The Princess of Wales Conservatory at the Royal Botanic Gardens, Kew

A. Sarkar, G. D. Wilson and D. Lambert

Authors' Introduction

At the heart of the successful design activity related to this project was effective functioning of the team and a clear understanding of objectives. It was also very important that all team members developed an understanding of the thinking and working methods of their fellow professionals.

2. Careful planning and close co-operation between the designers, the contractor and the subcontractors of the project team were of paramount importance. Designers should do more than simply provide a design and prepare the specifications, leaving everything else to the contractor. The contractors should be concerned as to why the design is as it is, and not refuse to be involved with the designers. This project has proved that a good team effort is needed—an effort which may involve a full and frank exchange of views between members of the team, with a pragmatic approach to solve problems, but one which never loses sight of its goal.

P. F. Reilly, Ronald Leach Associates

I understand there was a problem with some debonding of the protection system. Could the Authors say what the problem was and how they overcame it?

4. Obviously there are maintenance problems with the internal roughcast glass, and access cannot be easy with all the planting in position. Was there a specific reason for the reduction of light into the building? Was the use of laminated glass, with smooth surfaces on both faces, considered instead?

H. Clamp, Manning Clamp

I notice that the concrete took about 15 months to erect, that the steelwork took only five months, the mechanical and engineering services took 17 months, and the glazing took eight months. In other words, erection of the steelwork was quicker than anything else. With hindsight, would the Authors have reprogrammed that or amended the workforce on site?

6. Was there any alternative to the use of chlorinated rubber paint, which I gather caused problems?

B. K. Bardhan-Roy, Jan Bobrowski and Partners

The features of the building which impressed me most are its elegant structural form which blends with the landscape, its low maintenance

requirements and the simplicity and neatness of connection details.

8. Under the PSA management and under the supervision of the Authors of Paper 9525, other buildings have been built in Kew Gardens, including the Sir Joseph Bank Centre which houses the reference collection library, museum, an administrative office, workshop and public concourse (Figs 1–3). The brief for the design of that building was that it should be sympathetic with the environment, energy-efficient, cost-effective, functional and require low maintenance—similar to the design brief for the Princess of Wales Conservatory. A different medium of construction was chosen because of other conditions there, but there is a basic harmony between the two buildings. For environmental reasons most of the area is below ground level so that the structure does not dominate the landscape. This led to the problem of water pressure as the water-table was high and the structure had to be designed for one metre of hydrostatic head. The solution was to design the slab on grade as post-tensioned with unbonded tendons, using water-proof quality concrete. The retaining walls were in reinforced concrete and tanked with bituthene.

9. For low maintenance, the glazed area was provided with stainless steel framing. The area was comparatively small and did not require big sections of stainless steel.

10. The roof of the administrative area was constructed as a reinforced concrete flat slab, but over the reference collection library and the museum area, which supports 600 mm of earth in addition to other loading, cast in situ, post-tensioned box section was used.

11. With regard to the Princess of Wales Conservatory, what fire resistance period was necessary? How did the Authors achieve this with steelwork and how was the problem of fire escape solved?

12. For metal protection, flame aluminium spray was applied which was coated with chlorinated rubber for permanent protection. However, any flame metallic spray is porous and can attract moisture so that normally within six hours of spraying a sealing coat needs to be applied. Was that sealing coat applied on the conservatory?

13. Two reasons given for not selecting polycarbonate were ultraviolet degradation and the fact that at a high temperature and humidity it loses its stability. However, I have used it

*Fig. 1. Sir Joseph
Bank Centre in Kew
Gardens
(Crown copyright)*

*Fig. 2. Plan of Sir
Joseph Bank Centre*

in Abu Dhabi and other places where the temperature and humidity are high, on the advice of the manufacturers. I understand that up to 120°C, the stability of polycarbonate is not affected and it is also treated with an ultraviolet resistance substance which protects it from ultraviolet degradation.

14. Do the Authors know why there should be an apparent discrepancy between my information and theirs?

Dr R. J. Pope, Blight & White Ltd

The debonding problem was in fact between the aluminium spray and the substrate, not between the chlorinated rubber and the aluminium spray, and so the question of an inter-coat between the aluminium spray and the chlorinated rubber was not an important issue.

16. The debonding occurred because of imperfect application of the aluminium spray. The large frames were difficult to blast, and to cover the entire length within the time-scale set meant that dust or humidity could accumulate on the steel before the aluminium was sprayed. The primary requirement of the aluminium spray is to provide an electrolytic shield over the whole surface, and much of it did bond properly. The fact that local areas did not bond under the test was not necessarily a problem if they were themselves attached to other areas that were bonded locally, and if there was an integrity between the whole surface coating in the electrolytic action which is sacrificial.

