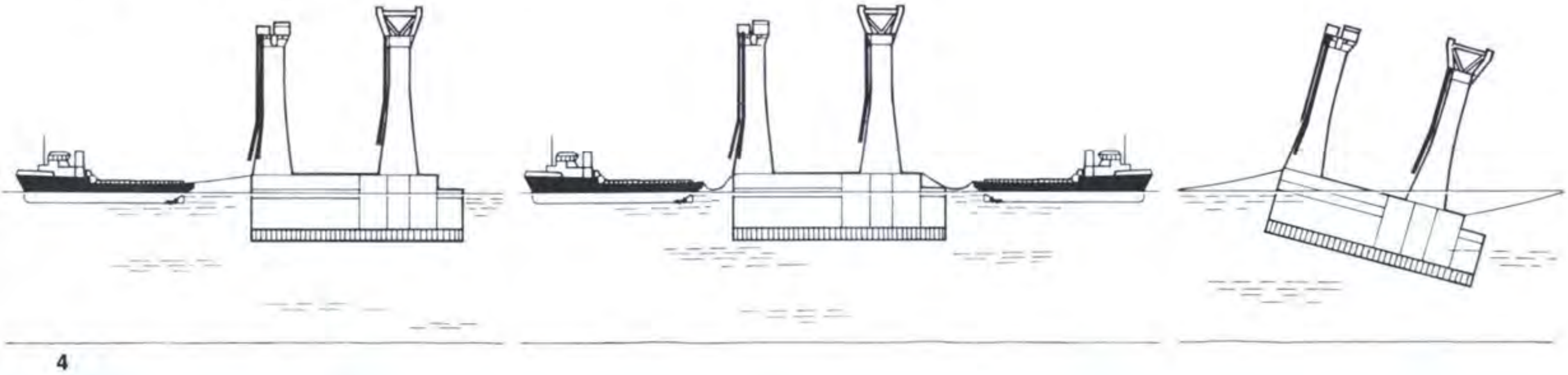
A number of CGS designs based on these principles, having two, three and four shafts, were identified during the feasibility study. The concept favoured by Hamilton Brothers involved the novel idea of two separate decks, the main production deck supported by two shafts and a compression deck by a single shaft. It was possible to show that the size of the base caisson would be approximately the same regardless of whether the CGS had two or three shafts. Conventionally, two decks would have been supported by two separate steel jackets. The cost of supporting the compression deck was therefore equivalent to the marginal additional cost of providing the third shaft on the CGS.

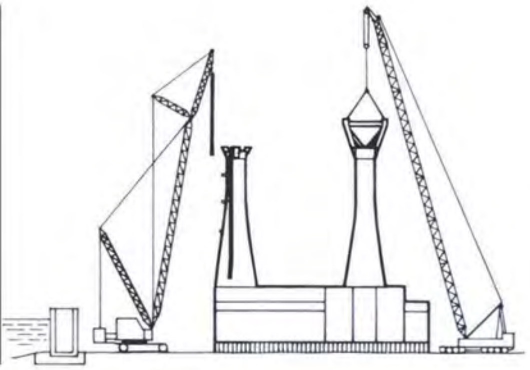
The conceptual design work was undertaken in the period from March-July 1987. The detailed design was carried out in parallel with the tender and assessment period from October 1987 to March 1988, and project sanction obtained in May 1988.

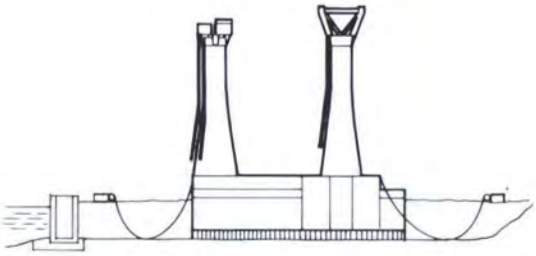
The design solution

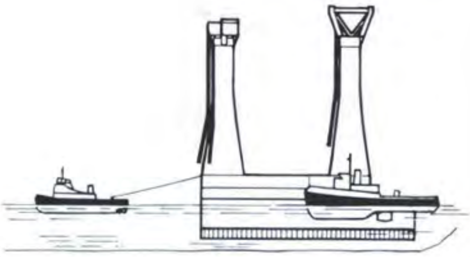
The component parts of the Ravenspurn North CGS are very simple: connections for the decks, concrete shafts, concrete base caisson and steel foundation skirts. Initially a number of parametric studies were carried out so we could better understand the behaviour of the structure and optimize the size of the structural elements. At the outset of the design the most difficult task was to determine the size of the base caisson.

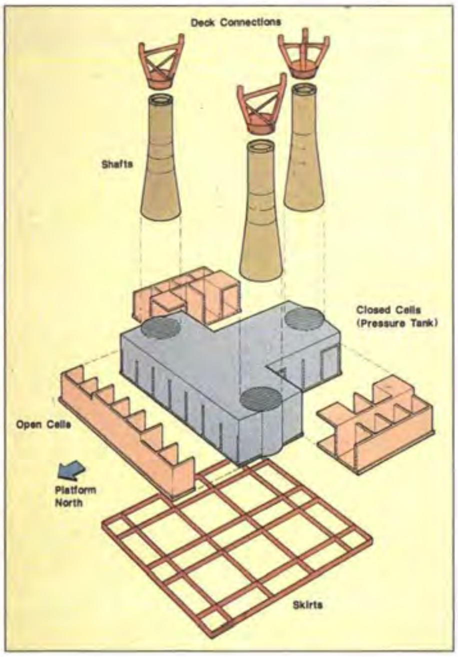
4b. Tow out to scour protection and solid ballasting.

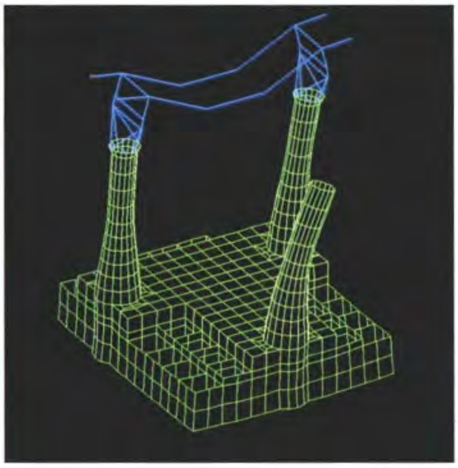








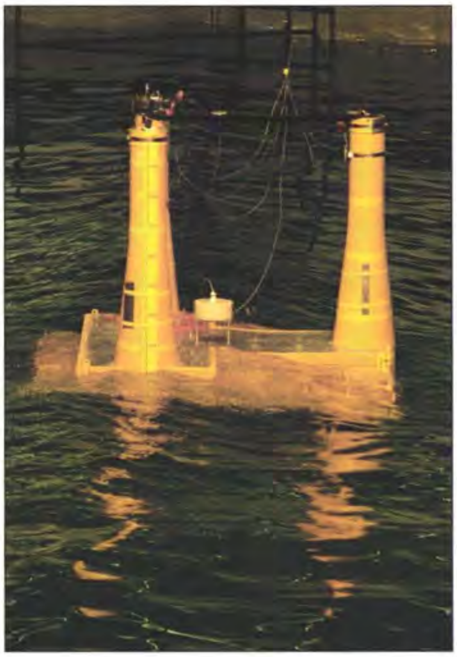




5. (left) Anatomy of Ravenspurn North CGS.

6. (Above) Finite element model mesh and deflected shape for incident wave from west (much exaggerated!).

7. (Right) Tank testing: CGS under tow in summer storm conditions.



This depends on:

(1) *Hydrodynamic loading*
Approximately 80% of the horizontal load from wave and current action is generated on the base caisson. The load generated is proportional to the enclosed volume of the caisson, and it is desirable to keep the latter as small as possible. It is also desirable to keep it low since the magnitude of hydrodynamic force reduces exponentially with water depth.

(2) *Structural considerations*
The caisson must be of sufficient size to transmit the forces from the shafts and those generated on the caisson itself into the seabed soils.

(3) *Geotechnical considerations*
Sliding of the structure along the seabed rather than bearing pressure is the governing mode of foundation loading. The base area of the caisson has to be such that the shear stress in the soil at the level of the tips of the skirts is less than the soil strength.

On cohesionless seabed soils, such as those at Ravenspurn, the resistance to sliding is therefore a function of the mobilized shear strength of the sand and the submerged weight of the platform.

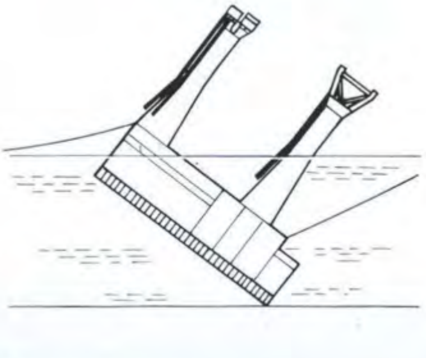
(4) *Naval architecture*
The CGS must possess sufficient buoyancy and remain stable at all times while it is still floating. Generally speaking the larger and taller the base caisson and the greater the diameter and spacing of the shafts, the easier it is to provide adequate stability. It is essential to keep the centre of gravity as low as possible.

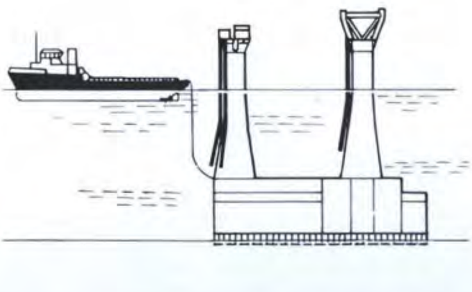
(5) *Floatout draught*
The size of the base caisson must be such that on floatoff, the draught is well within the limit imposed by existing UK docks; the larger the base area, the lower the floatout draught.

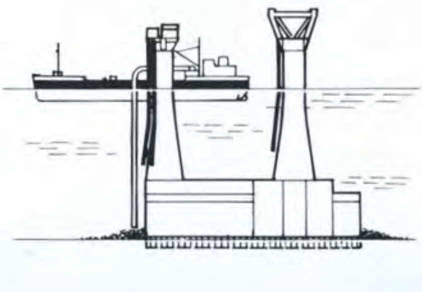
Some of these requirements are conflicting.

The design solution was to develop the base caisson having the lowest density (weight in air divided by enclosed volume) and to divide the caisson up into open and closed cells.

The latter provide the buoyancy for towout and installation and enable the floating stability criteria to be met. They also permit the eventual refloating of the structure for abandonment. The open cells improve floatout draught, reduce the centre of gravity of the structure (since the cells have no roofs) and enable the onbottom weight of the CGS to be varied by the addition, after emplacement, of solid ballast. This can be used as a means to improve resistance to sliding.







Together the open and closed cells provide a robust structure to transmit loads from the shafts to the skirts and provide a base suitable for founding on cohesionless seabed soils.

The size of the cells into which the base caisson is divided was optimized for least caisson density. The optimal size for square cells is 6-7m square. Below this size the concrete cover to the tension reinforcement adds weight without adding to the strength of the section; above this size, shear rather than bending begins to control wall and slab thickness. Cells 7.5m square were selected as this dimension was the multiple of the desired support spacing for the main deck.

The geotechnical design problem was to determine the extent and the length of the skirts cast into the underside of the concrete base slab. The determining factors are:

(1) The need to reach competent soil.

(2) The contributions of passive resistance and the self-weight of the soil within the skirt compartments.

(3) The need to avoid 'piping' during both installation and operation.

(4) The need to guarantee full penetration of the skirts at installation so that substantial contact between the seabed and the underside of the base slab could be achieved.

The last point was important because most previous CGSs had relied on grouting of any spaces remaining between the seabed and the underside of the base after installation. Grouting offshore is extremely expensive and makes subsequent refloating for abandonment technically difficult and costly.

Steel skirts manufactured from 18mm thick Grade 43C steel plate, profiled in a form resembling sheet piling, were adopted. The skirts run under the majority of the base caisson walls.

The design of the shafts is comparatively simple. The principal loadings are from the deck itself and from hydrodynamic loads. In addition it was decided to prestress the shafts vertically to ensure that cracking did not occur (Class II to *BS8110*), and taper them so as to reduce the hydrodynamic forces generated.

Deck connections

The deck connections reflect a problem specific to the Ravenspurn platform. The size and arrangement of the topside facilities are similar to an existing platform operated by Hamilton Brothers whose deck layout they considered very successful. In this deck, the support points were spaced at 12m centres compared to the diameter of the CGS shafts of 6m. Alternative solutions were considered, the majority of which resulted in considerable additional weight at the top of the shafts. The deck connections or 'antlers' developed are relatively lightweight, being fabricated from Grade 50E plate up to a maximum of 50mm thick, thereby avoiding extensive post-weld heat treatment. Each main strut of the deck connection must support a maximum of approximately 2500 tonnes in operational conditions. The deck connections are fire-protected with *Chartek*, an intumescent epoxy ablative coating up to 14mm thick.

