INQUIRY INTO THE AUCKLAND POWER SUPPLY FAILURE
TECHNICAL REPORT - CABLE FAILURES

The Ministerial Inquiry engaged Integral Energy Australia (IE) as technical consultants to prepare this report. IE was assisted in its task by TransGrid.

The two technical experts who were involved in this consultancy were:-

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and

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Section 1
Executive Summary
(That Part Relating to Cable Failures)

In addressing the terms of reference Integral Energy (IE) received the full co-operation of Mercury Energy particularly in terms of access to key people and "in house" policy documentation. Access to reports prepared for Mercury Energy by third party experts also proved to be of value in the short time available to conduct this investigation.

IE independently approached the chief engineers of BICC and Pirelli, UK for supporting information in regard to cable rating data relevant to the cables supplied by them to the Auckland Electricity Power Board (AEPB) and particularly in regard to soil temperatures and soil resistivities as they actually apply to the conditions in Auckland, as opposed to the conditions originally specified by AEPB. This information was provided promptly and is included as Appendices 4 and 5.

In order not to be biased by the views of others, IE was keen to form its own initial opinion based on site visits, examination of remnant failed cable components, examination of documentation including files related to technical specifications, contract matters, and discussions with relevant people. Only then was material provided by other experts reviewed.

In relation to the reasons for the cable failures there was some commonality in the findings of IE and that of other experts, however IE went further in assessing the root causes.

The factors which led to the failure of the four 110kV cables directly supplying Auckland's CBD were:

i. There was insufficient technical expertise related to cable technology and insufficient appreciation of the importance of soil conditions within AEPB at the time of preparing the specifications for the gas filled cables and the oil filled cables, and later during installation.

ii. Cable manufacturers supplied, and AEPB accepted, cables which were in accordance with AEPB specifications. Both the gas and oil cables were installed in soil conditions which did not allow the cables to achieve their specified rating.

iii. The two gas filled cables were installed contrary to good engineering practice. In at least one location ground stability was inadequate for the purpose of properly supporting the joints and the cables leading into them. A number of electrical faults subsequently occurred at that location.

iv. Insufficient investigation was undertake by AEPB/Mercury in assessing the causes of repetitive electrical faults on the gas filled cables. Most of these faults were as a result of poor installation.

v. Not all of the “low gas pressure” alarm functions provided as part of the gas filled cable installations were appreciated nor exercised by Mercury at the time of IE’s investigation. No automatic cable disconnection facilities were in place in case of “extremely low gas pressures” within the cables.

vi. Mercury assigned a low reliability to the gas filled cables and did not place emphasis on improving the condition of these cables.

vii. Mercury had a view that the two oil filled cables were fully reliable - up to their full nominal rating of 60MVA. (MEL113, page 23) In fact the rating of these cables was much lower due to the ground conditions in which they were buried. When they were loaded to more than half their nominal rating they would have started to overheat.

Once the cables were installed most of these issues would not be detected by conventional routine cable maintenance practices and there are grounds to believe that Mercury Energy may have been lulled into a false sense of security.

Mercury’s false sense of security is confirmed by an apparent lack of precautions that other operators may have taken following the failure of the two gas filled cables. For example:

a) securing these now critically important oil filled cables from external damage by arranging regular route patrols, and,

b) monitoring for possible overheating by installing and interrogating temperature monitoring devices at known, or suspected, hot spots along the oil cable routes.

viii When the two gas filled cables failed, additional load was placed on the two oil filled cables. The first oil filled cable failed due to thermo-mechanical reasons. This means that the higher than allowable cable temperature facilitated the metallic conductors to move with respect to their insulation and metallic sheath. This movement caused a joint to be compressed internally resulting in the electrical failure of that joint.

ix The remaining oil filled cable then took on additional load and became overheated, to the extent that it failed under “thermal run-away” - meaning that the cable generated more heat than its environment could dissipate causing the insulation to break down and the cable to fail electrically.

x Mercury does not have an adequate maintenance policy for 110kV gas and oil filled cables. It did not comply with manufacturers recommendations in regard to the routine testing of gas pressure and oil pressure alarms and accuracy of their initiating devices, and electrical checking of the integrity of the outer coverings of the cables.

Section 2
Technical Report – Cable Failure

2.1 General Description and Common Causes of Failure of Gas Filled and Oil Filled Cables Similar to the Ones Installed in Auckland

2.1.1 Gas Filled Cables

The type of gas filled cables in question are known as “impregnated pressure cables”, or “IP” cables. Basically their make-up consists of three separate copper conductors each insulated with paper tapes mass impregnated with what is known as a “draining type compound”. The three conductors are encapsulated within one common metallic sheath, the purpose of which is

(a) to contain the nitrogen gas with which the cables are charged, and

(b) to keep out moisture.

In the case of “lead sheaths” steel reinforcement tapes are applied to contain the high pressure gas. In the case of “aluminium sheaths” no additional reinforcement is necessary. Finally in both cases a serving is applied to protect the metallic components from corrosive elements found in the environment in which the cables are normally buried.

Mercury’s installation comprises predominantly aluminium sheathed cables, however there are two sections of lead sheathed cables.

