Independent Enquiry
Into Casuarina Substation Events
And Substation Maintenance across Darwin

Final Report

Chairman: Mervyn Davies

4th February 2009

Overview

This enquiry was established, in response to concerns about the continued security of supply to the Northern Suburbs of Darwin, which arose following a series of equipment failures, in late September and early October 2008, at the Casuarina Zone Substation and within its surrounding network.

The scope of the enquiry was to undertake an assessment of the failure incidents and examine substation maintenance practices more generally across Darwin.

The Incidents

Of the six failure incidents investigated by the Enquiry:

- Only one was directly related to maintenance effectiveness.
    - This was the No 1 Transformer Breaker failure – the first and most catastrophic of the failures. It was the first failure of its kind on the PAWC system. It was age and condition related, nevertheless with more effective maintenance and condition monitoring it is likely that it could have been avoided.

- One was attributable purely to age and condition.
    - This was the first of the two Nakara Feeder endbox failures. It too was the first failure of its kind on the PAWC system. There is no meaningful requirement for the routine maintenance or in situ condition monitoring of the component of the endbox which failed – an insulating bushing.

- One was attributable to an installation defect.
    - This was the second Nakara Feeder endbox failure. The root cause of this failure was the omission of four holding bolts, the absence of which allowed the endbox to become displaced from its mounting. Consequent changes in the electrical stress distribution within the endbox resulted in electrical breakdown of the bushing insulation.

- One was a simple and quite unremarkable cable failure.
    - Cables of this type operate without the need for routine maintenance. The only connection to the earlier failures at the zone substation was, that additional heat generated by the unusually high load being carried as a consequence of temporary network rearrangements adopted following the earlier failures, was probably the trigger for what was already an incipient fault.

- Two were attributable to overloading, the root cause of which was inaccuracies in recording systems.

- These were two other cable faults. Whilst the unusually high loading on these cables at the time was also attributable to temporary network rearrangements adopted following the earlier failures, the root cause of the failure was the inaccurate recording of the cable capacity.

For all three of the substation incidents problems were experienced with a crucial electrical protection system, known as Frame Earth Leakage (FEL). As a consequence the severity of two of the incidents concerned was considerably greater than it otherwise would have been. Investigation of these problems was hampered by access restrictions, the destruction caused by the breaker failure, and a lack of routine testing of the FEL systems. The root cause of the most significant of these problems has not yet been established. However a more effective maintenance and test programme could have been expected to resolve these problems, before the FEL systems were ever called upon to operate. The investigation that was carried out also identified an apparent design weakness in the earthing system and another example of the omission of holding bolts.

Casuarina Zone Substation is a thirty six year old substation equipped with a GEC-OLX2 switchboard. It is the only substation in Darwin equipped with a switchboard of this manufacture. Given past industry experience with OLX switchgear and what is now known about the condition of the Casuarina switchboard, the switchboard should be replaced. PAWC has plans in place to do just that, and have actually commenced replacement.

Most other zone substations within Darwin are of similiar age and are equipped with similiar technology switchgear. The switchgear is however of a different manufacture and, though undoubtedly suffering some degree of degradation, the likelihood of imminent catastrophic failure is not considered to be as great. Rigorous condition monitoring and maintenance is nevertheless required.

The implementation of a comprehensive condition monitoring and remedial programme for all zone substation equipment is recommended. PAWC have advised that the planning for such a programme has already commenced and implementation begun.

Substation Maintenance across Darwin

Over a period of decades the approach to substation maintenance across Darwin has shifted from what was originally a very traditional approach involving routine preventative maintenance as the dominant task type, to one which is now a minimalist approach, dominated by corrective and breakdown tasks.

This shift is considered to have come about as the inevitable outcome of attempts by those responsible for delivering maintenance to cope with competing demands and budgets constraints, in an environment which required little or no systemic reporting of either asset condition or maintenance works delivery. And an asset and works management system that so poorly served and demoralised the delivery workforce that it was ultimately switched off.

Along with this shift there has been a gradual erosion of workplace skills and custodial pride in the condition of the assets.

Given the age and likely condition of PAWCs substation assets a new approach to Substation maintenance is required. This has been recognised by the current PAWC management.

The transition, by PAWC, to a more "condition based" approach to substation maintenance management is recommended. However given PAWCs size it will need to be a pragmatic approach, which leverages off the collective knowhow of the wider industry and adapts that knowhow to the environment and circumstances and asset set of PAWC. Such an approach broadly accords with PAWCs current planning commitment to move to a new maintenance framework based on "objective need".

There is a sufficient foundation of fundamental core engineering knowledge and technical and craft skills on which to build an effective substations maintenance capability and condition based approach. But this foundation will need to be augmented, developed and up skilled. It will also need to be supported with additional equipment and systems, and re energised.

The predominant leadership and supervision style, affecting substation maintenance at PAWC, is hierarchical, remote and uninvolved. With some exceptions, there is little sense of "ownership" of the substation maintenance function or the problems of asset condition and work delivery, by managers and supervisors. Overall, so far as substation maintenance is concerned there seems to be a "disconnect" between management and the workplace and between the various management functions. This is characterised by a lack of trust and respect.

It was nevertheless apparent to the Enquiry that there is a sizeable relevant base of "motivatable" people within PAWC. But the creation of an environment in which this potential can flourish will require substantial intervention.

A significant Human Resources Development programme will be required.

The current PAWC management does have plans in place, some of which could do with some fine tuning and additional initiatives will be required. Many of these plans are in their infancy, nevertheless it would be inappropriate to blame the present management for the current position and not to recognise the steps currently being taken to address the situation.

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Acknowledgements

The Enquiry acknowledges the willing support and cooperation received from PAWC and its people. Their contribution, and the manner of the contribution, greatly assisted the Enquiry.

1. Introduction

Casuarina Zone Substation was originally constructed, in 1972, as a two transformer 66/11kV substation with 11kV oil filled switchgear, with compound filled cable endboxes, connected to two sections of 11kV busbar.

In 1974, the roof of the switch room was blown away by Cyclone Tracy necessitating the reconstruction of the building. This reconstruction took place around the existing switchgear which, following some reconditioning, was retained.

In 1975 the substation was extended by the addition of a third section of 11kV busbar and associated oil filled switchgear, with compound filled cable endboxes.

In 1980 an additional transformer was installed and three additional panels of switchgear were added to the third section of busbar. This additional switchgear was vacuum insulated gear, with air insulated cable endboxes. Subsequently, during the early eighties, all compound filled cable endboxes were converted to air insulated endboxes.

In 1999 a catastrophic failure of a capacitor breaker, connected to the No 1Busbar Section occurred. As a direct consequence, in 2000 two complete panels of switchgear were replaced with vacuum insulated gear and a third was decommissioned. And between 2000 and 2004, all remaining oil filled breakers, were replaced with vacuum breakers, with the exception of the six large transformer and bus section breakers, for which no suitable vacuum replacement breakers were available.

On 19 September 2008 the oil filled circuit breaker in the switchgear connecting the No 1 Transformer to the No 1 Busbar Section failed catastrophically. This event lead to the loss of supply to more than 11 000 customers for periods of up to 14 hours, 16 minutes. Following this event there were several other power outages in the northern suburbs, two of which were caused by faults in a cable endbox on the rear of the Casuarina Zone Substation switchboard.

In response to these outages, and growing concerns for the continued security of supply to the northern suburbs of Darwin, the Northern Territory Government activated the Counter Disaster Plan and commissioned this Enquiry.

A copy of the Terms of Reference of the Enquiry is attached as Appendix 1.

These Terms of Reference call for a three stage reporting process: with an initial Preliminary Report, to be followed by a Draft Report and a Final Report. The Preliminary Report was delivered on the 10^{th} November 2008. That Preliminary Report did not seek to address the full scope of the Terms of Reference, but focused instead on determining the root causes of the failures, from a technical standpoint. This current report addresses the full scope of the Terms of Reference and fulfills the combined requirements of the second and third stages in a single Final Report.

This Final Report, in addition to addressing matters not covered in the Preliminary Report, incorporates all of the material contained in the Preliminary Report. It also corrects a number of factual errors of detail contained in the Preliminary Report and, provides some additional factual and explanatory material, pertinent to that report. Its format and structure is the same as that of the Preliminary Report.

A list of the substantial differences between the Preliminary and Final Report is provided in Appendix 3 Corrections to the Preliminary Report.

In addition to a considerable amount of descriptive material the Report: makes findings, draws conclusions and, makes recommendations.

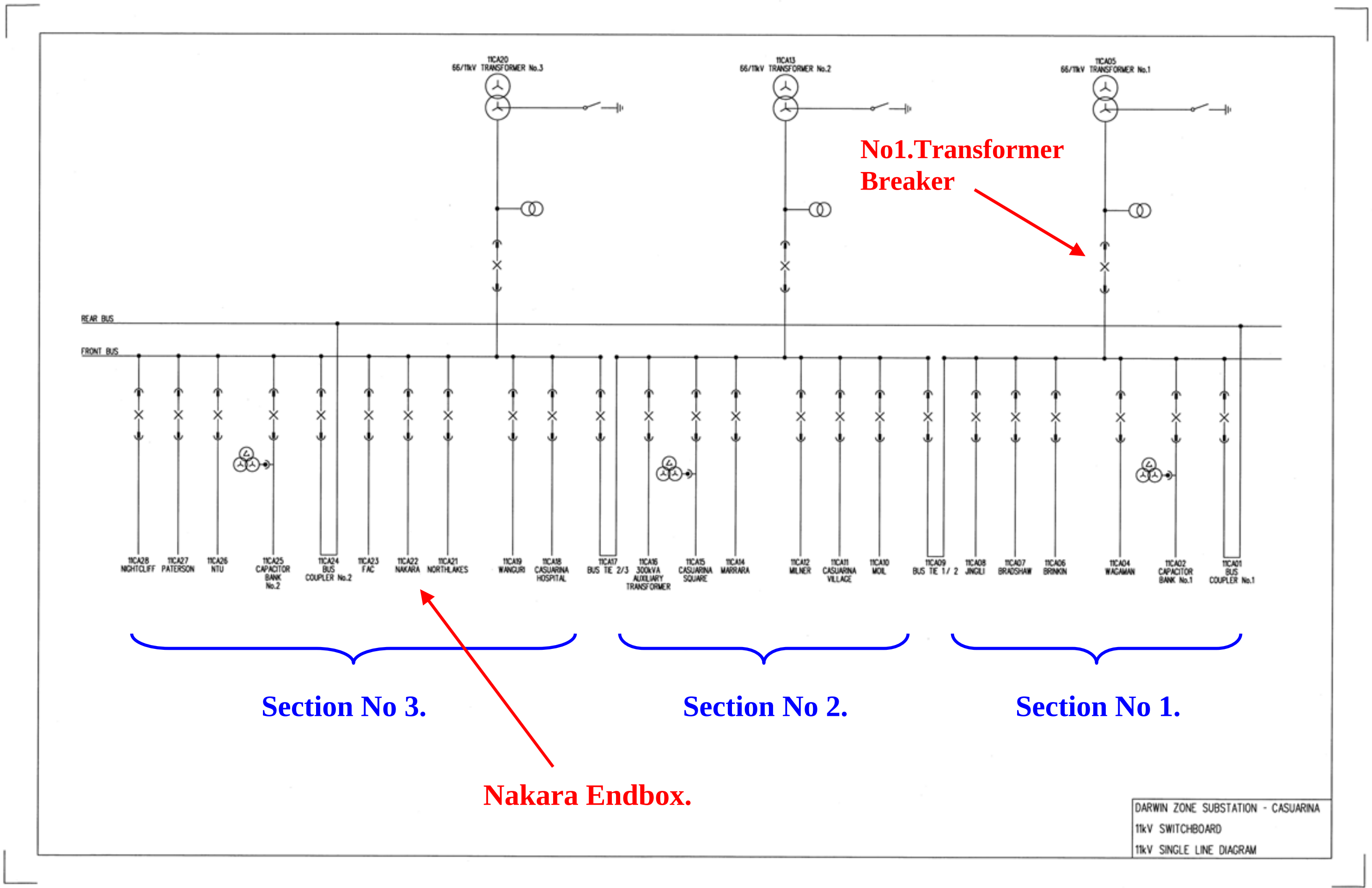
Findings are determinations made as to matters of fact. They are based on what is predominantly an objective assessment of available evidence. Whilst much of the available evidence was physical and capable of verification by inspection, considerable reliance was also placed on documentation and advice provided by PAWC and its people. Documentation was assessed in terms of the credibility of its source and where possible, by cross referencing alternative sources. Advice received from individuals, was subjected to informal questioning, but was not subject to a rigorous formal validation processes. Given the nature of the enquiry the use of formal validation processes was not considered appropriate.

Findings, many of which relate to causal factors, are for the most part made with a high degree of certainty, and where there was an element of uncertainty, have been expressed in terms of likelihood.

Conclusions, on the other hand, are judgments made from an assessment of the findings, and either offer an explanation of the findings or prospects for the future. They involve an element of subjective as well as objective judgment.

Recommendations are the actions considered necessary to address the issues raised by the conclusions.

Simplified Single Line Diagram of Casuarina Substation



2. Summary of Findings and Conclusions

2.1. The Root Causes of the Failures

2.1.1. The Breaker Failure

The breaker failure was caused by an electrical insulation breakdown which resulted in a short circuit between the active conductor within an insulating bushing and the external metal housing of the breaker tank.

The trigger for the insulation breakdown is considered to be heat, generated by high contact resistance, leading to "thermal runaway" within the insulation.

The root cause of the failure is considered to be progressive deterioration, attributable to prolonged exposure to overheating generated by high contact resistance, exacerbated by the hot and humid tropical environment.

2.1.2. The Endbox Failures

The first of the two cable endbox failures was caused by a breakdown of the degraded insulation of the cable endbox bushing.

The degradation is considered to be due to the ingress of moisture absorbed from the unmodified humid tropical Darwin environment, which the bushing was subject to for most of its life. The trigger for the breakdown is considered to be the elevated temperature of the bushing associated with the unusually high load imposed by the abnormal switching arrangements adopted following the breaker failure of the 19th September. The loading was nevertheless within the design rating.

2.1.3. The second of the two cable endbox failures was attributable to an installation defect.

This defect has arisen as a result the re-installation of a thirty six year old degraded Wagaman feeder endbox bushing into the Nakara endbox. Whilst there were a number of installation defects, any one of which could have eventually led to failure, the particular defect which was clearly the root cause of this failure was the omission of four mounting bolts. The omission of these bolts allowed the endbox to "walk away" from its mounting, due to vibration, and cause a relocation of critical insulation material within the box. The consequent changes in the electrical stress distribution within the both the box and the bushings resulted in electrical breakdown. This breakdown is likely to have occurred, regardless of the initial condition of the bushing. The degraded bushing has simply failed earlier than an un-degraded bushing would have.

2.1.4. The First Cable Failure

The first of the three cable failures was caused by one or other of several common failure mechanisms typical of this cable and environment, all of which are unrelated to the earlier Substation incidents. Elevated temperature attributable to the unusually high loading on the cable at the time was probably the trigger for the failure. The loading was nevertheless within the design rating of the cable.

The precise cause of this failure is not critical to the Enquiry, as it is not considered to be an endemic problem, directly related to the substation failures.

2.1.5. The Second and Third Cable Failure

The last two of the three cable failures were caused by overloading.

These failures are related to the earlier Substation incidents in so far as the increased loading was due to the abnormal switching arrangements, adopted in order to restore supply following the earlier failures.

The root cause of the overloading however was inaccuracies in the cable sizing information available to the Control Room staff.

