

Independent Enquiry
Into Casuarina Substation Events
And Substation Maintenance across Darwin

Preliminary Report

Chairman: Mervyn Davies

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1. Introduction

Casuarina Zone Substation was originally constructed, in 1972, as a two transformer 66/11kV substation with 11kV switchgear 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 transformer and a third section of 11kV busbar.

On 19 September 2008 the circuit breaker in the switchgear connecting the No 1 Transformer to the No 1 Busbar section failed catastrophically. This event led 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 A.

These Terms of Reference call for a three stage reporting process. This report fulfills the requirements of the first stage. It is a preliminary report only and does not seek to address the full scope of the Terms of Reference, in depth. The emphasis, in this preliminary report is on determining the root causes of the failures, from a technical standpoint.

At this stage of the enquiry only a limited assessment has been made of the wider issues raised in the Terms of Reference. The limited commentary that is provided records impressions gleaned from PAWC's responses to a selection of highly specific enquiries and a viewing of sample documentation only. This commentary should not be taken to be indicative of the Enquiry's final assessment of the generalized wider position.

It is, in particular, far too early to generalize as to the wider position regarding maintenance and internal accountabilities. These issues will be addressed fully in the draft and final reports.

The report is, nevertheless formatted and structured in the proposed form and structure of the draft and final report.

2. Summary of Immediate Findings

2.1. The Root Causes of the Failures

- 2.1.1. The initial 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 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.

- 2.1.3. The second of the two cable endbox failures was also caused by a breakdown of the insulation of the cable endbox bushing.

However it is considered most likely that the immediate cause of this failure was accidentally inflicted mechanical damage.

- 2.1.4. 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.

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

- 2.1.5. 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.

2.2. 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. 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 not the first endbox failure at Casuarina. There is anecdotal evidence of some prior endbox failures, although the causes of the prior failures are not ascertained.

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 therefor 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 similiar 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. The Retrofit Programme

- 2.4.1. The retrofit programme was instigated by PAWC in response to the principal recommendation of the Mehta Report.
- 2.4.2. The decision to widen the retrofit programme beyond the Mehta recommendation was an appropriately prudent step in minimising the oil hazard.
- 2.4.3. Whilst the widened programme is currently behind schedule, the requirements of the original principal Mehta recommendation have been fully implemented.

2.5. The Recovery Effort

- 2.5.1. The strategy adopted by the recovery team and the decisions, made throughout were appropriate, in the circumstances.
- 2.5.2. The decision by System Control, to utilise 95 sq. mm. cables as a significant alternative supply route, on two occasions, was regrettable.

This decision relied upon inaccurate cable data recording. In the circumstances the decision was appropriate.
- 2.5.3. The performance of the recovery team and the workforce was, on each occasion, commendable. The recovery effort for the first event was particularly commendable.
- 2.5.4. 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
- 2.5.5. The speed and accuracy of the information made available to customers and other stakeholders was satisfactory and comparable to industry peers, in similar circumstances.

3. The Incidents

3.1. The Breaker Failure

At 4.29 pm on the 19th September 2008, the No. 1 Transformer 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 CO₂ 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 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 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 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 Bus Section of the Casuarina Zone Substation.

On this occasion the electrical protection systems operated almost in accordance with the intended design 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 5100 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 initial failure.) The Nakara feeder was returned to service on the 22nd September 2008.

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 operated fully in accordance with the intended design and successfully cleared the fault with minimal fault duration.

Supply restoration, on this second occasion was however affected by access restrictions imposed following the earlier failures. In order to work within the constraints of the access restrictions, supply was disconnected to adjacent parts of the substation. The number of additional customer interruptions was minimised by first undertaking field switching, but this took considerable additional time. More than 4500 customers were affected and the maximum outage duration time was ten hours, thirty seven minutes.

3.3. The Cable Failures

Subsequent to the Breaker failure and prior to the establishment of this Enquiry 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 a feeder cable failed at a point, adjacent to a joint in a pit, approximately 500m from the Casuarina zone.