Note: The purpose of the gas under pressure is to “assist” the insulation provided by the paper tapes. The gas IS NOT there to “cool” the cables.

At intervals of around 200 metres, in this instance, lengths of cables are jointed together. Joints are fairly sophisticated with their componentry finally encapsulated within a copper sleeve (approximately 2 meters long and 300 mm diameter).

IP cables were first introduced in the 1940s. Since then problems listed below have given these cables a reputation of reduced reliability and coupled with technical developments of oil filled and polymeric cables, IP cables have become unattractive.

Problems Association with IP Cables:

- Gas Leaks - through a number of causes for example:-
  - failure of anti-corrosive tapes which then exposed steel tapes to the environment causing them to fracture and in turn causing the lead sheath to bulge and open up under the internal gas pressure.
  - relative movement between cable and joints either through unstable ground conditions, vibration from adjacent traffic, or insufficient mechanical support during installation
  - fractures of lead sheaths due to recrystalisation, again due to vibration, load variation and other causes
  - difficulties by some jointing staff in "wiping" aluminium sheaths to copper jointing sleeves. Wiping is the process of applying a lead alloy under heat to both the "cable" metallic sheath and the "joint" copper casing to make a seal which is water proof and gas proof. A special skill is required when aluminium is involved.

- Gas Blockages in Gas Ducts within the Cables

  Within each cable is a small lead pipe to transport gas to various parts of the cable installation to ensure that a positive gas pressure is applied to the entire cable length - particularly under gas leak conditions.

  Over time impregnating compound drains out from the paper insulation and finds its way into the gas pipes. This causes blockages impeding the free flow of gas. This creates a problem when a cable has to be de-gassed prior to repairs and an even larger problem later when re-gassing is required because unless extraordinary steps are taken, parts of the cable may be underpressurised leading to eventual electrical failure. (The electrical insulating qualities of nitrogen gas are pressure dependent).

- Non Availability of Cables

  The location of gas leaks along a cable route and the subsequent de-gassing and re-gassing processes can be very time consuming sometimes taking weeks to conclude. From an asset management point of view this represents very poor utilisation.

2.1.2 Oil Filled Cables

The cables in question are known as “self contained oil filled” cables, or “SCOF” cables. The particular form of SCOF cable used by Mercury is a three core cable, ie. where the three conductors are encapsulated within one metallic sheath similar to the gas filled cables mentioned above.

In SCOF cables degasified, low viscosity oil, is transported along the entire cable by one or more integrated perforated (spiralled) oil ducts which distribute oil continuously along the cable. As an approximation half the content of oil is generally contained within the oil ducts and the other half is contained within the paper tapes where the oil assists the insulating qualities of the paper tapes.

Again, the purpose of the oil is not to cool the cables but to assist the paper insulation.

SCOF cables can be operated at higher electrical stress levels than gas filled cables. Further, their insulating papers are “non-draining”, meaning that the problems of blockages encountered with the abovementioned gas filled cables do not apply.

Advances in technology also resulted in the development of superior dielectric materials, impregnating compounds and anti-corrosive sheathing materials.

Problems Related to SCOF Cables:

SCOF cables have attained a very high degree of reliability. This is confirmed by CIGRE Working Group 21 - 10, Document 90.03 (H. Kent was a member). Contingent to achieving this level of reliability is the need for a certain level of routine maintenance which basically includes the monitoring of oil pressures and integrity of anti-corrosive sheathing and, where hot spots are suspected, the monitoring of temperatures. Some authorities also arrange for routine cable route patrols and fix cable markers to street kerbs where security of the system is considered to warrant this.

Generally the problems associated with oil filled cables are:

- Oil leaks - through a number of causes, for example:
  - associated with faulty workmanship where cables are wiped to joints (as for gas filled cables)
  - faulty installation practices where cables are insufficiently well supported mechanically as they enter joints (as for gas filled cables)
  - due to external damage
- Damage to cable outer coverings - usually due to external interference. This can lead to corrosion of the metallic sheath and subsequent oil leaks.

- Extrusion damage during manufacture
- Cracks of cable sheaths due to mechanical fatigue

2.1.3 Cable Movement

The phenomenon of an external condition causing an entire cable to move within a conduit and/or a cable conductor moving with respect to its insulation and metallic sheath was first reported by the UK Post Office in 1921. Since then the incidence of such movement has increased significantly. It is the view of IE that this phenomenon may be a contributory cause of at least one of the cable failures. Due to its significance to this investigation this aspect is covered in detail in Appendix 2.

2.1.4 Cable Ageing

Exceeding assigned operating temperatures shortens the service life of a cable, principally because of deleterious effects on the insulation. The extent to which life is shortened, or the degree of accelerated ageing, is related to the extent of overheating and the times involved. While the exact mechanisms involved are still the subject of further study by groups including CIGRE associated research has established tests which can identify if insulation has been exposed to overheating. Results of such tests were conducted by a third party acting for Mercury and are contained in MEL 113.

Due to its significance to this investigation the aspect of cable ageing is covered in greater detail in Appendix 3.

