Battersea Power Station

Review of the listed building consent application for the demolition and rebuilding of the four chimneys

23 September 2005

Summary

This report looks at the structural and technical aspects of a proposal by Parkview International to demolish and rebuild the four listed chimneys at Battersea Power Station.

The conclusions by Parkview's consultants are that methods to locate reinforcement and cracks in the concrete, and trials to fill the cracks, failed. As a result it is not possible to install a cathodic protection system that would prevent future corrosion of the reinforcement and a general deterioration of the concrete. From this they have concluded that it is not possible to repair the chimneys.

We believe that this assessment is based on an incorrect understanding of the chimneys as structures, in particular the likely causes of the cracks in the concrete. This has led to an incorrect assessment of their location, form and extent. As a result it appears that the wrong brief for the trials and tests has been set.

No evidence to support the statement that the chimneys are close to the end of their design life has been seen. On the basis of what we have seen we do not agree with this statement.

There is no evidence that the four chimneys are structurally unsound. This is despite the absence of any repair and maintenance work since the station was closed in 1983.

The majority of the cracks look to be due to early shrinkage of the concrete and thermal movements. We have not seen evidence of widespread corrosion of the reinforcement and associated spalling of the concrete.

As the four chimneys were built over a 24-year period our view is that each chimney needs to be appraised and considered on an individual basis.

Access to all of the structure is fundamental to the appraisal of any building or structure. This has not happened here. We accept that there are health and safety issues to be addressed but we consider that access to both faces of the structure for investigations and repairs is essential.

On the basis of the information we have received the argument that demolition and rebuilding of the four chimneys is the only option has not been justified. It does appear feasible to carry out a comprehensive repair of the four chimneys that will meet the requirements of Parkview's brief. This will include patch repairs, the rebuilding of the top sections where there is more significant corrosion and spalling of the concrete, and the introduction of a cathodic protection system to reduce the risk of future corrosion of the reinforcement.

1. Introduction

This report has been prepared for use by the Twentieth Century Society, Battersea Power Station Company Limited and the World Monuments Fund to help in their response to a proposal to demolish and rebuild the four chimneys at Battersea Power Station.

Applications for planning permission and listed building consent for the proposed works were submitted on 11 July 2005 on behalf of Parkview International. The reasons put forward for the rebuilding are set out in an Executive Summary by Buro Happold; the consulting structural engineer for the proposed refurbishment of the building.

This report has been prepared by the structural engineers Stuart Tappin (Cameron Taylor) and Alan Conisbee and Gary Johns (from Alan Conisbee and Associates). Specialist advice on non-destructive investigations and concrete repairs has been provided by George Ballard (G B Geotecnics) and Roel van Els (Martech).

The report is primarily a technical review of the investigations that have been carried out and the conclusions that have been drawn from the findings. It then considers whether there is an alternative approach that repairs the chimneys. It also considers the technical aspects of the brief.

Two meetings have been held to review the information provided by Parkview and to discuss what information is required and the possible options to demolition and rebuilding.

A site visit was made on 30 August 2005 attended by Alan Conisbee, Gary Johns, Stuart Tappin, Jim Martin (CT) and George Ballard with representatives from Parkview, Reid Architecture, Buro Happold and Concrete Repairs Limited.

A meeting was held at Buro Happold's office on 6 September 2005 with Catherine Croft and Cordula Zeidler (20th Century Society) Alan Conisbee, Stuart Tappin, and George Ballard, Jim Solomon and Stephen Brown (Buro Happold) and John Broomfield (Broomfield Consultants).

This report, dated 23 September 2005, supersedes all previous revisions.

2. Summary of the Structure of the Existing Chimneys

The power station was built in two phases. Station A, the western half, was built 1929-33. Chimney 1 at the northwest corner dates from 1931; the southwest chimney from 1932 – July 1933
Station B1 was built 1937-mid 1940s with Chimney 3 at the northeast corner built c1939-40. B2 1955-57 and the southwest chimney 4 was complete in 1955.