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 (240 sq mm copper) cable.

Event 2.

At 4.46 pm on the 7th October 2008 a small capacity (95 sq mm copper) cable, remote from the Casuarina zone failed.

The electrical protection systems operated to isolate the faulty cable section. The approximately 2000 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 a small capacity (95 sq mm copper) cable, remote from the Casuarina zone failed.

The electrical protection systems operated to isolate the faulty cable section. The approximately 2600 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 similiar 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,
- 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 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 substation.

4.2.2. Physical Inspections

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



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 phase transformer circuit breaker bushing. The breakdown occurred between the active conductor within the bushing and the external steel 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. Neither the primary isolating contacts nor the main contacts however showed any significant signs of discolouration, typical of overheating.

4.2.3. Fault Recording Apparatus Records

Examination of the SCADA recordings of the Sequence of Events indicated that the breaker had not operated and had 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

4.2.4. **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.

4.2.5. **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, in the time available for the preliminary report, to provide any systematic record of other aspects of the operating history (specifically the number of fault interruptions).

4.2.6. **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 Mino Mehta of Energex. The Mehta findings and recommendations and the subsequent actions taken by PAWC will be discussed in Section 7.1 The Mehta Investigation, of the draft and final reports.

PAWC have also advised that there are no recorded actual switchgear failures at any of the other PAWC zones 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 will be discussed in Section 7.4 The Manton Investigation, of the draft and final reports.

PAWC were unable, in the time available for the preliminary report, to provide any systematic record of condition reporting.

The results of tests conducted as part of the supply restoration effort were however available. An evaluation of these results will be provided in the Technical Appendix.

4.2.7. **Maintenance History**

PAWC were unable, in the time available for the preliminary report, to provide any systematic record of the maintenance history.

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.

4.2.8. **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 steel 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.

The dry, flaky delaminated condition of the electrical insulating papers adjacent to the point of failure supports the conclusion that the bushing has been subjected to a prolonged period of “drying out” due to heat exposure. The position of the failure, just above the oil line is consistent with a source of heat from below, indicating that high main contact resistance was the likely primary source of the heat. However heat from the primary isolation contacts may also have been a contributing factor.

The fact that none of these contacts showed significant signs of discolouration is not considered significant as the temperatures required to cause discolouration are considerably higher than that required to cause insulation degradation.

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. Details and an analysis of these test results will be provided in the Technical Appendix.

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. This endbox, unlike the endboxes of the No. 2 and 3 Bus Sections was originally installed as an air insulated endbox. (The endboxes of the No 2 and 3 Sections, when originally installed, were compound filled, but were converted to air insulated endboxes approximately thirty 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 late 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

An “out of service” endbox at Casuarina Zone substation was inspected, in conjunction with the “Breaker Failure” inspection.

The recovered first failed bushing and several “spare” and previously recovered bushings were closely inspected at the Ben Hammond workshops.

These inspections 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. None were suitable for service.

Inspection of the recovered first failed bushing revealed that insulation breakdown had occurred at the point where the bushing passed through the inner steel casing and insulating barrier of the busbar chamber.

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.



Fig 1 – View of the endbox showing the cables bolted to the ends of the bushings and covered by heat shrink boots. The failed bushing is in the left. Note the burn mark above.



Fig 2 – Close up of the damaged bushing showing the position of the puncture through the bushing insulation.

Because of the access restrictions imposed following the earlier failures, the second failed bushing was not available for inspection; however examination of photographic evidence, taken at the time of the failure 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.



Fig 3 – View of the endbox showing the cables bolted to the ends of the bushings and covered by heat shrink boots. The damage to the LHS cable end and insulating boot is apparent.

