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The Sydney Opera House The Contractor and Some Aspects of Stage III

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Abstract. The article briefly recounts the history of the area known as Bennelong Point, and then describes in some detail the Sydney Opera House project from the time of the architectural competition when the design of the now famous shells was chosen, to its completion as a complex catering for many forms of arts and sciences. The paper deals with the various activities of the main contractor's site organization, the difficulties of design and construction posed by this unique building, and the resultant solutions gained by the teamwork of the architect, consultant and builder.

The Site

When the First Fleet arrived in 1788, it landed its small herd of cattle on an isthmus they named Cattle Point. Later the name was changed to Bennelong Point after the aboriginal who lived there with his wife and achieved some fame by his services to Governor Phillip.

The site had its first association with the performing arts when it was the locale for the first corroboree performed by aboriginals for the entertainment of white men on 3rd August, 1811.

The first structure on the point was a fortification consisting of a small redoubt with two guns completed on New Year's Day, 1789. This was later superseded by Fort Macquarie, built by convict labour with stone from the Domain during the period December, 1817, to November, 1819. The structure was in the form of a square and became a Sydney landmark until it was demolished to clear the site for the construction of the Opera House. Its guns were never fired in defence. In 1903 the interior of the fort was converted into a tramway depot, which it remained until demolished.

The point has been described as an isthmus with a narrow approach at high tide. Although the earlier pictorial records do not clearly illustrate this, it is a fact that all manner of filling material was dumped on the approaches to the point. Apart from what is reputed to be ship's ballast, namely river gravel and some highly corrosive slag, the debris from construction works in the new Colony was deposited here, no doubt to form a serviceable wharf from the original jetty-Man-of-War Steps, which is still used and recently repaired. Rubble from the rock excavation to the Quay, and especially from the large excavation of the Argyle Cut in the Rocks, was deposited here. It has been encountered in all the excavation for the substructure work of the Opera House, as well as at least three stone sea walls that formed the early limits of Circular Quay.

This, then, was the site chosen for the Sydney Opera House by a committee appointed by the New South Wales Government in 1954.

The Architects and Engineers

On the basis of a design submitted as a result of a world-wide competition, Mr. Jørn Utzon of Denmark was appointed architect for the Opera House in 1957. The consulting structural engineers appointed on his recommendation were Ove Arup and Partners.

Jørn Utzon resigned in 1966 following disagreements with the New South Wales Government at a time when the erection of the concrete shells was substantially complete.

A consortium of Australian architects, Messrs. Hall, Todd and Littlemore, was commissioned to complete the building, and commenced a review of the project in the latter part of 1966.

The Construction Contracts

The work has been carried out by private contractors under the supervision of the New South Wales Government and appointed architects and engineers. There have been three main contracts, three separate contracts, and with fees and charges the project has cost approximately $100M, as follows :

		$
Stage I, 1959—Podium, Civil & Civic Pty. Ltd. .. approx.		5.5M
Stage II, 1962—Roof Shells, M. R. Hornibrook (N.S.W.) Pty. Ltd. .. approx.		12.5M
Stage Ill, 1966—Completion, The Hornibrook Group		56.5M
Separate contracts — Stage Equipment, Stage Lighting, Organ		9 M
Fees and other costs		16.5M
	Total	$100 M

Stage I was let by competitive tender, and work commenced before the superstructure and the roof design had been finalized. Modifications to the plan and uncertainty regarding the roof structure extended contract time and cost.

Stage II. Whilst Stage I was under construction the engineers and architects investigated many different ways in which the roofs could be constructed.

Originally intended by Utzon to be a system of parabolas built in off-form concrete, it finally appeared that the only viable solution would be precast and stressed concrete, using pairs of balanced shells, necessitating modification of the geometry to spheroid in curvature. Utzon redrew his design, making use of a constant radius of 246 ft (75 m) for all shells, and gained the volume or shape that he desired by a variation in the pitch of the arches.

More than two years of work, involving the use of digital computers and extensive model tests, was necessary to evolve a practical design. Even during construction computer programmes designed to check the erection procedure required access to the computer used by the Weapons

Research Establishment in South Australia. It is estimated that computer work undertaken would have required 100,000 man-years of mathematicians' time.

Construction of the roof shells involved techniques never before attempted in building construction, and in the words of Ove Arup, "on the boundaries of what is technically possible". For this reason it was not considered that the contract could be the normal firm price system, and M. R. Hornibrook (N.S.W.) Pty. Ltd. entered into a cost plus fixed fee arrangement to undertake the work.

Stage III. In 1966, with the end of the Stage II contract in sight, and coincident with a change in the architects, the New South Wales Government entered into a further contract with Hornibrook, by then a division of Wood Hall Ltd., to complete the remainder of the building. This was by far the greatest value of the main contracts placed, and whilst it consisted of more traditional building works and services, did include work unique to the Opera House.

The infill walls between the concrete shells such as the bronze walls and glass walls had not been designed, and the whole concept of the Opera House as a Performing Arts Centre was under review by the new architects.

Separate contracts let by Utzon for stage machinery to Waagner-Biro of Vienna, and stage lighting to Siemens Industries Ltd. had also to be revised.

Revision of Use

Utzon's scheme envisaged two main halls, namely:

(1) A dual-purpose Concert Hall and Opera or Ballet Theatre;
(2) a Drama Theatre.

A small chamber music room and rehearsal and experimental halls were also provided.

Peter Hall, the design architect in the new consortium, was not satisfied that the dual purpose hall could be achieved in view of the conflicting demands of concert and theatre in both seating arrangements and acoustic qualities. Thus he and his partners eventually proposed to the Government that the project be revised to provide

(1) a Concert Hall,
(2) an Opera and Ballet Theatre,
(3) a Drama Theatre,
(4) Music Room and Cinema.

In addition, a Recording and Rehearsal Studio, a large Rehearsal Theatre, an intimate Recital Room, as well as an Exhibition area, were to be incorporated.