The deck connections were attached to the top of the shafts by 20 prestressing tendons. High strength neoprene bearings developed with Tico Manufacturing Ltd. have been provided between the steel and the concrete to spread the concentrated load from the struts around the perimeter of the top of the concrete shafts.

The CGS supports process pipework consisting of gas risers (which connect the seabed import and export pipelines with the process deck), caissons (which allow seawater to be lifted to the platform, cleaned and dumped) and J-tubes (which are the ducts for electrical cabling to the remote wellhead platforms). It was recognized that the sizes and layout of this pipework could easily change both during the design and during the platform's operational life. The design that evolved was to mount all the process pipework externally on the shafts. Circular tubular supports or 'cowhorns' have been provided at regular vertical intervals up the shafts, welded to steel embedment plates cast into the concrete. The uppermost cowhorn is attached to the steel deck connection and supports the self-weight of the pipework; the lower cowhorns are guides which allow axial movement only.

The cowhorns were designed to support pipework at a regular spacing but with no particular arrangement in mind. This design decision was vindicated at an early stage. Three months after construction of the CGS began, the Piper Alpha accident occurred. As a consequence it was decided to change the routing of the risers from one shaft to another. The location of a number of caissons was also changed. No alteration to the concrete structure or the cowhorn supports themselves was required and, as a result, there was no impact on the construction programme.

The operating pressures of the risers are up to 400 bar and the routings were modelled for analysis purposes from a point on the seabed some distance from the CGS to the pig launchers (pipe testing devices) and receivers in the deck. Careful detailing was required to avoid longitudinal welds on the pipe.

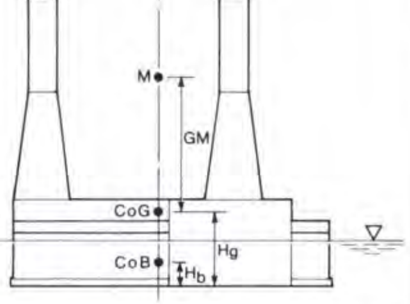
Weight control is an essential part of designing a CGS. Apart from regularly monitoring the weight of the structure as shown on the drawings (the 'Current' weight) it is essential to establish at the outset a highest expected weight (the 'Contingency' weight). During the design, floating stability and draught calculations were based on the contingency weight and the corresponding position of the centre of gravity of the structure. During construction, weights calculated from the drawings were replaced by data from weighings of individual elements or, in the case of the concrete itself, a weight devised from as-built surveys and densities assessed from 100mm cubes and core samples taken from the structure. The results from over 1800 cubes and 400 50mm diameter cores were used to calculate the Estimated Final Weight. The weights established were as follows:

Current weight:	26 938 tonnes
Contingency weight:	28 875 tonnes
Estimated Final Weight:	28 625 tonnes

The Estimated Final Weight includes over 600 tonnes representing solid concrete ballast to control heel at floatout, and additional caissons and supports required by Hamilton Brothers at a late stage in the design.

Another novel feature of the CGS is the method of installation. Previous CGSs have been installed by keeping the structure very nearly level as it is ballasted down to the seabed (parallel installation). In terms of floating stability the crucial stage is when the water level overtops the base caisson for at that point the water plane area is substantially reduced. The GM (see Fig. 8) can be as low as 1m in this position.

It was realised that if the CGS were deliberately ballasted down to a steep angle, so that the skirts touched the seabed, and was then rotated to a level position, the GM would be higher than for the equivalent parallel descent. The reason is that in the inclined descent with water ballast in the edge cells, H_g is correspondingly lower and H_b correspondingly higher than for the parallel descent. The higher the GM the greater the floating stability and the stiffer the response.



Floating stability is measured in terms of metacentric height (GM) which is given by:

$$GM = -H_g + H_b + I/V$$

Where H_g is height to centre of gravity CoG
H_b is height to centre of buoyancy CoB
I is the second moment of water plane area cut by the structure
V is the displacement volume
M is the metacentre

GM is measured in metres and must be positive for stability.

8. Floating stability.

Selection of construction contractor

Among Hamilton Brothers' concerns in adopting a CGS had been the availability of construction docks and the willingness of civil engineering contractors to undertake the works. During conceptual design a list of 35 potential tenderers was drawn up and each firm contacted. Interest was strong and it proved hard to reduce the list to the seven firms finally approved. By that time each tenderer knew a great deal about the project and the design team also knew, in some detail, of each tenderer's intentions in terms of the docks they would use, how they would be made available, their proposed construction methods, programmes, choice of sub-contractors, and so on.

A two-stage tendering process was recommended to Hamilton Brothers whereby tenders were sought, based on approximately half of the construction drawings and the full specification. The Conditions of Contract were the Institution of Civil Engineers' 5th Edition modified to suit oil company needs and the peculiarities of the project. First stage bidding was on a bill of quantities.

Almost all the tenders received were technically acceptable and commercially sound. The mid-range tender price was in line with the Arup estimate, and hence the client's confidence increased.

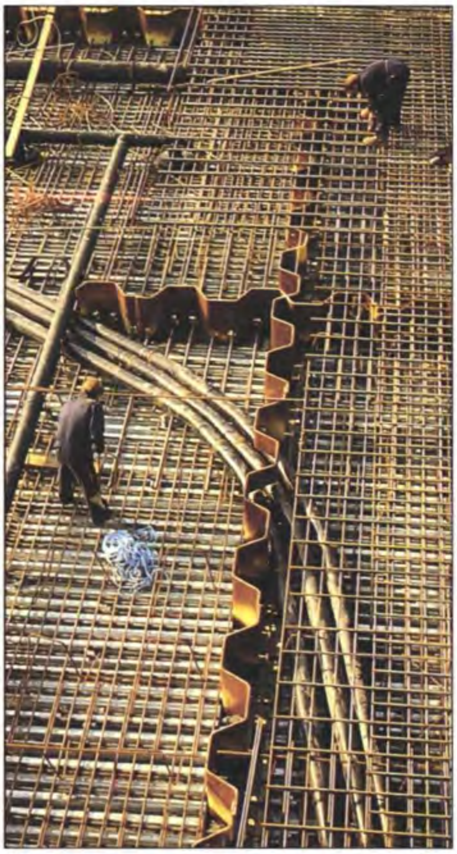
In the second stage a limited number of tenderers had the opportunity to resubmit prices, taking into account the remainder of the construction information. They were however obliged to maintain the rates originally tendered. During the final negotiations, the general items and measured works were converted into a lump sum and the bill of quantities was converted into a schedule of rates which was to be applied in evaluating variations. John Laing ETE (Energy Technology Environment) were awarded the contract at the end of April 1988. The construction period was 15 months starting at the beginning of May 1988, using Laings' Graythorp Dock near Hartlepool.

Construction

Graythorp Dock is located on the Seaton Channel 1.5km from the River Tees. It was constructed in the early 1970s for the fabrication of the large steel jackets for the Forties A and B and Thistle platforms. Consequently, there were substantial pile foundations in the dock floor. Further piles were provided for the CGS contract to suit the pattern of foundation skirts. After temporary works piling and the construction of ground beams, the steel skirts were erected in sections. No propping to the skirts was required since the cruciform sections provided their own stability.

The concrete base slab was constructed on permanent metal decking supported on shelf angles welded to the skirts. Modified high-density polyethylene (MHDPE) pipework for the under-base drainage and for closed cell ballasting was cast into the concrete.

9△



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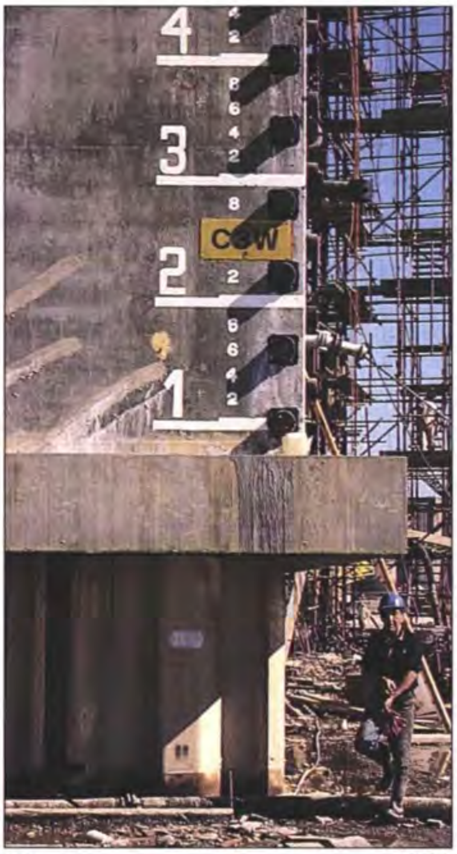

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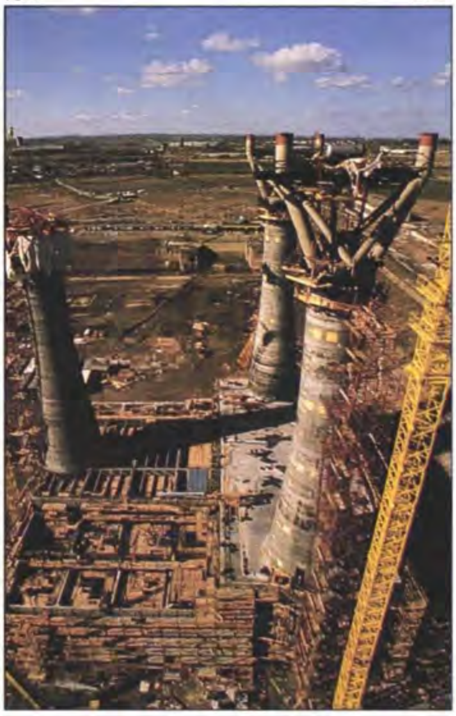


14▽

The skirts were detailed with slots to enable reinforcement to be fed through them at the wall positions. The base slab was cast in five sections with the largest pour being approximately 650m^3.

The base caisson walls were cast as a series of cruciforms with each leg approximately 3.75m long on plan. Three lifts of up to 4.8m high were required for the full height of the base caisson. The formwork was erected and positioned by holding it on a crane, often for extended periods, as adjustment proved more difficult than Laing had envisaged.

The wet concrete was vibrated using electrically-operated, shutter-mounted vibrators. Their use resulted in high quality dense concrete with few instances of honeycombing. Both horizontal and vertical joints in the caisson walls were keyed and scabbled.

The concrete mix provided by Laings' ready-mix supplier contained 475kg of cement and pfa per m^3 of concrete. The average cube strength achieved was 68N/mm^2 compared to the 50N/mm^2 required by the specification.

As with the base slab, the caisson roof was constructed on permanent metal decking supported in this case on steel beams spanning across the 7.5m cells. The roof is reinforced and prestressed, and also contains pipework which vents air from the closed cells during ballasting.

The shafts within the caisson height were constructed using adjustable steel shuttering to form the circular shape. Above caisson roof level the shafts were slipformed using the *Interform* system. Construction rates of up to 225mm per hour were achieved with an average of about 150mm per hour. A variety of steel embedment plates forming attachment points for the process pipework supports were cast in as slipforming progressed.

9. Steel skirts and base slab construction.

10. Base slab reinforcement showing embedment of profiled steel skirts, drainage and ballasting pipework, and electrical ducts.

11. Corner detail showing skirts, base slab, and surface-mounted prestressing anchorages.

12 & 13. Concrete construction nearing completion; deck connections installed and mechanical outfitting under way.

14. Close-up of pipework.

Offsite fabrication of process pipework, supports and the deck connections took place in parallel with onsite concrete construction. The deck connections supporting the main deck each weighed over 160 tonnes. They were lifted into place using a 1000 tonne mobile crane and temporarily held in place using steel dowels before being prestressed to the concrete structure with part of the vertical prestressing in the shafts. The deck connection on Shaft 3, which was not provided with antlers since the design had not yet been finalized, weighed 78 tonnes. It was lifted into position using a smaller mobile crane.

With the deck connections in place two activities proceeded in parallel. On the outside of the shafts the 'cowhorns' were welded to embedment plates. On the insides of the shafts, work began to complete the mechanical and electrical systems required for installation, the majority of which were concentrated at the bottom of each shaft. When all the supports on the shafts had been welded into position, individual risers and caissons were lifted onto the dead weight supports at deck connection level and the halving clamps at the other guide positions bolted into place. The infield, export and methanol risers are routed over the caisson roof and erected on 'goalpost' supports. After completion each riser was hydraulically tested to 1.5 times operating pressure.

The design of the structure is such that, apart from the need to prestress the deck connections to the shafts, all other prestressing operations could be carried out fairly independently of other construction activities.