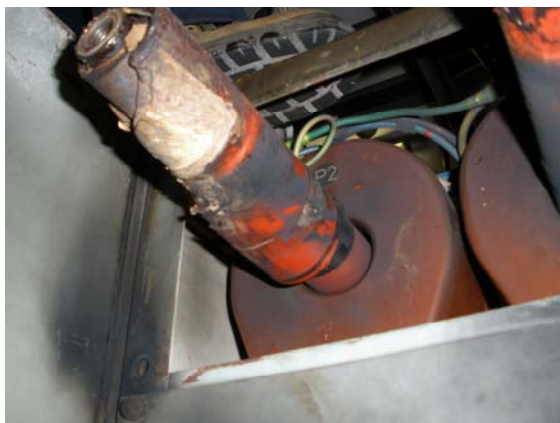


Fig 4 – Close up of the damage to the end of the Bushing. (The rear plate of the endbox has been removed)



Fig 5 – View of the endbox. The damaged C phase bushing is on the (LHS). The cables have been unbolted from the bushings. The heat shrink boots have been removed.



Fig 6 – Close up of the damage to the end of the Bushing and the cable termination. (The rear plate of the endbox is still in position)

Examination of the photographic evidence also suggests the possibility that the heat shrink boot may not have been fully shrunk and that other internal componentry may not have been properly fitted.

4.3.3. **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 of the No 1 and 2 Busbar Sections, 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.

4.3.4. **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 similiarly 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 breaker endbox and would have been subjected to considerable mechanical forces transmitted during the period of the fault and subsequent explosion.

4.3.5. **Performance History**

PAWC have advised that, in the early history of Casuarina Substation failures inside the compound filled endboxes were “not uncommon”. But that after the boxes were replaced with air insulated boxes, the incidence of failures decreased.

Details of the actual number of failures or failure frequencies are not available.

There has, until recent times, been no 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 “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.

4.3.6. **Maintenance History**

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

4.3.7. **Assessment of the Causes of Failure**

Having regard to:

- The environmental history,
- The observed physical condition of the insulation of the failed bushing and that of other identical bushings and,
- The physical damage to the bushing, attributable to the flashover,

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. It is also possible that the bushing may have suffered surface damage inflicted accidentally during some previous maintenance or repair activity.

SRBP bushings are subject to rapid insulation degradation due to moisture ingress. Normally the management of moisture ingress is achieved by protecting the bushings from exposure to moisture (including humidity) by encasing them in compound or by various surface treatments (the continued integrity of which is vital). In more recent times this approach has been enhanced by using air

conditioning to provide a low humidity, temperature controlled environment.

For most of their lives the SRBP bushings at Casuarina have been relying in the continued integrity of either the original surface treatments or the surface treatments applied at the time of the endbox conversions to “air insulation”. It is also apparent from visual inspection of the bushings that in some cases the surface treatment, applied at the time of the “air insulation” conversions, was applied over the top of residual traces of compound. These and the other surface irregularities observed would have had the effect of degrading the surface integrity against ingress of moisture and of disrupting the electrical stress distribution.

Given this environmental history, it is highly likely that all the bushings at Casuarina have experienced some degree of degradation, and that some have experienced considerable degradation. Such degradation is being experienced, to at least some degree, in OLX switchboards, throughout the industry. Temperature swings and increased temperature or accidental mechanical damage can be sufficient to trigger failure, in badly affected bushings. The ongoing management of such boards is discussed briefly in Section 10.1 The Future of the Casuarina 11kV Switchboard.

The unusual loading pattern, associated with the Zone outage of the 19th September and the subsequent abnormal network switching arrangements, though well within the design capacity, would undoubtedly have given rise to abnormal temperatures and temperature swings.

With regard to the second bushing, it is considered most likely that the immediate cause of this failure was accidentally inflicted mechanical damage.

The location of the damage caused by the failure is at the end of the bushing (immediately adjacent to the cable attachment, beneath the “heat shrink” boot which insulates the cable connection), where the electrical stress across the bushing insulation is least. Failure at this location, occurring as it has shortly following re-installation, is almost certain to be due either to mechanical damage or, some other installation defect. In this case it is most likely that the failure was triggered by mechanical damage to the surface treatment and possibly also the outer papers of the bushing, inflicted accidentally at the time of its removal from the Wagaman Feeder endbox. Elevated temperature may also have had a part to play.