Utzon's scheme had depended upon the isolation of the two main halls to overcome sound attenuation, but in Hall's scheme the auditoria were much closer to each other (in fact they are not only cheek by jowl but overhead as well), so that reliance had to be placed upon engineering structural design to achieve the sound isolation that was necessary for the extremely high acoustic criteria.

Furthermore, the original concept had only intended to air condition the main hall or the smaller hall, but not both together. There was no air conditioning to the dressing rooms. The proposal to air condition all the areas within the complex not only meant designing a much larger plant but called for its installation within a concrete structure of such complexity that to cut any hole more than 9 in square (5,800.0 sq mm) called for a structural engineering decision.

However, the New South Wales Government was convinced of the advantages of the proposal, and in 1967 authorised the revision to proceed.

Revision Work

As a result of the revised plan, some structures already partly complete had to be demolished or modified. Principally these were:

(a) The stage tower steelwork to the main hall already complete was dismantled and removed;

(b) the minor hall pit structure was progressively demolished and reconstructed further south to provide a larger orchestra pit;

(c) the experimental theatre stage area was remodelled to provide a revolving stage structure as well as a thrust forestage for drama.

(d) the mechanical stage and lighting equipment was redesigned to accommodate the revised areas in the minor hall and the Drama Theatre.

At this time, however, the problems of the infilling external bronze and glass walls were still unresolved as well as the major decision regarding the ceiling structures within the two main auditoria.

Target Programme

When the review of programme was undertaken in mid-1967, it was decided that the target completion date was to be December, 1972.

To realize this, it was apparent that progress must be such as to expend in excess of $1M per month at peak production, and this to be maintained for some months; Doubts were expressed that this could be achieved on such a complex project, for such an output had only been possible on one previous project in Australia: a large airport terminal which was more suited to concentrations of labour and repetitive construction.

Not only was the project used for a full-scale concert in December, 1972, but as is reported later, the rate of output was more than double the anticipated $1M per month due to greatly increased budgets and requirements.

Site Management

From the contractor's point of view, the biggest difficulty in the early months of Stage III was to weld together a construction team that had to work hand in glove with architects and consultants as the design progressed on the board and who had to start work as soon as the drawings came out of the printing machine.

The production task was subdivided into five main responsibilities:

(1) Co-ordination. This was the team who from initial co-ordination with the designers checked out and overcame the inevitable physical conflicts in design, the routes of pipes, the preference of one service over another, etc.

(2) Planning. This team worked alongside the co-ordinators and from network diagrams of each area built up the overall programme.

(3) Field Supervision. This was the labour control under a Project Superintendent, who on average had five area superinteridents answering to him.

(4) Subcontractors' Control. This team administered the whole of the subcontractors other than the field control. As the subcontracts were valued at more than the direct labour component, this administration accounted for the greater part of the project.

(5) Administration. This control dealt with all clerical work, stores, wages, bookkeeping and accounts, as well as the formal industrial matters not handled by the field office.

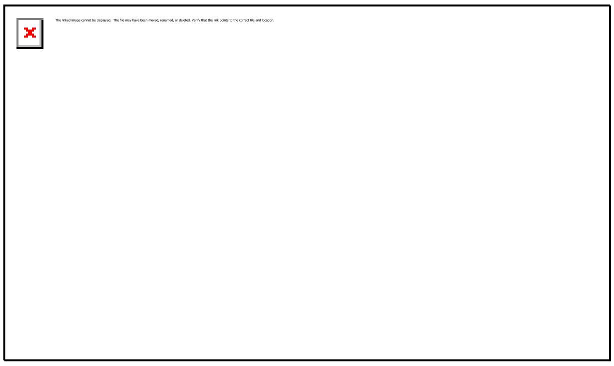


Figure 1 — Site staff organization. [*The original is hand drawn and unsuiitable for reproduction via this medium. The above is a generalised and redrafted version more suitable for a web site diagram; click image to enlarge*]

All these site executives reported to the Project Manager, who was resident on site (Figure 1). Their duties are recorded in more detail later in this paper.

Apart from numerous day-to-day meetings at all levels, the continuity of communications and control was maintained by the following regular assemblies:

(a) weekly management meeting of Project Manager and his staff,

(b) weekly meeting of Project Manager with Architects and Client Authority on policy and technical matters,

(c) fortnightly meeting with Architect and Client on administrative matters,

(d) weekly meeting (later fortnightly) with Architect, Client and Quantity Surveyor on Cost Control,

(e) monthly meeting of Architect and all contracting firms on progress.

Co-ordination of Services

The Co-ordination Group was initially set up during September, 1970, between the Architects (Hall, Todd and Littlemore), Mechanical Consultants (Steensen and Varming), Electrical Consultants (Julius Poole and Gibson) and the Head Contractor (the Hornibrook Group) to handle all aspects of the co-ordination of services throughout the complex. All parties worked together as a complete team.

The Hornibrook Group section of the team participated in the design co-ordination of all areas in checking combined service layouts as regards their feasibility for installation. All the relevant subcontractors were consulted in detail at this stage prior to the preparation of their shop drawings. This enabled direct information to be given to them so that they were aware of all other services that could conflict with their own.

There were many very complex areas and it was necessary in direct consultation with the subcontractors to prepare detailed combined service drawings with enlarged cross-sections at strategic points to sort out the "jungle" of services.

The main area of activity was in direct site control and liaison with subcontractors. Each member of the Hornibrook section was directly responsible for a set area. They would make regular site inspections and check the levels and positions of all services against both the shop drawings and the combined services drawings. They were also responsible for the initial approval. of shop drawings before they were approved by the architects and consultants. If a "foul" were encountered, then the group gathered all the interested parties together and resolved the problem in the best way possible.

There were two main criteria in these solutions : economics and job progress. Site sketches were prepared as a result and approved by all parties. These sketches were issued under site instructions from either the consultants and/or the architects.