Station A was closed in 1975. Station B closed in 1983.

Battersea Power Station was listed grade II on 14 October 1980.

For Station A the structural engineer was L G Mouchel & Partners. Chimneys 1 and 2 were built with 1:1.5:3 ferrocrete cement:sand:aggregate mix. Ferrocrete was rapid-hardening Portland cement from the Hennebique patent. Sand and aggregate (max 1/2 inch) were supplied by the Ham River Grit Co Ltd. The external reinforcement is a double helix with vertical and hoop bars. The internal reinforcement is vertical and hoop bars. The chimneys were built at a rate of three lifts of 4 feet per week. The external finish was referred to as "Stic B". Each chimney weighs in the order of 546 tons.

No information has been seen on the design or construction of Station B.

3. Summary of the issues presented in support of the demolition and rebuild proposals

The Executive Summary report dated 1 June 2005 prepared by Buro Happold (BH) summarises the brief for the chimneys as requiring a minimum design life of 60 years. Annual inspections would be undertaken and maintenance should be by cradle access rather than "substantial scaffold". The repair techniques should be "tried and tested" and "must be acceptable to the funders and insurable at commercially acceptable rates".

The BH report says that a "comprehensive structural survey" was undertaken in 2003 that identified "the most significant findings were the high levels of chloride, carbonation, cracking and delamination within the concrete and the extent to which the reinforcement was corroded". They concluded that "the chimneys were close to the end of their design life'.

A Steering Group was set up in 2004 which included the design team, English Heritage and concrete repair specialists.

A repair scheme was agreed, which was considered to be the only viable scheme, to provide the employer's brief, and a trial of this scheme arranged to test its feasibility.

The trial repairs were carried out to the outside face at the base of the southwest chimney and involved:
(i) preparation of the outside face,
(ii) determining electrical continuity of the reinforcement in advance of installing a cathodic protection system,
(iii) non-destructive testing (NDT) to locate reinforcement and voids in the concrete,
(iv) trial filling of the voids with a grout.

This trial was successful in providing methods of cleaning the surface of the concrete, and the placing of a weatherproof coating containing a GRP textile capable of containing any minor loose material demonstrated at that level that there was adequate electrical continuity of the reinforcement for installing an impressed current cathodic protection system, the heart of the remediation scheme.

The trial was unsuccessful in locating reinforcement and voids in the concrete sufficiently accurately with non-destructive tests (NDT), and in reliably filling of the cracks with grout.

The repair scheme proposed by the Steering Group was to replace the structural function of the chimneys with a new internal structural support to which the original chimneys would be attached as a cladding: this patently assumes that the original structure is no longer viable as a self supporting column. There is no evidence that modeling or analysis of the existing structure has been carried out to verfy this assumption.

Cracks and delaminations have been found within the chimneys and offered as evidence that the chimneys have reached the end of their useful life. There is no analysis of the mechanism which produced the cracks and delaminations, nor whether the mechanisms are present which will cause these cracks and delaminations to worsen, either compromising the new structural support or the surface concrete (which might then subsequently fall off) or indeed compromising or damaging the remaining steel reinforcement. When asked about whether a structural appraisal or modeling had been carried out we were told that understanding the cracks was only "of academic interest".

Chloride contamination has been located, the measurements of which, (by drilling dust samples at three heights and four locations round the circumference of each separate chimney, and various other points) can only be approximately located on the surface. Therefore the environment from which they have been taken, the presence or absence of cracking, and whether it is penetrative cannot be adduced It is also not possible to determine whether or not there is any correlation between high chloride levels and corrosion.

There is no evidence that a definitive analysis of the source of chlorides has been made or correlated with any sub-analysis of the chloride contamination levels to produce a risk profile from the chloride.

The 0.4% by weight of cement chloride level used by the Steering Group as a trigger for concern for chloride induced corrosion, although accepted as a useful trigger level for concern, is conservative in this instance. The value itself is based on an assumed cement content within the concrete of 14% whereas we have been told that the average cement content greater than 20%. Its distribution throughout the chimneys tends to indicate that it was included within the original aggregate and is not a post construction contamination. It is therefore in all probability chemically bound within the cement paste and will not present a corrosion risk except where the concrete has become carbonated.