17. The chlorinated rubber provided an integrated sheath that covered the whole surface. To establish whether the substrate debonding was a problem, pinhole tests were done on the chlorinated rubber coats to see whether or not there was residual porosity in the chlorinated rubber which would then lead to porosity in the basic surface. This was relatively low. Pinhole testing showed little loss in the multi-coat chlorinated rubber, and in order to make doubly sure an additional coat was

added on the site. Obviously the chances of the holes lining up between the pinholes in the outer layer and the sublayers was relatively small. It was on the basis of this that the fact that the perfection aimed for on the original aluminium spray had not been achieved was accepted.

R. S. Shipman, PSA Services

There is a paint coat omitted from the paint specification as printed in Paper 9525. After the aluminium spray, to seal the porosity in the aluminium, a two-pack zinc chromate etch primer was applied before the chlorinated rubber paint coating system.

M. R. Sutton, PSA Services

I am intrigued by the fact that in the specification, steelwork had to be erected during the summer. To what extent did that constrain planning of the construction process? In fact, summer seems to be an indeterminate period. What were the reasons for specifying summer?

C. Broadbent, Andrews Kent & Stone

Is the watertightness of a glasshouse structure important? If it is then how was watertightness specified and achieved in the project, and what methods of test were employed to ensure compliance with the specification?

R. S. Baxter, Fellow

When I worked as a consulting engineer under assignments with the PSA, there was a requirement to operate a strict formalization quality assurance procedure. Long life is a major criterion of this project and a formalized quality assurance procedure might well seem appropriate. Was this project initiated in the early days of quality assurance procedures? If it were being built today, would a formal quality assurance procedure be imposed?

22. The conservatory is full of plants and

Fig. 3. Elevation of Sir Joseph Bank Centre

the design fits in beautifully with the internal use. However, this is not obvious from the outside, so the structure has to stand on its own as a building amid elegant Victorian structures. To what extent did that composition influence the design of the building?

R. Holland, PSA Services

This is an unusual building. I wonder how it was possible to control and integrate all the input into something as unique: the input from Kew Gardens, civil engineers, mechanical and electrical engineers and others?

24. I have two greenhouses, neither of which stood up to the storms of 1987 and 1990 without considerable expense afterwards on repairing the woodwork and glass. Where two pieces of glass join on a slope, moss, algae and dirt accumulate. How was this overcome at Kew?

25. All offices in the PSA are moving towards quality assurance procedures. Two out of seven offices already operate them continually.

26. Could the Authors say how they set out the conservatory and ensured that the steel-work would fit? How was it levelled up?

J. B. E. Simmons, Royal Botanic Gardens, Kew

Designed to cater for both plants and people, the building creates a series of different habitat analogues which allow visitors to experience the environments associated with each of the discrete plant displays.

28. The severest test of these controlled environments happened in the first month following the official opening when one third of a million visitors queued to go round the house. Despite the consequentially endless opening and closing of doors, the systems compensated, maintaining the required conditions; and — most important — the plants prospered.

29. A visitor survey in 1987 showed that the conservatory gave the highest level of satisfaction of all the buildings and features at Kew. The conservatory's subsequent appeal has only been enhanced by the successful growth of its plantings. It attracts dignitaries as well as the visiting public from around the world.

30. It carries an estimated 1000 species, many never previously displayed, such as the unusual *Velloziaceae* from Brazil and the ant-inhabited *Myrmecodias* and *Hydnophytums* from the forests of south-east Asia. The giant Amazon water lily (*Victoria*) produces 2.3 m dia. leaves in its first summer. This plant, which is especially sensitive to any adverse affect on its environment, provides a true test of function.

31. Equally pleasing is the successful growth of the sea-fronting mangrove (*Rhizophora*), which has stabilizing prop roots.

32. Designed to run more efficiently on all cost inputs, at a lower design temperature than has previously been used for tropical plants, while taking advantage of solar gain, the Conservatory uses approximately half the fuel of the many separate houses it replaced.

33. The conservatory functions very well, excites the visitor and is relatively easy to maintain. The key to this was having an architect who was willing to listen and who created trust and mutual respect within the multi-disciplinary design team that also involved the client. This leadership brought the best from all involved and achieved, within tight cash limits, a significant advance in the design of the world's great botanical conservatories.

34. The symbol it has created of a new Kew has given immense satisfaction to the design team, contractors and Kew's horticultural staff. The building easily holds its place alongside the Victorian conservatories.