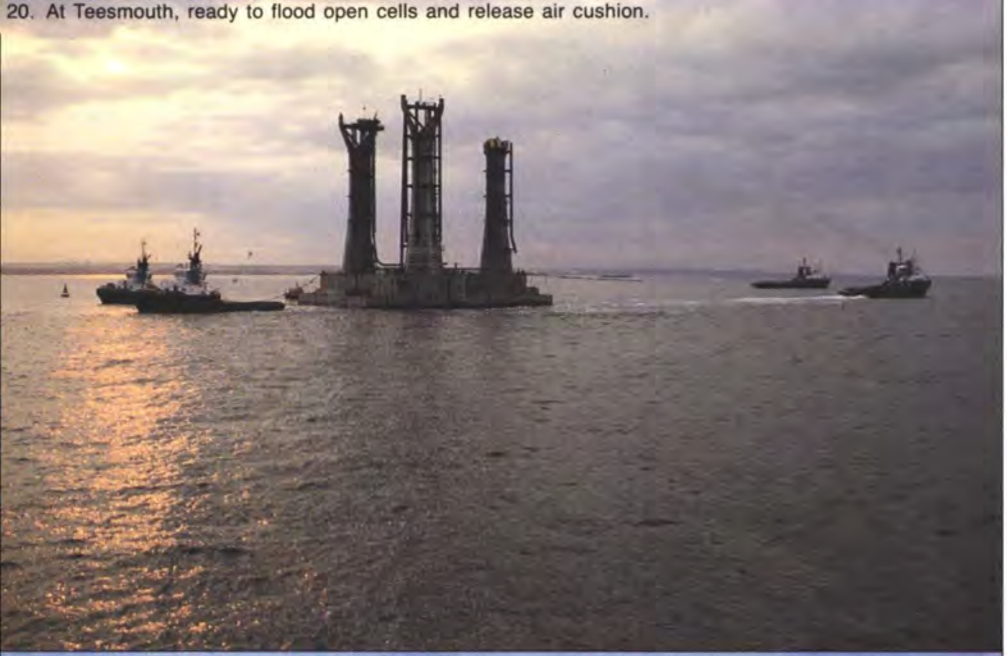
Moreover, access to the anchorages at both ends was freely available, as they were either surface-mounted on the sides of the caisson walls or accessible from the tops of the shafts or from the skirt compartment below the base slab. In practice, prestressing was completed at about the same time as the mechanical fitting out. The remainder of the construction operations involved the testing and precommissioning of the installation systems, including the hydraulic testing of each open and closed cell. Minor leaks were encountered during testing and repaired. Those construction joints which it was not possible to test hydraulically were visually inspected, tested ultrasonically if their integrity was in doubt, and repaired if necessary.

The installation control cabin and power generators were lifted onto the top of Shaft 3 by crane and hooked up to the onboard electrical and control system. Each component of the ballasting system, including valves, flowmeters, pumps and air pressure bubblers, had been individually tested at the works. The assembled system was pre-commissioned on site.

After pre-commissioning was complete, mooring lines were laid from the CGS to four winches on the sides of the dock and the dock flooded. During flooding, air in the skirt compartment was released via the underbase drainage system and water admitted to the open cells via manually-operated sluice valves to prevent premature floatoff of the CGS. The final part of the construction contract was the removal of the cellular concrete dock gates. They were deballasted, floated off the spillway and towed to a temporary foundation area at the rear of the dock. At this point the CGS was ready for the installation operations to begin.

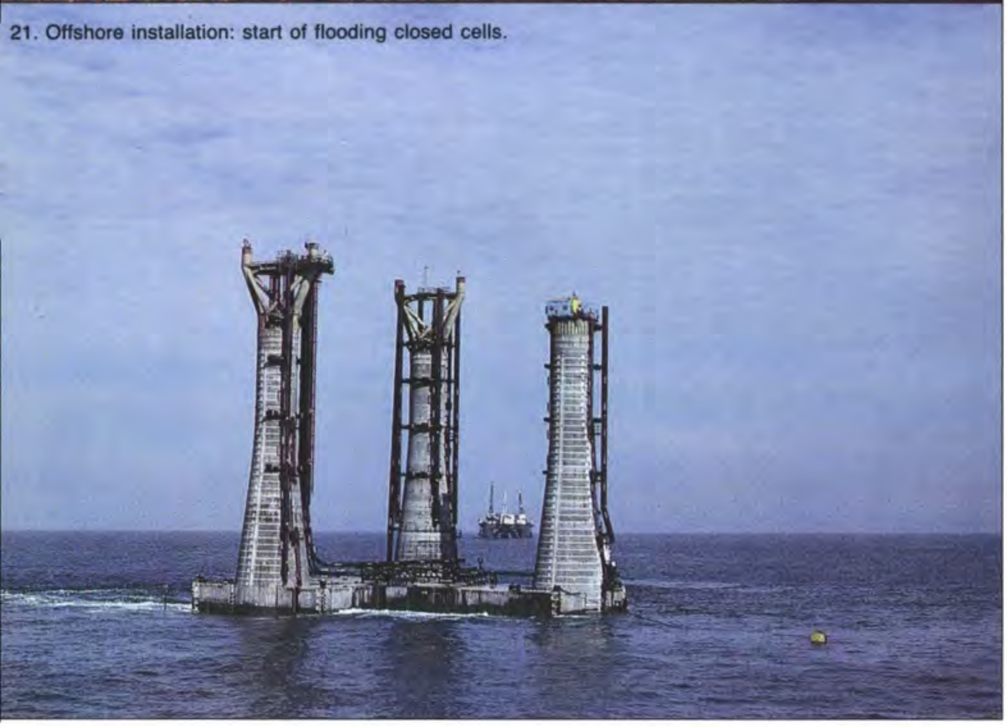
15. Far left: Construction complete.
16. Left: Dock flooded, ready for floatoff.
17. Below: Floatout from Graythorp Dock.
18. Below left: The tow down Seaton Channel.
19. Bottom right: The caisson roof during floatout.

20. At Teesmouth, ready to flood open cells and release air cushion.



22. Offshore installation: touchdown on seabed.

21. Offshore installation: start of flooding closed cells.



Installation

The CGS was installed in four stages: flooding the dry dock, towing the structure to the Ravenspurn field, sinking it to the seabed in a controlled ballasting sequence and finally placing ballast in the open cells and scour protection around the entire structure.

The first stage of installation was to manoeuvre the CGS out of the dock and down the Seaton Channel to a location off the mouth of the River Tees. Four harbour tugs were attached to it inside the dock, two moored alongside the shafts which support the main deck and two attached to the main towing points on the caisson roof adjacent to the third shaft. Once the tugs were in position the mooring lines to the dock winches were tensioned.

As the tide fell below mean water level, submersible pumps inside the open cells were started and compressors began to pump air into the skirt compartments below the base. With the open cells empty and a 1.55m air cushion under the base, the CGS floated off in the rising tide.

When the underkeel clearance to the deck floor reached 1m, manoeuvring the CGS out of the dock began using both mooring lines and tugs. As it reached the dock entrance the first of two ocean-going towing tugs was attached. The Ravenspurn North CGS then proceeded down the Seaton Channel at a stately 1 knot, reaching Teesmouth three hours after floatoff. The harbour tugs were then demobilized and the second ocean-going tug attached to the bow.

The CGS was then held while the open cells were flooded, the compressed air released and items of floatout equipment (pump, switchgear and positioning systems) removed. On completion of these activities we were able, for the first time, to obtain a definitive measurement of the CGS's final weight from reading the draught marks on the sides of the base caisson. The mean draught recorded was 13.8m, equivalent to a dry weight of 28 125 tonnes. This compared with the Estimated Final Weight of 28 265 tonnes.

The second stage of installation was towout. The CGS was towed using the two ocean-going tugs with one of the other tugs as the attendant vessel, the 84 nautical miles to the field taking 27 hours. At the field four anchors had been laid forming a square around the CGS location. The two towing tugs and two further sister vessels were moored to the pre-laid anchors assisted by a fifth anchor-handling tug. Using the winches on the tugs the CGS was manoeuvred into the correct position for emplacement to begin. From that time onwards its position was monitored by surveyors from the wellhead platform 70m from the CGS.

The third stage of installation was sinking the CGS to the seabed. The installation crew boarded it from an inflatable dinghy and climbed the external ladders up the shafts. Four men were stationed in each shaft with four others, including the offshore installation manager, in the command position at the top of the shaft which will eventually support the compression deck.

The predefined sequence of ballasting began and the CGS gradually trimmed down by the stern until contact with the seabed was achieved at an angle to the horizontal of 37°. The touchdown position was confirmed as being within acceptable tolerance. Water ballast was then admitted to more of the closed cells to bring the CGS level, with all skirts in contact with the seabed. Finally water was admitted to the remaining closed cells, resulting in full penetration of the skirts into the seabed soils. 10 hours after ballasting began, the CGS was safely installed on the seabed 2m away from the target position and 1° from its intended orientation. The entire procedure from the start of floatout from the dry dock to completion of installation on the seabed had taken 55 hours.

The final stage of installation took longer. The open cells were filled with crushed rock, and a scour protection blanket, also of crushed rock, was installed around the base caisson. The priority was to install scour protection around the corners of the CGS where we had predicted scouring of the seabed sand would occur at the extreme ebb and flow of the tide. In the event the extent of scouring was minimal and the scour protection was laid before damage occurred.

The *Rocky Giant*, a side dumping barge, placed the initial scour protection blanket around the CGS, comprising a 400mm thick filter layer and 200mm thick armour layer. A few days later the *Trollness*, an 8000 tonne vessel equipped with a steerable fall pipe, arrived to complete the work.

Altogether 9600m^3 of ballast was placed in the open cells and over 10 000m^3 of scour protection laid. The three shafts were also flooded, adding about 6500 tonnes onbottom weight to the CGS. With these activities complete, the CGS is able to resist the design storm having a 10-year return period. The weight of the main deck installed next spring will increase further the platform's resistance to sliding, to a level corresponding to the 100-year return period environmental conditions.

23. Offshore installation: start of final ballasting to bring CGS to level position on seabed.

24. Offshore installation: complete.

25. Offshore installation complete, with skirt having fully penetrated the seabed.

Future developments

The installation of the Ravenspurn North CGS marks the end of Arups' main involvement in what has been a most successful project — completed on time and within budget.

The Ravenspurn project has led us into a number of field development studies for other oil companies. From these studies we have concluded that for a wide range of applications — water depths from 20m to over 120m — concrete gravity substructures may be more economic than steel jackets. The greatest cost savings are likely to result where:

- Multi-purpose platforms are required (drilling, production and quarters).
- Platforms with relatively heavy topsides in comparatively shallow water are required.
- A phased field development is envisaged such that future topside equipment is difficult to define initially.
- Safety considerations lead to the requirement for a spatial separation between the accommodation and process areas.
- Oil storage (which can be accommodated within the base caisson) combined with tanker export is more economic than laying a new pipeline.
- The presence of rock close to the surface makes piles difficult to drive.

The ramifications of the Piper Alpha accident are yet to be felt fully by the oil industry.

Without doubt, future designs for offshore platforms will incorporate the lessons learnt.

From a fire engineering point of view alone, concrete as a structural material has much to offer. It is hard to imagine that another 10 years will pass before the next CGS is installed in the UK sector of the North Sea. And that one is much more likely to resemble Ravenspurn North than Gullfaks 'C'.

Credits

Client and operator:
Hamilton Brothers Oil and Gas Ltd.

Partners:
Amoco British Ltd., British Petroleum Development Ltd., Enterprise Oil plc, Renown Petroleum Ltd., Trafalgar Oil and Gas Ltd., and Ultramar plc.

Design, construction management and site supervision:
Ove Arup and Partners

Construction contractor:
John Laing ETE

Principal mechanical sub-contractor:
Davy Offshore Modules

Photos:
6, 7: Gordon Jackson
9, 10, 11, 20, 24, 25: John Roberts
12, 13, 14, 17, 19: Niki Photography
15, 16, 18: Peter Mackinven
21, 22, 23: Rob Wallis

Illustrations:
Fred English

Rank Xerox, Welwyn Garden City

Architects:
Nicholas Grimshaw & Partners

Ian Gardner
Roger Johns

Introduction

Rank Xerox approached the design team with a familiar scenario in early 1986. Their production complex on a large site in Welwyn Garden City was no longer fully utilized, while at the same time a new specialist research group was rapidly establishing itself. The new group was not involved in any manufacturing. Instead they were doing the clever, original thinking and software development for the business and office systems of the future; something the British are particularly good at.

This Systems Business Development/Engineering research group was located outside Welwyn Garden City in the grounds of a large house in run-down 1950s buildings, which it was rapidly outgrowing. Rank Xerox were seeking to relocate the research group on their main Welwyn Garden City site. However, in doing so they did not want to disrupt or upset the remaining production facilities on the site, and wanted to maintain the specialist identity of the new research group.

The brief for the new project was incomplete. The turnover of research projects within the Systems/Business group was so rapid that at any time they might be refitting up to 20% of their occupied floor space to suit the needs of the next research programme. The growth in staff had been fast: 30 in 1983, 80 in 1985, 130 in 1986. Xerox were not sure how to predict future staff numbers. They did, however, know that the group's continuing success would be dependent on attracting high calibre staff in the face of stiff competition. The new project should therefore provide an exciting working environment in a building with 'recruitment appeal'. Through discussions with Xerox we also recognized that team working was an important factor and that the community feeling within the group as a whole was strong. Any new building should seek to reinforce these concepts.

A 'generic building'

Grimshaw and Arups were initially appointed to carry out a feasibility study to assess the possibility of accommodating a new building within the main site.