Each member of the Hornibrook section worked in with the relevant area site supervisor on site matters and also the area programmer on the programming of the services. They also helped in site clearances such as areas above ceilings, together with the Clerk of Works prior to the erection of any ceilings and partition walling surrounding service ducts.

One of the main areas of activity was the co-ordination of services and equipment in the kitchen and bar areas. Hornibrook worked in direct conjunction with the architectural design office, and drew up set-out points for kitchen ceilings, electrical points and equipment together with all the cool rooms.

The team functioned very well and the results bear witness to the effectiveness of the participation of all the consultants, architects and subcontractors in this aspect of the project.

Planning Phase III

Planning for Stage III was unlike most contracts because there were no definite start dates, no detailed design for majority of the works, few output activity rates, as most design entailed new, or relatively new concepts. The only programme criteria in most cases were design start dates and target completion.

The three major programming steps were as follows:

Major Overall Job Network
This was a very broad network, splitting the job, into five sections (Concert Hall, Opera Theatre, "A" Areas, "B" Areas, "C", "D", "E" Areas) and showing overall priorities.

Major Section Networks
These were still very broad networks, but projected the design, construction and finished durations of major trades.

Detailed Programmes
This stage of the planning saw the setting up of a large programming/co-ordination team to compile and progress these programmes. Sections of the job were split into smaller areas (total 64) and a detailed programme compiled for each area, group of areas, or in some cases part of an area. These programmes covered all phases, i.e. architectural and consulting engineers' preliminary and final design, shop drawings and all relevant approvals, and checking off site fabrication. Planners and co-ordinators liaised with all parties, endeavouring to meet this design and construction programme.

The use of a computer programme was considered and was initially commenced but soon abandoned as so much flexibility was required due to the continued changing and updating resulting from the design, that the staff necessary to handle this operation successfully could produce progress and action sheets with more accuracy and regularity than would have been probable with a computer.

Furthermore, the use of the computer to produce a print-out programme appeared to make the logic too remote when considering the innumerable variations that were necessary, nor was the available experience and assistance from the trade supervision readily forthcoming when a computer programme was produced.

Field Supervision

As can be seen from the organization chart,the supervision of works was a key post and thus was filled by the Project Superintendent. His control in the field was through five superintendents, consisting of four area supervisors and one general services supervisor. The former was responsible for an area of the project, e.g. the Concert Hall, and the latter for support services such as concrete batching, rigging crew and survey, etc. Each area supervisor controlled work similar in value to a large size city building of some $5-10M.

In addition, and from time to time, a supervisor would be appointed to oversee special features; e.g. the suspended ceilings in the main halls, which were the responsibility of one supervisor to maintain continuity with the subcontractor and to take advantage of the experience gained.

Liaison and co-ordination with the mechanical and electrical consultants and subcontractors were maintained by the main contractor's Mechanical and Electrical Engineer. This was a particularly demanding task in view of the magnitude of the installations, especially, since commencement of one trade depended upon the progress of another. For instance, the central heat pump was needed for hot or chilled supplies to the air conditioning, which had to function before the vast timber linings could be installed in the auditoria, and all of which needed transformers and electrical power to supply energy.

Subcontract Control

This division dealt with the documentation, calling of tenders, entering into contracts and the general administration of contractual matters including payments.

Documentation was subdivided into four headings, viz.:

(a) Tender Conditions.
(b) General Conditions of Subcontract.
(c) Specification.
(d) Appendix to the General Conditions.

A Bill of Quantities was usually part of the above documents, either as information to tenderers or as a measured basis if conditions of tender called for remeasure on completion.

(a) Tender Conditions
These generally set out the requirements of the tender, such as lodgment of documents, tender closing date, what hours and/or days are worked, etc.

(b) General Conditions of Subcontract
These were the rules and regulations under which the subcontract would be administered and were of a general nature as it was impracticable to write special conditions for every subcontract. The conditions dealt with insurance, drawings, method of payment, submission of claims, arbitration procedure, subletting, time for completion, etc. However: because these conditions were of a general nature there was a specific appendix.

(d) Appendix to the General Conditions
In the appendix reference was made to the particular clauses under the General Conditions, and then pertinent facts were given, such as:

Time for completion: The exact date was given.
Payment: The exact date of submission of claims and payments was given.
Liquidated damages : The exact formula was stated.
Drawings: To be supplied or not.
Defects Liability Period: The exact period was given.
Etc.

(c) Specification
This part of the documentation dealt exclusively with the technical aspect of the job and, in combination with the tender drawings, enabled the tenderers to arrive at a proper tender price. It was usually imperative to inspect the site during the tender period.

(e) Tender Form
The documents contained a special tender form on which the contractor stated his price and any schedules of rates if applicable. The form was signed, witnessed and submitted on or before the due date.

(f) Selection of Subcontractors
Invariably the tenderers for sections of the work were selected and invited. Having invited tenders, it became almost obligatory to accept the lowest bid unless there was some grave error in pricing, in interpretation of the requirements, or if there was some qualification to the offer.

It was therefore necessary to carefully investigate the potential stability of the subcontractor before inviting tenders. This scrutiny was not only concerned with financial stability but also with the availability to the subcontractor of proper and adequate supervision and whether their work load was such that they could cope with the Opera House demands within the given time.

Not the least consideration was the labour force engaged by the subcontractor, whether he could sufficiently augment it, and whether the terms of engagement and rates of pay by the subcontractor were such as to cause dissatisfaction with other terms existing on site.

(g) Variations
It was imperative that the financial position between main contractor and subcontractors was up-to-date, and the regular placing of variation orders ensured this. Issuing first as a request for pricing, a standard form of variation was utilized that enabled the contract value to be recorded in a monthly statement to the client.

(h) Payments
Payments on account and in finalization of subcontracts were made through the normal accounts section of the project, but only after checking and authorization by the Subcontract Controller. This necessitated a form of bookkeeping and ledgers in the Subcontract Controller's division dealing solely with those contractual accounts and their adjustments, containing more detail of variations, etc., than that usually contained in a set of company accounts.