2.1.5 Internationally Known Weaknesses or Inadequacies Associated with the Type of Cables Utilised by Mercury Energy for the Auckland CBD Supply

- The weaknesses associated with gas and oil filled cables described in 2.1.1 and 2.1.2 above are echoed by the cable manufacturer (BICC Electric Cables Handbook - Granada Publishing).

- CIGRE Working Group 21 - 05 “Diagnostic Methods” reinforces these principles (George Bucea was a member of this group). The general view of this working group is that SCOF cables, if properly installed, maintained and operated in accordance with their design limits represent one of the most reliable elements in an electrical system.

In regard to gas filled cables it is acknowledged that this type of cable due to its limitations represents an outdated technology which is gradually being replaced by polymeric cables, however if these cables are operated with no overload and properly pressurised they will continue to provide reliable service.

2.2 Review of Mercury's Factual Report on Cable Failures (MEL113)

Document MEL 113 is Mercury's overview of what happened and Mercury's response to the cable failures. It is supported by third party expert reports and extracts from manufacturers' and contractors' documents.

IE found the report fair in its content of data in the lead up to the cable failures (there is no data of faults and repairs during the warranty periods, although there are references to a number of faults having occurred quite early in the service life of the gas filled cables). IE found the reported conclusions of the causes of the cable faults to be plausible. IE agrees that thermomechanical forces and thermal runaway figured prominently in the cable failures but in the case of the gas filled cables IE cannot discount a possibility that had "low gas alarm " functions been better understood some faults could have been averted. (During a site inspection on 8 April 1998 and again at a meeting on 23 April 1998 Mercury stated that they were not sure if the cable low gas alarm pressures - as distinct from the gas cylinder pressures - were alarmed.)

There is evidence that the cables have been operated at temperatures above the permissible limits from an early stage of their commissioning (BICC report contained in fax dated 21 April 1998, Appendix 4, and Pirelli report contained in fax dated 21 April 1998, Appendix 5).

Document MEL 113, received by IE on 18 April highlighted some facts which were not made clear to IE during discussions with Mercury Energy. For example the report explains that the oil filled cables were not installed by Pirelli as previously stated in casual conversations, but rather by AEPB itself. Pirelli supplied the cables to an AEPB specification and, once installed and with the cable trench backfilled by AEPB, later jointed them. AEPB tested and commissioned the cables.

MEL 113 does not spell out, nor refer to, a detailed maintenance policy specific to pressure assisted cables. Discussions with Mercury on 23 April confirmed that such policy has not been documented and that there remains a reliance on maintenance staff (now contractors) to do what their experience tells them is appropriate.

IE makes the following additional observations from the report :-

2.2.1 Technical Specification and Design

All four cables were designed and manufactured to AEPB's technical specifications which reflected technology available at the time. Of interest is that for both gas filled and oil filled cables the specifications stipulated maximum allowable conductor temperature, soil temperature and thermal resistivity of backfill. This is significant in that it demonstrates an awareness of the importance of these fundamental facts and it poses the question of why during installation, and later during maintenance, greater emphasis was not given to monitoring backfill to ensure that the environment was conducive to attaining the temperature limitations of the cables. Further, it demonstrates that even at the time of specification preparation and installation, the significance of these basic considerations may not have been sufficiently well understood by AEPB. The technical specification did not make provision for seasonal adjustment of cable ratings. For example:

Re: Soil Temperature

In accordance with the third party report "MEL 113, Appendix B, page 2.5" the specified soil temperature of 15°C was inappropriate for Auckland. Based on data collected over the period 1910 to 1984, the abovementioned report states that maximum soil temperature, at cable burial depth is above 22°C in the month of February. In addition an actual measurement taken by BICC this year, put the soil temperature at 24°C (MEL113, Appendix H).

Re: Soil Thermal Resistivity

AEPB's specification called for soil thermal resistivity "g = 1.2°C m/W." Even at the early stages of installation it was observed that the excavated soil was unstable with "peaty" characteristics, known by local residents as "smoulder" ground during dry weather.

The abovementioned third party report states measured values of thermal resistivity of cable bedding/backfill material in the range of "g = 0.56 to 6.0° C m/W. In addition it describes the backfill material to be thermally unstable, ie, prone to thermal runaway even under normal cable loads.

2.2.2 Cable Current Rating

2.2.2.1 General Comment

To load the cables to the current ratings specified by AEPB (Appendix 1) under the abovementioned soil conditions would overheat the oil filled and the gas filled cables. (The actual soil temperatures are at least 7°C above those specified to the cable manufacturers, and the actual soil resistivities varied up to 500% of the values specified.)

That the cables remained in service so long without failing is likely due to the cables being underutilised for the most part and attributable to the high reliability of impregnated cable systems even under adverse conditions.

Failure of oil filled cable circuit number 2, due to thermal runaway was accentuated by the fact that none of the failed cables were designed to carry overload, ie, not to exceed 85°C (Appendix 5). Appendix 5 also contains manufacturer's data testifying the extent to which cable temperature increases dramatically with higher values of thermal resistivity.

2.2.2.2 Cable Current Ratings - Gas Filled Cables

IE contacted the manufacturer of the gas filled cables, BICC, for additional information pertinent to Mercury's gas filled cables when operated singly and in pairs and for soil temperatures and soil resistivities more appropriate to actual conditions in Auckland. BICC's faxed replies of 21 and 23 April 1998 are attached as Appendix 4.