Carbonation has been examined and found to be generally minimal in the surface cover concrete, such that carbonation induced corrosion is expected to be low over the next 50 years.

The trial testing carried out to locate the steel and cracks as well as the grouting exercise was premised on the assumption that the steel was already corroding due to extensive chloride contamination and that the steel had therefore lost contact with the passivating concrete electrolyte, thus necessitating an ICCP remedial solution, with the restoration of the electrolyte contact. As above this assumption is not well proven and there is evidence to suggest that the reinforcement nearest the surface remain for the most part free from corrosion and well embedded in sound concrete.

The evidence from the NDT data is that there is no continuous plane of delamination available for grouting cracks and that a different approach to reconsolidation might well be more successful, if necessary.

Throughout the review of the testing and assessment of the longevity and durability of the chimneys there has been difficulty in tracing connectivity between the various strands of data, all of which must by definition be derived from and relate to the four chimneys. The quality of reporting has increased this difficulty: for example only minimal information has been reported on the cores where compliance with BS1881:Part 120 would have been expected. Given that the entire purpose of the investigation was to assess the remedial needs of the chimneys as a conservable architectural feature then it is surprising that detailed photography has not accompanied every test and exposure carried out.

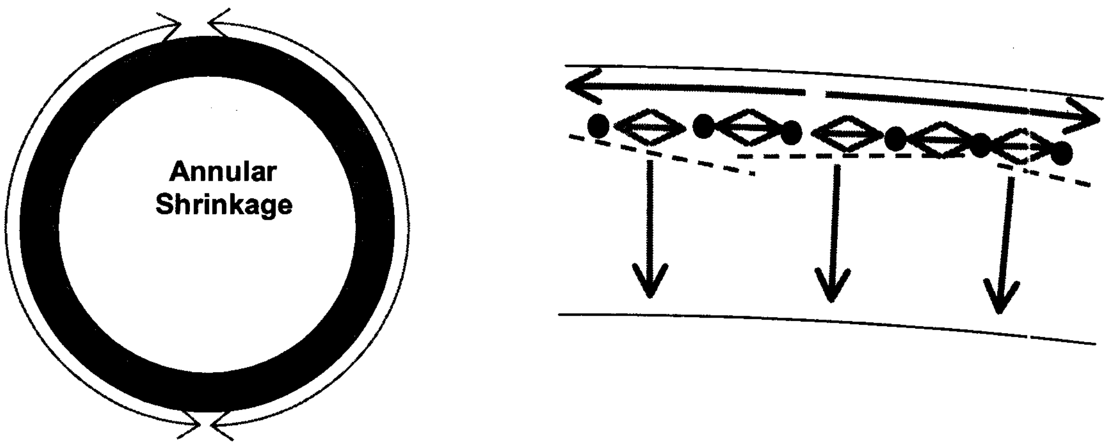
4. Corrosion, delamination and cracking

It is reported that "this was the most severe case of concrete delamination seen" by the Steering Group and the assumption implied is that the delamination is driven by corrosion. The evidence for the general delamination and cracking arising from corrosion does not exist.

At the most simplistic level, if the delamination, had been the result of corrosion it would have occurred on the outside face of the reinforcement and the spalling would have been outward, with the expansive force reacting against the inner concrete, with sheets of concrete falling off. There is almost no outward spalling concrete apart from at high level where the chimney reduces in thickness. Our view is that the delamination and the cracking is almost certainly due to early age shrinkage of the concrete and has therefore been present in the concrete since construction

Normal shrinkage of concrete of this type would be of the order 5 parts in 10^4 to 1 part in 10^3 in the first year (IBIS: water/cement ratio is normal to above normal). This corresponds at the base to a linear shrinkage of 15-30mm, or a reduction in diameter of 5 -10mm around the circumference.