We elected to do this by developing the client's given parameters into what we came to call a 'generic building' — a preliminary scheme design which identified a building type, depicting its likely architectural form and the appropriate approaches to its engineering design.

Our 'generic building' served two purposes. It was used to test the implications of developing the four available areas of the site, and it stimulated the definition of a project brief.

In developing the generic building concept a number of key objectives were identified:

(1) The target usable floor area would be 4000m^2 to accommodate 200-250 staff.

(2) The building would ideally be compact in plan to maintain group unity and, if multi-storey, would permit good contact between floors.

(3) Good electrical and teledata cable management was critical to the building's success.

(4) The building design should suit the extensive use of desktop computers and VDU screen-based information.

(5) The building must provide planning flexibility, with all working areas being column-free and unimpeded by staircores or services risers.

The last of these objectives, flexibility, is a much-misused term in our industry. It is something that clients always want, but they seldom know how much of it they really need or what they are prepared to pay for it.

Do they mean built-in flexibility or the ability to adapt at a future date? The former usually entails investing additional capital at construction stage so that future changes in use can readily be accommodated. The latter sets out to provide only what is initially needed, but to do so in a manner that permits future additions or extensions within agreed guidelines.

There is no such thing as total flexibility.

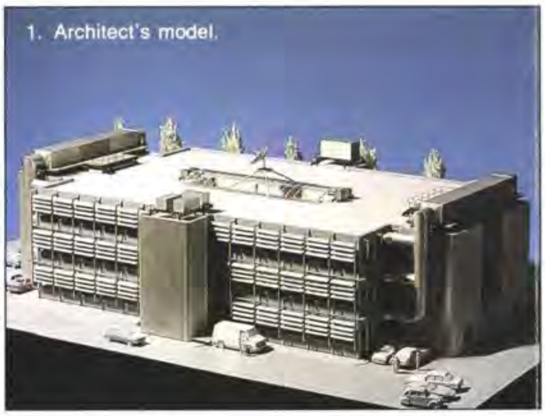
Much discussion took place on this issue during the early stages of the project and a 'value engineering' analysis was carried out shortly after our appointment in early 1987 to proceed with the project design. The intention was that no one part of the scheme should be extravagant at the expense of something else. We assessed the benefits of providing clear span internal space, different planning modules, the appropriate design diversity factors to apply to M&E systems, the use of prefabricated or conventional brick cladding, alternative shading devices, and the balance between speed of construction and cost. The design team outlined the options in terms of technical performance and cost and, with input from the client, value judgements were made. This resulted in a scheme design which had everyone's support and confidence.

Building form

Simplicity was the key to the development of the building form. Designs with one or two storeys were found during the feasibility study to be too large to suit the site options and tended to result in long horizontal travel distances for internal circulation. The three-storey concept overcame this (Fig. 1). Contact between floors has been achieved by wrapping the usable floor areas around a small central atrium, which also provides the focal point for internal circulation (Fig. 2). The atrium is 18m × 6m in plan and on all four sides the floor has clear spans of 12m to the perimeter (Fig. 3). A 1.5m planning module is used throughout.

The toilets, escape stairs, goods lift and services risers are pulled out of the main floor areas into six pods, which are located in pairs on the north and south elevations, and singly on the east and west. The boiler, electrical and sprinkler system plantrooms are formed by linking between the two pods at the rear, north side, of the building at ground floor. Air-handling plant and chillers are supported at roof level above the pods, with the main air-conditioning ducts dropping down outside the building envelope to serve the floors.

In developing the pods we realised that they were becoming the fixed, rigid elements of the building. This was further emphasized by enlarging each of the front and rear pods to accommodate a conference room and kitchen area. These provide what has become known as a 'home base' for each of the research teams. The rapidly changing research programme makes it likely that staff will be frequently moved around and the provision of a team conference room and kitchen helps to compensate for this by giving staff a space they can call their own.


1. Architect's model.

Energy considerations and solar shading

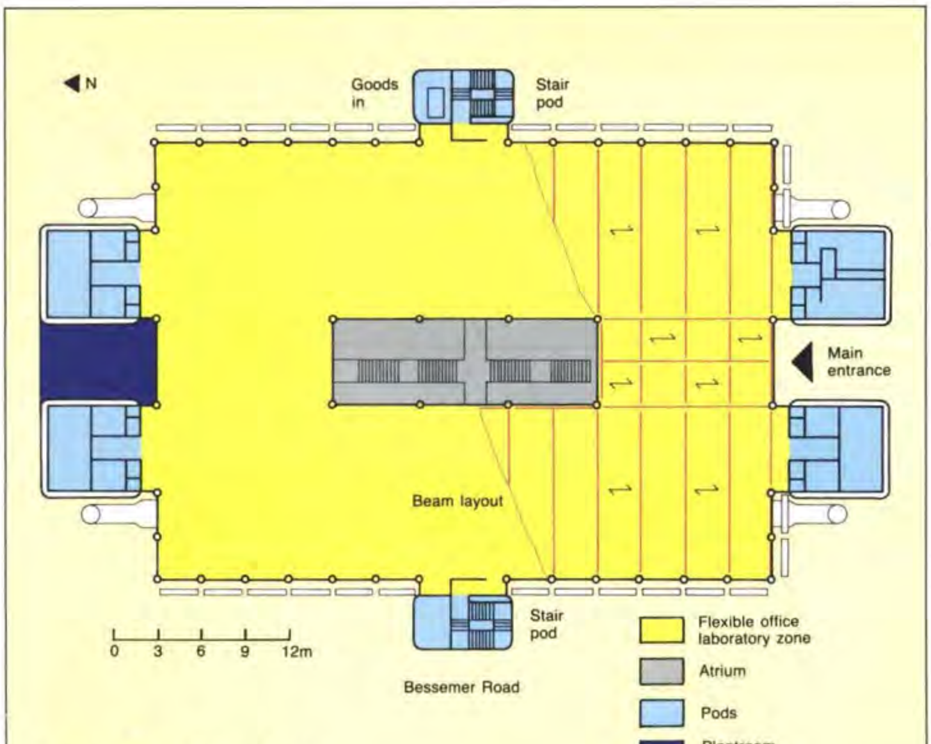
The internal heat gains generated by the many desktop computers and other electronic equipment mean that the cooling load on the air-conditioning system is high. We therefore set out to prevent significant solar gains which would have added unnecessarily to the already high cooling load.

The pods and external ducts provide shading to the main building. Further shading is provided by horizontal louvre blades on the elevations. The louvres are set clear of the main envelope and are highly reflective. Solar gains on the louvres are therefore not absorbed into the main building fabric, nor re-radiated off the louvres into the building. They allow clear glazing to be used and they greatly benefit VDU users by avoiding glare on screens (Fig. 4).

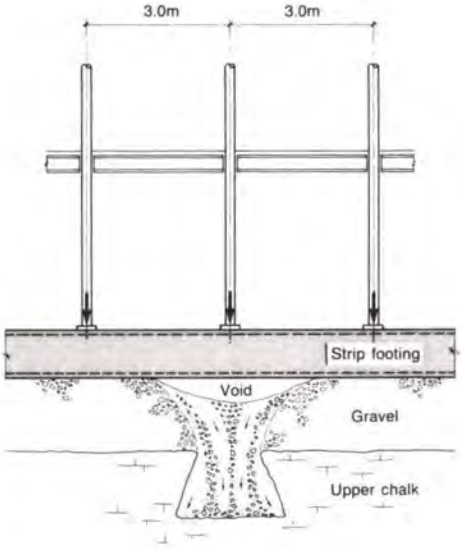
Foundations

Active swallow-holes are well-known in the area of Welwyn Garden City. The underlying stratum of Upper Chalk is predominately calcium carbonate, which is soluble in slightly acidic water (e.g. rainwater). Swallow-holes are developed by concentrated inflows of water causing localized solution weathering of the chalk surface. They take the form of enlargements of the joints in the rock, creating vertical inverted cone pipes.

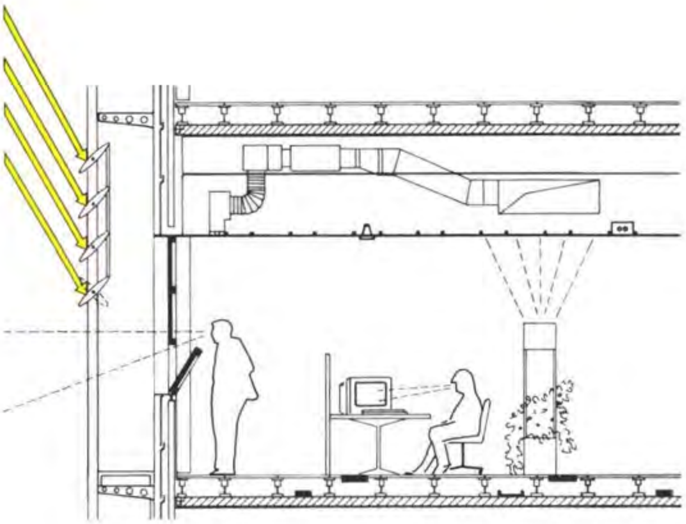

2. View of atrium.



3. Typical floor plan (first floor).



5. Swallow-hole.



4. Diagrammatic section showing louvres.

6. Corner detail of building showing louvres, catwalks, etc.

Usually, the pipes of swallow-holes are filled with gravel from overlying deposits. This gravel fill is often loosely compacted with weakly-bridged cavities and in such cases there is a risk of sudden subsidence (Fig. 5).

The ground conditions across the Rank Xerox site influenced the location selected for the new building. It is positioned in the north-east corner of the site in an area where Boulder Clay overlies the Glacial Deposits of sands and gravels. The impermeability of this clay stratum helps to prevent the inflow of surface water into the ground and therefore reduces the likelihood of swallow-holes.

Even so, it was agreed through discussions with our client that an allowance should be made to cater for a possible swallow-hole. The foundations were designed with some in-built redundancy. At the perimeter they are continuous strip footings, with sufficient reinforcement to enable a small local loss of ground support to be bridged. The internal foundations are a two-way grillage of strip footings.

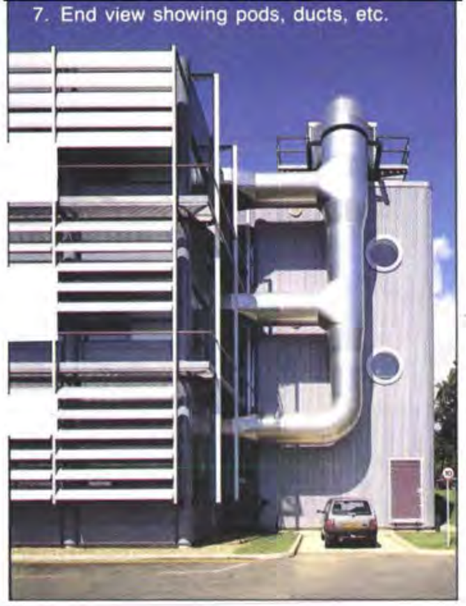
Structure

The building has a steel frame with lightweight concrete floors cast on profiled metal decking permanent formwork. The floor slabs act compositely with the steel beams to provide the 12m clear spans. Being only three storeys high the column sections were delivered in single lengths with no joints required on site. Therefore all structural members were completely fabricated off-site and were easily transported for rapid erection by simple beam/column bolted connections. The total structural steel weight is 195 tonnes ($42kg/m^2$).

The need to allow redundancy in the foundations had a significant impact on the building design. The easiest way to achieve the required spare capacity with simple strip footings was to keep the column loads as low as possible. This was done by placing the perimeter columns at only 3m centres.

Full benefit has been obtained from this close column spacing. The resulting columns are small enough to form an integral part of the elevations, rather than take up valuable floor space. Although not exposed, the cladding system expresses the column locations. Also, significant savings in the cost of the cladding were achieved; the shading louvres have not had to be supported off the cladding since the columns are close enough to provide direct support for them. This allowed the louvres to be supplied independently from the main envelope cladding and much more competitive tenders to be obtained for each. Steel cantilever brackets, shop-welded to the perimeter columns, provide support to the external cleaning catwalks and to the solar shading louvres (Fig. 6).

A further benefit of the close column spacing has been to save structural steelwork weight by eliminating the need for primary edge beams. In all cases the main floor beams span directly onto the perimeter columns, so only nominal tie members are provided at the edge of the floor slabs between the columns. Primary edge beams on all floors would have weighed considerably more than the additional columns.