2.1.6. The Performance of the Protection Systems

The root cause of the failure of the Frame Earth Leakage Systems to operate in the manner expected has not been determined.

A number of possible causes have been identified, but there is insufficient evidence available to support a firm conclusion.

2.2. Implications for Possible Further Asset Failures

2.2.1. Possible Further Circuit Breaker Failures

The breaker failure of the 19th September 2008 is the first and only such failure in the history of Casuarina Zone Substation. (The breaker failure of 1999 was a different circumstance.) There are, however five other such oil filled breakers in the Substation, all of which are likely to have suffered some degree of insulation degradation due to long term heat exposure.

Whilst the continued operation of these breakers is feasible, provided their condition is routinely monitored and maintained at a viable level, they do present an elevated risk when compared to the alternative of new, current technology breakers.

Whilst there are also oil circuit breakers at other PAWC zone substations, they are of different manufacture and the likelihood of catastrophic failure is not considered to be as great. Rigorous condition monitoring and maintenance is nevertheless required.

2.2.2. Possible Further Cable Endbox Bushing Failures

The cable endbox insulator bushing failure of 20th September was the first such endbox failure at Casuarina.

It is however clear from the investigation that the insulation of many of the other cable endbox insulator bushings at Casuarina is to some extent degraded. However, robust condition monitoring, of the sort possible for breakers, is not feasible for cable endbox bushings, in situ. The risk posed by these bushings is therefore not readily measurable and the best that can be done is to undertake regular thermo vision testing to assess whether a key failure trigger mechanism is present.

The failure of an endbox bushing does not have the same catastrophic potential as an oil circuit breaker failure. It does, nevertheless present both a reliability and personnel safety risk.

Whilst there are also similar bushings at other PAWC zone substations, they are of different manufacture and the likelihood of catastrophic failure is not considered to be as great. Regular monitoring is nevertheless required.

2.2.3. Possible Further Cable Failures

There is no reason to suspect that the incidence of cable failures in the network supplied by Casuarina (or any of the other Darwin Zone Substations, for that matter) is imminently in danger of escalating to unmanageable levels.

2.3. The Future of the Casuarina 11kV Switchboard

The overall condition of the Casuarina 11kV switchboard is such that attempts to recondition/refurbish it are likely to be futile. The switchboard should be replaced.

2.4. Maintenance and Maintenance Management

2.4.1. Maintenance Policy Documentation

With some exceptions, substation maintenance policy documentation is inappropriate for use by field staff. It also presents the traditional, somewhat intrusive, approach.

2.4.2. Maintenance Practices

With some exceptions, there appears to be no nexus between substation maintenance policy and practice. Maintenance practice appears to be being conducted in accordance with “on the job” “father to son” learning, on a best endeavours basis.

2.4.3. Condition Monitoring Capability

Whilst PAWC has some substation maintenance condition monitoring capability and some test results on file, there does not appear to be a systemic approach.

More training is required in the operation of some of the more advanced equipment and interpretation of test results.

2.4.4. Craft Skills

The knowledge and skill required to undertake effective and efficient maintenance of key substation equipment requires enhancement.

2.4.5. Supervision Skills

The knowledge and skills required to effectively supervise the carrying out of substation maintenance requires enhancement.

2.4.6. Engineering and Management Skills

The knowledge and skills required to:

- Determine document and deploy appropriate substation maintenance policy.
- Manage its effective deployment.
- Ensure that feedback and recording systems are relevant and working effectively.

require enhancement.

2.4.7. Processes and Systems

The current systems supporting asset management and works management as applied to substation maintenance are poor, and need to be upgraded. The systems are not being effectively used for substation maintenance.

2.4.8. Asset Condition Reporting

There is no systemic asset condition reporting, and condition records, to the extent that they do exist, are only used for local ad hoc decision making.

2.4.9. Works Programme Reporting

There is no systemic works programme reporting, other than the localised reporting of protection maintenance.

2.4.10. Expenditure Reporting

Maintenance expenditure is monitored, and compared to budget. The budget is however set without regard to any planned outcomes, apparently as an extrapolation of past expenditures.

2.4.11. Current PAWC Initiatives

There are initiatives already afoot to address most of the above issues:

- The adoption of a framework of "objective need" as the basis for future maintenance budgeting and an upgrading of condition monitoring is planned
- The Power Networks Division has been reorganised, with a view to facilitating a focus on asset management and improving planning and accountability.
- An Asset Management Capability project (AMC) has been initiated. Assessment of current asset management practices, processes and systems, has been completed and redesign commenced.
- The Board has initiated action in regard to the systemic reporting of asset condition and the maintenance works programme.

2.4.12. Organisation Structure

The recently adopted organisation structure places planning responsible, for both asset and works management with the Strategy and Planning group. This will need careful management.

2.4.13. Framework of “Objective Need”

The transition, by PAWC, to a more “condition based” approach to substation maintenance management is appropriate. A pragmatic approach, which leverages off the collective knowhow of the wider industry and adapts that knowhow to the environment and circumstances and asset set of PAWC, is feasible. And broadly accords with PAWCs planning commitment to move to a new maintenance framework based on “objective need”.

2.4.14. The Foundation Skills Set

There is a sufficient base of fundamental core engineering knowledge and craft and technical skills on which to build an effective substations maintenance capability. But this base will need to be developed, up skilled and re energised, and supported with additional equipment and systems.

2.4.15. Additional Maintenance Delivery Staff

Six additional craft employees should be allocated to substation maintenance.

2.4.16. The Legacy

The current position regarding substation maintenance at PAWC is not a recent development. It has developed over a very long period (decades), mostly during periods of different management and governance arrangements.

It would be inappropriate to blame the present management for the current position and not to recognise the steps currently being taken to address the situation.

2.5. Internal Relationships

2.5.1. The predominant leadership and supervision style, affecting substation maintenance at PAWC, is hierarchical, remote and uninvolved. With some exceptions, there is little sense of “ownership” of the substation maintenance function or the problems of asset condition and work delivery by managers and supervisors.

2.5.2. Overall so far as substation maintenance is concerned there seems to be a “disconnect” between management and the workplace and between the various management functions. This was characterised by a lack of trust and respect.

2.5.3. There seemed to be reluctance on the part of some relevant managers to strongly defend, either PAWC or their role in it.

2.5.4. Substation maintenance staff variously expressed feelings of frustration and disappointment, and a lack of respect for managers, and of being in a situation that was beyond their control. They complained of a lack of training and support. And some lacked confidence in their capacity to perform their role.

2.5.5. Whilst the above attitudes were not universal and whilst such attitudes will to some degree be found in peer organisations, the extent to which they were present among the substation maintenance staff at PAWC is of concern.

2.5.6. It was nevertheless apparent that there is a sizeable relevant base of “motivatable” people within PAWC. But the creation of an environment in which this potential can flourish will require substantial intervention.

2.6. The Recovery Effort

2.6.1. The strategy adopted by the recovery team and the decisions, made throughout were appropriate, in the circumstances.

2.6.2. The decision by System Control, to utilise 95 sq. mm. cables as a significant alternative supply route, on two occasions, was unfortunate.

This decision relied upon inaccurate cable data recording. In the circumstances the decision was appropriate.

2.6.3. The performance of the recovery team and the workforce was, on each occasion, commendable. Although, the installation defects of the first bushing failure replacement were avoidable. The recovery effort for the first event was particularly commendable.

2.6.4. Response and recovery times for all six events are considered to have been timely and similar to the response and recovery times of industry peers, in similar situations

2.6.5. The speed and accuracy of the information made available to customers and other stakeholders was satisfactory and comparable to industry peers, in similar circumstances.

2.6.6. Incident management was somewhat lacking in formality and, for at least two of the incidents, may have benefited from earlier escalation.

2.7. The Retrofit Programme

2.7.1. The retrofit programme was instigated by PAWC in response to the principal recommendation of the Mehta Report.

2.7.2. The decision to widen the retrofit programme beyond the Mehta recommendation was an appropriately prudent step in minimising the oil hazard.

2.7.3. Whilst the widened programme is currently behind schedule, the requirements of the original principal Mehta recommendation have been fully implemented.

2.8. Relevant Previous Reviews

2.8.1. The report on the Mehta investigation, into the explosive failure of a capacitor bank oil circuit breaker, at Casuarina Zone Substation, on 21st march 1999 contains eight recommendations which have contemporary relevance to the current Enquiry.

- Five of the eight recommendations, including the principal recommendation, have been appropriately implemented.
- The recommendations concerning: the implementation of post maintenance testing; condition monitoring; and the reinstallation of operation counters on switchgear, have not been effectively implemented.

2.8.2. The report on the Blanch review of various aspects of PAWC’s operations contains a series of findings that are of direct relevance to this review.

None of these findings are inconsistent with the observations of the current Enquiry.

A brief review of recent PAWC planning documentation indicates that PAWC’s recent planning has been influenced by the Blanch Review.

2.8.3. Sinclair Knight Mertz (SKM) was engaged during 2006 by the Northern Territory Treasury to assist in a review of PAWC’s financial reporting management systems. Within their report there are a number of findings and recommendations which are relevant to the current Enquiry.

A brief review of recent PAWC planning documentation indicates that PAWCs recent planning has progressed in directions that are consistent with the SKM recommendations.

2.8.4. The Manton Investigation was an internal PAWC investigation into the bus bar failure on the YSF6 22kV switchboard at Manton Zone Substation on the 21st March 2008. The Investigation did not establish a root cause. Further investigation work is warranted.

3. The Incidents

3.1. The Breaker Failure

At 4.29 pm on the 19th September 2008, the No. 1 Transformer 11kV Circuit Breaker at Casuarina Zone Substation failed explosively. The electrical protection systems operated to isolate the fault and the resultant fire was extinguished by the operation of the CO_2 fire protection system. The explosion and fire caused limited damage to adjacent equipment, consistent with and typical of this type of failure and fault duration.

The electrical protection systems however failed to operate in accordance with the intended design and, as a consequence, the fault duration was considerably longer than it otherwise would have been and the protection systems when they did operate isolated the whole of the zone substation rather than just the affected section. Consequently the extent of the resultant damage was greater than it otherwise would have been, the extent of the resultant supply outage was approximately three times greater and, the outage duration was considerably longer.

An extensive clean up and testing operation was undertaken, before commencing supply restoration, from the Casuarina zone. However some early supply restoration was achieved by field switching to the Berrima and Snell Street zones.

Supply to the 11 200 affected customers was progressively restored between 8.43 pm and 6.45 am the following day. The longest customer outage duration was fourteen hours, sixteen minutes.

3.2. The Endbox Failures

At 11.14 pm on the 20th September 2008, the C (blue) phase electrical insulating bushing of the Nakara feeder cable endbox failed and an electrical flash over occurred. The Nakara feeder is connected to the No.3 Busbar Section of the Casuarina Zone Substation.

On this occasion the electrical protection systems operated almost in accordance with the design intention and despite a latent fault in one component of the system successfully cleared the fault with minimal fault duration. The only consequence of the latent protection fault was that, the restoration time for one of the ten affected feeders had to be extended, to enable the fault to be corrected.

Supply to the 4 400 affected customers was restored by field switching. The bulk of customers were restored within one hour, fifty four minutes, while those affected by the latent protection defect were restored within four hours, four minutes.

The faulty insulating bushing was replaced with an identical, but out of service bushing, from the Wagaman feeder. (The Wagaman feeder is connected to the No. 1 Bus Section, at a location immediately adjacent to the failed No.1 Transformer breaker. It has been out of service ever since the failure of that breaker.) The Nakara feeder was returned to service on the 22nd September 2008.

Some twelve days later, at 8.23 pm on the 2nd October 2008, the replacement C phase electrical bushing of the Nakara feeder cable endbox failed and an electrical flash over occurred.

On this occasion the electrical protection systems failed to operate in accordance with the design intention, in that the Frame Earth Leakage protection initially failed to operate. The fault was nevertheless cleared by feeder protection, with minimal fault duration and outage extent.

Some 29 minutes later the Frame Earth Leakage protection operated and cleared all the remaining breakers of the No. 3 Busbar Section, thus greatly and unnecessarily increasing the extent of the outage.

Supply restoration, on this second occasion was affected by access restrictions imposed following the earlier failures. In order to work within the constraints of the access restrictions, supply to the whole of the zone substation was disconnected. The number of additional customer interruptions was minimised by first undertaking field switching, but this took considerable additional time. Some 6 700 customers were affected and the maximum outage duration time was ten hours, thirty seven minutes.

3.3. The Cable Failures

Subsequent to the No 1 Transformer breaker failure some three 11kV cable failure incidents occurred within the supply area of the Casuarina zone. Whilst these incidents were not technically substation events, they did have a bearing on public perception and, it is appropriate that the Enquiry address the possibility of linkage between these cable failure events and the substation events.

Event 1.
At 11.36 am on the 20th September 2008 the 11kV feeder cable which supplies the Casuarina Shopping Square, from Casuarina Zone Substation failed at a point, adjacent to a joint in a pit, approximately 500m from the Casuarina Zone Substation.

The electrical protection systems operated to isolate the faulty cable section. The 81 affected customers were restored by field switching with a maximum outage duration of two hours, fourteen minutes.

Load on the cable, at the time of the fault, was abnormally high, due to the abnormal switching arrangements adopted in response to the circuit breaker failure of the 19th September 2008. It is also notable that this abnormally high load, which persisted for a period of approximately four hours, followed upon the fourteen hour period of no load occasioned by the September 19th Zone outage.

The abnormally high load was, nevertheless well within the design capability of the (400 sq mm aluminium) cable.

Event 2.
At 4.46 pm on the 7th October 2008 a section of small capacity 95 sq mm XLPE aluminium cable on the Bradshaw feeder, which is supplied out of Casuarina Zone Substation, failed at a location remote from the Substation.

The electrical protection systems operated to isolate the faulty cable section. The approximately 2 200 affected customers were restored by field switching with a maximum outage duration of two hours, forty four minutes.

Load on the cable, at the time of the fault was abnormally high, due to the abnormal switching arrangements adopted in response to the Circuit Breaker failure of the 19th September 2008.

The load is assessed to have been considerably in excess of the design capability of the 95 sq. mm. section of cable.

Event 3.
This event was virtually identical to Event 2, at a different but nearby location.

At 4.18 pm on the 12th October 2008 another section of small capacity 95 sq mm XLPE aluminium cable on the Bradshaw feeder failed, but at a different but nearby location.

The electrical protection systems operated to isolate the faulty cable section. The approximately 2 200 affected customers were restored by field switching with a maximum outage duration of one hour, two minutes.

Load on the cable, at the time of the fault was abnormally high, due to the abnormal switching arrangements adopted in response to the Circuit Breaker failure of the 19th September 2008.

The load is assessed to have been considerably in excess of the design capability of the 95 sq. mm. section of cable.

4. Investigation of the Incidents

4.1. Approach

The approach taken to the investigation of the incidents was to:

- Inspect the physical evidence and gather other pertinent data.
- Analyse the data and physical evidence in the light of wider industry experience of similar incidents and knowledge of relevant failure modes.
- Draw conclusions as to the causes of each failure.

The data gathering variously involved:

- Site inspections.
- Physical inspection of the damaged equipment and documenting details of the physical evidence.
- Some limited testing.
- Interviewing of relevant staff.
- The collection of documentation.
- The collection of photographic evidence.

Details of the results of this process, as applied to each of the incidents investigated, are reported below.

So far as the cable incidents are concerned, site and physical inspections were not undertaken, and only very limited other data collection was required, in order to understand the likely causes of these faults and any potential relationship to the substation failures.