The annulus however means the shrinkage is unrelieved, causes the shrinkage to appear as compression on the helical steel, which is well designed to resist this. Linear, vertical shrinkage cracks in the concrete cover to the outer reinforcement will be the inevitable result. These cracks have been recorded on elevation drawings, albeit with the cracks shown at a much larger scale than is actually the case. The core concrete beyond the outer reinforcement is however unrestrained and the annulus diameter reduces, generating a stress field between the restrained outer and the unrestrained inner, with significant shear developing parallel to the external face.



Concrete Shrinkage and Failure Planes

The cracking and delamination is thus general, but is not ongoing.

5. Non-Destructive investigations

Steel positioning: Locating by radar the positioning of the nearer surface layers of steel set at angle nearer to vertical than horizontal was have been hampered by the space between the flutes as pointed out by CRL. The Ferroscan system would have been too restricted in space, and the close spacing at angles off normal would have resulted in apparent displacement of bars by the software.
If the exact location of steel were critical then use of X-ray imaging from the interior could have been achieved without man entry to the interior. This would, as informally advised by Aperio - who carried out the NDT, have produced the level of accuracy required.

Crack location: the investigators were expected to locate a continuous planar crack or delamination, as might arise as a result of expansive corrosion, with a horizontal dimension greater than the footprint of their investigative tools. Their software data processing was arranged to achieve this, and failed. Similarly the grouting work expected to grout a similarly formed continuous delamination failed to achieve logical flows from packer to packer with wide variation in the transit of air, water and grout.

Failure by the specifiers of the tests to appreciate the cause and nature of the cracking, and their insistence that a continuous plane of delamination was to be found, and failure on their part to attempt to understand why the investigators and grouters had failed to achieve what appeared to be a simple objective, led to the rejection of their performance.

The trial repair failed as it was attempting to achieve an impossibility.

Note that other elements of the trial repair, where the specifiers could see what they were attempting to specify, and respond to differences between assumptions and physical observation, were successful. There was no response to physical observations of the rest of the trial repair team and no feedback of the physical investigations to the

NDT trials.

Based on the above, the reported failure of void filling is effectively irrelevant. The steel appears generally to be still well embedded in sound concrete, and, as the 'delamination' is not generated by expansive corrosion and does therefore not compromise the bond. A CP system can be introduced without any need for additional electrolyte. The surface cracking needs investigating to determine whether or not it does actually compromise the steel: the lack of corrosion products on the surface suggests it does not; distinction needs to be made between the major cracks which can be seen at each sixth flute, and the minor cracks between the panels.

6. Comments on the Structural Appraisal

We have not seen any indication in either BH's report or during our site visit that the present condition of the chimney is causing significant structural problems.

While there is a great deal in the report about the problems due to the concrete there is no structural analysis of the chimneys and the defects. For example how many of the cracks date from the original construction? The horizontal cracks are at regular centres and may be at construction joints. Similarly, many of the vertical cracks on the outside face are probably from drying shrinkage of the wet concrete (we have seen nothing on how the concrete was protected while it cured, nor any consideration of the importance of this). Other vertical cracks are likely to be due to thermal expansion and contraction of the chimney. We would expect to see some assessment of what changes in circumference would result a temperature variations.

The northwest chimney has far less cracking than the others. There is no evidence that why this is the case has been investigated.

The causes of cracks are not discussed, and so there can be no understanding of whether they are historic or ongoing, or structurally significant. One possible cause is from differential drying shrinkage between the outside and inside faces within the zone of unreinforced concrete. Without this understanding it is not possible to assess whether the cracks are historic or ongoing or whether they are structurally significant.

There has not been any access to appraise the inside surface and so there has been no opportunity to look at the structures as a whole.

The four chimneys we built at different dates over a 24 year period. While it is reasonable to assume that the station B chimneys followed the design of station A, we would expect this to have been confirmed.

It is probable that the concrete between the A and B chimneys will be different even if the specified mix proportions were the same. This will be due to the different source of materials and water and the different contractors. Because of this we will be concerned about extrapolating the results from one to all of the chimneys.