35. It has been in operation for some years but there have now been cuts in funding. Have the builders and the designers reviewed their predictions of the life of the building?

M. P. W. Scarth, Beazer

The conservatory has probably one of the largest curtain wall buildings in the UK. Why does it not leak like many others?

K. Jeremiah, Michael Barclay Partnership

When my company was designing the Uxbridge shopping centre cover, which was structural steel design over a wide area, a great deal of thought was given to the deflexion of the supports to the glass and how much the glass could tolerate, particularly in terms of warping, without breaking. How was that problem addressed in this particular project?

M. R. Sutton, PSA Services

The thing that strikes me most about the conservatory is not the plants but the semi-circular mural which is rather like a cowboy set and seems to set the scene perfectly for what one is going to see. Where did this idea come from?

A. M. Sparkes, PSA Services

What flexibility did the client request in the layout of the building? Can certain areas be extended in the future so that exhibits can be changed from time to time?

S. Xavier, formerly PSA Projects, now Department of Transport

Did the wind tunnel testing reveal any interesting or useful data on local suction/pressures on the roof ridges, valleys and eaves? If so, how do these compare with the best estimate for the same, arrived at using the current British Standard on wind loading?

41. In the design of structural steel frame

for the temperature range of -12°C to $+47^{\circ}\text{C}$, were there any surprises? Was it necessary to increase previously designed structural sizes? Was it necessary to revise or strengthen bolted and/or welded connections as a result of this temperature check?

42. Was the structural work subject to independent appraisal and checking, and, if so, was this a useful exercise and did it result in revisions or modifications to the designer's design philosophy or the design details?

43. How many structural steelwork fabrication drawings were involved, and how long did it take for them to be checked and cleared by the designer?

44. How much staff time and travelling expenses were involved by all the respective disciplines at all stages? Was there any run-away staff time during the life of the project as a result of any unforeseen activity and, if so, how was it contained by the project manager?

45. Were there any useful contributions by graduate trainees at the design stage or construction stages? From the staff time point of view, did this project make a profit or loss or did it break even? Were any useful lessons on staff time learned by the project manager?

Mr Sarkar and Mr Wilson

With reference to *Mr Reilly's* question on the use of roughcast glass, there were three overriding reasons for choosing this type of glass rather than opting for the slightly higher light values of clear glass. Firstly, roughcast glass diffuses bright sunlight to reduce the burning effect on plants, and, for this reason, it has become the convention at Kew, even in the support houses, to have roughcast glass. Secondly, it hides much of the structure seen from inside, as approximately two-thirds of the structure is hidden by the glass, but seen from outside that roughcast glass is helping to express the structure. Roughcast glass throws the structure into relief to fulfil the fundamental design aim of expressing it as much as possible externally and playing it down internally. The need to play the structure down internally was vital because of the relatively low roof which might otherwise dominate the planting. Thirdly, and perhaps most important, was the need to provide a very calm and non-distracting background for displaying the plants. This effect can be seen most clearly in the greenhouse when comparing the background of both roughcast and clear glass behind a delicate-shaped plant. The silhouette is picked out much more easily against a roughcast background than against a clear glass background where visually there is competition with what is behind externally, such as the trees, clouds, etc.

47. On the question of the glazing overlap, this conventionally creates a gap not only for the collection of algae, which becomes a main-

tenance problem, but also for heat loss as a result of air transference, especially when the wind blows. We developed a new detail which was tested on the prototype glasshouse, and which we believe to be helpful to the technology of conservatory design. It has a gap which is slightly larger than the conventional glass to glass gap, sufficient to allow an aluminium extrusion which runs between the two panes of glass; this effectively seals the glazing skin and reduces heat loss. Also, it separates the two panes of glass to avoid the holding of moisture by capillary action, which is the medium in which algae grows. Any moisture, e.g. condensation, is allowed to run out through weep holes and discharge externally. We believe we have resolved a most difficult maintenance problem at a relatively low capital cost.

48. With regard to *Mr Bardhan-Roy's* question concerning polycarbonate glazing, certainly the double skin polycarbonate product currently available was considered. There is anecdotal evidence arising from visits to greenhouses which have used polycarbonate that this material did not meet the special needs at Kew. We know for a fact that all plastic is porous, and moisture from both inside and outside will pass through the plastic. A process of leeching is taking place, and over time the balance of chemicals in the plastic will change. Inevitably, there are uncertainties, including an increasing risk of brittle fracture which has become apparent in places. This is in addition to the anecdotal evidence from some users that the surface finish will deteriorate to some extent and increase the problems of maintenance. While it is a very satisfactory material, and in certain situations is perfectly acceptable, it was not considered appropriate for the special requirements at Kew.