Administration

Administration of the project covered the fields of accounting incorporating actual cost control, personnel and industrial relations, insurance, security and sundry items of a general administrative nature.

To maintain and report progressive costs, a computer programme was designed to produce a purchase journal, general journal, list and value of goods received and not yet invoiced, list of outstanding commitments, list of current outstanding orders, labour and material used in both hours and value, and finally a cost summary produced on a monthly basis. To enable the examination of costs against estimates, these accounting returns were broken up into areas and subdivisions to cover all breakdowns of work performed. A series of progressive code numbers was used to denote the various functions. The cost summary then gave a period (monthly) and an accumulative total for the overall job to date.

By feeding in orders as placed with estimated values, it was always possible to obtain fairly accurate costing of goods delivered by using a percentage of the total order represented by the delivery, thus ensuring the inclusion of costs on items for which no creditor's charge had been received.

The programme was based on the minimum number of account dissections commensurate with the detailed costing required, bearing in mind that much of the work on this project was of a " one off " nature and historical costing would be of little value.

The use of the computer enabled monthly costs to be available for examination within 7-10 days of the conclusion of the period. Whilst a staff saving results from the use of the computer, it does not obviate the detailed preparation of weekly input, which still requires personnel, though not necessarily all qualified.

The computer has also been used for the calculation of wages for several hundred employees. This was a great time saving.

Industrial relations on a project such as this have called for constant attention. Following as we did from Stage I of the project, during which a site allowance was agreed with the unions, considerable industrial unrest was experienced when it was made known that Stages II and Ill would be completed under award conditions and that no allowance would be paid unless appropriate rates or conditions were recognized by the Industrial Commission and inserted in the various awards. Despite constant pressure this condition has been achieved.

Insurance cover on such a complex project required special attention, calling for a very comprehensive Contractor's All Risks cover, including Latent Defects and Legal Liability. Because of the amount of cover required and the unusual features of the construction, the underwriting had to be spread over world markets, and some proportion of this insurance is underwritten in every continent of the globe.

The safety record is one of which we are very proud, considering the difficulties encountered in construction. Special attention to safety has been the constant concern of both the company's Safety Officer and employee safety representatives. This has paid handsome dividends in the prevention of lost time and insurance claims. The site boasts a full-time Industrial Nursing Sister and a well equipped First Aid post.

Security on such a large site, with both land and water frontages, has been a constant source of concern, but the use of private security guards and special site procedures covering entree and inspection of vehicles, has enabled us to protect the structure and keep losses within reason for the industry. Losses cannot be stopped, but they have been reasonably contained.

Area Definition

The whole project was subdivided into areas for the purpose of identification and control. In broad principle, the Concert Hall and ancillary areas became "A", the Opera Theatre and support areas became "B", and common areas were "C", "D" and "E".

These broad divisions were further divided into operational areas indIcated by a number; for instance the Concert auditorium was known as A.25, whilst the foyers around it became A.23 and A.26.

This system of area coding proved so successful that the system has been adopted as the permanent code and is incorporated in all signals manuals and operational signs.

In addition, each room had a construction number and each door opening was scheduled. This facilitated the door scheduling and the group master keying system which has been adopted.

Industrial Condition

When the contractor for Stage 1 commenced work he faced a demand for special site allowance. In those days a site allowance was a new form of reimbursement and generally confined to isolated Projects or hazardous or unpleasant work. To expect a site allowance on a job in the heart of the city of Sydney was unexpected, but eventually the contractor established such an arrangement.

With the commencement of Stage II on a cost basis, the New South Wales Government was emphatic that only proper award rates should be paid, and there began a protracted and sometimes bitter industrial fight to obtain at least the over-award payments enjoyed on the previous contract. No agreement was reached to pay a site allowance but an award by Mr. Commissioner Menser made payable certain rates for disabilities and hazard when working above ground, on, and in the concrete shells.

During the period of Stage III this agreement was observed by all parties and was instrumental in bringing about a state of comparative harmony in industrial relations.

The site suffered from being involved in most of the disputes in the city, as well as a few peculiar to itself.

It also received much more than its share of publicity in this regard, especially from the TV news teams-due no doubt to the photogenic qualities of the building.

However, bearing in mind the scope of the work and the enormous number of man-hours involved, lost time was reasonable, as the following figures indicate. (Period 1st April, 1970, to 31st July 1973)

Hornibrook Labour:		
Total effective hours	2,147,482	(92.10%)
Total spread hours	49,071	(2.12%)
Total lost hours . .	134,886	(5.78%)
Total available hours	2,331,439	

Note: Spread time is that time spent in general services, e.g. gate control, stores, off loading. etc.

Labour Force and Rate of Progress

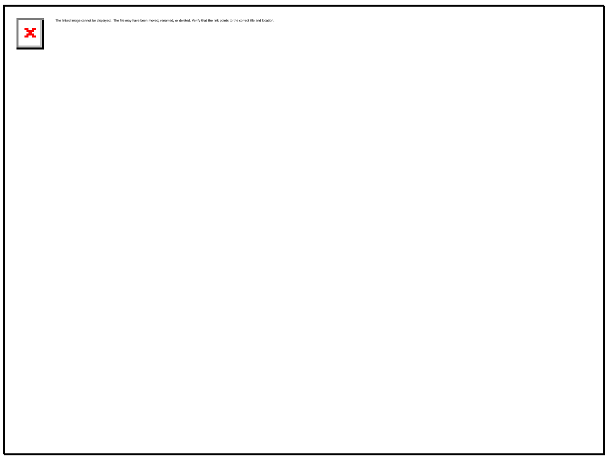
The target programme had envisaged a work force of approximately 1,000 men, and it was considered that this would only be recruited with difficulty. For a number of reasons the anticipated rate of progress was not achieved in the years 1968 and 1969 and it became obvious that the work force needed to be well in excess of 1,000 in the years 1970–1972 to achieve the completion date.