7. An Alternative Approach

Understanding the form of the four chimneys, their previous structural performance , the causes of the defects that have been observed, and correlation of these with all the phenomena observed is fundamental to the appraisal of the structure.

Access to the inside of the chimneys is strongly recommended, with the tile linings removed along with any loose concrete. It will then be possible to review the cracks with those on the outside face, and carry out NDT without the obstructions encountered on the outside face.

Any future NDT should be checked against cores and opening up to improve understanding and to correct the models of performance and durability, and to improve the accuracy of results.

The cracked concrete and any corroded reinforcement can be made good by conventional repair techniques and rebuilding at high level. Removal of concrete on the outside and inside faces is likely to expose any damaged concrete within the core of the structure, which can then be replaced or repaired by pins and grouts.

On the basis of the information, it does appear feasible to install a cathodic protection system that will help protect the reinforcement against future corrosion.

In terms of meeting the Employer's brief, the issue of access for future maintenance and repairs is similar whether the chimneys are retained or rebuilt: inspection and on going regular minor maintenance are correctly viewed by the Employer as a necessary part of the conservation of the existing structure.

8. Conclusions

The tests and investigations that have been carried out are not sufficient to conclude that there is no alternative to demolition and rebuilding of the four chimneys.

There is no sign of distress in chimneys caused by problems in the original structural design.

There is no evidence produced of general severe, i.e. greater than1%, levels of chloride throughout the structure, rather there is evidence of chloride marginally above acceptable.

There is no evidence of sufficiently deep carbonation to warrant concern.

There is no evidence of general, distributed, expansive corrosion of the reinforcement.

There is no evidence to support the need for the installation of a new structure inside the existing chimneys.

Many of the cracks date from the construction process. There is little evidence of spalling concrete to the majority of the shafts. There are no signs of significant cracks due to the levels of carbonation or chlorides that have been recorded.

The reported 'failure' of the non-destructive tests should have been reviewed with the findings from the core samples so that alternative methods, and changes to the calibration of instrumentation could be made.

It is not surprising that the NDT from the outside face was unable to locate the inner reinforcement Internal access would record the inner reinforcement and allow correlation of the inner and outer readings to give a greater degree of accuracy to the results.

There are other methods of discovering the location of the steel, such as X-ray, which were not employed.

Access to the interior is vital to the general appraisal of the chimneys.

As 24 years elapsed between the start of the first chimney and the completion of the fourth there will be variations in the construction and the amount of decay of the chimneys. Each should be considered on it's own merits.

The alternative approach is to gain access to both sides of all shafts to carry out a visual structural appraisal and tests. From this we believe that a strategy for repairs and cathodic protection will meet the requirements of the brief.

A conventional repair that removes the damaged concrete will provide direct access to most of the voids and they can then be filled either by grout (using a vacuum if tests show this is needed) or by the concrete patch repair. Even if all the concrete between the flutes was removed to the face of the outer reinforcement this would likely result in a loss of in the order of 10% of the total volume of concrete. Removing all the concrete from the inner face (which may not be necessary) will mean about a further 10% of the original material is lost. There are therefore sound environmental reasons, as well as listed buildings/PPG 15 benefits, in repairing the chimneys.

9. Information used in the preparation of this report

From Parkview's team:

Taylor Woodrow report no TWC/N950/03/13372
Buro Happold Report on the Chimney Trial Repairs - Executive Summary dated 1 June 2005
Concrete Repairs Limited Trial repairs to chimneys report dated 15 June 2005
Buro Happold Report on the Chimney Trial Repairs dated 1 June 2005
BH drawing No 00001 dated 21 February 2006
CCCP's report on additional chloride testing dated 14th July 2004.
CCCP's report on additional testing of the Taylor Woodrow cores dated August 2004.