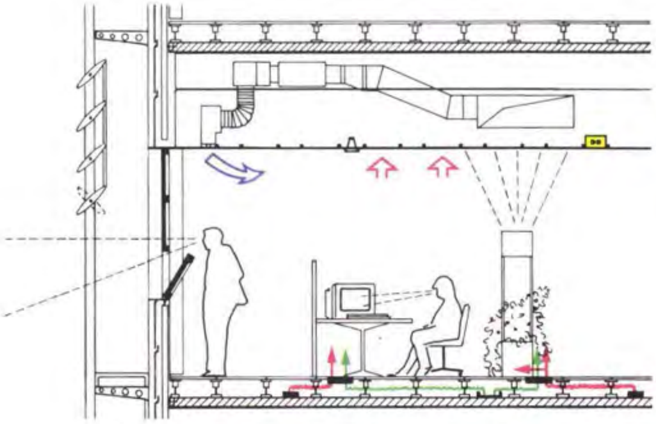

7. End view showing pods, ducts, etc.

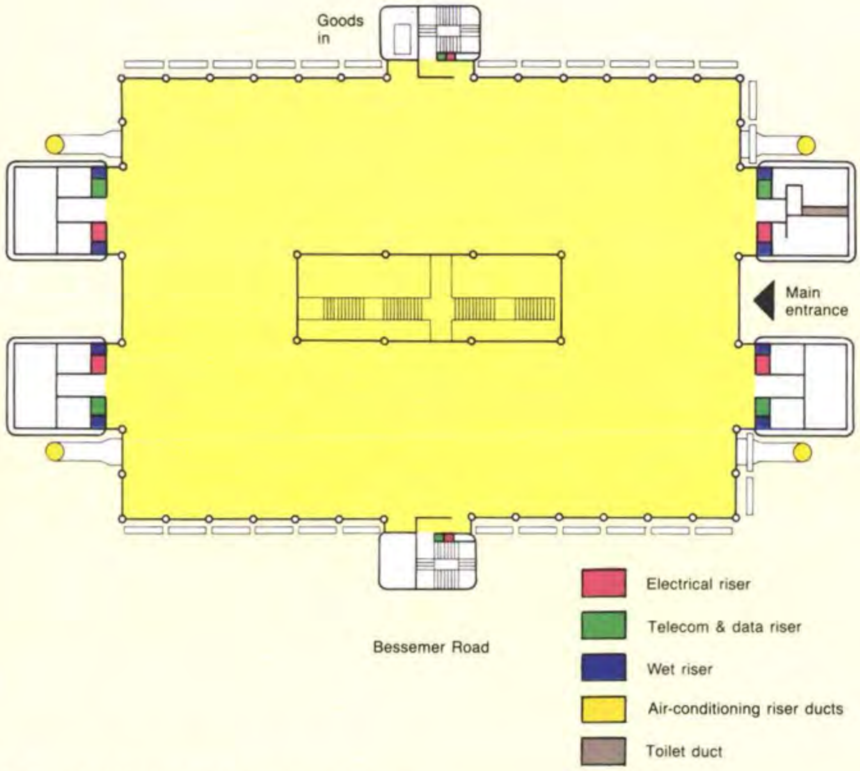

8. General view from north east.

Around the atrium a column spacing of 6m is used, this time with primary edge beams to support the intermediate main floor beams and the stairs and bridge links across the atrium. The building therefore has only eight internal columns.

The pods were previously described as containing the rigid, fixed elements of the building. The larger ones at the north and south ends are planned on a 6m × 6m grid, with those on the east and west on a smaller 6m × 3m. All of the pods are spaced 1.5m clear of the main building floor plan, but are structurally continuous with it (Fig. 7); the floor slabs and steelwork frame carry through directly at each level. Consistent with the planning, these pods provide the structural rigidity for the building with stability cross-bracing located behind their profiled metal cladding.

Use has also been made of the smaller spans of the pods to provide support for roof-mounted services plant and for high level water storage tanks. Structural gantries support plant clear of the roof to avoid complications in the design of the lightweight roof decking and to give better expression of the design concept. Like the pods, catwalks and louvres, the plant platforms appear to have been clipped onto the simple rectangular box of the main building envelope (Fig. 8).


10. Diagrammatic section showing services distribution.



9. Key plan diagram showing services risers.

Electrical installations

Advanced electrical works were carried out on the site to provide power and standby generation for interim temporary accommodation and the new building. This comprised a new 1000kVA substation and a 500kVA standby diesel generator.

Additionally, underground ducts were laid to provide teledata links from the nearby existing buildings on the main site to the new building.

A low voltage switchboard is installed in the new building with provision for the anticipated expansion of its power requirements. Space and cable access provision are also made for uninterruptible power supply equipment (UPS). We have assisted the client in the specification and selection of UPS equipment which can be purchased as and when required.

A very clear discipline has been developed for the distribution of electrical systems. Separate vertical risers are provided for power and teledata in each of the six pods, positioned to feed directly out into the main floor areas (Fig. 9). All final distribution is co-ordinated within the raised floor void to reach three-compartment outlet boxes mounted flush with the raised floor. Only emergency lighting and smoke detection electrical systems are within the false ceiling (Fig. 10).

Local distribution boards are located in the electrical risers at each floor and include provision for 415V, three-phase supplies. Small power is distributed in the floor voids by means of multiple runs of underfloor bus-bar trunking, spaced in parallel runs at 4.5m centres (Fig. 11). The selected bus-bar system provides 32 amp tap-offs at 300mm intervals along its length and can be easily extended. Each floor outlet box is wired with a 2.5m long flexible connection plugged back into the bus-bar trunking. Each floor is on a separate phase of the supply.

Similarly, teledata cable provision is made to feed outlets in the floor boxes. Parallel runs of cable trays are provided to encourage good cable management. These are spaced to achieve reasonable separation from the power trunking and are cross-linked at the ends and in the middle of the floor plan to connect back to the teledata risers.

The ample provision made for distribution of power and teledata has gone a long way to eliminate congestion and to permit simple and tidy cable management, both for the initial installation and for future changes by Rank Xerox. The few months that the building has been occupied have already proved the validity of these distribution concepts.

Main lighting has been installed by the client post-contract, to our design. Uplighters are used and located as required at work stations, supplies being taken from the socket outlets in the floor boxes. Recessed fluorescent luminaires with local battery packs are used for circulation and escape lighting, laid into a 1200 × 300mm zone of the ceiling, which is planned on a tartan grid of 1200mm and 300mm widths to fit the 1.5m planning module. Escape lighting can therefore be readily relocated to suit floor layouts.

Air-conditioning

The building is fully air-conditioned to cater for the high densities of electronic equipment. The variable air volume (VAV) system is designed for peak equipment loads of 100W/m^2 in any zone of the building and an average load across the whole building of 50W/m^2. Two air-handling units are located externally above the pods at the north and south, each rated at 10m^3/s (Fig. 12). An air-cooled water chiller, rated at 428kW, serves the VAV plant.

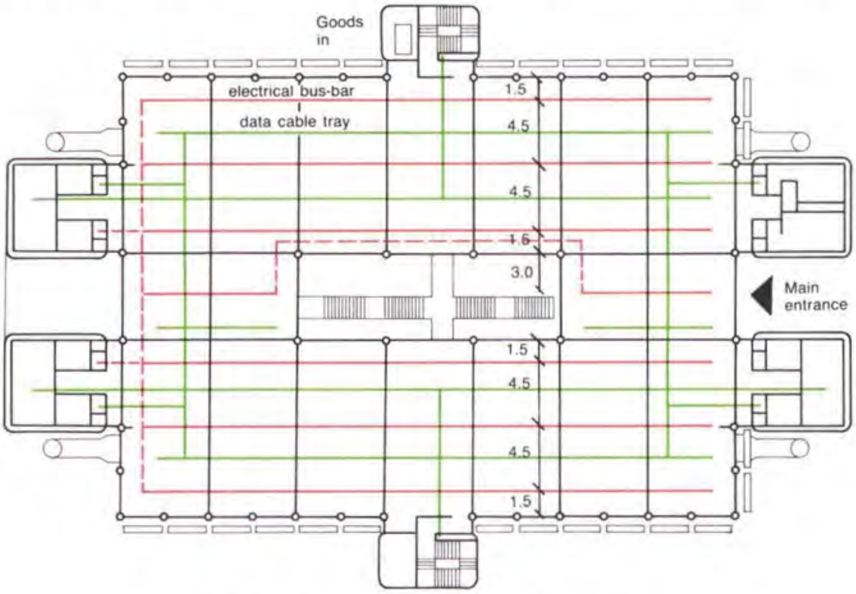
Supply air ductwork within the false ceiling at each floor forms a closed loop fed jointly from both air-handling units. This provides flexibility, to cover concentrations of load in one half of the building or one unit being temporarily out of service. VAV control boxes each serve a 6m square bay, with perimeter slot diffusers for supply air. Terminal reheat on the control boxes is by low pressure hot water from gas-fired boilers. Return air is extracted through the ceiling plenum.

VAV air-conditioning was selected because of its ability to compensate for changes of load in different zones of the building, and because during much of the year the ambient air temperature will be low enough to provide free cooling. Discussion took place on the need for terminal reheat in a building where the air-conditioning is expected to be always in a cooling mode, but it was decided that heating should be installed to deal with cold start-up after the Christmas break. This also enhanced the building's future marketability.

Downflow air-conditioning units are installed in the mainframe computer room and a specialist printing room, both on the ground floor. These are served by three air-cooled chillers mounted at roof level, each rated at 110kW, with two duty and one standby. The downflow units are floor-standing and force air down into the raised floor void which acts as a supply plenum. The building has a fully accessible raised floor with bonded carpet tiles throughout. At ground level the raised floor height is greater than on the upper floors and a number of the tiles are predrilled, allowing air from the plenum void to enter the space.

The main air-conditioning plant can be used to extract smoke. Also four smoke extract fans are provided at high level at the ends of the atrium (Figs. 13 & 14).

12. View across the roof of one air-handling unit, supported on a gantry above the roof surface.



11. Key plan diagram showing services floor distribution.

13. Upper part of atrium showing high level extract fan grills.

14. Close-up of two smoke extract fans on the roof.

Sprinkler system

Although not required by the Fire Officer, Rank Xerox asked mid-way through detail design for the building to be fully sprinklered to comply with their corporate world-wide policy. A sprinkler system based on FOC Ordinary Hazard Class 3 is installed.

Having rigorously kept to the 1.5m planning module with the electrical and HVAC installations, the introduction of a sprinkler system resulted in some inevitable loss of flexibility. A sprinkler system has yet to be devised which respects a planning module and which can accommodate different partition layouts without modifications to the sprinkler heads. The ceiling construction has however been designed to impose a discipline on changes to heads and thus maintain visual control.

15. View from south east.

16. North side of the building showing pods, air-handling plant, ducts, and ground floor plantroom.

Summary

This building provides a prototype for small/medium-sized offices in which particularly heavy reliance is placed on electronic business systems. Xerox have put considerable resources into the electronic office of the future, and their new building truly reflects this commitment. They appreciate they have got good value and that the completed building cost of £820/m^2 compares favourably with the Spons 1988 adjusted rates for computer buildings of £760-£1140.

The high-profile design image of the project and the technical engineering interest meant that contractors were keen to be associated with the project. Tenders were returned within budget and following a construction period of 14 months it was handed over on time in December 1988. Since handover it has been coping continuously with change.

Credits

Client:
Xerox Research UK Ltd.
Architect:
Nicholas Grimshaw & Partners
Structural, civil and services engineers:
Ove Arup & Partners
Quantity surveyor:
Davis Langdon & Everest
Main contractor:
Wimpey Construction (UK) Ltd.
Photos
1: Nicholas Grimshaw & Partners
7, 8, 12, 14, 16: Peter Mackinven
2, 6, 13, 15: Jo Reid & John Peck
Illustrations:
Veronika Hrga

Les Tours de la Liberté

Architects:
Jean-Marie Hennin + Nicolas Normier

Bernard Vaudeville
Brian Forster

It was decided a long time ago that the celebrations for the Bicentenary of the French Revolution would be marked by a temporary, but imposing, monument in Paris. Originally, it was to be a World Exhibition, on which Arups began work in 1983. Then, owing to repeated changes of programme, soul-searching about the significance of the anniversary, and shifts in the balance of power in the French Parliament, the Government were in the position of having to choose a project as late as October 1988, to be completed before April 1989.

The scheme that was finally selected had the advantage of having been drawn up quite carefully by the architects Hennin and Normier, as well as being supported by a bold and ambitious steelwork contractor, Viry (who, incidentally, built two other Arup projects — a Commercial Centre near Nantes by Rogers and the Nuage at Tête Defense, Paris). It consists of two 35m high towers, situated in the Jardin des Tuileries in front of the Louvre, within a fair commemorating events during the Revolution.

Each tower has a central pylon, 4.5m × 4.5m square on plan, carrying at a height of 12.5m a two-storey cantilevered box 18.6m × 15.6m on plan. The two boxes house a radio studio, information stand, party reception rooms and, at roof level, observation decks. In essence, the construction is welded hollow sections with solid round-bar bracing.

The towers also serve as a framework to which layers of wings, fins and canopies — each covered by semi-transparent materials — can be attached and suspended in mid-air. Indeed, above all the towers are sculptural landmarks, each crowned by two imposing wings which can be seen from a long way down the River Seine. The project explores space and air by means of an open, even exploded form, with the characteristic shapes of early 20th century aeroplanes serving explicitly as formal references for Hennin and Normier.

Ove Arup & Partners, through the office of RFR in Paris, did the technical studies and the conception of the main details for the steel structure and the wings, in close collaboration with Viry.