Interpreting the contents of Appendix 4 reveals the following:

a) With only one cable in service, and without exceeding the maximum operating temperature of 85°C, and soil temperature of 25°C the maximum cable current rating varies between:

296 amps for g = 1.0°C m/W
and 150 amps for g = 6.0° m/W *

∗ This equates to approximately half the rating of 55 MVA expected by AEPB (MEL 113, page 19).

b) With only one cable in service operated at maximum rating of 55 MVA with soil temperature 25°C and g = 2.0°C m/W the conductor temperature would become 119.2°C, ie, 34.2°C above the maximum allowable.

c) With both cables in service and operated at 55MVA, soil temperature of 25°C and g = 1.2°C m/W the conductor temperature would rise to 16.3°C above the maximum allowable.

2.2.2.3 Cable Current Ratings - Oil Filled Cables

IE contacted the manufacturer of the oil filled cables, Pirelli, for additional information pertinent to Mercury's oil filled cables when operating singly and in pairs and for soil temperatures and soil resistivities more appropriate to actual conditions in Auckland.

Pirelli's faxed reply of 21 April 1998 is attached as Appendix 5.

Interpreting the contents of Appendix 5 reveals a similar situation to that described in 2.2.2.2 above for example:

a) With only one cable in service and calculating the cable rating in accordance with AEPB's specification the maximum rating is 70MVA.

b) With only one cable in service but with the more relevant soil temperature of 22^oC the cable rating is reduced to about 65MVA.

c) With only one cable in service but with g = 6.0^oC m/W and soil temperature of 22^oC the cable rating is reduced by approximately 45% (38.5MVA).

d) With both cables in service, soil temperature of 22^oC and g= 4.0^oC m/W the rating of each cable is reduced to approximately 30MVA, ie less than half their nominal rating.

e) With both cables loaded to 55MVA (8% below their nominal rating of 60MVA), soil temperature of 22^oC and g = 4.0^oCm/W conductor temperature rises to 300^oC!, ie 215^oC above maximum allowable.

Based on these facts, together with data that portions of the cable routes have soil conditions with g = 4.0^oC m/W it is understandable why all cables failed while operated within their nominal ratings. In fact cable temperatures of as much as 300^oC or more were possible under operating conditions which were considered normal. They were possible because the initial cable rating was based on inaccurate environmental data and conditions including unknown soil characteristics.

These aspects highlight the lack of proper engineering expertise in regard to preparation of feasibility studies, evaluation of environmental conditions, design installation and elaboration/verification/updating of operating instructions of high voltage cable systems.

It appears that Mercury Energy did not investigate the initial documentation and installation condition of cables as inherited from AEPB and there is no indication that this was planned for the future.

2.2.3 Relevant Expertise

There is evidence that relevant expertise related to the types of cables in question was lacking within AEPB.

In the case of the oil filled cables there was a fragmented approach during cable installation in that a trenching contractor dug the trench, AEPB laid the cables, the contractor backfilled the trench and AEPB hired Pirelli to joint the cables. (MEL 123, page 22 and MEL 78 The Board will not require supervisory services as we have adequate staff available to control the operation.”). That left responsibility for checking the thermal qualities of the backfill with AEPB, but there is no evidence of any such testing having been performed. This fragmented approach, usually adopted as a cost saving feature is only accepted universally if the client has a high level of in-house expertise.

Then there is a statement under the signature of the then AEPB Chief Engineer which implies that earth resistivity does not have a significant effect on the rating of the cables (MEL 63) Appendix 7.

In addition there is evidence of an underestimation of the skills required by jointers working on oil filled cables. There was a reluctance by AEPB to engage qualified Pirelli jointers with a preference to using local “supertension jointers”. There is no evidence of local jointers at the time having had exposure to local or overseas experience with oil filled cables. (MEL 7) There is also a significant difference in the skills required between jointing oil filled and gas filled cables.

In fact Mercury Energy states that it and AEPB beforehand have always relied on overseas cable jointers to carry out repairs on 110 kV cables (MEL 40).

Other observations by IE in regard to relevant expertise are contained in 2.4 below.

2.2.4 Previous Cable Faults

2.2.4.1 Penrose-Quay 110kV Gas Filled Cables

Appendix F (MEL 113) gives the cable fault history of gas filled cables. The first event recorded in this document was on 23 August 1963. However it is appreciated that not all events were reported. This appreciation is based on the fact that in the contract correspondence the first series of gas leaks on both Penrose-Quay cables were recorded as early as 19 October 1959, ie, at a very short period of time after commissioning date.

The 47 incidents within a period of 33.5 years represent a significant figure of 1.4 incidents per year of service. This figure is even higher when as reported “*on average, each gas cable has a non electrical fault every second year”* (MEL113), page 22). This number could be significantly reduced if Mercury Energy devoted resources to locate and repair the multitude of gas leaks which, at the present, require a significant amount of nitrogen gas to maintain the cables within the operational pressure.