Furthermore, costs and estimates were constantly increasing, not only because of the escalation in cost of labour and materials but also in the anticipated prices of some services. For this reason the budgets and designs were carefully controlled and it is a satisfaction to record that the work was completed within the framework of the 1967 estimate, but escalation in wages and material had inevitably and contractually to be met, which increased that estimate of $85M to $100M in the space of five years.

There were many nationalities employed on the works. All important signs on the site were in four languages. When a count was made on one occasion for a news article a total of 14 languages was recorded without distinguishing between the Australian tongue and the English.

The following graphs indicate the labour force engaged (Figure 2) and the progress that was recorded from the actual wages and accounts paid (Figures 3 and 4). It should be remembered that these amounts paid do not include work executed but not paid, retentions, and the like.

The labour force peaked at approximately 1,350 site operatives. An exact tally was not possible as some subcontractors and their supervision did not accurately record their attendance.



Figures 2 & 3 [*The originals are hand drawn and unsuitable for reproduction by this means. The above are generalised and redrafted versions more suitable for web site diagrams; click image to enlarge*]

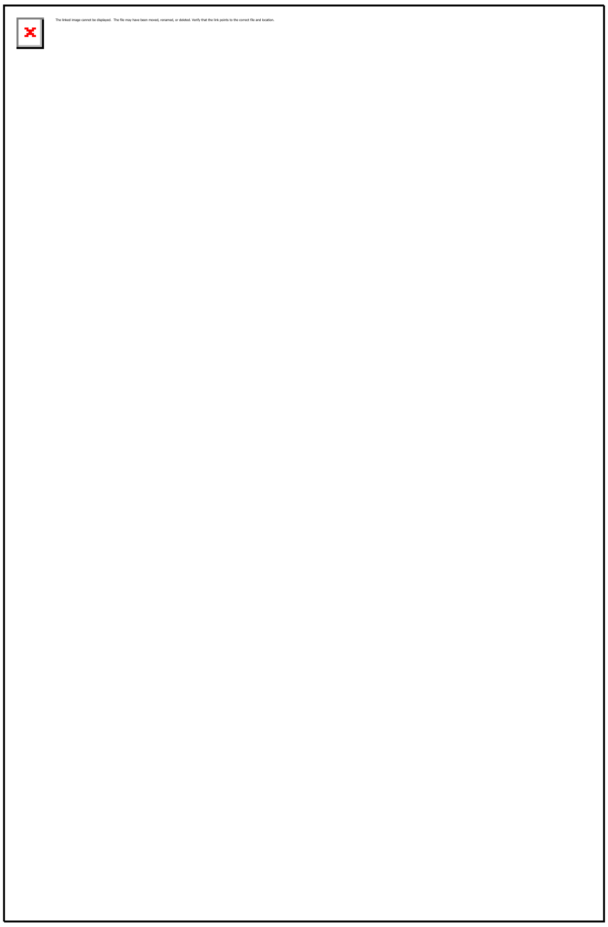


Figure 4 – Sydney Opera House accumulative expenditure. [*The original was hand drawn and unsuitable for reproduction by this means. The above is a generalised and redrafted version more suitable for web site diagrams; click image to enlarge*]

The maximum expenditure in one month was $2,450,000 approximately.

Both these figures are well in excess of any other similar construction performances in Australia.

Safety

As is generally found, those tasks that appear dangerous are treated carefully and usually are completed without mishap.

The whole of Stage II, the roof construction, was completed without one fatality and with very few serious accidents. This excellent record persisted into the latter period of Stage III when, unfortunately, a fatal accident occurred to a crane operator while rigging his machine.

Safety precautions were an important consideration in planning and supervising the work.

A resident Industrial Nursing Sister was located in the central First Aid station, and other First Aid posts were established throughout the building.

Personnel holding First Aid certificates were responsible for each post, and their names and locations were prominently displayed at the post.

A supervisor was appointed Safety Officer and two safety representatives were detailed from the work force. Their job was to correct minor breaches of safety, receive safety complaints from the men, and bring these to the attention of the Safety Officer.

Statistical records were kept by the Nursing Sister and detailed analyses of the types of injuries and circumstances under which they occurred were made. During the currency of Stage III full accident compensation became operable in the trade, but it is pleasing to report that the accident rate causing lost time was remarkably low and despite fears that full compensation may be abused there was little evidence of this.

Subcontracting

When awarding the contract to Hornibrook as main contractor for Stage III, the Minister for Public Works had assured the building trade that as much of the specialist work as was practical would be offered to subcontractors so that opportunities for participating in the project would be available.

It was therefore the intent from commencement of Stage III to subcontract as much work as was practical and economical, and the project was divided into sections and trades that enabled tenders to be called and subcontracts to be let.

The decision whether to sublet a particular section or to execute with directly employed labour generally revolved around the likelihood of obtaining satisfactory offers. It was soon found that the Opera House complex had engendered a hesitancy in the various trades, due, no doubt, to the involved geometry, the large scope of the work, and in some cases the unenviable reputation for industrial disputes that had surrounded the work in the early stages.

Some work could not be pre-priced. It was either too complicated and novel or the extent of the work was unpredictable. In such cases directly employed labour was invariably used, as it was if quotations received appeared to be excessive and unacceptable.

All other work was sublet, but even then the terms of subcontract were drawn with a view to removing from the contract unusual risks or liabilities, thus attracting a more acceptable offer.

For instance, the original intent with the timber ceilings to the main halls was to leave to the subcontractor the responsibility for all survey, setting out, checking of panel sizes, etc. From preliminary discussions with the shortlisted tenderers, it was evident that these responsibilities were causing considerable concern and being over-valued accordingly.

For the survey and setting out, one company intended using a firm of surveyors at a cost of $30,000, and other firms had not even reached that solution. There was not a shop large enough for a full-scale shop layout of the ceiling.