4.2. The Breaker Failure

4.2.1. **The Breaker**

The breaker concerned is the No. 1 Transformer Circuit Breaker, which supplied the Number 1 Bus Section at Casuarina Zone Substation. It is an original, unmodified, 36 year old 1600 amp GEC-OLX2 bulk oil circuit breaker, which had been installed at the time of the original construction of the Casuarina Zone Substation.

4.2.2. **Physical Inspections and Photographic Evidence**

A site inspection of the damaged section of the 11kV switchboard at Casuarina Zone Substation was undertaken on the 8th October 2008. Evidence of residual smoke and fire damage was noted, but most notable was the 700mm split/tear in the 10 mm. thick metal casting of the circuit breaker oil containment tank. The breaker was observed to be in the closed position.

Following the site inspection, the damaged No. 1 Transformer Breaker was taken to the Ben Hammond workshops where it was disassembled and more closely inspected.

Fig 1 – Damage to Circuit Breaker Bushing at the point of failure inside the tank

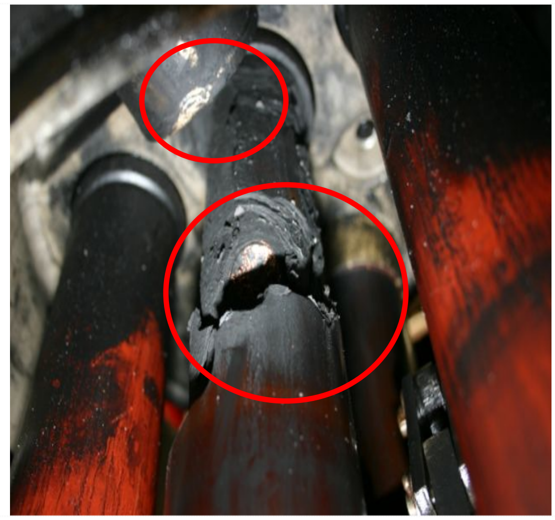


Fig 2 – Evidence of Flashover from Bushing to tank

Close inspection of the breaker revealed evidence of a breakdown in the electrical insulation of the B (yellow) phase transformer circuit breaker bushing. The breakdown occurred between the active conductor within the bushing and the external cast metal housing of the breaker tank, at the position of the pressure vent, just above the oil level.

The condition of the electrical insulating papers adjacent to the point of failure was dry and flaky and exhibited the characteristic signs of delamination due to long term heat exposure.

Additional details of the physical and photographic evidence are provided in the Technical Appendix T1.2 The Breaker Failure

4.2.3. The Protection Operations

At the time of the fault the substation was operating with all bus section switches closed and the No.1 and No. 2 Transformers operating in parallel. The No. 3 Transformer was energised, but not connected to the 11kV bus at the time. (This is the normal arrangement. It provides standby capacity, thereby enhancing reliability, without exceeding the fault level interruption capability.)

The No. 1 Bus Section Frame Earth Leakage protection failed to operate in accordance with design intentions for this type of fault. Had it done so, it would have cleared the fault in about 0.25 seconds by de-energising the whole of the No.3 Bus Section, but would have left the remaining two busbar sections connected to the No. 2 Transformer.

In the event the 66kV Breaker, supplying the No1 Transformer operated after approximately 0.17 seconds, thus removing that source of supply into the fault. The No. 2 Transformer however continued to supply the fault, until the operation of the No 2 Transformer 11kV Breaker, after a further, approximately 1.2 seconds.

A full explanation of the protection operations, at least in so far as the Enquiry was able to establish, is provided in Technical Appendix T1.5 Protection Issues.

4.2.4. **Fault Recording Apparatus Records**

Examination of the SCADA recordings of the Sequence of Events indicated that, despite a number of SCADA signals relating to the No. 1 Transformer Circuit Breaker, the breaker did not operate and remained in the closed position throughout the incident.

Examination of the transient recording of the 66kV current waveform at the time of the fault provided evidence that the fault had started as a single phase fault, had subsequently developed into a two phase and earth fault, and finally into a full three phase and earth fault, before being interrupted by the operation of the No. 1 Transformer 66kV Circuit Breaker and the No. 2 Transformer 11kV Circuit Breaker

A copy of the transient recording is included in Technical Appendix T1.1 Transient Fault recordings and Fault Levels. A copy of the recordings of the SCADA Sequence of Events record is included in Technical Appendix T1.2 The Breaker Failure.

4.2.5. **Environmental History**

As noted above, the breaker concerned was an original that had been installed in the Casuarina Zone Substation at the time of its construction in 1972. It has operated for most of its life in the unmodified, hot and humid, tropical environment of Darwin, until about three years ago when air conditioning was installed in the Casuarina Switch Room.

PAWC advised that the breaker had also experienced a period of more than a week of intense exposure to heavy rain and wet season weather in 1974, following the loss of the switch room roof, caused by Cyclone Tracy.

4.2.6. **Operational History**

PAWC also advised that the breaker has, throughout its life, been operating well within its nominal 1600 amp current rating.

PAWC were unable to provide any systematic record of other aspects of the operating history (such as number of fault interruptions) of the breaker in question, or more generally. This issue is discussed in greater detail in Section 6 Maintenance

4.2.7. **Performance History**

PAWC have advised that there are no recorded previous switchgear failures at Casuarina Zone Substation, other than the failure of a capacitor circuit breaker in 1999. That failure was the subject of an investigation by Minoo Mehta of Energex. The Mehta findings and recommendations and the subsequent actions taken by PAWC are discussed in Section 7.1 The Mehta Investigation.

PAWC have also advised that there are no recorded actual switchgear failures at any of the other PAWC zone substations either, but that there has been one incident of a flashover inside a Yorkshire YSF6 22kV breaker at Manton Zone Substation in March 2008. That failure was the subject of an internal investigation and report. The findings and recommendations of that report are discussed in Section 7.4 The Manton Investigation.

PAWC were unable to provide any systematic record of condition reporting for, the breaker in question, or more generally. This issue is discussed in greater detail in Section 6 Maintenance.

The results of tests conducted as part of the supply restoration effort were however available. An evaluation of these results is provided in the Technical Appendix. T1.2 The Breaker Failure

4.2.8. **Maintenance History**

PAWC were unable to provide any systematic record of the maintenance history of the breaker in question, or more generally. This issue is discussed in greater detail in Section 6 Maintenance

However from a review of the available “field reporting worksheets” it has been established that the breaker in question was maintained in November 2002, and that three of the other five oil filled breakers at Casuarina, were maintained in October and November 2002 and one in October 2003. No record of maintenance on the remaining breaker was able to be located.

Current PAWC policy is for such breakers to be maintained every two years.

It is also unclear from the available record, as to what the full extent of the maintenance undertaken was and whether the maintenance tasks critical to the management of this particular failure mode were actually performed.

4.2.9. **Assessment of the Causes of Failure**

From the evidence of the physical inspection and the examination of the transient fault recording and SCADA records, it is apparent that there has been an electrical insulation breakdown of the B phase transformer bushing, which has resulted in a short circuit between the active conductor within the bushing and the external cast metal housing of the breaker tank.

The electrical energy of the short has caused oil vaporisation and the resultant pressure build up of the vaporising oil has split the tank. An oil fire has ensued.

It is also apparent that the conducting zone of the initial short circuit has rapidly extended as the oil has vaporised within the tank, allowing the initial single phase short circuit to develop to a two phase and earth and ultimately to a full three phase and earth short circuit.

The trigger for the insulation breakdown is considered to be heat, generated by high contact resistance, leading to “thermal runaway” within the insulation of the B Phase Bushing.

Heat generated by the normal load current of the main breaker and busbar primary isolating contacts has been sufficient to trigger a “thermal runaway” failure of the bushing insulation. Whilst the initial condition of the insulation is unknown, and now unmeasurable, there is physical evidence that it has been in a state of progressive deterioration, attributable to prolonged exposure to overheating generated by the high contact resistance, exacerbated by the hot and humid tropical environment.

Further collaborating evidence for the above conclusions can be found in the results of tests conducted by PAWC on the No. 2 Transformer Circuit Breaker, prior to its return to service after the incident. These tests revealed significantly elevated main breaker contact resistance, and confirmed that the failure mode described above was present and well advanced in the No. 2 Circuit Breaker as well. It too would have eventually failed had no corrective action been taken to improve the resistance of the contacts.

A fuller explanation of the assessment of the causes of this failure, including details of test results are provided in the Technical Appendix T1.2 The Breaker Failure.

4.3. The Endbox Failures

4.3.1. **The Endbox and Insulation Bushings**

The endbox concerned is the Nakara Feeder Endbox which is connected to the No. 3 Bus Section at Casuarina Zone Substation. The end box, when originally installed, was compound filled, but was converted to an air insulated end box approximately twenty five years ago.

The bushings themselves are original bushings, from the 1970s. Whilst the precise history of each bushing is not confidently known, it is likely that the bushing which was the subject of the first failure was an original Nakara feeder endbox bushing (from the mid 1970s) and that the bushing which was the subject of the second failure, was an original Wagaman feeder endbox bushing (from the early 1970s) (relocated to the Nakara endbox). It should be noted however that as a result of maintenance and repair activity carried out throughout the history of the Substation some bushings have, from time to time, been relocated and/or interchanged with spares.

The bushings are of the Synthetic Resin Bonded Paper (SRBP) type, with an earth screen for electrical stress distribution.

4.3.2. **Physical Inspections and Photographic Evidence**

The recovered bushings and several "spare" and previously recovered bushings were closely examined.

The recovered bushings and the two "not failed" bushings, from the other two phases of the Nakara endbox (which had been removed along with the second failed bushing) were also sent for testing and dissection at the Testing Facilities of Energy Australia.

Inspection of the actual end box was not possible due to the access restrictions in place at the time. Photographic evidence was however provided by the recovery team.

General Condition of the Bushings

Examination of the available bushings revealed the presence of surface irregularities on most of the bushings. These irregularities were of varying magnitude. Most were small.

Some of the out of service "recovered and spare" bushings exhibited evidence of flaking of the insulation layering and breaches of the protective outer moisture sealing. These were unsuitable for service.

The two "not failed" bushings from the Nakara endbox that were sent to Sydney for testing, though degraded, tested as being satisfactory for service.

The First Failure

Examination of the recovered first failed bushing revealed that insulation breakdown had occurred at the point midway between the earth ring and the end of the bushing, well in front of where the bushing passes through the Bakelite insulating barrier at the back of the busbar chamber.

Fig 5 – View of the endbox showing the cables bolted to the ends of the bushings and covered by heat shrink boots. The failed C phase bushing is on the left. Note the burn mark above.

Fig 6 – Close up of the damaged bushing showing the position of the puncture through the bushing insulation.

Photographs of the endbox clearly show an electrical burn mark on the back left hand corner of the steel ceiling of the endbox.

Testing was not conducted in this bushing.

The Second Failure

Examination of the second failed bushing revealed a different pattern of failure. Significant damage was apparent at the end of the bushing immediately adjacent to the cable attachment, beneath the "heat shrink" boot which insulates the cable connection. Despite considerable tearing of the insulation there was little evidence of arcing to the busbar itself. Moreover a second puncture is apparent further along the bushing.

Fig 11 – View of the LHS of the endbox showing damage and missing components.

Fig 7 – View of the damaged C phase bushing, showing the full length tear.

Fig 15 – View from the top, showing that the endbox has come adrift from the CT chamber by approximately 7.5 cm.

Fig 9 – View of the damaged C phase bushing, from the other side, showing the shallow second puncture clearly visible 13.3 cm from the end.

Fig 13 – View of the endbox. The damaged C phase bushing is on the (LHS). The cables have been unbolted and the heat shrink boots removed.

Fig 14 – Close up of the damage to the end of the C phase bushing and the cable termination. (The rear Bakelite plate of the endbox is still in position)

The above photographs of the endbox and bushing provide evidence of:

- **Damage to the inside of the box**
    - A flash mark on the LHS of the box, immediately adjacent to the failed bushing.
    - Burn marks and crazing on the Bakelite and insulation apron at the back of the box
    - The dislocation of the heatshrink boot, which normally covers the cable termination.

- **Installation Defects**
    - The insulation panels at the side of the endbox are missing.
    - The four holding bolts which secure the endbox to the Current Transformer (CT) Chamber are missing.
    - The cable termination lug is installed with the "offset" to the back, instead of the front of the box.

- **Physical Dislocation of the Box**
    - The top of the box has been displaced by approximately 7.5 cm. from its mounting.
    - The serrated scrape marks on the top of the failed bushing indicate that the endbox has "walked" away from its mounting position.

Additional details of the physical and photographic evidence are provided in the Technical Appendix T1.3 The First Endbox Failure and T1.4 The Second Endbox Failure.

Details of Testing and dissection of this bushing are provided in Technical Appendix T1.5 Energy Australia Test Report – Bushings.

Other Bushings

Photographic evidence was also available of the external appearance and condition of some of the other "in service" endbox bushings of the No3 Busbar Section. These photographs were taken during the recovery work following the second failure. The most notable of these are shown below.

FAC Feeder Endbox bushings and cable terminations. (A and B phase only).

4.3.3. **The Protection Operations**

At the time of the **first endbox failure** the substation was operating with the bus section switch between Sections 2 and 3 closed and with the No.2 and No. 3 Transformers operating in parallel. (At this stage, following the breaker fault, the No 1 Bus Section was out of service and virtually all the load of the station was being supplied through Sections 2 and 3.)

The Bus Section No. 3 Frame Earth Leakage protection operated, in accordance with the design intentions. (Although one circuit breaker supplying one of the ten feeders connected to this busbar section failed to open. This failure to open was due to a burnt out coil in the frame leakage relay of this circuit breaker. There were, fortunately no serious consequences and the burnt out relay was replaced, before returning the breaker to service.)

The feeder Instantaneous Overcurrent Earth Fault protection operated as well, which was also in accordance with the design intention and the fault, was cleared in about 0.14 seconds.

At the time of the **second endbox failure** the substation was operating with the bus section switch between Sections 2 and 3 open. Thus only the No 3 Transformer was supplying the fault.

On this occasion the No. 3 Bus Section Frame Earth Leakage protection failed to operate, in accordance with design intentions for this type of

fault. However the feeder Instantaneous Overcurrent Earth Fault protection did operate, in accordance with the design intention, and the fault was cleared in about 0.15 seconds
A full explanation of the protection operations, at least in so far as the Enquiry was able to establish, is provided in Technical Appendix T1.6 Protection Issues.

4.3.4. **Fault Recording Apparatus Records**

Examination of the SCADA recordings of the Sequence of Events indicated that: on both occasions the fault had been cleared by the operation of the feeder Instantaneous Overcurrent Earth Fault protection; that on the first occasion the Frame Earth Leakage protection for the No. 3 Busbar Section, had in accordance with the accepted design intent, operated as well but; that on the second occasion the Frame Earth Leakage Protection, did not operate until some 29 minutes, after the occurrence of the fault.

Examination of the transient recordings of the 66kV current waveform at the times of the faults provided evidence that, on both occasions the fault had been a single phase fault only: that the duration of the fault on the first occasion had been 0.14 seconds and on the second occasion 0.15 seconds but; that the magnitude of the fault on the second occasion was, of the order, of only 63% of that of the first occasion.

The transient recording apparatus also provided evidence that there was no fault anywhere on the system at the time of the operation of the Frame Earth Leakage protection 29 minutes after the second fault.

Copies of the SCADA Sequence of Events records are provided in Technical Appendix T1.3 The First Endbox Failure, and T1.4 The Second Endbox Failure.

Copies of the transient recordings are included in Technical Appendix T1.1 Transient Fault recordings and Fault Levels. A copy of the recordings of the SCADA Sequence of Events record is included in Technical Appendix T1.3 The First Endbox Failure and T1.4 The Second Endbox Failure.