Taking into consideration the number of recorded incidents, the level of gas leaks and the view expressed in a third party report to Mercury it may have been appropriate at the time to conclude that the cable system was poorly designed or faulty materials used. Under such conditions, if proven, it is accepted contractual practice to seek to have the warranty in respect of the repaired items extended or elements of the system replaced. There is no evidence of either of these options having been exercised.

In regard to this multitude of events the impact of soil conditions was ignored. In the early stages of contractual works it was observed that sections of the cable route were very unstable. This view was expressed in Appendix B (MEL 113, page 2.9) where it was suggested that the soil under the cable be consolidated by injection of cement based grout. The lack of proper fault investigation by local engineering expertise, external consultants or cable manufacturer made possible the high number of incidents. If Mercury Energy had carried out fault investigations as presented in (MEL 113), ie, by paying attention to all possible influencing factors and by applying a proper asset management strategy then a significant number of critical events could have been avoided. This type of strategy did not eventuate on the grounds that Mercury Energy always considered that "*the failure of both gas cables was regarded as manageable by Mercury Energy*" (MEL 113, page 12) a statement which suggests that these two cables were given low consideration for system security.

2.2.4.2 Roskill - Liverpool 110kV Oil Filled Cables

No faults were reported prior to 19 February 1998. (Reference MEL 113, Appendix F)

2.2.5 Cause of the Cable Faults In January/February 1998

2.2.5.1 Penrose-Quay 110kV Gas Filled Cables

The likely cause of the two gas filled cable failures is due to the following chain of events:

- Unstable ground conditions at joint locations caused relative movement between cable and joint.
- This fractured the seal between cable and joint causing gas to escape.
- The reduced gas pressure in this vicinity reduced the degree of electrical insulation of the cable resulting in the cable failure.

The possibility exists that operating the cables above recommended maximum temperature may have contributed to the electrical failures.

In the case of the first cable failure a gas alarm was received six hours before the cable failed. Had the cable been de-energised at the time the alarm was received, or shortly afterwards, this electrical failure could have been averted. There is evidence that

Mercury’s alarm monitoring system does not distinguish between “cylinder gas presure and “cable gas pressure”.

2.2.5.2 Roskill - Liverpool 110kV Oil Filled Cables

In regard to the two initial oil filled cable failures IE concurs with the views expressed in the third party report commissioned by Mercury Energy.

The first cable failed due to thermo-mechanical reasons. The higher than allowable cable temperature facilitated the metallic conductors to move with respect to their insulation and metallic sheath. This movement caused a joint to be compressed internally resulting in the electrical failure of that joint.

The second oil filled cable then took on additional load and became overheated, to the extent that it failed under “thermal run-away”. This is a condition where the cable generated more heat than its environment could dissipate causing the insulation to break down and the cable to fail electrically.

State of Cable Insulation

- **Gas Filled Cables (Penrose-Quay)**

MEL 113, Appendix B gives results of the “degree of polymerisation” tests which, in considering the age of cables and the environmental conditions, show a reasonably good quality of insulating paper. It can be concluded that the cables lost only approximately 25% of their initial mechanical properties.

- **Oil Filled Cables (Roskill-Liverpool)**

Paper samples of Cable 1 are reasonably good; just 20% below the mechanical properties of new cable, while the samples from Cable 2 show about 30 to 40% of their initial strength.

The paper insulation tapes sampled from close proximity of cable fault 4 generated by thermal runaway, have lost about 40 to 65% of their expected life.

Oil cable degasified analysis tests (DGA) revealed high level of gases in both cables. On both cables are visible activity of partial discharges (PD) and low energy discharges. On Section C, the section containing Fault Number 4 significant amounts of Acetylene was recorded. As this type of gas is generated at arcing (temperatures above 700^o) it may be concluded that Fault Number 4 was initiated by high energy discharges.

If Mercury Energy had in place diagnostic procedures to investigate cable oil (DGA) and other oil tests at reasonable time intervals the activity of discharges could have been identified and decisions taken for testing and location of faults developing at points along the cable (Diagnostic Methods: CIGRE WG21-05/1996).

2.3 Review of the Design and Manufacture of the Four Cables, Their Fitness for Purpose and Maintenance Standards

2.3.1 Gas Filled Cables

Two types of this cable make up the circuits currently in use by Mercury, viz, "aluminium sheathed" and "lead sheathed with steel reinforcing tapes", the latter type being used on two longer sections where the manufacturer was not able to make those lengths in aluminium. (MEL 89, Section 1)

At the time of installation, in 1957, this technology was appropriate for the purpose intended. The difficulties outlined in 2.1.1 above were not yet established to the extent that these cables could be regarded as problematic.

The aluminium sheathed cables, constituting by far the majority of the installation, are in fact the superior of these two cable types over the longer term provided that:

a) they are installed properly initially - with particular reference to where these rather rigid cables enter their joints and the manner in which they are wiped to the joint components, and

b) have gas pressures and the integrity of their anti-corrosive serving monitored at appropriate intervals.

In regard to (a) above, concern of mechanically and thermally unstable ground and lateral movement between cable and joint (by as much as 50 mm) was registered at the very commencement by installation staff (MEL 79, Document 201 and 202).