The main technical difficulties that had to be overcome are summarized as follows.

The tight schedule

This was the overriding challenge and we had to establish a strategy, so that Viry could start manufacturing while we were still designing. To this end, we split the structure into three sections: the central pylon, the glass box, and the hung elements (wings, fins, and canopies).

Outline schedule

End of November 1988
Beginning of the technical studies

15 December 1988
Sections and forces in the central pylon established

24 December 1988
Structure of the 'box' resolved

15 January 1989
Changes in the structure of the 'box', at Viry's request, owing to manufacturing difficulties

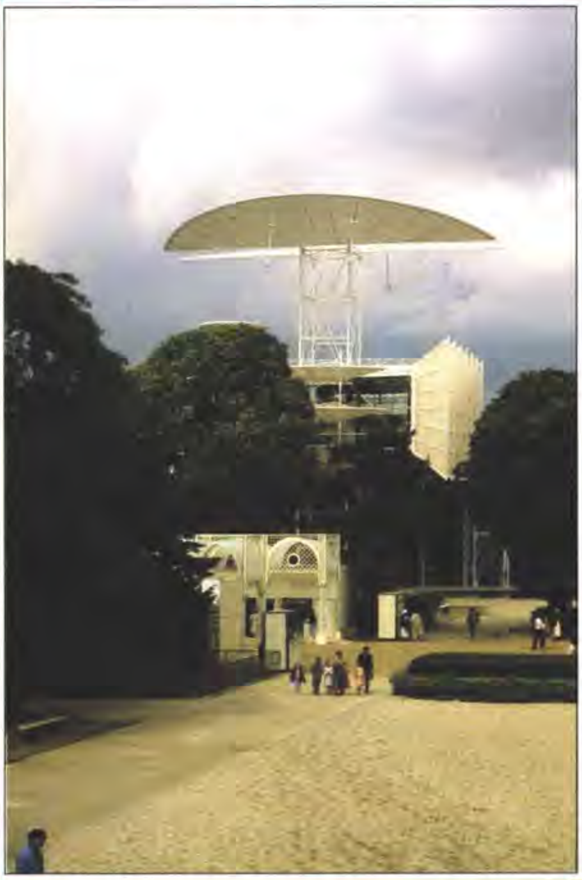
15 March 1989
Detailed calculation of wings and canopies completed.

Computer models

Given the close interaction of these three sections, we created various overlapping computer models.

First stage

Pylon + simplified box (calculated with the Arup general structural analysis program GSA), to determine the forces in the pylon.



Left: View from the entrance ramp of one tower across the Tuileries to the second tower.

Above: Flying strut at the top of the pylon.

Where the pylon goes through the box, the bracings have been omitted to allow free circulation. Here, the structure of the box itself has to provide the bending and torsional rigidity to the tower. At this stage the rigidity of the box was set very high, by means of simplified bracings, in order to lower the torsional dynamic response of the pylon (see later).

Second stage

Pylon + definitive box + simplified modelling of the loadings applied by the wings (calculated with GSA). On this model, we defined the structure of the box according to the architects' requirements (with as few visible cross-bracings as possible) and in order to achieve the previously set torsional rigidity of the whole tower. We used the concrete floors as rigid diaphragms between the pylon and braced external facades of the box.

Third stage

Partial models of the wings, fins and canopies (by means of GSA and Arups' non-linear space frame program FABLON). In order to investigate the local effects these included some elements of the main frame on which the wings are fixed. Thanks to the margin we had kept in the previous stages, none of them had to be reinforced.

Wind

The intricacy of the shape required a wind tunnel test, conducted by Aerodynamique Eiffel. This was the first wind tunnel laboratory in the world, founded by Gustave Eiffel himself. For each direction, the measurements provided, on the one hand, the local pressures on the principal elements and, on the other, the resultant force/moment vector resulting from wind at the base of the towers.

In the results, there was a lack of information concerning the detailed distribution of the wind along the height of the tower. To remedy this, we established the following method:

For both overall axes of bending and for torsion, we assumed a wind distribution on the basis of the measured pressures and of the wind code. After calculation, for each case, we got one of the three components of the resultant moment.

We then adjusted these values on the measured ones for the same direction, by factorizing each basic case. In order to simplify, in practice we considered only one conservative direction.

Dynamic response

The bending and torsional dynamic behaviour was the main weakness of the principal structure, because of the absence of any cross-bracing where the pylon goes through the box. We had to multiply the wind forces by a high dynamic amplification coefficient (Beta), which was calculated according to the natural frequencies for each mode of vibration.

We had:

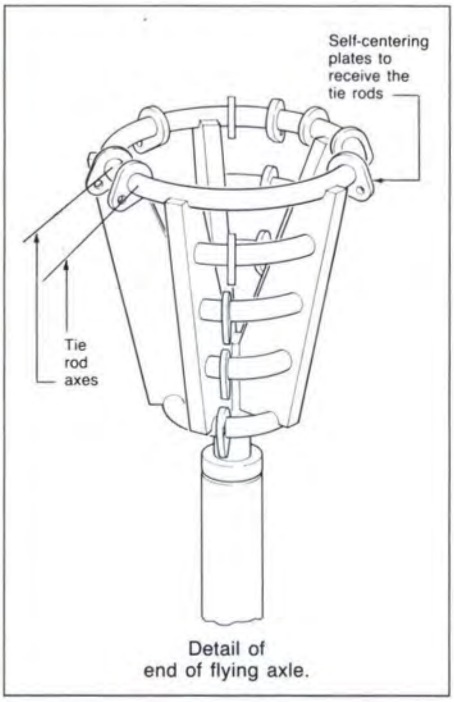
- for torsion, frequency = 0.64Hz
  Beta = 1.65
- for bending, frequency = 1.00Hz
  Beta = 1.5

These coefficients were applied on each component of the measured resultant moment respectively.

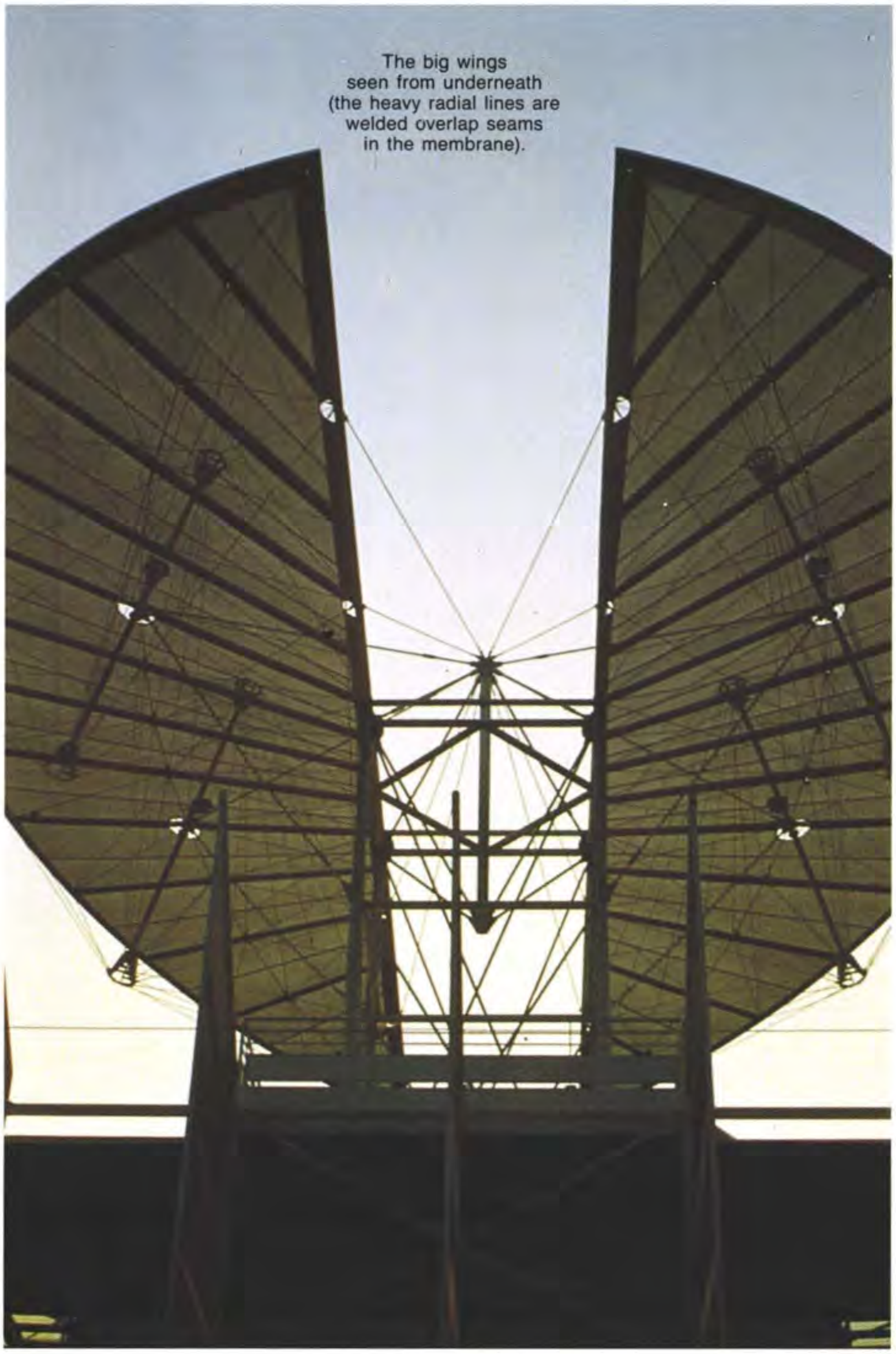
The big wings

The wings on top of each tower are large enough and high enough to be seen from many points around the city. Each wing is a segment of a circle 31m long, 10m deep, and inclined at 15° from the horizontal. Each is a thin plane covered with a white PVC-coated polyester membrane perforated to about 30%. At close range this gives a degree of transparency that reveals elements of structure beyond.

Close-up of the end of an axle through a big wing.



Detail of end of flying axle.



The big wings seen from underneath (the heavy radial lines are welded overlap seams in the membrane).

The architects had determined the outline dimensions of the wings and Arups' role was to add substance to them in developing a structure which was constructable yet did not lose the 'esprit' of the original concept.

The wings had to be seen as thin planes appearing to have minimal contact with the pylon. It was also clear that in the short time available for construction, each wing would have to be assembled complete at ground level and lifted by crane onto the tower. Thus the structure of each wing would have to be stable within itself before being attached to the tower.

We therefore introduced the use of flying axles that pass through the surface of each wing and from the end of each axle we arranged a fan of 16mm diameter tie-rods running out to the 168mm diameter circular edge beams. This system provides the out-of-plane bending stiffness needed in each wing. In-plane stiffness is provided by radially aligned strut/beams 139mm diameter CHS, with 12mm diameter rod cross-bracings. To reduce the bending imposed on these beams there are fans of tie-bars from the ends of each axle that pick up the mid-point of these beams, forming a tension spine in a curved plane. This spine enhances the wings' out-of-plane stiffness as well as reducing the diameter of the beams. Modest prestress was introduced into the tie-bars sufficient to maintain the straightness of each bar in its erected position. The straight edges of each wing are hinged directly onto the corners of the towers. Each wing is then held against global rotation by further tie-bars from above and below.

The membrane was manufactured in a single piece from strips welded together following the lines of the radial beams. A prestress of approximately 300kg/m was put into the membrane by pulling its exterior boundary onto the perimeter beams of the wing. The extension in the material to get this force was allowed for in the cutting patterns that we supplied to the contractor. Having clamped the fabric to the edge beams it was then fastened continuously along each radial beam using a rope lacing detail. This was done to limit the deflection of the membrane surface under combinations of wind and snow load.

The wind pressure coefficients were derived from the results of the wind tunnel test. Loading combinations were deduced which would produce the worst effects both on individual wings as well as on the pylons. The structure was analyzed using FABLON. This permitted correct modelling of the changing stiffness of the structure as ties came in and out of action under different loading conditions. Stability analyses were also performed with FABLON to establish elastic buckling loads for the edge beams, braced out-of-plane only by tie rods.

Finale

Viry erected the wings successfully and as planned during the weekend 8-9 April 1989 and the project was opened in early May 1989 by M. Rocard, the French Prime Minister.

Credits

Client:
Production Tuileries '89:
SCIC-SA/Bouygues/RCI/Viry/Geteparc
Architects:
Jean-Marie Hennin + Nicolas Normier
Structural engineers:
RFR SARL
Ove Arup & Partners International Ltd.
Foundation contractor:
Bouygues SA
Superstructure contractor:
Viry SA
Photos:
Reproduced by courtesy of RFR

Matters of concern

Jack Zunz

This is an edited version of the address given by Jack Zunz at the Institution of Structural Engineers, 23 February 1989, on the occasion of his receiving the 1989 Gold Medal 'for personal contributions to the advancement of structural engineering'.

I am very honoured and flattered, as well as somewhat surprised, to receive the Institution's Gold Medal. I am not sure that I deserve it, but I am sure that it is more a tribute to the firm which I have been privileged to serve for many years than to my personal contribution.