Mechanical damage of the type envisaged (scoring with a knife) would permit moisture ingress and be sufficient to trigger failure in an otherwise un-degraded bushing. Failure of a degraded bushing would simply occur more quickly.

4.4. The Cable Failures

4.4.1. The Cables Concerned

The cable concerned in Event 1 is a 240 sq. mm. copper conductor Paper Insulated lead Covered and Steel Wire Armoured cable.

The cables concerned in Events 2 and 3 are both 90 sq. mm. copper conductor Paper Insulated lead Covered and Steel Wire Armoured cable.

This cable type is of a traditional design, typical of that used throughout the industry thirty to fifty years ago. Provided that it is loaded within its capacity and installed in a predictable, stable and “not too aggressive” environment, it has a long life, potentially well in excess of fifty years.

4.4.2. Physical Inspections

No physical inspections were made.

4.4.3. Environmental History

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

4.4.4. Performance History

There is no reason to suspect that, the 240 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 90 sq. mm. cables and had assumed them to be 240 sq. mm. cables. These cables were loaded well beyond their capacity, in the hours prior to the failure events and may well have been similiarly loaded (for shorter periods) on previous occasions.

4.4.5. Maintenance History

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

4.4.6. 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.

4.5. The Performance of the Protection Systems

For two of the six incidents, the protection systems failed to operate in the manner intended.

For the first incident (the circuit breaker failure), frame leakage protection, which would have been expected to clear the fault in about 0.25 seconds, by interrupting one bus section only (the No. 1 Bus section), failed to operate.

The fault was eventually cleared, by the operation of other slower protection systems and took 1.3 seconds to clear, by interrupting the whole substation. The fault magnitude grew, during this additional clearing time, to more than double.

The benefits of high speed busbar protection, and alternative means of providing it, were the subject of one of the recommendations of the Mehta Report.

The reason that the frame leakage protection failed to operate, on this occasion, has not yet been established. Work aimed at understanding the precise nature of the protection operations that did occur, and the reasons for the failure of the frame leakage protection, is currently in hand. This work has been hampered by the limitations of the access controls put in place following the failure. A full analysis will be included in the final and draft reports.

For the second incident (the endbox failure), the frame leakage protection did operate and did isolate the relevant bus section (the No. 3 Bus Section). However, 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.

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 7.1 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 will be discussed in greater detail in Section 5. Maintenance, and again in Section 7.1 The Mehta Review, of the draft and final reports.

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 SF₆ insulated replacement breakers. Replacement of these breakers would have required the complete reconstruction of the switchboard.

6. Maintenance

The material presented in this Section of this preliminary report is an attempt to document preliminary impressions only. It is based on the anecdotal material gathered in various staff and management interviews and on the cursory examination of limited documentation and equipment. A thorough exposition of this topic, based on a fulsome analysis of a wide range of available material and documentation will be provided in the draft and final reports.

6.1. Policy

At this stage of the enquiry only limited policy documentation has been reviewed. The index of a suite of Substation Maintenance Instructions which were acquired by license from ETSA Utilities in 2006 has been sighted. The suite appears to be comprehensive, but no work on assessing the relevance and appropriateness of these instructions to the PAWC asset set has, as yet, been undertaken.

It is too early to make any generalised assessment of the position regarding maintenance policies.

6.2. Practice

At this stage of the enquiry only limited and cursory consideration has been given to actual field practices.

It is too early to make any generalised assessment of the position regarding maintenance practices.

6.3. Condition Monitoring

At this stage of the enquiry only a limited assessment has been made of the adequacy of the depth and extent of the condition monitoring undertaken by PAWC.

So far as 11kV switchgear is concerned, interviews with staff and an initial assessment of the available test equipment indicate that there is some condition monitoring capability and some test results on file, but considerably more work is required to achieve a full understanding of the depth and extent of the capability.

It is too early to make any generalised assessment of the position regarding condition monitoring.

6.4. Capability

At this stage of the enquiry only limited consideration has been given to the PAWC maintenance capability.