In regard to (b) above the original installation was provided with facilities to enable this to be done.

Joints For Gas Filled Cable

The type of joint used in Mercury's installation incorporates a gasket as part of the gas pressure retainment regime. As such it is superior to earlier designs which employed a complicated arrangement of castings. Nevertheless in addition to electrical considerations critical points remain the mechanical stability of the joint and proper wiping techniques.

Discussions with maintenance staff have revealed that poor wiping has been the cause of a number of gas leaks.

IE was also somewhat surprised to find that four of the five electrical faults to date have occurred at one location, in the close vicinity of joint bay 42 (MEL 113, Appendix A, page 9), and that a more detailed investigation of what appears to be a "type fault" and repair methodology has not eventuated.

Maintenance Standards and Asset Management Practices

Manufacturer's operating and maintenance instructions are contained in document (MEL 89). They are devoted entirely to the management of the gas supply system. There is no reference to routine sheath IR checks, route patrols, temperature monitoring or other visual checks. There is also no reference to "Cable Low Gas Alarms" (as distinct from "Cylinder Low Gas Alarms" despite the fact that they are fitted. In the experience of IE cable low gas alarms are of great assistance in the early detection of gas leaks and appropriate asset management practice.

While Mercury has quite a sophisticated system of displaying alarms via their SCADA network (MEL112), maintenance and operating staff were not aware of the existence of cable low gas alarm initiations, and subsequently of the different response methodologies available.

The possibility exists that had these facilities been known one or more electrical failures could have been averted.

2.3.2 Oil Filled Cables

At the time of this installation oil filled cables had already reached a stage of technical maturity. Any further improvements then generally took the form of design modifications by manufacturers to cater to specific situations. It is understood that the manufacturer of these cables modified later versions of its joints to ameliorate the problem of cable movement at inclines.

Some users also made enhancements to suit their own specific requirements. An example of this is the fitting of more sophisticated oil monitoring systems to provide improved system security. Mercury part-duplicated its oil pressure monitoring system by installing pressure transducers.

Maintenance Standards and Asset Management Practices

No operating and maintenance instructions specific to these two cables were available from Mercury.

While the installation of oil pressure transducers mentioned above and their detailed display via the SCADA system is a positive improvement on the original installation Mercury does not regularly check the accuracy of these monitoring devices nor the accuracy of the original pressure gauges in the field. Further, Mercury's method of checking the validity of the transmission of low oil alarms is incomplete in that it only checks the continuity of the electrical signal between field and control room. It does not check the integrity of the actual alarm initiating devices. All of these aspects are contrary to manufacturer's instructions and expose Mercury to a situation whereby a genuine oil leak may go undetected or where a signal in the control room may misrepresent actual site conditions.

Contrary to manufacturer's instructions Mercury does not carry out routine cable sheath insulation resistance (IR) testing. These tests, normally carried out once per year, are designed to highlight defects in the cable anti-corrosive serving. Such defects, if ignored, can lead to corrosion of the cable metallic sheath resulting in oil leaks. It is then left for the low oil alarms to alert appropriate staff.

Mercury's reasoning for not performing IR tests is that most of the cable joints have moisture, or free water, in their anti-corrosion protective boxes. This would render IR testing useless, and to repair these joint box defects is not considered warranted.

IE is however in agreement with the view of others that oil leaks did not cause the original cable breakdown.

Of greater significance is the lack of any monitoring of temperature. Temperature is an important factor when assigning a "rating" or "transmission capacity" to a cable. It is the cable insulation which is the limiting component and which will fail when overheated. It is therefore important to either have an awareness of the operating temperature of a cable in service or to have it underutilised to an extent where temperature limitations will not be exceeded.

Most important high voltage cable installations are provided with thermocouples (temperature measuring devices) at likely hot spots along a cable route. These devices are permanently wired to the underground cables with their control wiring brought to gattic type pits located in roadways. It is then possible to interrogate temperatures with external instruments whenever it is thought prudent to do so. There are examples where users have gone a step further and installed temperature measuring devices at locations where continuous data (usually via SCADA) can be relayed to a control center. None of these features were specified nor installed on any of the Mercury cables under investigation.

2.3.3 Soil Conditions

Since the early stages of development of high voltage power cable technology knowledge of environmental factors has been of extreme importance. The design of cables and cable installation systems depends on a proper knowledge of ambient temperature variations, of extreme variations of soil temperature, of soil thermal characteristics and mechanical stability.

Ambient temperature and soil temperature are easily recorded. Thermal resistivity measurement requires specialised instrumentation. This data influences the size of the cable conductor and installation conditions for a specified cable rating.

Thermal resistivity varies by the nature of soil, compaction (density) and content of water. It is a fact that industrial waste areas are susceptible to very high thermal resistivity as are native soils similar to those from Auckland area as well.

Data presented in (MEL112/Appendix B) covers in depth the specific details of soil and backfill thermal and mechanical stability along the 110kV cable routes.

IE and Mercury understand that the Roskill - Liverpool cable failures were principally caused by thermal runaway and cable core movement, and that some faults (type fault) on Penrose - Quay cables were generated by soil subsidence and mechanical instability near a busy road and railway track.