The conditions of subcontract eventually issued omitted all these requirements of the subcontractors—the main contractor's surveyors carried out the instrument work, the engineers computer defined the panel sizes—so that the subcontractor was left with work he well understood and could bid competitively.

Some subcontracts were let on a cost an material basis and one, the cutting and framing of the glass, was on a fee basis to a consortium of major glazing companies. These. were negotiated with a view to obtaining the services of selected tradesmen.and supervision.

The following is a list of the major subcontractors, with approximate values of the work executed in Stage III:

<td	$
Angus & Coote Acoustics Pty. Ltd — Acoustic Doors	250,000
Arcos Industries Pty. Ltd — Stage Tower Steelwork	300,000
A.W.A. Ltd — Closed Circuit TV and Sound Systems	1,250,000
Aygee (Merchants) Pty. Ltd — Dressing Room Furniture	135,000
W. Broomhead Pty. Ltd — Steel Mullions	450,000
S. A. Butler Pty. Ltd — Internal Painting	75,000
Carpet Manufacturers Ltd — Carpets to non-Public Areas	130,000
Cemae Brooks Pty. Ltd — Plywood Ceilings and Panels	1,250,000
Co-ordinated Design & Supply Pty. Ltd — Auditoria Seating	1,250,000
E.I.L. Special Projects — Signals and Inter-communications	275,000
E.P.M. Concrete Pty. — Precast Cladding	2,750,000
Fire Control Pty. Ltd — Fire and Timber Doors	250,000
Frigrite Limited — Heat Pump	700,000
F. & T. Carpets — Carpets to Public Spaces	200,000
G.E.C.-Philips Pty. Ltd — Lighting	2,500,000
George Hudson Pty. Ltd — Timber Flooring	650,000
Goldstein Pty. Ltd — Kitchen and Bar Equipment	380,000
Haden Engineering Pty. Ltd — Air Conditioning and Hydraulic Fire Protection	4,750,000
J.M. Hargreaves & Son Pty. Ltd — Plumbing Services.	800,000
Hawker de Havilland Aust. Pty. Ltd — Glass Wall Brackets	100,000
Indent Wall & Floor Tiles Pty. Ltd — Ceramic Tiling	150,000
Instalrite Plastics Pty. Ltd — PVC Piping	40,000
John M. Thomson & Co. Pty. Ltd. — Plastering	45,000
John Deck & Sons — Bronze Doors	40,000
Melocco Bros. Pty. Ltd. — Granolithic Paving	250,000
Nonoys Pty. Ltd — Sliding Acoustic Doors	140,000
Nonporite (N.S.W.) Pty. Ltd — Waterproof Rendering	45,000
Nucrete Pty. Ltd —Pneumatic Concrete	200,000
O'Donnell Griffin Pty. Ltd — Electrical Design and Installation	2,275,000
Permasteel Windows Pty. Ltd — Bronze Architectural Metalwork	1,600,000
G. Polhill & Sons Pty. Ltd — Internal Painting	50,000
Premier Joinery Pty. Ltd. — Timber Flooring and Wall Panelling	900,000
Quick-steel Engineering Pty. Ltd — Glass Wall Maintenance Equipment	60,000
Roof & Building Service Pty. Ltd — Water-proof Membrane	180,000

S.T.C. Pty. Ltd — P.A.B.X. System	95,000
Vasob Glass Pty. Ltd. — Glazing	450,000

Bronze and Glass Walls

Both of these sections of the work posed problems concerned with infilling the spaces between the overlapping concrete shells, and the solutions by both the architect and engineer were ingenious and intricate. Having devised the schemes, the designers looked to the contractor to implement them, which was done, but not without some misgivings and anxious moments until the unusual became commonplace.

Fortunately, there were still at hand the supervision and skills that had erected the concrete arched shells and had later threaded huge steel members through inadequate holes in the structure to form the internal steel skeleton from which the massive ceilings were suspended.

In the case of the bronze walls, the first problem consisted of providing access by way of working scaffold. The walls consist of an inner steel structure with vertically ribbed bronzed cladding externally, and sprayed concrete forming an inner face. The whole is warped and wreathed as the walls curve over the roof shells and twist forward as they rise.

To construct a scaffold on each side of the future wall necessitated surveyors constantly controlling the scaffolders so that an adequate and accurate working space was formed.

This and the subsequent construction of the steel and bronze work had to be executed high over and under the roof shells which form natural tunnels for wind currents and turbulent conditions.

The same crews of men were responsible for the erection of the steel mullions to the glass walls. These members were fabricated in lengths as long as practicable, pre-finished off site, so that handling and site working had to be with care.

The working tolerances allowed the manufacturer were more than could be permitted in the true line of the assembled structure as the depth of the rebate holding the glass was limited.

These unwieldy components had to be transported in special cradles, hoisted up and hung from the concrete shells, and then cross-braced and trued up by adjustable bracings until the line and position were within the acceptable tolerance of ¼ in. This tolerance was reduced to ±1/16 in for bronze and glass.

All the glass sizes and shapes were computed, and although frequent checks from site measurements were made these were generally confined to abutments against the concrete structure at intersections. The accuracy of the steel structure was of paramount importance.

Mechanical Services

The whole project is air conditioned or mechanically ventilated at a cost of $4M. The basic design principle was as far as practicable to provide localized plant rooms with heating and cooling coils throughout the building, thus reducing the amount of duct work and causing heat gains and losses to be kept to a minimum. Use is also made of vertical concrete shafts and double floor arrangements for air distribution. The air conditioning comprised installation of over 70 separate air handling systems, located in 24 plant rooms around the building and fed with heated and chilled water from a central refrigeration system. The air handling side consists of 120 fans (many of them two-speed fans), which move more than 1,000,000 c ft of air per minute when all the systems are running.

The conditioned air is distributed through approximately 12 miles of duct work to some 3,000 grilles and diffusers. The majority of rooms, and there are over 800 in this complex, are provided with individual temperature selection.