It is too early to make any generalised assessment of the position regarding maintenance capability.

6.5. Capacity (Resourcing Levels)

At this stage of the enquiry only limited consideration has been given to the PAWC maintenance resourcing requirements.

However, a simple high level benchmark, related to the number of zone substation distribution breakers and the relevant maintenance and testing manning levels of one east coast distributor indicates that the appropriate number of “hands on field workers” (with the right mix and range of skills), is between 4 and 7 “hands on field workers” per hundred breakers, depending upon locational factors.

A full analysis of the number of PAWC “hands on field workers” deployed on this type of maintenance and an analysis of their mix and range of skills and relevant locational factors will be undertaken and included in the draft and final reports.

7. Relevant Previous Reviews

7.1. The Mehta Review

This will be dealt with in the draft and final reports.

7.2. The Blanch Review

This will be dealt with in the draft and final reports.

7.3. The SKM Review

This will be dealt with in the draft and final reports..

7.4. The Manton Investigation

This will be dealt with in the draft and final reports.

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, “de-briefs” 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, it was identified that this breaker was at serious risk of imminent catastrophic failure, similiar 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.) It is regrettable that the recovery team had to resort to such a “stop gap” measure, but it is an indication of their resourcefulness that they did so. Regrettably it also seems likely that in the hurry to recover and refit the bushing it is likely that it sustained some accidental physical damage. (See Section 4.3 The Endbox Failures)

The ten hour, thirty seven minute recovery time for the second cable endbox outage, was attributable the need to work within the constraints of assess 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 assess restrictions themselves were, in the absence of further testing, also appropriate.

The decision by System Control, to utilise 95 sq. mm. cables as a significant alternative supply route, on two occasions, was regrettable. This decision relied upon inaccurate cable data recording. In the circumstances the decision was 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.

8.3. Timeliness of Response

Response and recovery times for all six events are considered to have been timely and similiar to the response and recovery times of industry peers, in similiar 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 stakeholders was satisfactory and comparable to industry peers, in similiar circumstances.

8.5. The Incident Management System

This will be dealt with in the Draft and Final Reports.

9. Internal Communications and Accountabilities

9.1. Affecting Incident Management and Recovery

Thorough consideration of internal communications and accountabilities as they affect incident management and recovery will be provided in the draft and final reports.

9.2. Affecting the Maintenance Delivery

Thorough consideration of internal communications and accountabilities as they affect maintenance delivery will be provided in the draft and final reports.

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. 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 not the first endbox failure at Casuarina. There is anecdotal evidence of some prior endbox failures, although the causes of the prior failures are not ascertained. 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.

In regard to this recommendation, it is noted that, a system of access controls is in place and that PAWC has now instigated a “**Power System Remedial Asset Management Programme**”, the objective of which is to:

- restore a secure power supply to the northern Suburbs,
- assess the condition of all Power and Water power system assets, by the end of February 2009 and,
- implement critical remedial works by end of the wet season 2010.

10.2. Implications for Possible Further Asset Failures

All oil circuit breakers and SRBP bushings, suffer from similiar 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 similiar age and have similiar environmental circumstances, Casuarina is the only one with OLX switchgear.

Industry experience shows there is a history of similiar 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 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.

11. Recommendations

11.1. Immediate Recommendations arising from the Preliminary Report

A rigorous condition assessment of all Zone Substation Distribution Switchboards, (11 and 22kV) should be initiated immediately. A high level risk analysis should be undertaken to determine programme priorities and timetable. It is noted that PAWA has initiated the planning for such a programme.

The efficacy of all frame leakage protection systems (or other high speed busbar protection systems) should be verified and remediated, if necessary.

Immediate action should be taken to replace the Casuarina Zone Substation 11kV switchboard. It is noted that PAWC has commenced such planning.

11.2. Other Recommendations

A full list of other recommendations will be provided in the draft and final reports.

Appendices

A. 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 be 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.

B. Technical Appendix.

This will be provided with the Draft and Final Reports.