These aspects confirm again that the soil conditions and their characteristics were not properly investigated at the time of cable installation or at a later date when the soil mechanical instability generated several failures.

2.4 Availability Of Appropriate Expertise At Critical Decision Times

Comments in regard to cable expertise that was resident within AEPB are made in 2.2.3 above.

In order to evaluate Mercury’s abilities in this regard a number of questions were forwarded formally to Mercury on 20 April 1998.

In response Mercury provided a substantial list of its staff at management/decision making level with cable technology expertise. Also provided was a listing of industry affiliations exercised by Mercury to keep abreast of developments/trends in cable technology (Appendix 6). These responses were discussed at a subsequent meeting with Mercury on 23 April.

There is insufficient evidence to conclude that there is resident in Mercury a great depth of expertise and experience specific to the more sophisticated technical aspects related to pressure assisted cables - particularly oil filled cables. The type of expertise I.E. was trying to establish is that normally exhibited by people with training from cable manufacturers, or staff capable of demonstrating a long association with hands-on experience in the installation, operation and emergency maintenance of such cables or people who have actively participated in relevant and serious industry committees, perhaps even in working groups, or having perhaps prepared at least one relevant technical paper, or operating and maintenance manuals.

Above the level of oil mechanic there is no one person at Mercury solely in charge of cable installation and maintenance. That perhaps is a reason for the absence of maintenance policies for pressure assisted cables and a reason for the single page devoted to “operational maintenance” in Mercury’s factual report (MEL 113, page 40).

In regard to spare parts for the gas filled cables a cable fault in February 1997 consumed all spare joints. Due to technical and administrative reasons these spares were not available at the time of the failure of the first gas filled cable.

Section 3
Acknowledgments

IE acknowledges the co-operation received from BICC and Pirelli, particularly their prompt response with cable rating data.

Appendix 1
Current Rating Specified by AEPB

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Appendix 2
Movement Of Cables In Ducts Or Of Cable Cores Inside Of Cable Metallic Sheath(s)

by George Bucea
TransGrid

1 General

The movement of power cable cores inside their metallic sheath is a particular case of telecommunication or power cables movement in cable ducts; phenomenon which was first reported by the Post Office UK in 1921. Since then the incidence of cable movement/creepage in ducts has significantly increased becoming a serious reason of concern in relation to telecommunication and power cable network.

It was observed that the cable creepage phenomenon was affecting only cables installed in ducts laid under traffic lanes.

The first investigation into the cause of cable movement in ducts was carried out in 1921 by the Post Office. Based on the result of that investigation, the cable creepage was attributed to vibrations caused by vehicular traffic.

A few years later the British Electricity Supply utilities experienced similar problems with their power cable network. In several instances the creeping force (motive force) was so great that the power cable conductors moved inside their metallic sheaths.

Initial investigations of electricity supply utilities reached a conclusion, which was in opposition to the Post Office view by stating that power cable creepage was caused by cyclic loading (alternating heating and cooling) ie a thermomechanical effect.

As the heating effect due to carried load is negligible for telecommunications cables, it was generally accepted the view that cable movement in ducts or within their metallic sheaths was produced by vibrations or another unknown cause.

2 Fundamental Investigations of Cable Movement (Creepage) in Cable Ducts

2.1 Investigation Methodology

Since the late 1930's the incidence of cable creepage both telecommunication and power cable (oil and gas filled) has increased to an alarming rate. As a direct consequence the Post Office Research Branch and other utilities carried out extensive field and laboratory investigations studying the following aspects:

- Measurement of vertical and horizontal vibrations generated by road vehicles on the road surface and in the soil beneath the road.
- Road surface depression caused by the passage of vehicles.
- Effect of different types of road surface.
- Effect of sub-soil composition.
- Effect of cable construction with respect to its stiffness/flexibility.
- Tension developed in cables due to cable movement/creepage force.
- Effect of speed and weight of vehicles.
- Effect of cable rating pattern.

2.2 Field Observations

Field observation associated with cable movement/creepage inside the ducts, or movement of cable-core(s) inside the metallic sheath, has identified the major conditions influencing cable movement, as follows:

- Cable moves/creeps in the direction of the traffic directly above it.
- Cable movement is greater under roads with poor sub-soil composition such as clay, shingle, peat, etc. than under more solid sub-soil.
- Movement is greater under poor drained roads than under well-drained roads.
- Movement is greater under embanked roads than under roads passing through a cutting.
- If the sub-soil is bad the condition of the road surface has no effect on the extent of cable movement with the exception of solid concrete roads.
- If the sub-soil is good then the condition of the road may have an attenuating effect on cable movement.
- The movement is greater on uneven “bumpy” surface than on smooth and level one.
- The movement occurs mainly on cable routes under driveways. When the cable run is under a footpath or other spaces adjacent to the road the movement is minimal unless the cable route is within about 1.2 metres of the nearside traffic wheel.
- Movement of cables is greater on a long straight section of road than on a winding one.
- Movement is more pronounced on downhill sections than on uphill; and
- Cable movement occurs mostly in earthenware self-aligning ducts than in steel ducts.