4.3.5. **Environmental History**

As noted above, the bushings concerned were original bushing that had been installed in (or held as spares for) the Casuarina Zone Substation either at the time of its construction (Bus Sections 1 and 2) in 1972 or its extension (Bus Section 3) in 1975. They have operated for most of their life in the unmodified, hot and humid, tropical environment of Darwin, except for the first five or so years during which, the bushings would have been encased in compound and until about three years ago when air conditioning was installed in the Casuarina Switch Room.

The bushings of the No 1 and 2 Busbar Sections would also have been in service at the time of the Cyclone Tracy inundation, but would have been encased in compound at that time.

4.3.6. **Operational History**

PAWC have advised that the Nakara Feeder has been operated well within its design rating throughout its life.

During the previous 30 hours prior to the first flash over, the Nakara feeder had been de-energised for 7 hours and then loaded for 24 hours before the fault occurred.

Load on the feeder, at the time of the first flashover was abnormally high, due to the abnormal switching arrangements adopted in response to the Circuit Breaker failure of the 19th September 2008. It was, nevertheless well within the design rating of the feeder.

Load on the feeder, at the time of the second flashover was similarly high. This abnormally high load had persisted throughout the twelve day period between the two failures. It was, nevertheless well within the design rating of the feeder.

PAWC have also advised that the Wagaman Feeder had been operated well within its design rating throughout its life.

The Wagaman Feeder Endbox is located immediately adjacent to the failed No 1 Transformer Circuit Breaker Endbox and would have been subjected to considerable mechanical forces transmitted during the period of the fault and subsequent explosion.

4.3.7. **Performance History**

PAWC have advised that, in the early history of Casuarina Substation failures inside the compound filled endboxes were “not uncommon”.

Anecdotal evidence is that these failures were failures of the cable and not the SRBP bushings. The original compound filled endboxes were quite small and failures occurred at the trifurcating point (or frog) where bending radii were tight and the electrical stresses greatest. These failures were probably associated with small voids in the compound. These failures stopped occurring once the conversion to the larger air insulated endboxes was effected.

Anecdotal evidence is that there have been no previous failures of the SRBP endbox bushings themselves.

There is moreover, no straightforward reliable measurement equipment available, to the industry, for determining, in situ, the condition of this type of busbar endbox bushing. Therefore there is, generally throughout the industry very little that is known of their condition.

The use of portable partial discharge detection devices is emerging as a potentially useful technique. The interpretation of results is, however problematic and as a technique is most useful when applied in conjunction with other testing.

The use of "Infra Red Scanning", as was used during the physical inspections of the Casuarina Zone Substation, is a crude diagnostic tool, which so far as these bushings are concerned is really only capable of identifying a particular imminent risk factor.

4.3.8. Maintenance History

There is no meaningful requirement for the routine maintenance of cable endbox bushings.

4.3.9. Assessment of the Causes of Failure

The First Bushing Failure

Having regard to:

- The environmental history.
- The observed physical condition of the insulation of the failed bushings and that of other identical bushings.
- The physical damage to the bushings.
- Knowledge of other failures of this type of bushing.

it is considered most likely that the insulation of **the first bushing**, having suffered considerable environmental degradation throughout its life, finally failed due to "thermal runaway", triggered by elevated temperature.

The root cause of the failure is considered to be insulation degradation, due to aging and moisture ingress, from a lifetime spent in the hot humid tropical environment of Darwin.

A fuller explanation of the assessment of the cause of this failure is provided in the Technical Appendix T1.3 The First Endbox Failure.

The Second Bushing Failure

Having regard to:

- The nature and location of the physical damage to the bushing and
- The physical evidence of the dislocation of the endbox

The **second bushing failure** is attributable to an installation defect, which has arisen as a result the re-installation of a thirty six year old degraded Wagaman Feeder Endbox bushing into the Nakara Endbox. Whilst there were a number of installation defects, any one of which could have eventually led to failure, the particular defect which was clearly the root cause of this failure was the omission of four mounting bolts. The omission of these bolts allowed the endbox to “walk away” from its mounting, due to vibration, and cause a relocation of critical insulation material within the box. The consequent changes in the electrical stress distribution within both the box and the bushings resulted in electrical breakdown. This breakdown is likely to have occurred, regardless of the initial condition of the bushing. The degraded bushing has simply failed earlier than an un-degraded bushing would have.

The root cause of the failure is considered to be an installation defect.

A fuller explanation of the assessment of the failure mechanism and cause of this failure is provided in Technical Appendix T1.4 The Second Endbox Failure.

4.4. The Cable Failures

4.4.1. **The Cables Concerned**

The cable concerned in Event 1 is a 400 sq. mm. aluminium conductor Paper Insulated lead Covered and Steel Wire Armoured cable.

The cables concerned in Events 2 and 3 are both 95 sq. mm. aluminium conductor XLPE Insulated, Copper Screened, Nylon and PVC covered cable.

These cable types are of traditional designs, typical of that used throughout the industry. Provided that they are loaded within their capacity and installed in a predictable, stable and “not too aggressive” environment, they have a long life, potentially well in excess of forty years.

4.4.2. **Physical Inspections**

No physical inspections were made.

4.4.3. **The Protection Operations**

In all three cases the cable faults were cleared in accordance with design intentions for this type of fault, by the correct operation of the feeder Instantaneous Overcurrent Earth Fault protection.

4.4.4. **Environmental History**

There is no reason to suspect that any of these cables have been operating in a particularly aggressive environment.

4.4.5. **Performance History**

There is no reason to suspect that, the 400 sq. mm. cable of Event 1 has at any time been operated beyond its loading capability. However, due to record keeping inaccuracies, it is apparent that the Control Room was unaware of the limited capacity of the 95 sq. mm. cables and had assumed them to be 400 sq. mm. cables. These cables were loaded well beyond their capacity, in the hours prior to the failure events and may well have been similarly loaded (for shorter periods) on previous occasions.

4.4.6. **Maintenance History**

Cables of this type operate without the need for routine maintenance.

4.4.7. **Assessment of the Causes of Failure**

Event 1.

The precise cause of this cable failure is still under investigation by PAWC. The most likely cause is considered to be either corrosion, white ants or collateral mechanical damage occasioned by work previously performed adjacent to the cable. So far as this enquiry is concerned the precise cause is not critical as it is considered to be an isolated event, with a root cause which is unrelated to the substation events.

It should be acknowledged however that the abnormally high loading, despite being well within the designed capability of the cable, may have been the trigger, for what was already an incipient fault.

Events 2 and 3.

These failures were caused by overloading.

The heating caused by the overloading has caused insulation degradation. Insulation breakdown due to thermal runaway has occurred at the most vulnerable point. Permanent degradation of the insulation is likely to have occurred at other locations throughout the length of the cable.

PAWC has subsequently replaced these 95sq. mm. cables with 400 sq. mm cables.

4.5. The Performance of the Protection Systems

As discussed in previous Sections, for three of the six incidents (all those that occurred within the substation), the protection systems failed to operate in the manner intended.

The key matters that were not readily explained and understood were:

- The failure of the Frame Earth Leakage (FEL) systems to operate on the occasions of the breaker fault and the second endbox fault.
- The spurious operation of the FEL system 29 min after the second endbox fault.
- The protection system that did operate to open the No 1 Transformer 66kV breaker on the occasion of the breaker failure.

Considerable effort was made by PAWC personnel, to assist the Enquiry in trying to understand these matters. A small “Protections Operations Investigation” group was convened and this group met on three occasions to collate and assess the available data.

This group reported and provided some details of prior malfunctions of the FEL systems, and in particular reported a notable incidence of “spurious” operations.

The work of the group was hampered by the lack of recent testing of the Frame Earth Leakage Systems and by the access restrictions put in place following the first endbox failure. Nevertheless considerable data was assembled and assessed.

Full details of the assessment of all protection issues are provided in Technical Appendix T1.5 Protection Issues.

In summary:

- Whilst there is insufficient evidence to confirm this possibility, a possible root cause of the problems with the Frame Earth Leakage systems is the unconstrained proximity of the earthing busbars, (to which the feeder cable sheaths are connected,) to the frame of the switchgear, and their proximity and configuration relative to the cables entering the endboxes.
- Another possible cause is intermittent relay malfunction or intermittent wiring defects.
- Regardless of whether proximity of the earthing busbars is the root cause on these occasions, the construction of earthing busbars in such close proximity to the switchgear frame without close regularly spaced insulating supports is poor practice.
- Whilst it is considered unlikely, it is possible that the spurious operation of the Frame Earth Leakage system, 29 minutes after the second endbox failure, may have been triggered by the entry into the substation by the Fire Brigade. (As near as can be ascertained, there is time alignment between the two events.)
- No credible explanation of the 66kV breaker operation has been identified.

It may well be possible, once full normal access is available, that more evidence will become available and shed further light on these matters.

5. The Existing Circuit Breaker Retrofit Programme

5.1. Background

A circuit breaker retrofit programme was established by PAWC in response to the principal recommendation of the Mehta report into the failure of an 11kV, capacitor bank, oil circuit breaker at Casuarina Zone Substation in March 1999.

The Mehta report (See Section 7.l The Mehta Review) recommended replacement of all capacitor bank oil circuit breakers. PAWC, after due consideration and risk assessment, decided to implement a programme to replace all oil circuit breakers, for which suitable replacement breakers could be found.

Capacitor bank circuit breakers perform a particularly onerous switching duty, both as to frequency of switching and the electrical characteristics of their load. Feeder, transformer and, bus section breakers, because of their different loading characteristics, are not subject to the type of failure, identified in the Mehta report as the root cause of the capacitor bank breaker failure of March 1999.

The decision to widen the retrofit programme beyond the Mehta recommendations was an appropriately prudent step in minimising the oil hazard.

5.2. Risk Assessment and Prioritisation

The risk assessment, on which the decision was based and the programme established, was conducted by PAWC's, then Technology Services Division and documented in a report dated 10th July 2002.

It is clear from this report that a thorough and systematic approach has been taken to the risk assessment and prioritisation of the replacement work. A limitation of the work however, was the lack of availability of key elements of data, from which to make the risk assessment.

As a consequence the risk assessments were made without reference to actual condition data and relying on "out of date" operational data. These issues are discussed in greater detail in Section 6. Maintenance, and again in Section 7.1 The Mehta Review.

5.3. Implementation Progress

All capacitor bank oil circuit breakers have been replaced with vacuum breakers. This work was completed in 2004.

Feeder breakers at Casuarina and Snell Street substations have been retrofitted with vacuum breakers. This work was also completed in 2004.

The program to replace the remaining feeder breakers (in another four zone substations) has come to a halt in the past few years. PAWC advise that this was due to competing priorities.

5.4. Exclusions from the Programme

Transformer breakers (such as the one which failed on the 19th September) and Bus Section breakers were not included in the retrofit programme because of the unavailability of suitable vacuum or SF_6 insulated replacement breakers. Replacement of these breakers would have required the complete reconstruction of the switchboard.

6. Maintenance

6.1. Approach

The approach taken to the assessment of the adequacy of substation maintenance practices and accountability around maintenance issues was to:

- Review the available policy documentation and assess its adequacy by comparison with wider industry approaches.
- Review the actual field practices, as carried out by those personnel who undertake the maintenance tasks, and compare those field practices with documented policy.
- Review job documentation and field reporting to assess the relevance and usefulness of this documentation and reporting compliance.
- Review PAWCs condition monitoring capability, both as to equipment suitability and personnel skills, and compare it to relevant wider industry capabilities.
- Assess the maintenance delivery skills of the personnel undertaking the maintenance delivery tasks, to assess the adequacy of the skills base and identify any training requirement.
- Review the systems used for generating the maintenance works programme.
- Review the process flows, from the generation of the programme, through the works management and works delivery, to job close out and reporting.
- Review the organisational arrangements supporting the process flows.
- Review asset condition and maintenance works programme reporting, as applicable at various relevant management levels, including Board Level.

Implementation of this approach was achieved by:

- Reviewing documentation supplied by PAWC.
- Interviewing relevant staff.
- Obtaining input from representative members of the PAWC “Asset Management Capability Project” (AMC).

In general the reviews undertaken were not exhaustive, but were performed at a depth and width sufficient to make broadly reliable findings. The findings made were also informed by the results of the analysis of the causes of the Casuarina Breaker and Endbox Bushing failures.

For the purposes of the Preliminary Report a truncated version of the above approach was employed, which focussed purely on GEC-OLX switchgear maintenance. The approach was broadened, for this final report, to provide coverage of an appropriately wide range of substation maintenance tasks including the maintenance of Protection Systems.

6.2. Policy

In 2006 PAWC acquired by license, and formally adopted with minimal adaptation, a suite of Substation Maintenance Instructions from ETSA Utilities. A copy of the index to this suite of Instructions is provided as Technical Appendix T2.1 Policy Documentation. This set of Instructions does not cover protection systems maintenance.

A selection of six of these instructions covering key substation maintenance tasks at both 66kV and 11kV were reviewed. The six selected are listed in Appendix T2.1 Policy Documentation.

The documentation reviewed suffers from a lack of appropriate adaptation to PAWCs asset set and working environment. As a consequence it lacks clarity, and is inappropriate for use by field staff. Furthermore the documentation, as adapted and proposed for use by PAWC, also presents the traditional, somewhat intrusive, approach to substation maintenance.

From interviews with various managers it was apparent that the adoption of these standards did not receive widespread support and that their adoption in practice was put into abeyance.

A limited number of policy documents dating from the 1960s and 1970s were also sighted, but these were apparently not in use either.

Whilst no protection systems maintenance policy documents were sighted, the programmes used for the testing of relays do appear to be adequate.
The lack of documentation or defined process in regard to Frame Earth Leakage Systems is however a problem.

Full details of the assessment of the policy documentation are provided in Technical Appendix T2.2 Evaluation of Policies.

6.3. Practice

From interviews with staff and the information recorded in the maintenance job records that were sighted, it is apparent that, with the exception of protection systems maintenance, the requirements of the policy documentation are not being followed and, that a minimalist approach to maintenance is being adopted.

In short, with the exception of protection systems maintenance, there appears to be no nexus between policy and practice. Maintenance practice appears to be being conducted in accordance with "on the job" "father to son" learning, on a best endeavours basis.

The maintenance of protection systems, despite some identified problems with the Frame Earth Leakage systems, appears to be being conducted appropriately and in accordance with policy.

Full details of the assessment of substation maintenance practices are provided in Technical Appendix T2.3 Evaluation of Practices.

6.4. Condition Monitoring

Interviews with staff and an assessment of the available test equipment indicate that whilst there is some condition monitoring capability and some test results on file, there does not appear to be any systemic approach in place.

The monitoring that has been undertaken appears to have been either: ad hoc testing in response to incidents or; commissioning testing. No records of circuit breaker tests results could be found in the PAWC Electronic Data Management System for the Casuarina Substation. The only test results that were sighted were the original paper test result records.

It is noted however that Dissolved Gas Analysis test results that are routinely carried out on transformers are recorded in the Electronic Data Management.

Operational records, such as the number of fault operations of circuit breakers are similarly scant. PAWC advise that operation counters were removed from switchgear some years ago and that proposed alternate SCADA counting has not yet been implemented.

Full details of the assessment of condition monitoring capability are provided in Technical Appendix T2.4 Evaluation of Condition Monitoring Equipment and Capability.

6.5. Capability

Interviews with staff and an assessment of sample records and available test equipment indicate that:

- Whilst basic test equipment is available, the suitability of some of the equipment is questionable. It is also apparent that additional staff training is required in order to ensure sufficient depth of the skill required to operate some of the more advanced equipment and interpret test results.
- The knowledge and skill required to undertake effective and efficient maintenance of key substation equipment requires enhancement.