CgMs Historic Buildings Research and assessment report dated June 2005
Reid Architecture letter to Wandsworth Council dated 11 July 2005

Samples of Radar and acoustic Data supplied by Aperio Ltd

Other sources:

Concrete and Constructional Engineering vol. xxviii, April 1933 pp238-240 and vol. xxv March 1930 pp. 178 - 180

Minutes of Proceedings of the Institution of Civil Engineers Vol. 240, 1937 pp. 37 - 120

Battersea Power Station Conservation Plan dated May 2000 prepared by Inskip and Jenkins

Landmark of London: The story of Battersea Power Station by Rob Cochrane

10. CV's

Stuart Tappin
BSC Civil Engineering MIStructE MA (Art and Archaeology) SOAS

Stuart is a technical director with Cameron Taylor. He graduated in 1981 and worked with Alan Baxter & Associates for 13 years on some of the country's most important and historic buildings. He has deep understanding of the special issues relating to listed buildings, scheduled monuments and buildings within conservation areas. Work on 20th century buildings includes the Barbican Centre, Wallis House, Dorich House and the British Galleries at the V& A Museum. He has lectured on building conservation at both Bath and De Montfort Universities, to various amenity societies and to conservationists in the UK and India. His MA dissertation was on the early use of reinforced concrete in India. He is a member of the 20th Century Society Casework Committee and the ICOMOS (UK) Structures Committee and chairs the Tenants and Residents Association at the listed Brunswick Centre.

Alan Conisbee
BA BAI CEng MIStructE

Graduated from Trinity College, Dublin in 1972 with degrees in Fine Arts and Engineering. Alan worked with Alan Baxter & Associates for many years as an Associate, before setting up his own practice in 1982.

Through his work at the Almeida Theatre and award-winning housing schemes, built up a reputation for excellence in the design of residential, arts and sensitive restoration projects.

His particular interest in the repair and re-use of old buildings culminated in his co-authorship of CIRIA Report 111 Structural Renovation of Traditional Buildings and he now heads the involvement of the firm in Urban Regeneration Projects.

As well as leading the practice in large-scale re-development projects, Alan was, in 2002, the leader of the multi-disciplinary team promoting the highly acclaimed 'Urban Jungle' project – an initiative to create a £60million rainforest exhibition and visitor attraction inside the old gas holders at King's Cross.

Alan is the director responsible for developing the practice's philosophy and application of sustainable engineering design and he is a director of the low-energy consultancy XCO2conisbee.