When I was first told about this award, I thought thankfully that, as Oscar Wilde said, this was 'the precise psychological moment when to say nothing'. The benefits of saying little or nothing are nicely illustrated in the rhyme by Edward Hersey Richards:

'A wise old owl sat on an oak
The more he saw the less he spoke
The less he spoke the more he heard
Why aren't we like that wise old bird?'

But it was not to be. No 'wise old bird' act for me. The last paragraph of the Secretary's letter said that I was expected to deliver a discourse on a subject of my choice. As though this wasn't enough, this ranging shot of the Secretary's was soon followed by the real salvo from the President who . . . 'was sure that I would regard this as an opportunity to express an important message concerning the art and the science of Structural Engineering'.

So here I am feeling somewhat exposed, with no message, let alone an important one. What I *will* try and do is to convey to you some impressions and ideas which have evolved during my professional life, impressions and ideas which have come together rather late and have become matters of concern to me. I will give you a brief indication of how I got there and indeed will touch on some structural engineering matters on the way.

I obtained a degree in Civil Engineering in 1948 after interrupting my studies to do war service in World War 2. I left university feeling under-educated — not only in some of the technical subjects which interested me, but also in the arts and the humanities, not to mention economics and other matters associated with the society we serve.

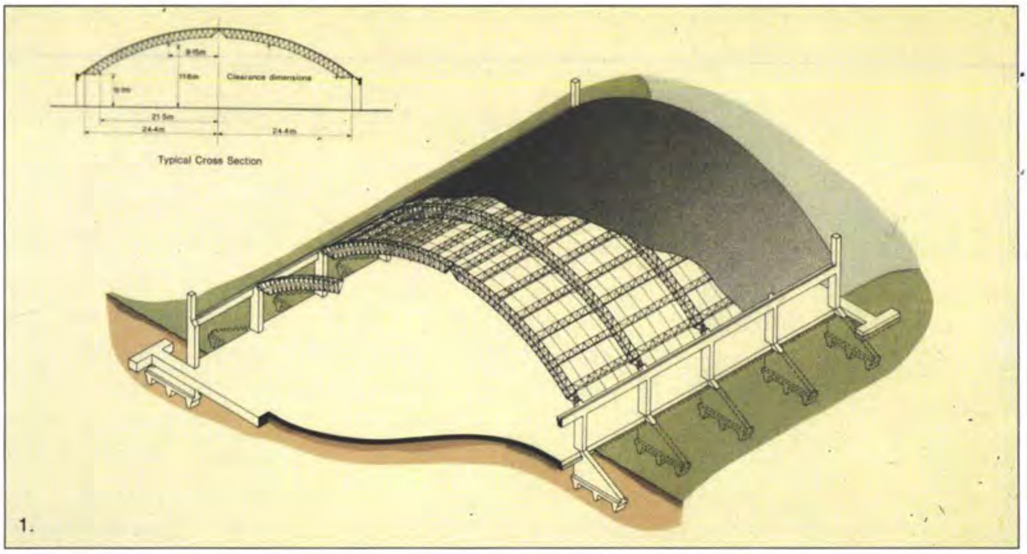
Those of you who are of the same generation may recall, even with some nostalgia, the tremendous relief that the War was over, that something very evil had been disposed of and that technology, which appeared to have no bounds, would prove to be the salvation of mankind and would help to solve the social and economic failures of the '20s and '30s.

Moreover, I was doubly fortunate to come under the influence of Ove Arup in 1950, who together with his partners, particularly Ronald Jenkins, was bringing his own brand of technological creativity, supplemented by a high level of intellectual rigour, into the construction industry.

Life was exciting — there was so much to do, to be rebuilt or renewed. We had few of the analytical or practical tools which are available to us today, but the confidence, sometimes bordering on arrogance, with which we tackled the problems of the time was in stark contrast to the caution with which so many great enterprises are beset today. Life was exciting — no mountains were too difficult. Mind you, by today's standards we had no money, but we had fun.

In hindsight the work, though heady and exciting at the time, lacked refinement. I will try and explain by showing you two projects on which I worked. One was built, and the other — though thought to be a good idea at the time — was never realised.

In 1953 we were asked by John Laing to assist in a design/construct bid for some aircraft hangars for the Royal Air Force. The hangars were required for the 'V' bombers which were coming into service in the '50s.



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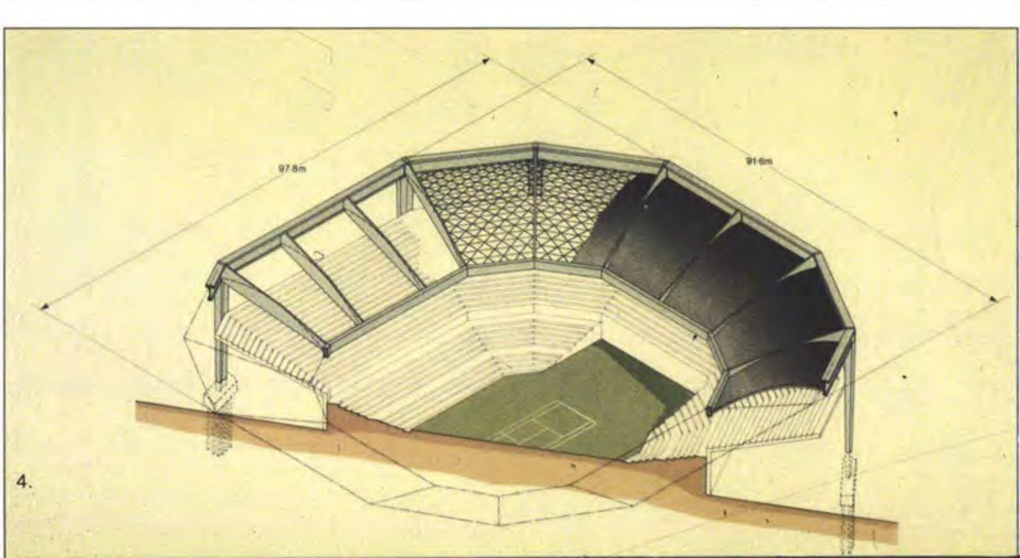

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Laings came to us because we were thought to have acquired some expertise in light, thin concrete roofs, shells and domes. They thought a solution using some form of concrete membrane would be both economic and suit their particular construction expertise (Figs. 1-2).

The RAF specification was simple and clear — the dimensions of the hangars were dictated by the size of the aircraft to be sheltered, insulation requirements were modest and the doors, always the most testing problems in aircraft hangar designs, were as simple as they could be.

We advised Laings that the most economic solution was not a concrete structure but a hybrid. The roof should be light, in steel, and dimensioned as closely as possible to meet the RAF's clearance requirements. This roof should be supported on a concrete structure, which in turn was proportioned to transmit the forces to the ground as simply and directly as possible — on the one hand maintaining the required clearances and on the other not exceeding the specified allowable soil pressure.

Laings' tender was successful and a number of these hangars were built. (Needless to say we, as consulting engineers, were only paid for one.)

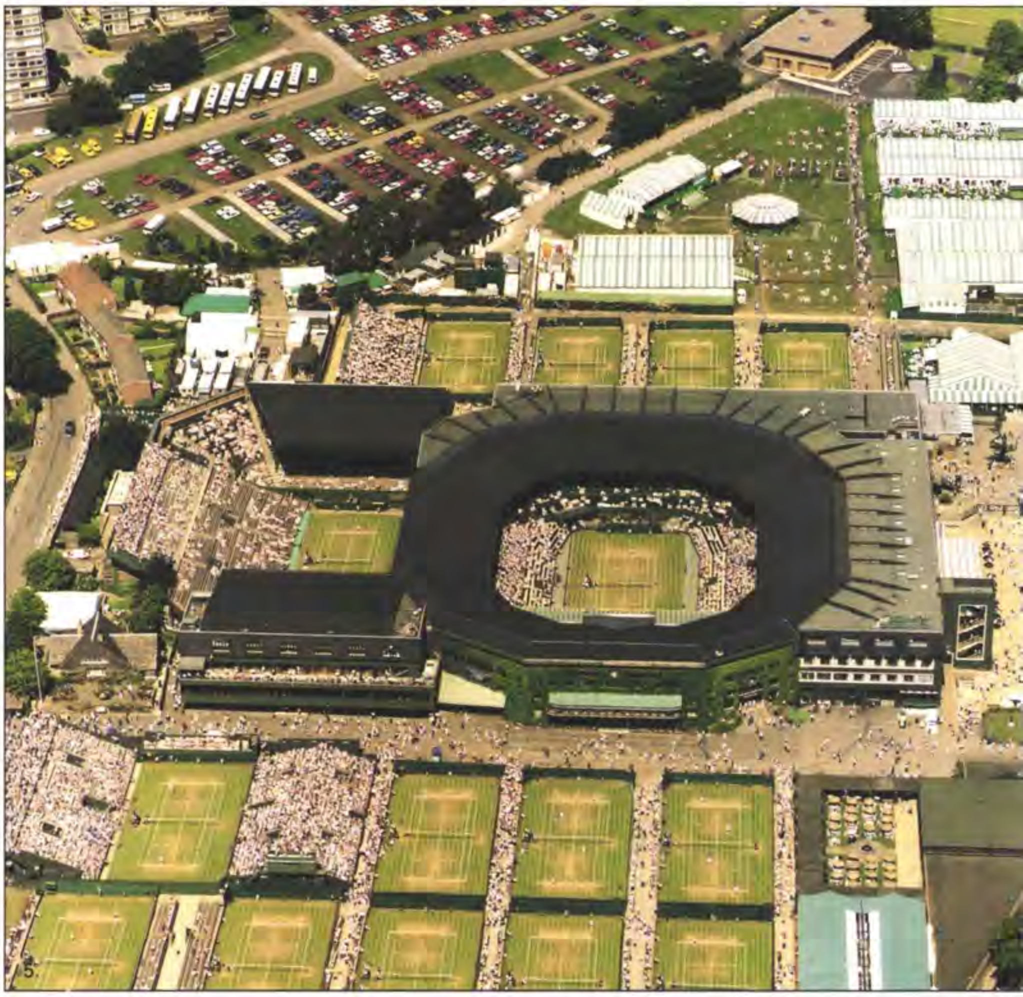
The other scheme, the unbuilt one, was a proposal to rebuild the Centre Court at the All England Lawn Tennis Club in Wimbledon. The Centre Court, the 'Mecca' of world tennis, as yet unsullied by the financial hype which has alas taken over so much of our sporting life, was built in 1922. Essentially it has a 12-sided plan, symmetrical about two orthogonal axes. There were 48 columns, many obstructing the sight-lines of the spectators. Moreover, the years had taken their toll and the structures supporting the roof, as well as the roof cladding itself, were in urgent need of maintenance or replacement.

We were approached by a firm of surveyors/architects, a combination not as much in vogue now as it was then, with a bold request to remove all the columns except those at the corners of the duodecagon, the 12-sided plan. Moreover, the quality of the grass on the playing surface was thought to be so good that nothing was to be done which might have any effect on it whatsoever and, since it was thought that this quality was the result of light and shade, as well of the ventilation which the existing roof structure provided, we were requested to maintain all existing roof angles and the proportion of covered to open areas precisely as they were. There was not a great deal of room for manoeuvre.

The proposed solution, shown in Fig. 4, consisted of 12 columns placed at the corners of the duodecagon, a compression ring joining the tops of these columns. A lattice shell made of tubular steelwork comprised the general roof structure. Beams radiate from the tops of the columns towards a tension ring, which together with the tension and compression rings form a stiff prestressed concrete structure which takes care of unsymmetrical loading.

This solution came to us late in the day and tender documents had to be prepared in a hurry. You can imagine how in this pre-computer era (calculating machines had only just become acceptable) some shortcuts had to be taken and much reliance placed on the beneficent nature of the materials with which we worked.

Tenders came in early in 1954 and the cost, £197 000, was thought to be too high a price to pay. The scheme, perhaps fortunately, was never built. Considerable rebuilding has, of course, taken place at the Centre Court over the years (Fig. 5), but none was so ambitious as to remove all the columns, as those of you who watch tennis there will know. Incidentally, we ceased to be involved after this scheme of ours was shelved.


5.

These two schemes held some valuable lessons. In their own way they were very exciting to a 30-year-old structural engineer. It was heady stuff, but both schemes were typically the result of analytical deductive reasoning — in other words typical engineer's solutions.

In hindsight both schemes were flawed. In the aircraft hangars everything seemed to fit together logically — the steel tubes could not be more than 6in. in diameter, which were the largest available at the time, and the arches were proportioned accordingly. There was some adjustment of the pin positions to give some bending moment relief — all very sensible. But the limitation in tube sizes meant that the arches lacked elegance. And the hangars are awful visually — they are large structures and a blot on the landscape — fortunately Prince Charles was too young to notice. Equally, the Centre Court proposals were not really thought through properly. Water, the eternal enemy of all roof structures, had to be pumped away somehow. One could possibly argue that had we been asked to realise the scheme we would have worked our way through this and some of the other more obvious problems which remained unsolved, but I have a feeling that the detailed design both on engineering as well as on architectural grounds would have fallen short of what was desirable.