- The knowledge and skills required to effectively supervise the carrying out of substation maintenance requires enhancement.
- The knowledge and skills required to;
  - Determine document and deploy appropriate substation maintenance policy.
  - Manage its effective deployment.
  - Ensure that feedback and recording systems are relevant and working effectively.

  requires enhancement.

6.6. Capacity (Resourcing Levels)

Simple high level benchmarking, relating the number of zone substation distribution breakers and the number of distribution network switching devices to the relevant maintenance and testing manning levels of one east coast distributor provided the following indicative figures:

- Between 4 and 7 "hands on field workers" (with the right mix and range of skills) per hundred breakers, depending upon locational factors.

  And

- Between 0.3 and 0.5 "hands on field workers" (with the right mix and range of skills) per hundred distribution network switching devices, depending upon locational factors.

On this basis PAWC' would require a total of somewhere between 10 and 17 "hands on field workers" (with the right mix and range of skills), depending upon locational factors.

Given PAWC's onerous operating conditions and environment, a figure at the upper end of this range, or even somewhat higher would be appropriate.

Given also, that PAWCs present workforce requires considerable up skilling and the likelihood that new recruits will as well, it is considered appropriate that, at least initially, the target workforce level be set at 19 workers, i.e. an additional 6 over and above the present actual numbers.

It is also considered appropriate that all new recruits be assigned to the maintenance delivery group. (This is in keeping with the recommendation that all routine testing be assigned to that group.)

It would be appropriate to review Protection and Testing numbers, once the full extent of the use of advanced testing techniques is decided. Any additional recruitment into this area would be offset by a comparable reduction in the maintenance delivery area.

6.7. Systems and Processes

The main system available within PAWC for managing maintenance is the Works Information Management System (WIMS).

Other relevant systems are the Facilities Information System (FIS) (which is the PAWC spatial/geographic recording system), the Electronic Data Management System (which is an electronic records management system) and, the Financial Management System (FMS). There is also a number of paper and PC based systems.

The following is a brief overview of the pertinent capabilities and features of these systems:

- The WIMS system is principally a works requisitioning system and has only limited asset management capability (i.e. capability for systematically and analytically determining what work needs to be done).
- The system's works requisitioning capability is delivered through the production of "planned maintenance" orders.
- Time based and reactive triggers initiate the production of these orders.
    - Time based trigger intervals are set within WIMS in accordance with policies set by Asset Management.
    - Reactive triggers are the faults and Defective Apparatus Reports (DARs) which are fed into WIMS from the FIS system.
    - Faults and DARs are entered into FIS by: System Control; the Call Centre (in response to customer reports) and; maintenance staff (to initiate corrective action after maintenance inspections).
- The "planned maintenance" orders incorporate "maintenance routines" listing the tasks to be carried out.
- Despite its capability and use in generating orders for routine maintenance inspections, the system has very limited capability for recording asset condition (i.e. the results of inspections).
- Such asset condition recording that does take place (notably dissolved gas analysis and some switchgear test results), takes place outside the WIMS system, in manual or PC systems and the Electronic Data Management System.
- The normal avenue for initiating work in response to an unsatisfactory "as found" condition, from an inspection, is by DAR.
- The system does not force an obligation to report "as found" or "as left" condition.
- The system does not and apparently is not readily able to produce forecast work schedules, or forecasts of resource requirements - it simply produces orders.

The extent to which the system is used varies across the different functional groups within PAWC. It is reported to be used effectively by some parts of PAWC, although usually in conjunction with other manual or PC systems.

So far as its use for managing substation maintenance, across Darwin, is concerned:

1. **The Protection and Test Section** makes only minimal use of the system.

    - Protection testing and maintenance programmes of work are periodically set by the Senior Protection Engineer in Strategy and Planning and protection personnel in Capital and Maintenance Delivery, plan and deliver the programme implementation. Implementation progress and outcomes are routinely discussed with the Senior Protection Engineer. Records are held in the Electronic Data Management System. Whilst there are some problems with programme coverage, due mainly to system access limitations, the process itself is effective.

    - Other substation equipment testing, on the other hand, is predominantly only undertaken in response to system incidents and for commissionings. Testing undertaken as part of and in association with routine substation maintenance is minimal. The reason for this is allied to the experience of the Substation Maintenance Section. Test results are recorded manually and held locally. Arrangements affecting the coordination of testing with routine substation maintenance are discussed further, later in this Section.

2. **The Substation Maintenance Section**'s experience with the system has led to its use being discontinued.

    The Section is responsible for new connections and reactive and breakdown maintenance as well as planned maintenance. Priority is given to new customer connections and reactive breakdown work, ahead of planned maintenance. The Section's experience with the WIMS system is summarised below:

    - The routine substation maintenance and inspection intervals incorporated into the WIMS system are unrealistically short and (by comparison with peer organisations) generally unnecessarily so.
    - Consequently the volume of orders produced by the system is way beyond the capacity of the Section to deliver.
    - The various responses to this unrealistic volume have been:
        - To minimise the scope of tasks performed, thereby compromising the task outcomes.

- o To complete paperwork for work not actually or only partially performed.
- o To discard backlogs of orders.
- o To turn off the system for generating routine works orders.

The system does not produce a forward plan or programme of the work to be undertaken and there are no alternative planning systems in operation. Work is simply organised, on a day to day basis, in reaction to the WIMS orders and minimal routine work is done, as a last priority.

The flow of orders from the WIMS system goes, in general, directly to the Coordinator, with no system in place for monitoring volumes or backlogs.

Job closure does not routinely occur resulting in FMS and WIMS accounts that do not reconcile. Accordingly, the accuracy of job cost recording is compromised.

In summary there are no effective systems of:

- Work planning.
- Work measurement.
- Programme implementation reporting.
- Work outcomes (“as found” and “as left” condition) reporting.

within the substations maintenance area.

This situation is not a recent development. It has taken many years (perhaps even decades) to develop.

3. The routine testing of substation equipment, other than protection equipment, is currently a mixed responsibility of the Substation Maintenance Section and the Protection and Test Section. Basic testing such as insulation resistance and oil testing is performed by the Substation Maintenance Section, as part of routine maintenance. The more advanced testing such as partial discharge and Ductor testing is performed by the Protection and Test section.

- The more advanced testing should appropriately be carried out in conjunction with the routine maintenance testing, but is not listed in the WIMS routine maintenance orders. Nor is it the subject of separate WIMS orders.
- From a systems perspective this is not unsatisfactory, provided that such testing is specified in maintenance policy documentation and is arranged between the two Sections involved.
- With the progressive minimalisation of routine substation maintenance tasks, the requirement for the more advanced testing procedures has also been minimalised. And in the absence of direct WIMS orders to the Protection and Test Section the performance of such advanced testing, as

an integral part of routine maintenance, has fallen into decline. It would appear that very little such routine testing has been performed for an extended period.

It is noted that PAWC has recently established an Asset Management Capability (AMC) project and has engaged the services of KPMG to assist with the Project. Asset management and works delivery processes are a major focus of that Project.

6.8. Organisational Arrangements

Following considerable internal debate and staff and union consultation, PAWC has also recently undertaken a significant reorganisation of the Power Networks Division. The objectives of this reorganisation were to:

- Facilitate a focus on robust asset management.
- Improve planning and prioritisation of work.
- Clearly define processes.
- Improve role clarity and accountabilities.

To a considerable extent, the success of any organisation will depend upon the informal relationships and interactions of the people involved. Organisational structures provide the framework in which people interact and can facilitate or impede the development of constructive relationships.

Whether the objectives of PAWCs reorganisation will be achieved will depend to a considerable extent on the style and behaviours of the people appointed to key roles (See Section 9 Relationships), but will also depend upon how well the reorganisation:

- Fosters the relationships required to bring about the necessary behavioural change.
- Addresses the current disconnect between Asset Management (now Strategy and Planning) and Service Delivery (now Capital and Maintenance Delivery).
- Delivers the right focus within each of the newly established accountability areas.

The Focus of the Maintenance Management Role

A key function of maintenance management is the long term management of the mix of:

- Routine preventative.
- Routine condition monitoring.
- Planned corrective.
- Unplanned corrective and breakdown.

maintenance.

Different mixes are appropriate to different asset classes. Managing and optimising the mix, and integrating maintenance decisions with replacement/refurbishment decisions, for a “whole of life cycle” and system performance optimisation is a highly strategic role which, is best not subjugated to the day to day pressures and exigencies of works management.

It is also a role which, because it sets the works programme, must be informed about the resourcing requirements of the programme and programme implementation progress and the “as found” and “as left” asset condition. The quality of its relationship to maintenance delivery is therefore crucial.

Ideally organisational arrangements will be established that facilitate a focus on this role, without distractions.

The structure recently adopted by PAWC places planning responsible, for both asset and works management with the Strategy and Planning group. From discussions with the managers involved it seems that this has been done in the belief that centralising all planning within Asset Management will produce the best outcome. There is moreover a considerable management commitment to making it work. It is nevertheless, from a focus perspective, a distraction that would need careful management.

Relationship issues would also need careful management. PAWC senior management is aware of both of these needs and intend to be active in addressing them. It may however be prudent to implement some fine tuning of the structure. The objectives of which would be to ensure that:

- The current feelings of disenfranchisement and “lack of control”, of the maintenance delivery group are addressed.
- The emergence of an overly complex “ivory tower” approach to work planning, likely to lead to a “disconnect” between works planning and works delivery and consequent underperformance of the delivery process, is avoided.
- The asset management role does not become embroiled in the day to day exigencies of works management, thereby leading to a loss of emphasis on asset management and a dilution of the asset management skills set.
- The avoidance of an interface between the asset management and service delivery roles which fosters a “blame mentality” by ensuring a focus on - - programme coverage, programme delivery and costs and asset condition feedback, rather than - petty disputes about the coordination of various work teams, system access issues, and how work is delivered.

The reorganisation is some months from being fully implemented, with a number of key positions yet to be filled. It is noted that the events associated with Casuarina Zone Substation have delayed its implementation.

6.9. Measurement and Reporting

There is a paucity of measurement and reporting systems, pertinent to the substation maintenance function, at PAWC.

Ideally reporting systems would be in evidence at several levels of the organisation, including at Board level, and would cover the works programme and asset condition as well as financial matters. Ideally also, such systems would highlight the link between the works programme (both maintenance and replacement/refurbishment) and asset condition and the risks to the business of inadequate programmes and inadequate programme delivery.

Such transparent reporting of programmes, condition and risks could be expected to drive:

- The funding of adequate programmes, well matched to the business's risk appetite.
- Programme, cost and delivery performance.
- The development of measurement and recording systems which in addition to supporting the reporting systems provide the data for good asset management and risk assessment and management.

Reliable and sufficient underlying measurement and recording systems are not in place.

There is no condition reporting, and condition records, to the extent that they do exist, are only used for local ad hoc decision making.

There is no works programme reporting, other than the localised reporting of protection maintenance.

Maintenance expenditure is monitored, and compared to budget. The budget is however set without regard to any planned outcomes, apparently as an extrapolation of past expenditures.

Maintenance expenditure reporting is also included as part of the routine financial reporting to the Board, but is reported as an aggregate figure for the total business.

Consistent with the lack of local reporting there is no systemic reporting of either the substations maintenance works programme or of substation asset condition at Divisional, Corporate or Board level. The only relevant performance reporting to the Board is that of the lag indicators of "system reliability" and "customer response times".

Whilst there is a risk management framework in place which incorporates routine reporting to the Board, these reports do not deal with the specific risks relating to asset condition or maintenance outcomes.

The wider assessment of measurement and reporting systems across PAWC is beyond the scope of this Enquiry. Nevertheless it is noted that such systems were reported to be in operation in other parts of PAWC. However, other than for financial reporting and one other notable exception, such reporting is not elevated to Board level.

The notable exception is that of major project reporting. Major projects implementation progress, both physical and, as measured by budget performance, is routinely reported at Project level, to the Board.

It is also noted that the Capital Investment, Asset Management and Fuel Supply Committee of the PAWC Board has initiated action in regard to the Systemic reporting of asset condition and the maintenance works programme.

7. Relevant Previous Reviews

7.1. The Mehta Review

7.1.1. Findings and Recommendations

The Mehta investigation, into the explosive failure of a capacitor bank oil circuit breaker, at Casuarina Zone Substation, on 21st march 1999 found that the root cause of the occurrence was the failure of the OLX2 bulk oil circuit breaker to disconnect the capacitor bank, as a result of its inadequate capacitive current interrupting capacity.

The report of the investigation contains eight recommendations which have contemporary relevance to the current Enquiry. Each recommendation, PAWC's response to it and, the implementation progress is discussed in the following section.

7.1.2. PAWC's Response and Implementation Progress

7.1.2.1. Retrofit adequately rated vacuum (or SF_6) circuit breakers for capacitor bank switching

All capacitor bank circuit breakers were retrofitted with vacuum breakers between 2000 and 2004.

Additionally PAWC decided to replace all other, feasibly replaceable, oil circuit breakers as well. Feeder breakers at Casuarina and Snell Street substations were retrofitted with vacuum breakers between 2000 and 2004.

The program to replace the remaining breakers has come to a halt in the past few years due to competing priorities.

<u>The original recommendation has nevertheless been fully implemented.</u>

7.1.2.2. Avoid local operation of circuit breakers

PAWC advise that all circuit breakers in Zone Substations and Switching Stations are opened and closed remotely via SCADA. Standard operating procedure is for no personnel to be located in switch rooms when switching is being undertaken remotely.

<u>The recommendation has been fully implemented</u>.

7.1.2.3. Adopt restricted access procedures in substations with plant at risk

PAWC advise that restricted access to Zone Substations, Switching Stations and other HV areas has been adopted as standard practice. Only Authorised personnel are permitted to enter these facilities and access is provided subject to strict controls.

The recommendation has been fully implemented.

7.1.2.4. Retrofit fire protection in substations with oil switchgear

PAWC advise that all Zone Substations with oil circuit breakers have CO_2 fire suppression systems installed.

The recommendation has been fully implemented.

7.1.2.5. Implement post maintenance testing of circuit breakers

PAWC advise that appropriate post maintenance minimum test protocols are now prescribed policy.

However, as discussed in Section 6. Maintenance, the nexus between practice and policy, appears to have broken down. And test results are poorly recorded. (No records of circuit breaker tests results could be found in the PAWC Electronic Data Management System for the Casuarina Substation.)

The implementation of this recommendation has not been effective.

7.1.2.6. Implement condition monitoring of switchgear

PAWC advise that partial discharge detection using hand a held partial discharge detector (UltraTEV) was introduced in 2005 and that an annual thermal scan of substation assets also covers some switchboards but not the circuit breakers.

However as discussed in Section 6.4 Condition Monitoring, so far as 11kV switchgear is concerned, whilst there is some condition monitoring capability and some test results on file, there does not appear to be any systemic approach in place.

The monitoring that has been undertaken appears to have been either: ad hoc testing in response to incidents or; commissioning testing.

The implementation of this recommendation has not been effective.

7.1.2.7. Consider retrofitting high speed bus protection systems in substations with oil switchgear.

PAWC investigated the possibility of fitting high speed low impedance bus protection schemes, but found them to be unsuitable to the circumstances at Casuarina.

PAWC has also investigated optical bus protection schemes and has commenced an installation roll out.

This recommendation has been appropriately actioned.

7.1.2.8. Consider reinstalling operation counters on switchgear.

Reinstallation was not implemented and the proposed alternative of utilising the SCADA system for counting has not yet been implemented.