49. In reply to *Mr Bardhan-Roy's* comment about fire escape, we have a fire officer on the team who was obviously concerned to meet the appropriate requirements. In one sense, the issue was not really applicable, because all greenhouses in this country are, rightly or wrongly, exempt from building regulations. That does not, of course, remove any moral responsibility for providing safety to staff and public. Another fire officer might still regard this building as a place of assembly that requires eight means of exit in a state of emergency. However, it was agreed, to the satisfaction of our fire officer, that the provision of eight means of escape from the building and of a one-hour fire resistance of the structure was not appropriate.

50. *Mr Baxter* refers to the external appearance of the conservatory, which is one of the most emotive issues that has been raised. The question has been raised of why, while it was perhaps an interesting looking building, the Conservatory could not be more like the Palm

House. I would maintain that there are two fundamental reasons why it could not resemble the Palm House. The latter was designed specifically for trees; the Princess of Wales Conservatory was designed for herbaceous plants, which is why it is not appropriate to have a tall structure. Also, the Palm House is a single volume or space, whereas here we are dealing with ten separate environments under the one roof, all of different size.

51. These are the two principal factors that justify the choice of a design for the Conservatory different from that of the Palm House. One can add that technology has changed a great deal in 150 years, and different materials are now available. Also, horticultural knowledge has increased, and, most important perhaps, attitudes have changed in 150 years. We felt we were adopting the right approach by providing a building in tune with the late twentieth century. In that sense, there was no intention to compete with existing historic features at Kew. Rather, there was an intention to integrate, by using traditional greenhouse forms blended into the surrounding landscape.

52. *Mr Sutton* asks about the diorama feature at the south entrance, which is a recreation of the Mohave desert display that already existed on the site. Originally, the diorama was at the north end. We re-provided it at the south end, with better natural lighting and with a slightly modified shape and dimension. There was an element of competition in the redesign of the mural backdrop, and we would agree that it is an interesting rather formal set piece, which we think is appropriate at that entrance. It is also a link with the past, as it features the Sherman Hoyt collection of plants which has historic connections going back at least 50 years—we believe that some of the original plants are still on display.

53. *Mr Sparkes* raises the issue of flexibility: what happens if Kew wanted to extend? This issue was discussed, but it was understood by the client that extension was not a practical proposition. However, because there are ten separate climatic zones, and plant collections that are literally growing, there is a process of plant management and display to be catered for by the design. To assist with long-term flexibility, we made sure that the partitions separating the ten zones were removable and remountable under any beam position. This is not to say that this would be an easy task, but the potential for change in the relative sizes of the collections is there, but the total size of all collections cannot be increased.

54. *Mr Scarth* asks why the building does not leak. The simple answer is that it is down to quality of workmanship. Having said that, it should also be stated that there was considerable attention to design detail. The prototype has already been mentioned. Without doubt, a

greenhouse has considerable repetition of elements, and the value of carrying out prototypes and models cannot be overestimated. The full-size prototype that we constructed, which is still in operation at Kew, was worth every penny.

55. A question has been asked about how the design team was controlled. All we would say is that it was controlled in the normal way. It is a process which is cyclical throughout all the stages and is inevitably fraught with difficulties. We believe, however, that we had the right people on the team at the right time. These included Zahiruddin Nazerali, who also had the responsibility for supervising the contractor on site. The contractor, in turn, was supported very capably by the subcontractors, who each made their special contribution to the project. In particular, Matt Finlayson of Ruberoid made a significant contribution to the design development of the glazing systems. We also had time to do research, and that was of vital importance; we had time to construct a prototype and learn from it. Generally, we think, clients get the buildings they deserve. After all, it is clients that set the standards and have the values, and these were expressed clearly throughout this project. For that, we can thank the staff at Kew: in particular, the curator John Simmons. In that sense, it was the client who set the challenge and the Projects team at the PSA who responded to that challenge.

56. In response to *Mr Baxter*, a formal quality assurance procedure was not in operation in our office during the design and construction of this project, but a strict quality control was in operation during the design and construction of this project. All future PSA projects will go through proper QA procedure.

57. *Mr Jeremiah* raises a question about glazing deflexion. To minimize the breakage of glazing, the live load deflexion for steel frames was restricted to 20 mm vertically and horizontally, which was arrived at after intensive discussion with glazing specialists and following our experience during the construction of the prototype.

58. One aspect that was highlighted during the design and construction of the conservatory was the value of a prototype, as it enabled us to test many of the design assumptions and philosophies. Kew also used it as a test bed for planting.