It is probably true that most of us find our work flawed in some respects when we look at it critically after completion. I have yet to come across a project where in hindsight improvements could not have been made. But these two schemes, coming at the time they did, brought home to me more than any other that traditional analytical deductive reasoning to reach appropriate solutions to engineering problems simply isn't enough. Commodity and Firmness are necessary but Delight, the third partner in Sir Henry Wotton's aphorism, is as important as the other two.

So what's new?, you might say. Nothing ever is, but it gradually began to dawn on me that we, as engineers, have a much broader role to play in our society. To begin with, this understanding was linked with the role of the engineer in the total building process, what Ove Arup used to call 'Total Architecture'.

Modern technology has helped to bring about the gradual demise of the architect/builder or for that matter the engineer/builder. We have watched the evolution of the building 'team' which includes the many specialists whose expertise is necessary for the creation of a modern building. Volumes have been said and written about the necessity for teamwork to resolve the problems arising out of the seemingly conflicting needs of each discipline in the total design, as well as the increasing complexity of managing all the parties — contractors, suppliers and designers. A different kind of leadership has emerged to take the place of the traditional engineer or architect. It is more complex, more challenging, more interesting, and a consequence of the more intricate nature of our designs as well as the less direct and trusted relationships between the parties who take part in the building process.

All this is old hat but it is surprising how few of us really understand all the issues involved. We have clearly failed to serve our society as well as we might. The criticisms now levelled at the built environment created by us, amongst others, in the last 30 years have much justification and bite. The architectural profession attracts much publicity for its work and the engineers' contribution is often unrecognized. Equally, we as engineers are not exposed as much as we might be when architecture is under fire, as it is at present.

Anyway, we as civil and structural engineers (and sometimes I find it difficult to make a distinction) are playing our part as members or sometimes as leaders of multi-professional teams. The teams' success is not only dependent on the individual skills of its members all practising their own discipline, but also on their appreciation and understanding of the other disciplines and the totality of design they are attempting to create. It is a classic situation where the whole is, or at least should be, better than the sum of the parts, provided always that the holistic concept of the design is understood as part of the stock-in-trade of all, or at least most, members of the design team. Whether the members of the team work in totally integrated groups or in separate disciplines doesn't really matter — it is the end that counts not the means, although it must be said that geographical proximity does help.

So that over the years I have become increasingly conscious of our role in the construction industry in particular and in society in general. I have been fortunate in being able to continue to contribute to a number of interesting projects which, like some of these early endeavours, have been exciting and rewarding experiences. But more and more the role of engineers and engineering in our society has become a matter of concern.

Fragmentation of the profession

The fragmentation of the construction industry has been spoken about and debated for a long time, as indeed has the role of the engineer in society. The President in his excellent and wide ranging Presidential address touched on both topics. The launching of the Building Industry Council last September could well prove to be of benefit to our industry and it deserves our support, particularly if the circle is properly closed by including all the organizations involved with the industry. But I do not believe that this will get to the root of the problem. Albert Einstein suggested that 'everything should be made as simple as possible, but not simpler'. Our problem, put in the simplest possible terms, is that we live in an anti-technology society where the work and worth of engineers is not properly understood and hence appreciated. The most serious consequence of this lack of appreciation is that the quality and the quantity of young men and women attracted to industry is inadequate — a vicious circle which is difficult to break.

I have noted before the observation of Samuel Smiles, who found engineers to be 'strong-minded, resolute and ingenious men; impelled in their special pursuits by the force of their constructive instincts', and the then Prime Minister, Lord Gladstone's, that 'the character of our engineers is a most signal marked expression of British character'. Somewhat pompous and chauvinistic for current taste, but nevertheless even when translated into a late 20th century context an almost inconceivable comment from someone in a public and powerful and influential position.

So what has changed? What has gone wrong? Is it not true that civilised life is only possible as the result of the work of engineers? What would life be like without clean water, heated homes, effective means of transport, safe structures and so on . . .? Why, over the last 100 years or so, has the work of the engineer apparently not been appreciated by our society?

The answer is unfortunately complex and deeply rooted in the social and economic history of this country. There are no simple answers, no instant solutions. But we can at least make a start by recognizing that there *is* a problem and to try and understand *what* it is. Only then will we be able to formulate and work towards solutions. I fear that even now not many engineers, let alone the public at large, fully understand the seriousness of the lack of skills, both in quality and quantity, which is a direct consequence of the lack of appreciation for, and understanding of, the role of technology in our society.

And the consequent self-delusion and complacency simply have to be overcome if we are to stop rejoicing every time a Japanese company decides to set up a manufacturing capability in this country. We have to understand that creating jobs with imported technology has a proper place in industry but only in the context of a strong home base. It is the proper development of this home base which deserves our strongest endeavours. But, it will, I am afraid, be a long haul.

The construction industry is fragmented, but the engineering fraternity even more so, with I believe even more serious consequences. The Finniston Report, 'Engineering our Future', was thought to be more appropriate to productive industry than the construction industry, but where is the demarcation? Contemporary construction embraces the use of simple natural materials as well as sophisticated hardware and software.

In 1987 the United Kingdom's balance of trade deficit in building materials was in excess of £2bn. This represented 14% of our total deficit in manufactured and non-manufactured goods. In 1988 it was considerably more. The construction industry cannot dissociate itself from the rest of industry, not can it claim that its performance measured by the usual yardsticks is particularly inspiring.

Statistics are always suspect and should be viewed in context but if a series of indicators all point in the same direction, perhaps one should sit up and take note. The 10 top construction companies in the United Kingdom have 124 listed directors. Of these 12 have an engineering qualification. Is there a clue here, is it that in our lawyer/accountant-dominated economy, technology is something to be bought, like groceries from a supermarket? Or is it that engineers are not thought to be fit and proper persons to lead enterprises because their training and outlook, as well as their abilities, are thought to be too narrow and inadequate? Again no simple answer, but there is probably something in both propositions. It is interesting to make comparisons with the management structures of similar companies in Japan and Germany.

The cult of the professional manager

The structure of Japanese companies is of course quite different — their boards are large and have 30-50 directors. But in the top six Japanese construction companies about ⅔ of their board members are qualified engineers or engineer/architects.

Again, in eight of the leading German construction companies two out of every three directors are qualified engineers.

While there are some notable exceptions, British industry does not generally expect its leaders to be steeped or skilled in the expertise which it practices or the goods it produces. GEC, the flagship of our engineering industry, has one chartered engineer on its board. The cult of the professional manager is with us, backed up by a burgeoning management consultancy industry which feeds on the incompetence of the industry which it purports to serve. There is a role for the troubleshooter, the fire-fighter, but the long-term health of our industry is totally dependent on its people, their skills and the manner in which these skills can be harnessed for the common good. And anyone who understands even the beginnings of leadership knows that in general, leaders will only win the support and respect of the led not by imposition, but by example and performance. And this respect is more easily gained by a feeling of identity which can only be achieved when the leaders are steeped in the industry they are purporting to lead.

The oft-repeated proposition that engineers make poor managers and captains of industry is nonsense and is often made by those who have a vested interest in protecting their position. It is true that not *all* engineers make good managers, but then not all engineers are good designers. Nor are all doctors good diagnosticians. An engineering enterprise, like all others, needs members of varying abilities. There have been occasions, some recent, when there were serious suggestions that we may in the not-too-distant future have an oversupply of engineers.

Shortage of engineers

Most of us who have anything to do with recruitment of graduates into our, or for that matter other, industries believe this to be dangerous nonsense. There is a shortage now, there will be a shortage of talented people in the foreseeable future, and in any case there are many jobs in industry now filled by non-engineers which could sensibly be done by engineers. For engineering skills 'reach corners of industry which other skills cannot reach' (with apologies to an excellent TV commercial). And if that blissful state should be achieved where at some time in the future a surplus of engineers was turned out by the universities and polytechnics, I can think of no better grounding for other employment in the service industries; in the public sector, in politics; indeed in all those parts of our society which are currently dominated by lawyers, accountants or so-called career managers.

The solution to industry's problems in general and those of ours in particular have, of course, nothing to do with acquisitions or investment or any of the other inventive financial chicanery currently in vogue. It has simply to do with attracting more people and particularly more talented and able people into our industry. It is as simple as that — and as difficult! For to persuade young men and women to take up a career in technology (including of course the construction industry) flies in the face of the anti-technology trends in our society and requires a shift in our cultural attitudes.

There is the old joke about all economists being laid end-to-end and not coming to a conclusion; actually it isn't funny because even if they don't come to conclusions which we find acceptable they have seemingly become the acceptable face of astrology — which is the only way one can describe some of the tenuous forecasts with which we are bombarded. As if that were not enough, the forecasts are almost exclusively to do with money, as though this were the only yardstick with which to measure the health of our society. We have indices galore from money supply and stock-markets to retail prices and output — but where do we find out how our skills compare with those of our competitors? Do we have more skills this year than last, and do we not need to increase our skills potential so as to meet the needs of tomorrow as well as to enrich our lives today and perhaps even more important, have some to spare for those countries who need our help? Transferring technology and training is an important ingredient of aid to those who are less well-off than we are.

So we face a pretty tough task. For to shift entrenched attitudes and gradually achieve that necessary cultural change requires a sustained effort by all of us jointly and severally. It will be a long haul. We must certainly get into the schools to enthuse young men and women to take up careers in technology, to excite them about making and constructing things. That in itself is not all that easy as the Engineering Council has discovered with its Opening Windows scheme, which in principle ought to be supported, but which in practice has fallen short of expectations. There is a valuable lesson here — in today's world, in order to mount a major initiative such as to try and bring more of our talented young people into our industry, we require a professional approach with commitment, planning, resources (financial and human) and expertise in communication. For to be truthful we as engineers are not the best communicators. We are not particularly skilful about telling the public at large, let alone the young, what it is we do and what we contribute to society, so that in this age of revolution in information technology we must seek help and use the media to get our message across. Somehow the excitement as well as the usefulness of engineering must be brought home to the public at large and there is nothing more powerful than television to help achieve this end.

The role of the professional engineer is generally not properly understood. I have no patience with those who complain about our lack of status — we get the status we deserve. We must go out and do something about it. If we want to be seen as true professionals, and that is not easy at a time when *all* professionalism is under attack, we have to be seen to behave accordingly. A typical instance is the current headlong rush to embrace Quality Assurance schemes in professional offices. While the emphasis on quality in all we do is paramount and while appropriate quality control systems in the right context should be part of our everyday lives, ponderous bureaucratic procedures and kitemarks do nothing to enhance our standing with the public. Do we ask our surgeons or dentists for their kitemarks before we let them loose on our bodies or our teeth?

The way ahead?

R.H. Tawney articulated very clearly the differences, which he described as unmistakeable, between industry and the professions. The former is organized for the protection of rights mainly for pecuniary gain, while the professions are genuinely, if imperfectly organized for the performance of duties. And the professional engineer, no less than the surgeon or the dentist or for that matter the lawyer or the accountant, should be judged by his work not by the systems through which he achieves it. It is a question of means and ends — we and in particular institutions like the ISE, must be concerned with ends and leave the means to the judgement of its members to whom it grants the appropriate qualification. The role of the institutions is immensely important in establishing our credibility with the public, and here I must plead that collective action by the engineering institutions is imperative if our relationship with society at large is to be enhanced to a status equivalent to other professions.

Of course we also have a right to look to government to play its part. Whether or not government really understands the seriousness of the problem is open to question, although of late there have been some encouraging signs, coupled unfortunately with the now obsessive stringency in monetary restraint even when related to essential training and education. However, government can and should use its considerable powers of communication, privilege and legislation to help this cultural shift, this change in attitudes which is necessary if we are to prosper. Above all, government can exercise patronage of technical excellence by example and by encouragement. Here again, the institutions, particularly if they act collectively, can help.

But ultimately it is the young who have to be persuaded. I said at the beginning that my concern about society's lack of understanding of and concern for technology had come to me rather late in life. I would like to think that this concern can be kindled in the young, in schoolboys and girls by enthusing them to take up careers in technology, as well as in our younger engineering colleagues who are much more likely to become acceptable role models to their peers and younger brothers and sisters than my generation. The youth of today is immensely concerned about the world we live in, its environmental and social problems. Our young are very caring and they must learn to understand the role of technology in improving living and environmental standards. It will undoubtedly be a long haul but we must put our shoulders to the wheel so that our successors will be able to play their appropriate roles in society at large rather than being confined to a small engineering laager.

But I have strayed a long way from structural engineering, though deliberately, in order to convey to you some of my concerns about industry and our industry in particular.

I have tried to tell you, albeit very cursorily, how my concerns have evolved, so that the tone of this address has become rather sombre on an occasion which should be something of a celebration.

If I may, therefore, I would like to end on a rather lighter note. I said earlier on that most of us find our work flawed in some respects when we look at it critically after completion.

We can inevitably improve what we have done when looked at in hindsight.

I recently came across this picture of a balloon supporting something very familiar. Although hot air was not part of our structural vocabulary at the time — who knows?

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