This recommendation has not been implemented.

7.2. The Blanch Review

The Blanch review is a report of the findings of a joint Union and PAWC investigation into various aspects of PAWC's operations. It was a high level wide ranging review, covering the water and sewage operations as well as electricity transmission, distribution and generation. The review was conducted throughout the period October to December 2006.

Aspects of the findings and recommendations of the report, of direct relevance to the current Enquiry are précised below.

Findings

1. Assets are aging, and reliability is falling.
2. Assets have not been well looked after.
3. There has been a "run to failure mentality". Spare parts are inadequate.
4. Data records are poor.
5. Training is poor.
6. There are too many "single points of failure".
7. An increased focus on maintenance is need.
8. Staff turnover is high and recruitment is problematic.

None of these findings are inconsistent with the observations of the current Enquiry.

The Blanch report contains various recommendations aimed at addressing the issues raised by its findings. Key among these is recommendations for more staff, and greater spending. There are also various recommendations for improving knowledge transfer, and staff training and retention.

The most notable recommendation, so far as the current Enquiry is concerned, is for an increased focus on maintenance and refurbishment.

The Blanch Review was finalised in December 2006.

A brief review of recent PAWC planning documentation indicates that PAWC's recent planning has been influenced by the Blanch Review. Specifically, the Statement of Corporate Intent (SCI) and Power Network Divisions business plan: propose the upgrading of asset condition monitoring; the adoption of a framework of "objective need" as the basis for future maintenance budgeting and; make allowance for increased expenditure on maintenance and on asset replacement/refurbishment. It is also noted that additional ad hoc funding has been sought and granted by the Northern Territory Government.

7.3. **The SKM Review**

Sinclair Knight Mertz (SKM) was engaged during 2006 by the Northern Territory Treasury to assist in a review of PAWC's financial reporting management systems.

SKM's primary focus was on assessing the assets and associated budgets. Within their report there are a number of findings and recommendations which are relevant to the current Enquiry. These are précised below.

Findings and Recommendations

1. SKM noted that, other than for 66kV transformers, for which PAWC has relevant dissolved gas analysis (DGA) data, useful asset condition data was not available.
    a. Accordingly SKM based its replacement budget analysis on knowledge (some of it assumed) of age profiles and SKM data on the technical life of various asset classes.
2. SKM recommended that the current programme of individual oil circuit breaker replacement, be extended to full switchboard replacement, including secondary equipment.
3. SKM recommended capital expenditure of $m10 over the next five years, on the replacement of Zone Transformers and 11kV Switchgear.

4. SKM noted that current operating expenditure is adequate, provided the recommended replacement programmes are implemented.
5. SKM noted delays in the implementation of the current programme of switchgear replacement and expressed the view that the outstanding work was underfunded.
6. SKM recommended that condition monitoring techniques be adopted, particularly for switchgear at both 66 and 11 kV.

The SKM Review was finalised in November 2006.

A brief review of recent PAWC planning documentation indicates that PAWCs recent planning has progressed in directions that are consistent with the SKM recommendations.

7.4. The Manton Investigation

The Manton Investigation was an internal PAWC investigation into the bus bar failure on the YSF6 22kV switchboard at Manton Zone Substation on the 21st March 2008.

The investigation has established that the cause of the failure was an electrical flashover which had arisen as a consequence of insulation breakdown due to partial discharge tracking. The underlying cause of the partial discharge has not been established.

PAWC has a history of similar partial discharge on YSF6 22kV switchboards at Katherine and Sadadeen Zone Substations as well. In the past the discharge has been attributed to the high humidity environment, however the tracking is now evident in humidity controlled environments as well. The Manton switchboard has been air conditioned for the entire life of the equipment. The long term suitability of this equipment for service at 22kV is now being questioned.

The current recommendations for the ongoing management of these switchboards is for continued monitoring by testing for partial discharge and three yearly inspection for physical signs of insulation degradation. Whilst such condition monitoring is clearly warranted, it is not apparent that further investigation work is proposed to establish the underlying cause of the event.

The report of the investigation is dated 23rd April 2008.

Further investigation work is warranted, both in an attempt to establish the root cause of the failure and to assess whether better environmental controls would help to mitigate the risk.

8. The Recovery Response

There are five factors that have been considered in assessing the recovery response:

- The appropriateness of the recovery strategy, and the decisions made.
- The performance of those involved.
- The timeliness of the response.
- The appropriateness and timeliness of the customer and other stakeholder communication.
- The Incident Management System and escalation processes.

To assist in the evaluation of these factors, “debriefs” were conducted with representative groups of the PAWC people involved. The issues and concerns raised during these de-briefs, together with reviews of the recovery steps taken and actual supply restoration sequence and timing, formed the basis for the following assessment.

8.1. Recovery Strategy and Decisions Made

The fourteen hour, sixteen minute recovery time for the original circuit breaker outage of the 19th September was seriously impacted by the decision to undertake an extensive clean up and testing operation, prior to restoration.

This decision was entirely appropriate. Had this work not been undertaken, serious risk of further supply interruption, and risk to personnel safety would have resulted.

In the event the decision was vindicated by the outcome. From the results of the tests carried out on the No 2 transformer circuit breaker, details of which are provided in the Technical Appendix T1.2 The Breaker Failure, it was identified that this breaker was at serious risk of imminent catastrophic failure, similar to the failure of the No.1 transformer breaker.

The consequent decision to take the additional time required to overhaul this breaker prior to its return to service was also entirely appropriate. The breaker could not, responsibly, have been returned to service in the “as found” condition.

The decision to “cannibalise” the out of service Wagaman feeder endbox insulator bushing for refitting to the Nakara feeder endbox, was driven by the lack of appropriate spare bushings. (This has been a “not uncommon” problem throughout the industry.) Whilst their decision was an indication of the resourcefulness of the emergency response team, this cannibalisation may have been avoided by good asset management planning.

The ten hour, thirty seven minute recovery time for the second cable endbox outage, was attributable the need to work within the constraints of access restrictions that had been imposed following the earlier failures. The decision to first take the time to undertake field switching in order to maintain supply to critical customer loads was appropriate.

Given the circumstances, and the uncertainty surrounding the risk of further explosive failures, and consequent risk to personnel, the access restrictions themselves were, in the absence of further testing, also appropriate.

The two decisions by System Control, to utilise 95 sq. mm. cables as a significant alternative supply route, on two occasions, could have been avoided with accurate knowledge of their system assets. The decisions relied upon inaccurate cable data records. If the lack of data accuracy is discounted as a problem, then the decisions were appropriate.

8.2. The Performance of those Involved

Given the quantum of work involved in each recovery effort, the challenges faced and, the limited number of appropriately skilled people available to PAWC, the recovery performance of the workforce, on each occasion, was a commendable effort. The recovery effort for the first event was particularly commendable. The defects in the reinstallation of the Wagaman bushing into the Nakara feeder endbox may have been avoided, had there been a tradition of strong emphasis on training and supervision.

8.3. Timeliness of Response

Response and recovery times for all six events are considered to have been timely and similar to the response and recovery times of industry peers, in similar situations.

8.4. Stakeholder communication

Whilst some concern was expressed during de-brief sessions, regarding access to and the timeliness of information flow from the Control Room, the actual speed and accuracy of the information made available to customers and other external stakeholders was satisfactory and comparable to industry peers, in similar circumstances.

8.5. The Incident Management System

Whilst the overall management of the incidents, in terms of the speed of response and marshalling of resources, worked tolerably well, the approach was somewhat lacking in formality and, for at least two of the incidents, may have benefited from earlier escalation.

There was a clearly identified Incident Manager on site on each occasion; however the precise point at which an Incident was called, is not clear, from the log.

It also seems that there is no system for classifying incidents by their degree of seriousness and escalating the management of an incident accordingly.

For at least two of the incidents, given the widespread nature of the outages involved and the extent of the damage, escalation, for management by more senior levels of PAWC, would have been appropriate. (This is particularly so, given the size of PAWC.)

Ideally, incidents of these types, the recovery from which exclusively involve the application of PAWC resources, would be managed exclusively by PAWC. Even the arrangements for informing and taking care of vulnerable customers would be capable of implementation by PAWC.

Recovery from incidents of a more widespread nature, particularly those involving damage to other public infrastructure and private property, do of course require coordination with other Agencies, but even for these incidents, the relationship between PAWC and the central agency (Counter Disaster Committee (CDC)) would ideally be one of coordination and negotiated priority setting, rather than control.

The fact that it was deemed necessary to involve the Northern Territory CDC is no doubt a reflection of community concern about the situation, and of the CDC's place in Territory life. However, it is virtually unprecedented for an electricity utility not to manage its own asset failure incidents.

9. Internal Relationships

9.1. Approach

There are nine factors that have been considered in assessing the nature and effectiveness of internal relationships:

- Communication
- Role clarity
- Confidence in role performance
- Collaborative effort
- Staff attitudes
- Mutual trust and respect.
- Motivation, recognition and accountability
- Supervision style
- Leadership style

The approach taken to the assessment of these factors was to simply use the opportunities, presented by the various individual and group meetings used by the Enquiry, to observe staff interactions and listen to and challenge the staff involved. Aspects of the assessments are unavoidably, somewhat subjective.

Meetings that were broadly useful for assessing relationships, generally, were:

- Various one on one meetings with maintenance relevant managers.
- The "debriefs" - reported in Section 8 Recovery Response.
- The Maintenance Practice Assessment meetings - reported in Section 6 Maintenance.
- The Protection Operations Investigation meetings – reported in Section 4.5 The Performance of the Protection Systems.

Meetings that were particularly insightful were those that were set up on an ad hoc basis for the specific purpose of developing a collaborative understanding of incident management and recovery, in respect of the bushing failures. These were:

- Two special purpose meetings with staff and one with management regarding the installation defects which led to the second bushing failure.
- The review and consideration of a hazard report (Hazard/Incident No 1768) that had been lodged into the RISQ Hazard Reporting System, immediately following the second bushing failure. The report was drawn to the attention of the Enquiry at one of the "installation defect" meetings.

The technical findings regarding the installation defects are reported in detail in Section 4.3 The Endbox Failures, and will not be repeated here. Only matters relevant to the assessment of the effectiveness of internal relationships will be considered here.

The formal assessment of the hazard report is strictly a matter for PAWC and is beyond the Terms of Reference of this Enquiry. The review and consideration of the hazard report undertaken by the Enquiry was therefore limited to matters relating to the effectiveness of internal relationships.

9.2. Internal Relationships During Incident Management and Recovery

Feedback from the initial de-briefs and one on one interviews seemed to indicate that internal communication during both the incident management and recovery phases of all incidents worked tolerably well and that the various responsibilities and accountabilities were well understood and followed. However the detailed investigation of the second bushing failure and the review of the hazard report from the second bushing failure revealed that this was not entirely the case.

Reports from the “hands on” staff concerned asserted that during the recover from the first bushing failure, staff had been instructed to do things that they had had no previous experience of and that they had been expected to do so without adequate supervision or explanation of what was required. The results of the investigation, which are described in full in Section 4.3 The Endbox Failures, clearly concluded that:

- The staff concerned had only a limited understanding of the engineering detail of the cable end box and bushing;
- An inappropriate level of responsibility was placed on relatively junior staff (including apprentices) and
- Greater supervision and oversight of the work performed was required.

The review and consideration of the hazard report relating to the second incident concluded that, in respect of that incident:

- Details of the access restrictions imposed by PAWC management three days prior to the incident had not been adequately communicated to the relevant staff and that, as a consequence a number of staff had entered the Casuarina Substation in apparent contravention of the restrictions. They did so: either in ignorance of the restrictions or: in the belief that the status quo still prevailed or, that the conditions of the anticipated restrictions had been fulfilled.
- The details of various discussions held between the ETU and management were poorly documented and it is likely that a clear

articulation of the details of actions agreed and differences left outstanding, was lacking.

- Details of “work bans” said to have been imposed by the Electrical Trade Union (ETU), which would have had a similar effect, had similarly, not been adequately communicated to ETU members by the Union.

- Some of the staff interviewed were unclear about their roles and authority and were lacking in the confidence required to perform their roles effectively and to interact constructively with a senior manager. Others, on the other hand, were very clear and confident about their roles.

- A number of the staff interviewed used the opportunity to be critical of management.

These findings relate to the circumstances of a particular set of incidents, and should not, by themselves, be taken to be generally representative. However, when taken together with observations of staff interactions and attitudes in the other forums and the earlier assessment of the state of the works management processes, the following generalisations of Section 9.3 are considered to be valid.

9.3. Internal Relationships Affecting Maintenance Generally

9.3.1. Attitudes, Motivation and Accountability

Staff responsible for delivering routine substation maintenance (other than protection maintenance) expressed frustration and disappointment that, as they saw it:

- The task apparently expected of them was impossible to deliver with the resources available.
- Substation maintenance tasks had been compromised in an effort to cope.
- It really didn’t matter whether the tasks were performed adequately, because no one cared or bothered.
- They were, constantly having to respond to incidents or being reassigned to “more pressing” tasks.
- Their training was inadequate.

(The substance of these issues has been dealt with in Section 6 Maintenance.)

They also expressed a lack of confidence in and a lack of respect for some management. And felt a total lack of control of the situation they found themselves in.

Whilst the above attitudes were not universal and whilst such attitudes will to some degree be found in peer organisations, the extent to which they were present among the substation maintenance staff at PAWC is of concern.

The Blanch Report identified and was critical of a “run to failure mentality” at PAWC. What is clear from this enquiry is that, so far as substation maintenance is concerned, “run to failure” is not a deliberate and considered policy of PAWC, which everyone understands and supports.

Rather, so far as substation maintenance is concerned, “run to failure” appears to have been the inevitable outcome of, on going successive attempts over several decades, to cope with competing demands and operate within stringent budgets. This has fostered an attitude of “get supply restored”, by what ever means possible, to keep the customer satisfied.

The lack of control experienced by staff primarily stems from the manner of operation of the works management system.

Staff, responsible for delivering protection maintenance and testing services, were not so disenchanted. Work programmes are planned and locally oversighted. They did nevertheless convey a sense of frustration in regard to test capability and system access for certain protection testing routines. It is also clear from the performance of the protection systems as evidenced by the Casuarina incidents investigated, that aspects of the maintenance coverage are lacking.

Managers, on the other hand expressed disappointment in the attitude of substation maintenance delivery staff and the perceived failure of the skills based remuneration system. They also expressed disappointment that the works delivery people seemed unable to manage work properly.

Overall there seems to be a “disconnect” between management and the workplace and between the various management functions. This was characterised by a lack of trust and respect.

9.4. Role Clarity and Personal Confidence

On a number of occasions throughout the Enquiry situations arose in which PAWC staff and managers were called upon to justify or explain their role within PAWC. Whilst these situations were not contrived to be deliberately adversarial, they nevertheless did arise and at times individuals were presented with opportunities to defend either their own actions and decisions, or the actions and decisions of PAWC.

Whilst not universally the case:

- There seemed to be reluctance, on the part of some relevant managers, to strongly defend, either PAWC or their role in it.
- Staff did not feel confident in their capacity to perform some of the tasks apparently expected of them and
    - Cited lack of training and ad hoc assignment of work as a problem.
    - Lacked confidence in dealing with senior managers
    - Expressed feelings of disempowerment and “lack of control”.

9.5. Leadership, Supervision and Communication

The predominant leadership and supervision style, affecting substation maintenance at PAWC, is hierarchical, remote and uninvolved. With some exceptions, there is little sense of “ownership” of the substation maintenance function or the problems of asset condition and work delivery by managers and supervisors.