Ventilation, air conditioning and refrigeration machinery are all controlled by an electronic monitoring system located in the control room of the main plant room. This is the system's nerve centre. It automatically records an alarm when critical points of the system go outside predetermined limits. It raises an audiolvisual alarm signal and automatically prints out, on a line printing machine, the source of the fault and the limit which has been exceeded.

Particular attention has been given to the problem of sound attenuation. All of the plant, equipment, duct work and piping is fixed with resilient mountings to prevent the transmission of vibrations, while ducts are internally lined and provided with silencers at strategic points. In addition, much of the duct work is fabricated in sandwich construction form (consisting of a number of layers of metal with rubber sheets in between) as an added sound-deadening barrier to prevent the entry of noise from outside into the system and hence to the auditorium. This causes the duct work to be very heavy — large pieces weigh anything up to half a ton each. To obtain an indication of the size of some of the ducting, it is no exaggeration to say that a car could be driven through it.

The installation in the Drama Theatre is unusual in that here is installed the first cooled ceiling in Australia. The intention is to give to a large group of people in a small space the feeling of comfort without moving large quantities of air with the attendant noise and draught problems.

The refrigeration plant which supplies heated and chilled water to the various air conditioning systems cost approximately $800,000. This plant incorporates a heat pump system, which through heat exchanger vessels uses the harbour as a heat source whenever the heating load exceeds the cooling load, and as a heat sink whenever the cooling load exceeds the heating load. The plant has a capacity of 1,500 tons of refrigeration, generated from three centrifugal hermatic machines, and with its associated sea water and fresh water circulating pumps has an electrical load of over 2,000 hp. The same control system previously mentioned automatically adjusts the output of the plant to maintain the desired water temperatures.

Lifts for the Opera House worth about $250,000 comprise seven electric lifts and three oil hydraulic lifts. Because of the Opera House design, these lifts are all driven from the bottom of the lift shafts.

Electrical Services

The main power for the site comes via high-voltage 11 kV mains to feed two substations at ground floor level. The installation comprises six 1,000 kVA dry type Tyree transformers, each of which weighs nearly four tons and is again mounted on resilient pads to reduce sound transmission.

Directly beneath the substation is the Main Switch Room where, at a cost of $100,000, has been installed a 60 ft long switchboard which houses all the tariff meters, switch gear and distribution equipment for machinery, light and power.

Emergency lighting and panic light systems are installed for use if the mains supply from both substations is interrupted. The huge battery comprises two banks of 190 cells each, operating in parallel with a capacity of 1,000 ampere hours. The nickel cadmium batteries weigh 12 tons. They are designed for a two-hour sustained load of 95 kW.

The principal electrical subcontractor has installed 250 miles of wiring.

The lighting installation, worth over $2M, has been handled by a consortium company especially formed for this project. The lighting is designed to highlight the internal and external features of the Opera House. There are nearly 14,000 lighting fittings installed. Incandescent fittings are used generally throughout the public areas, with some small halogen lights for accent purposes. Most of the working areas employ fluorescent lighting. Workshops are illuminated by colour-corrected mercury lamps. There are about 1,200 incandescent fittings for the dressing rooms.

Stage Equipment

Stage lighting and control equipment was the subject of a separate contract, for a little over $1M. Much of the basic equipment is of German origin. A contract was let some years ago for the supply and installation of stage machinery and, of course, it was essential for the stage erection and the stage lighting organizations to work in close collaboration with each other. Both the Drama and Opera Theatres have 50 ft diameter revolving platforms. The Opera Theatre Stage is some 35 ft above the set changing and preparation area. A vertical transport platform can travel up from the set change area to the performers' level, change over a set, and disappear again whilst a performance is still continuing on the front of the stage.

Fire Precautions

All the usual safety and fire precautionary measures are built into the project, and particularly the stage areas. It would be true to say that more precautions have been taken here than with any other theatrical building in use anywhere. Drencher curtain systems are installed to protect the fire safety curtains for the stage openings of Opera and Drama Theatres.

The more conventional fire protection facilities are worth nearly $1M and cover hydraulic sprinkler installations in most areas of the building, totalling nearly 7,000 sprinkler heads and 140 hydrant stations. Areas housing expensive electrical equipment, where drainage from water could be as disastrous as that caused by fire, are protected with total flood B.C.F. gas-extinguishing systems. Kitchen areas have extract systems associated with cooking equipment, protected by CO. gas systems.

Communication Systems

Worthy of particular mention are some of the complex and advanced electronic systems associated with this project. There are electroacoustic and simultaneous interpretation systems worth over $1M.

The electro-acoustic system provides comprehensive sound amplification and distribution in the various theatres and public areas. The equipment incorporates features which allow producers to control sound reproduction to suit their individual requirements.

Of particular interest is the electrically tapered speaker column used in the Concert Hall, which is the first of its kind in the world.

As performing arts do not normally occupy a total yearly season within the building, provisions have been made for extensive conference facilities. The simultaneous interpretation system allows multi-lingual conferences to be held. Speeches from either the dais or the body of the hall will be translated simultaneously to conference members and relayed over a radio induction loop under the floor of the auditorium. Delegates are provided with pocket radio receivers and may listen to any language they wish by selecting the appropriate channel on their receiver. In the Concert Hall and the Opera Theatre there is provision for five languages, and in the Drama Theatre, Cinema and Recital Hall for three languages. These head-sets have a jack incorporated which allows a patron to tape record a conference in any language being used. The system can also be used for patrons with hearing problems.

Part of the conference facilities is an Optronic Paging Device: a sign which allows a message to be illuminated on stage. This sign has a built-in memory so that the message can be repeated at given intervals until the call is answered.

The importance of communication between stars, stage administration technicians and patrons has led to the installation of many sophisticated electronic communications systems within the Sydney Opera House complex.