Gary Johns

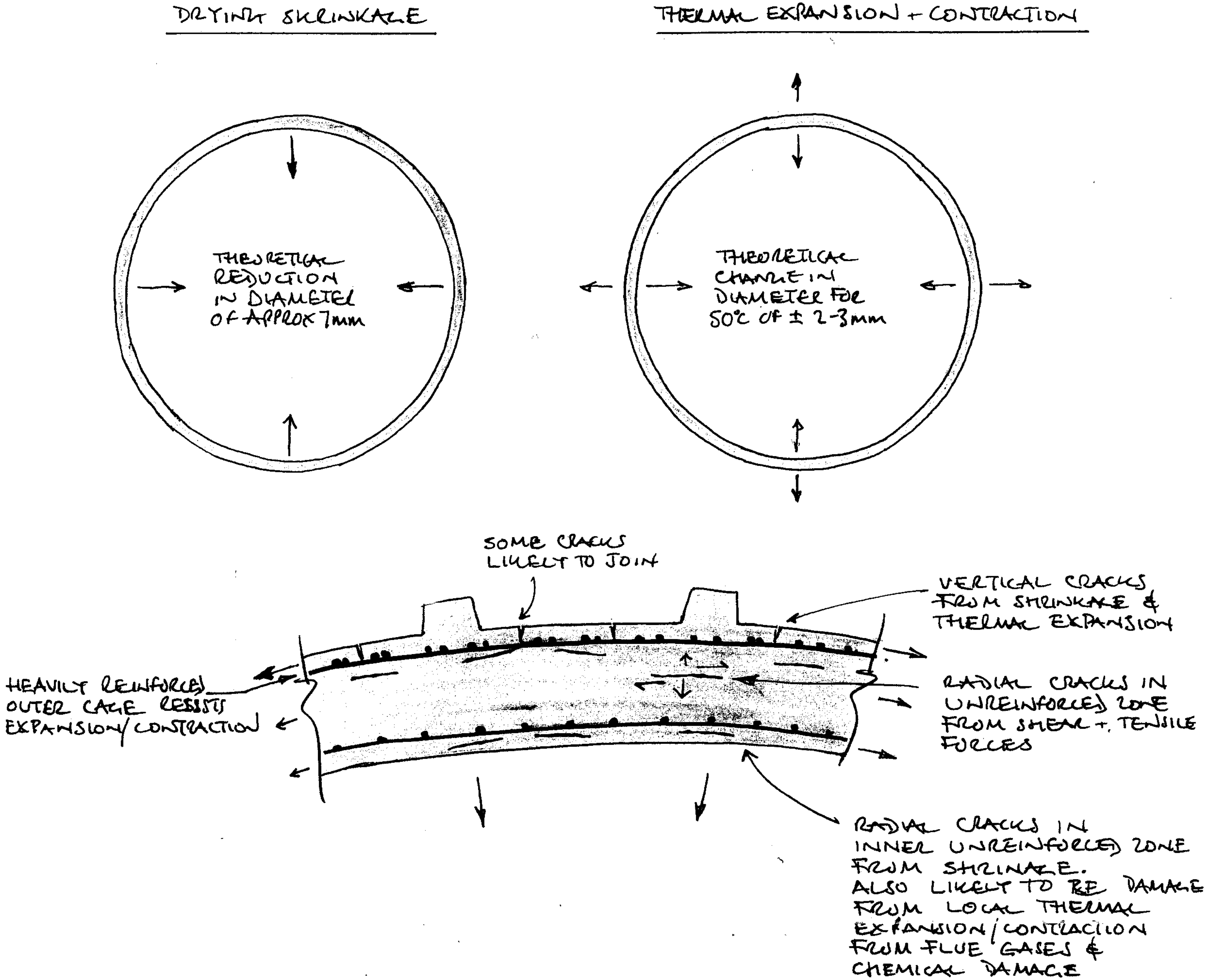
Gary Johns joined Alan Conisbee and Associates as a senior engineer specialising in regeneration in early 2004. Prior to this, he was with Mitchell Macfarlane Partnership for more than twenty five years, initially in their new build section and since the mid 1980s exclusively on the appraisal, repair and refurbishment of existing buildings and inner city estates for local and central government bodies, housing associations, HARCA's and HAT's. During this period Gary developed a special interest in the repair of reinforced concrete and masonry and is particularly experienced with the broader issues associated with refurbishment of the existing building stock such as liaising with residents.

George Ballard MA MSc

George Ballard has some 30 years experience in the application of instrumentation and non destructive testing to the structural investigation of engineered structures. Early research work in Earthquake detection, engineering and risk assessment at University of Cambridge led to formation of private practice in structural assessment. Particular expertise in Historic Concrete and Mortars, Concrete and Materials Technology, Concrete Repair Systems, Tunnel Construction Methods, and Historic Building Conservation. External Lecturer Universities of York and Greenwich in NDT Techniques and Conservation.

Preparation and editing of reference standards for the use of non destructive techniques in structural inspection.

George Ballard is a member of various Working Parties on Radar and Non Destructive Testing for The Concrete Society, The Concrete Bridge Development Group, English Heritage and the National Trust, Historic Scotland, the Society of Engineers, the British Institute of Non Destructive Testing and the Highways Agency in the UK, CROW (Centre for Road Construction Research) in Holland, Australian Road Research Board, and the Association of Preservation Technologies in the USA.



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CLIENT

PROJECT
BATTERSEA POWER STATION CHIMNEYS.

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1 - PRELIM 2 - INFO 3 - APPR 4 - TENDER 5 - BUILDING REGS 6 - CONST 7 - AS BUILT