There appears to be very little rapport between those charged with the asset management function and those responsible for work delivery and little rapport between “hands on” staff and their supervisors and managers. There is little evidence of genuine collaboration between these groups.

The lack of meaningful work planning and reporting against plan leaves the sense that the substation maintenance function is without an adequate sense of direction.

Staff, responsible for delivering routine substation maintenance, appear to be left largely to their own devices, until such time as something fails and are poorly supported when something does fail.

PAWC has recognised these shortcomings and does have plans in place, and in the process of implementation, to adopt a new organisational structure, and address the work flow and works management shortcomings.

However, as is acknowledged by PAWC’s senior management, a substantial change in leadership and supervision style will also be required, if these changes are to be effective.

10. Conclusions

10.1. The Future of the Casuarina 11kV Switchboard

The breaker failure of the 19th September 2008 is the first and only such failure in the history of Casuarina Zone Substation. (The breaker failure of 1999 was a different circumstance.) There are, however five other such oil filled circuit breakers in the Substation, all of which are likely to have suffered some degree of insulation degradation due to long term heat exposure. The testing carried out during the restoration effort identified that at least one of the other breakers was, prior to its overhaul also in imminent likelihood of similar failure. Whilst the overhaul of this breaker relieved the immediate trigger for failure (contact resistance), the insulation degradation, due to long term heat exposure remains.

Whilst the continued operation of these breakers is still feasible, provided their condition is routinely monitored, they do present, an elevated risk, when compared to the alternative of new, current technology breakers. And whatever remaining life there is, is limited.

Replacing or retrofitting these breakers, within the constraints of the present switchboard is not currently feasible.

The cable endbox SRBP insulator bushing failure of 20th September was the first such endbox failure at Casuarina. There is anecdotal evidence of some prior endbox failures; however these are reported to have been cable failures and not bushing failures.

It is clear from the investigation that the insulation of many of the other cable endbox insulator bushings at Casuarina, is to some extent degraded. However, robust condition monitoring, of the sort possible for breakers, is not feasible for bushings, in situ. The risk is therefore not readily measurable and the best that can be done is to undertake regular thermo vision testing to determine whether a failure trigger mechanism is present.

Whilst the failure of an endbox bushing does not have the same catastrophic potential as an oil circuit breaker failure, it does present both reliability and personnel safety risk. Whilst this risk is manageable with access controls and routine thermo scanning to identify failure trigger conditions, the remaining life of the bushings is limited.

There are also concerns about the integrity of the main busbar insulation system as well.

Having regard to all of the above factors, it is concluded that continued operation of the Casuarina 11kV switchboard, for any extended period of time is not feasible. The switchboard should be replaced as soon as is immediately possible. And until such time as it is replaced, it should continue to be subject to strict access controls, and rigorous, in situ condition monitoring of the switchboard should be undertaken.

It is noted that PAWC have already commenced implementation of this recommendation and that procurement and design work for the new switchboard is in hand.

10.2. A Wider Remedial Programme

To address the longstanding shortcomings of PAWCs substation maintenance practices and the risks posed by the current uncertain condition of its substation assets, PAWC will need to adopt a number of substantial reform programmes. These programmes will by their nature be long term and will, by themselves, and particularly in view of the backlogs involved take years to become fully effective and deliver the outcomes necessary for achieving sustained confidence in asset condition and performance.

It would be prudent therefore for PAWC to address the imminent risks posed by the unknown and uncertain condition of its substation assets by implementing an immediate ad hoc remedial programme, the purpose of which would be to:

- Rapidly assess the condition of all substation assets.
- Undertake immediate mitigation action in regard to those assets found to be at immediate risk of failure.
- Prioritise longer term remedial action consistent with the condition of other assets found to be at risk.

It would also be prudent that this programme be implemented as a separate accountability, resourced predominantly by external resources, experienced in substation condition monitoring and remedial work.

It is noted that PAWC have already commenced both the planning an initial implementation of such a programme.

10.3. Implications for Possible Further Asset Failures

All oil circuit breakers and SRBP bushings, suffer from similar failure modes, to those identified at Casuarina Zone Substation. However industry experience has been that the OLX switchgear presents the most serious level of concern. Whilst most of the other PAWC zone substations are of similar age and have similar environmental circumstances, Casuarina is the only one with OLX switchgear.

Industry experience shows there is a history of similar failures relating to OLX switchgear. These failures have had varying degrees of severity, depending primarily on the speed of operation of the protection system.

Rigorous, in situ condition monitoring of all PAWC substations should nevertheless be undertaken and a rigorous ongoing maintenance and monitoring programme established. The efficacy of the frame leakage protection systems (or other high speed busbar protection systems should be verified and remediated, if necessary. The need for immediate wholesale replacement is, however unlikely. Orderly replacement, prioritised according to condition and assessed remaining life, should be feasible.

From the limited information gathered for this investigation there appears to be is no real likelihood that the incidence of cable failures in the network supplied by Casuarina (or any of the other Darwin Zone Substations) is imminently in danger of escalating to unmanageable levels.

10.4. The Current Approach to Substation Maintenance at PAWC

The current position regarding substation maintenance at PAWC, as described in detail in Section 6 Maintenance, didn’t arise overnight. It developed over an extended period.

The fundamental reason that this could have happened is, that unlike so many other industries, where maintenance involves the short term serviceability of moving parts, maintenance in the electricity distribution industry, delivers what are predominantly long term outcomes (many of which are manifest as risk reduction outcomes) and can be deferred for long periods of time without immediate consequences for serviceability. But there is a day of reckoning.

The situation at PAWC is now such that the past approach to substation maintenance is starting to have immediate serviceability impacts and if not addressed is likely to have more serious serviceability consequences, in the near future.

The situation at PAWC is not without precedent in peer organisations.

It is a characteristic of the industry that whenever there is competing demand for resources, priority is given to customer connection work and system expansion, ahead of maintenance. This is particularly so in periods of high growth and in periods of economic stringency. Historically at these times it was not uncommon for maintenance to be deferred, and for routine periodicities to be extended, as an expedient. Significantly also little management and engineering effort went into developing optimal maintenance regimes.

For young and rapidly growing systems, the consequence of poorly managed maintenance are not so severe but as systems have aged this has proven to be no longer the case and the industry generally has had to come to embrace maintenance and asset replacement/refurbishment and the science of optimising maintenance regimes, as a priority.

The paucity of formal systems of accountability and control is also not unique to PAWC.

Decades ago a common approach, throughout much of the industry, was to run a highly devolved approach to maintenance management which relied upon the stature and prowess of local supervisors to ensure that nothing went wrong with "their" assets and "their" people. The approach relied upon "a strong sense of personal ownership" of the local assets and personal responsibility for staff. Engineering support was usually strong but, reporting systems were basic with minimal upstream requirements. Funding was as much determined by the personal authority and prowess of the individual, and the maintenance of "dargs", as it was on upstream reporting. ("Dargs" are the maximum work rates imposed by workplace custom and practice.)

This approach to the management of maintenance usually went hand in hand with a traditional conservative maintenance regime, which emphasised preventative maintenance and often involved an overly intrusive and resource intensive approach. This approach, when supported with adequate funding levels, though expensive and prone to producing its own failure outcomes, served the industry tolerably well.

At PAWC, the local supervisors have not been supported with the resources required to continue with this traditional approach. Nor have they been supported with the systems and knowhow required to implement the alternative better approaches, now being adopted throughout the industry. Current substation asset management policies at PAWC are still very much in the traditional intrusive maintenance mould.

So at PAWC a new approach to both the management and the practice of substation maintenance is required.

But what is appropriate for PAWC is not necessarily the same as what is appropriate for large distribution businesses elsewhere in Australia.

10.5. An Appropriate Approach to Substation Maintenance at PAWC

In an electricity distribution business the benefits of maintenance are:

- Reduced Safety Hazards affecting staff and community
- The preservation of asset life (prevention of premature end of life)
- Reduced risk of asset failure.
- Minimisation of outages due to failure and finally
- Continuing serviceability

Throughout the industry the traditional approach to maintenance regimes is progressively giving way to an approach which emphasises condition based maintenance. This approach requires routine condition monitoring but avoids intervention unless and until condition requires it. And when intervention is undertaken it is done so with the measurable objective of improving or restoring condition. It does not entirely eliminate routine preventative action but minimises it. Because it focuses on identifying what needs to be done and on only doing it when it needs to be done, it costs less than traditional interventionist routine preventative approaches and produces better outcomes.

It does however require an intimate understanding of failure modes. And such understanding requires extensive collection and analysis of asset failure data, which ideally is representative of the environment and circumstances of the assets under management.

Throughout Australia electricity distribution businesses have begun and are in various phases of transition to condition based approaches to maintenance management. Most of these businesses are characterised by:

- Size – typically 750 000 or more customers.
- Significant numbers of demographically similar maintenance territories and for some, externally focussed business units, as well.
- Highly diverse asset sets.

And have:

- Adopted organisational arrangements, designed to optimise asset management, works planning and work delivery, across significant numbers of demographically similar territories with centralised asset management and distributed service delivery.
- Deployed IT systems designed to support multi territory multi faceted works planning and delivery and centralised asset management of a highly diverse asset set.
- Embraced the management of complexity as a necessity for optimising performance.

By contrast PAWC is:

- Small – 74 000 electricity customers on the interconnected network. It is a multi utility, but there is no apparent exploitation of synergies in asset management or works planning and delivery, beyond the sharing of core IT systems.
- Operates across a limited number of small but diverse demographic territories. Darwin, in particular, is currently managed as a single territory and should continue to be so.
- Has a small asset set which, though it is more diverse than it ideally would be, is not particularly so.

Maintenance Policy and Practice

The transition, by PAWC, to a more "condition based" approach to substation maintenance management is appropriate.

PAWC does not; however by itself, have a sufficiently large asset set from which to collect adequate data, for it to be self sufficient in determining reliable "condition failure" criteria. Nor can it afford the resources required to undertake the level of analysis required to develop such criteria.

A pragmatic approach, which leverages off the collective knowhow of the wider industry and adapts that know how to the environment and circumstances and asset set of PAWC, is feasible. And broadly accords with PAWCs current documented planning commitment to move to a new maintenance framework based on "objective need".

To achieve this PAWC will need to have its own "condition monitoring" capability and retain the skills for common intervention tasks, but will probably need to look outside for the skills required for the infrequent and the more complex tasks (which it currently does for tap changer maintenance).

It will also need to address the shortcomings identified in the findings of Section 6 Maintenance.

Specific recommendations are provided in Section 11 Recommendations.

Organisation

Organisationally, PAWC is very small when compared to others in the industry. It essentially has only one substation maintenance territory in the whole of Darwin. There is, therefore, no requirement for the standardisation and coordination of maintenance practices and delivery, across a number of geographically contiguous but separate business units, as there is in the larger distribution businesses elsewhere in Australia.

Whilst separation of asset management (the “what” of maintenance) from service delivery (the “how” of maintenance) is appropriate, for the reasons described in Section 6.8 Organisational Arrangements, there is no need for the complexity of separating maintenance works management from delivery.

Organisational arrangements which place the responsibility for setting work procedures and for managing work, close to the delivery function, are more appropriate. Indeed arrangements which grant a high level of autonomy to the local Supervisor, along lines similar to the traditional industry arrangements of the past, but which drive accountability through a reporting framework, would not be inappropriate.

Systems

The current systems supporting asset management and works management as applied to substation maintenance are poor, and do need to be upgraded. PAWC is however too small an electricity distribution business to be able to embrace complexity as a means of optimising performance. Simple pragmatic systems are appropriate. It is understood that PAWC recognises this.

10.6. Prospects for Improved Substation Maintenance

The substation maintenance situation at PAWC is not irredeemable.

From the various interactions with “hands on” staff and technical and engineering staff and managers, described elsewhere in this Report, it was apparent that there is a sufficient base of fundamental core engineering knowledge and craft and technical skills on which to build.

But this base does need to be developed, up skilled and re energised, and supported with additional equipment and systems. Specific recommendations are included in Section 11 Recommendations.

Knowledge, training and improved systems can all be built or acquired relatively easily. But their effective deployment and implementation will also require, will and determination and improved internal relationships.

10.7. Prospects for Improved Internal Relationships

From the various interactions with “hands on” staff and technical and engineering staff and managers, described elsewhere in this Report, it was apparent that there is a sizeable base of “motivatable” people within PAWC.

- The response by most staff to the Enquiry was generally positive and supportive. Most expressed the hope that the Enquiry would “change things”.
- Key engineering staff welcomed the opportunity to become involved in technical issues and share knowledge, when invited to do so.
- On a comparative basis, the numbers of young engineering graduates and trade apprentices are very high.

The potential, for improving internal relationships, does exist. But to actually bring about the necessary improvements, PAWC will need to create an environment which:

- Embraces a more inclusive and collaborative supervision and leadership style.
- Requires accountability and, measures and recognises performance.
- Fosters communication and collaboration between functional areas and, up and down the responsibility hierarchy.
- Provides improved role clarity.
- Supports individual personal development.
- Ensures that all personnel are all in jobs which match their individual skills sets and personal relationship styles.

The creation of such an environment will not happen without substantial intervention. Specific recommendations to address this need are included in Section 11 Recommendations.

10.8. Current PAWC Initiatives

As noted in Section 10.4 The Current Approach to Substation Management at PAWC, the current position regarding substation maintenance at PAWC, has developed over a very long period (decades), mostly during periods of different management and governance arrangements. The current governance arrangements date from July 2002, when PAWC was constituted as a Government Owned Corporation. Most relevant senior management appointments date from less than two years ago. It would be inappropriate to blame the current management for the current position and not to recognise the steps currently being taken to address the situation.

It is important therefore to note that PAWC is aware of the need for change and does have some planning and some actions in place to address the current shortcomings.

As reported elsewhere:

- The Statement of Corporate Intent (SCI) and Power Network Divisions business plan: propose the upgrading of asset condition monitoring; the adoption of a framework of "objective need" as the basis for future maintenance budgeting and; make allowance for increased expenditure on maintenance and on asset replacement/refurbishment.
- Additional ad hoc funding has been sought and granted by the Northern Territory Government.
- The Power Networks Division has been reorganised, with a view to facilitating a focus on asset management and improving planning and accountability.
- An Asset Management Capability project (AMC) has been initiated. Assessment of current asset management practices, processes and systems, has been completed and redesign commenced.
- The Capital Investment, Asset Management and Fuel Supply Committee of the PAWC Board has initiated action in regard to the Systemic reporting of asset condition and the maintenance works programme. A report to the PAWC Board on this topic is proposed for the March meeting.

Whilst the recommendations of this Report go to another level of detail and are substation maintenance specific, the PAWC initiatives currently in place are broadly consistent with the recommendations of this report. And it can be expected that PAWC will embrace the recommendations.

However, there is likelihood that inertia from past management and governance regimes may present an obstacle to their effective adoption and implementation.

Therefore, because of the urgency created by the current uncertainty about substation asset condition, and the magnitude of the task required to address the past maintenance backlog and all of the systems and human resources issues associated with that, it would be prudent that implementation of any remedial programmes arising from this Report be the subject of ad hoc specific oversight and governance arrangements or, at the very least, regular transparent external auditing.

11.Recommendations

It is recommended that PAWC should:

11.1. Substation Maintenance Approach

11.1.1. Accelerate the implementation of its documented planning intention of adopting a “framework of objective need” as the basis for maintenance, progressively implement systemic and rigorous condition monitoring, and adopt asset condition as the prime basis for determining “objective need”.

11.1.2. Take into account the circumstances of size, remoteness, climate and the lasting effects of past legacies when implementing this, its new condition based approach, and not attempt to emulate too closely the maintenance arrangements implemented in the much larger distribution businesses elsewhere in Australia.