Apart from the systems which are available to normal occupants of the building, there are special systems which centralize around the Stage Doorkeeper's Office. All security services, alarm bells, fire warning lights, etc., terminate in the Doorkeeper's Office on a large mimic display panel. This panel is manned 24 hours a day and all building alarms are recorded on the panel. The lights throughout the project are indicated on mimic panel plans of the Opera House so that a constant monitor of lighting can be kept. Lights can also be switched from this panel when control is released from the local switch panels.

There is a Radio Paging Service throughout the building which can be initiated from the Stage Door or the telephone switchboard. If the Doorkeeper or the telephonist wishes to reach persons who are not at their telephone points, they can initiate a radio paging message which will be picked up by portable receivers issued to key personnel upon their arrival in the building.

In the case of key technical personnel, these radio signals are coupled with critical alarms. For example, a critical fault occurs in the mechanical ventilation system and records an alarm at the Doorkeeper's Office; it automatically sends a warning signal to the Chief Engineer, who carries one of the receivers.

Security was a major consideration in the planning of this project. All external doors to the building are monitored for forced entry and automatically show whether the door is in an open or closed position or has been tampered with. This is recorded on the panel in the Doorkeeper's Security Office.

Facilities are located in the offices of key personnel and in stars' dressing rooms. All other dressing rooms and many other staff offices within the building have similar systems, but on a less comprehensive scale. The facilities are centralized in a wall unit called a "Room Service Module".

Perhaps the best way to explain the capabilities of some of these systems is to take the example available in a conductor's room.

A conductor may wish to tune up an instrument in his room without having to resort to a tuning fork or calling in a passing oboist. He simply walks to his Room Service Module and presses a button. Through a speaker in this module a four forty cycle "A" tone is produced with all the overtones of a normal oboe. He is also linked through this module to the Stage Manager's call system. In each of the theatres the Stage Manager can call dressing rooms which are preselected to occur on an indicator on his desk. As there can be many performances at any one time, the dressing rooms for each of the theatres are allocated beforehand, so that each Stage Manager knows where the personnel for his performance are located. The allocated dressing rooms show up on his desk in the form of illuminated buttons. During a concert the Stage Manager might wish to call his conductor, and he does this by pressing a button and speaking into his microphone, which automatically reproduces his voice in the conductor's suite. The conductor, from anywhere in his suite, can speak at a normal voice level, his voice being picked up by a sensitive microphone and relayed to the Stage Manager's desk. A red light flashes over the Room Service Module when the area is being listened in to by the Stage Manager.

A conductor may wish to see how many people are attending his particular concert that evening, or watch a performance in another hall. He can do this by selecting the channel on his module, which will display on a 21 in television monitor screen in his room a closed circuit television picture of the selected auditorium. After the performance, or whilst relaxing, he may wish to watch normal television channels. These can also be picked up on his monitor by a selection made at the Room Service Module.

The conductor also has facilities to tune in and listen to the music or activities in any of the major rehearsal rooms or auditoria. This allows the conductor to get a high quality reproduction of sound of the activities in those rooms. He can listen to his orchestra warming up or rehearsing in his absence.

Attached to the module is a house telephone system which enables him to dial, without going through the operator, any other room in the building. There are facilities in each of these suites to have separately metered telephone calls, so that he may call any part of the world and have the charge debited against his personal account. He has the facility of using the main telephone operator for local calls or, for example, ordering a meal from the catering service.

The closed circuit television system previously briefly described, in the conductor's suite, has many other uses. Late-comers unable to enter the auditorium after the start of a performance can watch the performance in a Bar Area on the closed circuit television system. In the halls where a conductor will be operating there is a separate camera covering the conductor's movements. These are relayed to various rehearsal rooms and to the back stage area, so that artists who are awaiting their cue can come in on the correct beat. The major rehearsal room is coupled with the Opera Theatre through the sound system. An off stage choir can perform in this theatre and its sound be transmitted to the auditorium whilst having a visual display of the conductor.

Integrated with this system is a tele-cine machine. This allows any messages which need to be passed to the patrons, such as calling for a specific person or notification of changes of cast, to be put on to the television sets in exactly the same way as credits are given on commercial television at the end of programmes. It can also be used to transmit foreign language messages, 35 mm slides and 16 mm projection film.

Within the closed circuit television network provision is made for a videotape recording unit. This unit comprises a mobile trolley equipped with closed circuit television camera, a videotape recorder and monitors. The unit can be used for staff training, for example in the replacement of complicated pieces of machinery or in the setting up of scene sets for opera, for training performers during rehearsals by recording their sections on stage and replaying them after the production. It has potential also for use by visiting producers. In the past we have had producers from Covent Garden jetting to and from Australia whenever their time permits them, to produce an opera in Sydney. The frequency of these visits could be diminished and the production could be improved by sending videotapes to the producer overseas at significant stages during the rehearsals.

For overflow crowds at performances or big conventions, the closed circuit television network can be linked to other auditoria, indicating to them the activities in the hall of their choice.

Facts and Figures

Height of tallest shell	221 ft above sea-level
Weight of roof	26,800 tons
Weight of building (Excluding granite paving and cladding)	125,000 tons of concrete 6,000 tons of steel
Width of external approach stairway	282 ft
Ground area of building	4½ acres
External dimensions up to	611 ft x379 ft
Number of precast tile panels	4,253 (containing over 1,056,000 tiles)
Number of precast segments in roof	2,194 (weighing up to 15 tons each)
Surface area of roofs	About 200,000 sq ft
Total length of stressing cables in roofs	217 miles
Unsupported span of concourse beams	From 136 ft to 164 ft
Area of granite paving and cladding	10 surface acres
Supporting piers and columns	The building is supported on about 550 3-ft diameter concrete piers, many sunk to more than 70 ft below sea level. End to end, they would extend for more than 21 miles. The roofs are supported on 32 columns, ranging in size from 4 ft to 8 ft square
Electrical installations	400 miles of cable in 60 miles of conduit with supply governed by 120 distribution switchboards. A bank of 12 tons of batteries is installed for emergency lighting
Air conditioning	The plant rooms will supply 20 tons of air per minute throughout the building

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