59. *Mr Simmons* refers to the life of the structure. The building has a design life of 100 years and the coating system a life of 15–20 years. However, if the building is not abused and is properly maintained and coated, I do not see why it should not go on for many years longer.

60. *Mr Xavier* raises a number of points on design, project management and cost control.

Taking the design point first, as mentioned in Paper 9525, the wind loading arrived by model testing was less than first assumed during the preliminary design stage, on account of the particular shape of the structure. The temperature of -12°C to $+47^{\circ}\text{C}$ was an integral part of the design process, and appraisal of the design was part of the quality control process; there were no surprises. There were about 400 fabrication drawings and they were looked into as a part of the structural engineering support during the construction stage.

61. This project was a team effort, and included the graduate trainees. They played their part and resource cost was strictly controlled to give value for money.

62. We thank *Mr Shipman* for mentioning the two-pack zinc chromate etch primer which was inadvertently omitted from Table 3 of Paper 9525. The correct complete specification for coating of steel is given in the revised

Mr Lambert and Mr Sarkar

63. We believe that hindsight is the best planner known to us, and if we had the benefit of hindsight on every job, it would indeed be a very happy situation. Unfortunately, in this profession we tend to deal with unique projects and we do not have a second attempt. Therefore, we can use only the experience we have gained on one project and try to translate it to both our and the client's benefit on subsequent projects.

64. We think that *Mr Sutton* has really hit the nail on the head with regard to the major constraint on the planning, and that was the requirement to have the steel erected during the summer period. The summer in England is obviously not as warm or dry as that in India, but still during the period May to September we generally get less rain and higher temperatures. We wanted to take maximum advantage of that 'summer' period for the erection of steelwork. That meant that we had to carry out a great deal of concrete work before the erection of the steel, so that the steel had something to sit on, and we also then had to carry out a considerable amount of concrete work subsequent to the erection of the steel, and that was working in and around the other trades.

65. With regard to the question of the corrosion protection system, we think that the contributions by *Dr Pope* and *Mr Shipman* and also by *Mr Bardhan-Roy* highlight the amount of debate that there can be on such matters.

For aluminium sprayed surfaces

- (a) grit blast steel surface with chilled iron grit to BS 2451, to standard cleanliness Sa3 to BS 2569 to achieve a maximum peak to trough of $100\text{ }\mu\text{m}$
- (b) flame spray aluminium to a minimum thickness of $100\text{ }\mu\text{m}$ to BS 2569 within 4 hours of grit blasting; aluminium to steel adhesion to be not less than 50 kg/cm^2
- (c) one coat of brush-applied two-pack zinc chromate etch primer within 24 hours of aluminium spray
- (d) one coat of shop-sprayed chlorinated rubber/alkyd undercoat to achieve a minimum dry film thickness (MDFT) of $25\text{ }\mu\text{m}$
- (e) one sprayed or brush stripe coat of chlorinated rubber along exposed edges and into all corners
- (f) one coat of shop-sprayed chlorinated rubber undercoat to achieve MDFT of $50\text{ }\mu\text{m}$
- (g) repeat (f), but colour to suit finishing coat
- (h) one finishing coat of site-sprayed or brush-applied chlorinated rubber to achieve a MDFT of $50\text{ }\mu\text{m}$, with colour to suit architectural requirements

Minimum total paint dry film thickness to be $175\text{ }\mu\text{m}$

Indeed, it was an area of considerable debate during the project, in which the question of sealants and microporosity was discussed. Paper 9526 gives more detail as to the solution.

66. In response to *Mr Holland*, the main grid was set out and checked using one second theodolites and steel band tapes. This grid was then checked using EDM equipment, and an independent check was carried out by PSA Services. The grid was maintained throughout the construction period. The steelwork was set on jugged beds at the fabrication works, fabricated in complete portals and then broken down for road transportation to site. Close tolerance holes were used and no make-up pieces were required along the 150 mm length of the structure. The steelwork was levelled-in by means of standard optical tilting levels from a site bench-mark.

67. In response to *Mr Clamp*, the sequence of construction, and the timing, was dictated by the form and detailing of the structure and the requirement for erection of steelwork to be during the 'summer'. This required the steelwork to be erected as early in the construction sequence as possible, taking into account drawing, procurement and fabrication periods. Later erection of the steelwork would have deferred glazing as well as leaving the site exposed to the elements and preventing the installation of services.

68. In reply to *Mr Broadbent*, we can add that the use of copious quantities of water played on the elements from all directions, and the provision of natural precipitation proved the installations.

Table 3. Specification for coating of steel (revised)