11.2. Strategy for Implementing Condition Based Maintenance - In the PAWC Substations Context

11.2.1. Negotiate and implement arrangements with one or more of the larger distribution businesses in Australia to be supplied with access to “failure mode” data, inspection and test regimes, conditional failure criteria, and requirements for corrective action. In selecting a partner choose a distributor who is well advanced in the implementation of condition based maintenance, and has the best matched asset set.

11.2.2. Develop the “in house” maintenance policy resource to be a pragmatic adopter of what other distributors are doing. Adapt what other distributors are doing, to the specific environmental conditions and asset set of PAWC, with the minimum sufficient resort to analysis.

11.2.3. Specialise in monitoring and diagnostics. Develop the “in house” maintenance delivery resource to be a specialist in monitoring, testing and diagnostics.

11.2.4. Utilise the “in house” maintenance delivery resource for most routine preventative tasks and common corrective tasks, but engage outside resources for specialist and uncommonly needed skills, (as is currently done for tap changer maintenance). Negotiate and implement arrangements with external providers to undertake the highly specialised tasks, within appropriate time frames. Either as “fly in fly out “contractors or by shipping to other parts of Australia.

11.2.5. Foster a culture of local ownership by:

- Providing an appropriate level of autonomy and status to the Maintenance Supervisor.
- Providing adequate resourcing, and placing the responsibility and accountability for: the delivery of the substation maintenance works programme and; for maintenance task outcomes, with the Maintenance Delivery section.
    - Enforcing accountability through measurement and reporting.
- Routinely involving the delivery team in the maintenance policy decision process. (By systemically seeking feedback regarding failure modes and the effectiveness of corrective actions.)
- Placing responsibility and accountability for asset condition and performance with the Asset Management section.
    - Enforcing accountability through measurement and reporting.

11.2.6. Implement its new condition based approach at the maximum possible pace, consistent with circumstances, and prioritise implementation to address areas of greatest benefit first.

11.3. Organisation

11.3.1. In implementing the organisational changes, currently underway, ensure the following outcomes, or alternatively make changes which do:

11.3.1.1. Work priorities are managed so as to ensure continuity of an adequate resource allocation to routine substation maintenance.
11.3.1.2. The Maintenance Delivery group, are empowered by providing them with a sense of control and an environment which ensures a sense of ownership, pride in the assets and their performance.
11.3.1.3. The Asset Management group, are able to focus on asset management, without becoming embroiled in works and resource management issues. Ensure that this group can focus on integrating policies for the “what” of maintenance with replacement/refurbishment and whole of life cycle cost optimisation.
11.3.1.4. Works management and scheduling are kept simple.
11.3.1.5. Seamless integration of the routine condition based substation maintenance activity with the test activity is achieved.
11.3.1.6. System access for routine maintenance and protection testing is optimally coordinated.

11.3.2. Consider making the following changes to the organisational arrangements, currently in the course of implementation:

11.3.2.1.1. Establish “Substation Maintenance, Protection and Test” as a separate dedicated resource with direct reporting responsibility to the General Manager Power Networks.
11.3.2.1.2. Operate “Substation Maintenance” and “Protection and Test” as two separate sections, within that accountability.
11.3.2.1.3. Place responsibility for routine testing with the Substation Maintenance Section and upskill the workers in the Section. Advanced diagnostic testing (partial discharge, dielectric dissipation factor and high voltage withstand) should remain with the Protection and Test Section.
11.3.2.1.4. Place the responsibility for works planning as well as scheduling with the Substation Maintenance, Protection and Test Section.

11.4. Systems and Processes

11.4.1. Ensure that the next phase of the AMC project, does as it is expected to do, and:

- Deliver outcomes that are in keeping with PAWC’s size, and so far as possible, avoids complexity.
- Embrace the possibility of a continuing role for suitably controlled local PC systems and avoids the pedantic pursuit of a single enterprise system.
- Address the disempowering aspects of the current WIMS system.

11.4.2. Ensure that the systems and processes delivered by the AMC, do as they are expected to do and, provide capabilities for substation maintenance management and asset condition management, that support the recommendations of this report regarding:

- Substation Asset condition recording.
- Substation maintenance planning and programme works development.
- Substation maintenance works programme reporting.
- Substation Asset condition reporting.

And incorporate:

- Condition as well as time based triggers.
- Enforcement of condition reporting and other job closure procedures.

11.5. Policies and Policy Documentation.

11.5.1. Adopt a three tier approach to substation maintenance policy documentation, as described in Technical Appendix T2.2 Evaluation of Policies.

11.5.2. Either renegotiate the arrangements with ETSA, for the acquisition of a set of documentation that is more suitable to PAWCs requirements, or negotiate to acquire a set from another Australian distributor. Such negotiations should make provision for the routine updating of the documentation.

11.5.3. Adapt the acquired documentation to the PAWC environment and asset set.

11.6. Substations Maintenance Planning and Works Programme Development

11.6.1. Ensure that quantum planning is separate from delivery planning.

11.6.2. Set quantum plans for substation maintenance on a one and five year basis and resource to deliver.

- Ensure that firm preventative maintenance and condition monitoring programmes are set annually
- Ensure that the plan makes adequate provision for corrective tasks, based on expected conditional failure rates.
- Ensure that the plan makes adequate provision for “breakdown maintenance” tasks, based on historical breakdown rates and trends.
- Ensure that the planning process makes adequate provision for resourcing and that the assessment of resource requirements is informed by industry benchmarks and past reporting of task times.
- Five year plans should be set on an indicative basis, suitable for use in forecasting and workforce planning.

In the longer term (five to ten years) introduce 15 year planning as well.

11.7. Reporting Systems

11.7.1. **Substations Maintenance Works Programme Reporting**

- Develop simple multi level reporting of work delivery targets and delivery progress against targets.
  - Three levels of reporting are suggested – supervisor/coordinator; Management and; Board
- Report quantum (as well as dollars) progressively aggregated over tasks for the higher level upstream reporting.
- Report risk consequences of backlogs, monthly.

11.7.2. **Substations Asset Condition Reporting**

- Systematize condition data recording:
  - Maintain condition data records at the individual asset level.
  - Analyse and summarise the data by asset class.

- Develop simple multi level reporting of asset class condition, structured by asset class and reporting level:
  - Three levels of reporting are suggested – asset planners; Management and; Board.
  - Make reports available to the Maintenance Delivery. Section, as well as the Asset Management Section.

- Report key condition measures and risks, suitably aggregated or truncated for different reporting levels. For the higher level reports, highlight trends and forecast the outcomes of remediation programmes.

- Incorporate asset failure reporting, at all reporting levels. Board level reporting of all failures involving risk to personnel and public safety is suggested.

11.7.3. **Reporting Medium**

Implement ad hoc paper/PC based reporting systems, in the interim, before new AMC systems and reporting capability is developed.

11.8. Resources

11.8.1. **Workforce Capabilities - Training and Development**

- Provide training to refresh the craft skills of the current substation maintenance personnel. Engage an industry training provider to undertake a training needs analysis and provide tailored training.
- Provide training to refresh the testing skills of the current Protection and Test personnel. Provide specific training in the operation of all new test equipment and in the interpretation of results. Negotiate with other Australian distributors and test equipment suppliers, for assistance with the provision of such training.
- Provide specific condition monitoring training. Negotiate with other Australian distributors for assistance with the provision of such training.
- Provide generic Supervision training to supervisors (Coordinators).
- Negotiate opportunities for employee exchanges or secondments with the other Australian distributors, for trades worker, apprentices and engineering staff.
- Provide opportunities for ongoing participation by engineering staff, in relevant industry forums.

11.8.2. **Workforce Levels**

Initially recruit an additional 6 electrically trades qualified personnel. (Ideally such additional recruits would be experienced in condition monitoring techniques.)
Annually review the five year forecast of substation maintenance requirements and reassess the manning level required to deliver the programme. Implement appropriate manpower planning (a mix of recruitment and apprentice intake) to ensure the sustained level of manning required to match the forecast works programme.

11.8.3. **Equipment**

Upgrade and progressively acquire additional new condition monitoring equipment, as required to keep pace with the progress in implementing condition monitoring techniques and matched to the particular techniques adopted. Make a thorough review, of the equipment available and of the equipment in use in other distribution business around Australia. Undertake the review with the involvement of personnel who are to use the equipment, after they have received the specific training in condition monitoring techniques recommended in 11.8.1.

11.9. Human Resources Development

Devise and implement a Human Resources Development programme, incorporating the following key elements:

- Communication and Interpersonal skills development training, for all personnel, (structured to their role).
- Specific Leadership and/or mentoring programmes for those in "people management" roles.
- Personal development opportunities for those in key roles.
- Role and job requirements clarification.

And having the objective of delivering the following outcomes:

- A more inclusive and collaborative supervision and leadership style.
- Improved communication and collaboration between functional areas, and up and down the responsibility hierarchy.
- Strong personal ownership of roles and PAWC initiatives.
- All personnel are confident in their role and in their personal authority within the role.
- Acceptance of individual accountability.
- Improved performance measurement and recognition.
- All personnel are all in jobs which match their individual skills sets and personal relationship styles.

11.10. Miscellaneous

11.10.1. Incident Management System and Accountabilities.

Review the current incident management arrangements to ensure that the system of incident management provides for:

- Incident organisational and accountability structures.
- Intelligence gathering, consolidation and reporting arrangements.
- Escalation procedures.
- Resourcing flexibility.
- Stakeholder communication procedures.
- Procedures for coordinating with the Territory's other Emergency Management Agencies.
- Formal documentation.

That will provide PAWC with the credibility to manage its own system incidents.

11.10.2. Asset Failure Investigation Accountabilities

Assign responsibility for investigating asset failure incidents as follows:

- Asset Management be assigned accountability for deciding what incidents to investigate, for coordinating the investigation, and for “close out” and reporting. (Oversight by the “Power Technical Committee” would also be appropriate.)
- Assessment and diagnoses of the incident be assigned to the testing accountability of the Protection and Test Section.
- Assessment of OH&S issues be assigned to Employee and Organisation Services.

11.10.3. The Manton Investigation

Pursue further the Manton Investigation, and undertake investigation work in an attempt to establish the root cause of the failure and to assess whether better environmental controls would help to mitigate the risk of further failures. (This recommendation is strictly beyond ToR, as it concerns substation equipment which is only installed outside of Darwin. It was nevertheless drawn to the attention of the Enquiry and represents an asset condition risk that warrants a more conclusive resolution.)

11.10.4. Residual Casuarina Incidents Investigation

As soon as access conditions at Casuarina permit, perform the access dependent residual outstanding investigation work and attempt to resolve the outstanding aspects of the failure investigations.

11.10.5. RISQ Hazard/Incident Report System

- Complete the investigation of Hazard/Incident No 1768, without further delay.
- Implement a system of routine monthly reporting of the number of incidents logged and resolved and of backlogs of outstanding Hazard/Incidents.

11.11. Remedial Programmes

11.11.1. Initiate a programme of rigorous condition assessment of all Zone Substation equipment immediately. Undertake a high level risk analysis to determine programme priorities and set a timetable. (The original recommendation of the Preliminary Report has been extended from Distribution Switchboards to all Zone Substation equipment, for both 11 and 22kV zones. The inclusion of 22kV Zone Substations is strictly beyond the Terms of Reference, as all 22kV Zone Substations are outside of Darwin. Aspects of their condition were nevertheless drawn to the attention of the Enquiry and rigorous condition assessment of them is warranted.)

11.11.2. Implement a programme to verify the efficacy of all frame leakage protection systems (or other high speed busbar protection systems) and remediate, if necessary. Also review the associated earthing system designs, to verify their adequacy under all feasible fault conditions.

11.11.3. Take immediate action to replace the Casuarina Zone Substation 11kV switchboard.

11.11.4. Undertake a rigorous condition assessment of all Distribution Substation Equipment. (Nb: Arguably, this recommendation is beyond the scope of the enquiry, which has been interpreted to be limited to zone substations. However, as Distribution Substation Equipment is subject to similar asset condition risks and maintenance needs the recommendation is warranted. A high level risk analysis should be undertaken to determine programme priorities and timetable.)

Appendices

Appendix 1 Terms of Reference

TERMS OF REFERENCE

Following the 11 kV switchgear events which occurred at Casuarina Zone Substation on Friday 19 September 2008 and Thursday 1st October 2008, an independent investigation into the following matters is required:-

- Description of the incidents, plus any related subsequent incidents
- History of the performance of bulk oil switchgear and busbars at Casuarina and other substations
- Description of the maintenance regime that has been employed for this switchgear and substations
- An assessment of the causal factors and the contributing factors relating to the incidents
- Make an assessment of the adequacy and speed of the response to the incidents, including external communication.
- Recommendations for actions that may be required to prevent a recurrence of such an incident, including:
    - Critically examine the existing programme to retrofit vacuum circuit breakers in place of oil circuit breakers.
    - Critically examine substation maintenance practices more generally and provide detailed and practical recommendations for improvements.

On broader issues the Enquiry will examine recommendations from existing reviews and progress in implementation as well as barriers to implementation.

The Enquiry will also examine internal communications, discussion and accountability around maintenance issues.

The Enquiry should provide a Preliminary Report with three weeks of commencement, a Draft report within eight weeks and a Final Report within ten weeks.

All results from Power and Water's internal investigation will made available to the Enquiry.

The Enquiry will be able to draw on such Power and Water and external resources as they see fit.

The Enquiry Chair will be selected on the basis of demonstrated expertise in electricity distribution industry.

Given the importance of these matters, the Enquiry must ensure that any potential conflicts of interest are identified and addressed.

Appendix 2 Technical Appendices.

The Technical Appendices are provided in two separate documents. The first contains all of the Technical Appendices, other than T1.5 Energy Australia Test Report – Bushings. This Appendix is provided as a specific individual document.

Appendix 3 Corrections to the Preliminary Report

1. Chronology of Casuarina Zone Substation Development

The description of the staging and timing of the development of the Casuarina Zone Substation has been corrected.

The description of the history of the Nakara endbox, in particular, has been corrected. This endbox was initially installed as a compound filled endbox and later converted to air insulation. It was not initially installed as an air insulated endbox, as originally reported.

2. Cable Descriptions

The descriptions of the cables involved in the three cable incidents have been corrected.

3. History of Endbox Failures

The explanation of the nature of the reported previous endbox failures has been expanded to explain that these were cable termination failures and not bushing failures.

4. The Heat Shrink Boot Installation

The statement that the heat shrink boot of the second endbox failure may not have been fitted properly has been withdrawn. Whilst there is some evidence of this possibility, it is not conclusive. The position of the boot, in the “as found” condition, and the presence of “mastic” along the bushing surface, are more likely to have been the consequence of the fault, than an indication of improper fitting.

5. Root Cause of the Second Endbox Failure

The statement that the second failed bushing was not available for inspection has been corrected. The bushing was not inspected, for the purposes of the Enquiry prior to the conclusion of the Preliminary Report, but it was subsequently inspected tested and dissected.

The assessment of the root cause of the failure contained in the Preliminary Report has been significantly revised. This revision was made as a result of consideration of: additional evidence, the testing and dissection of the bushing and, extensive analysis of photographic evidence and further visual inspection of the endbox, which became possible as access restrictions eased.

6. Second Endbox Failure – Frame Earth Leakage Protection Operation

The explanation of the nature of the Frame Earth Leakage operation on the occasion of the second endbox failure has been expanded and corrected to make it clear that the Frame Earth Leakage operation occurred 29 minutes after the failure and that the protection operation which cleared the fault was not the Frame Earth Leakage.