2.3 Theoretical Interpretation of Cable Movement

It has been established that both thermomechanical effect and field conditions (traffic characteristics, sub-soil composition and road construction) can produce compressive and tensile forces causing movement of cables.

(i) Cyclic Movement Cables (Thermomechanical Effect)

A change in the load being carried by a power cable causes a variation of the temperature of the various components and this results in thermal expansion or contraction of the cable system.

Heating and cooling of power cables causes expansion and contraction phenomena which, under certain conditions such as on gradients or high friction coefficients between cables and ducts, result in movement of the cable along the duct.

The influence of temperature variation on cable movement is elaborated in the Part 3 of this report.

(ii) Surf-riding Theory

Surf-riding theory assumes that the soil is a quasi-elastic medium. Considering this hypothesis lets study the impact of one wheel of a heavy vehicle rolling on a macadam surface above a cable duct. The wheel will produce a temporary depression in front of it (Figure 1) of similar shape and curvature to that of the wheel. Due to its elasticity, the soil will recover gradually and return to its original geometry as soon as the wheel rolls forward.

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Figure 1. Exaggerated impression of cable movement due to “surf-riding” phenomenon.

> It can be noticed that the depression is steep in A and is trailing off gradually in B; the cable will drop into it in such a way that the upwards thrust of the duct will be practically without a horizontal component at A, whereas the cable will rest on the slope at B and there will be a horizontal component of the trust tending to push the cable forward somewhat as a surf-rider advances by sliding down the face of a wave.

The phenomenon could be summarised as follows:

a) The weight of a vehicle compresses the soil beneath the road and the duct line.
b) The depression moves along the duct line as the vehicle wheel rolls along road.
c) The cable moves forward in the direction of the vehicle as the duct restores. The movement is similar to that of a surf-rider whose advancement is B sliding down the face of a wave.

It is appreciated that the magnitude of cable movement is extremely small; of the order of 0.03mm per cycle. However considering the intensity of modern traffic the cumulative effect of hundreds of thousands of cycles will generate significant movement of cable. This phenomenon was studied on models and under real traffic conditions. The surf-rider theory was verified. In addition it was identified that a stiff steel rod or a perfectly flexible chain did not move inside the ducts when subjected to wave-riding phenomenon conditions.

2.4 Conveyor-belt Principle

The early investigations of cable movement in ducts concluded that cable movement/creepage was produced by the road vibration under traffic conditions in a manner similar to the movement of coal on a conveyor belt ie a slow forward movement of the belt and a quick backward jerk producing a forward movement of the coal.

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Figure 2 Displacement and velocity of a conveyor-belt action

It was assumed that the horizontal component of the movement of any particle in the road is not sinusoidal but has a saw-tooth form, like the movement of a shaking conveyor. However, later studies proved *that road vibration plays only a secondary part in cable movement*, as reported by a case study presented below.

A simple experiment carried out in 1936 included a section of road which was surfaced with special asphalt, giving an almost perfect surface. The road section was selected at a point where the sub-soil was marshy clay. In a very short period of time cable movement/creepage was evident.

The experiment was extended with other two lengths of cable; one length of cable was installed in ducts under the ordinary surface of the road. The difference in vibration was very significant when a car passed. Under the special surface there was depression only, whereas there were both depression and vibration under the ordinary surface. After three months the cable movement was about 120mm. The difference between the magnitude of cable movement was about 10mm in favour of the cable section installed under the ordinary surface.

This experiment and other similar investigations confirmed that vibration has only a slight influence on cable movement. It was clearly proved that road depression accounted for nearly all the movement, ie the cable movement was mostly due to the surf-riding effect and the vibration played only a secondary par. In fact, the vibration contribution to cable movement is materialised only by the reduction of the static friction between cable and duct or between cable core and cable metallic sheath.

2.5 Derivate (hybrid) Theory of Cable Movement in Ducts

Another possible interpretation of cable movement in ducts is based on both, the conveyor-belt and the surf-riding theories.

According to this interpretation the mechanism of cable movement in ducts is based on the travelling depression in the road, which induces a slow forward and quick backward movement of the ducts. The force, which produces the road depression, is generated by the impact of a heavy vehicle wheel assumed at about 45° forward from a perpendicular line drawn through the axis of the wheel of vehicle. The cable duct is forced forward by the horizontal component force and vertical downwards by the vertical component. As a consequence the static friction between cable and duct is broken.’

Behind the wheel, at the rear of the depression, there are symmetric components of the wheel in force. The horizontal component pushes the cable duct backwards and the vertical component downwards. After the depression has passed, the road/sub-soil composite recovers slowly and the cable duct returns to its original position. The cable movement inside the duct follows the following sequence of events:

a) Stationary Condition (Original Position)

Cable-core rests on the lower sector of the corrugated Al cable sheath.

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b) Action in Front of Wheel Depression

Cable sheath is forced forward and downward. The static friction between the cable-core and cable sheath is broken. Cable sheath is moving forward in relation to cable-core.

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c) Action Behind Wheel Depression

Cable sheath is forced backward and downward.
The static friction is maintained interrupted as in (b) above.
Cable sheath is moving backward in relation to cable-core.

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(d) Action After the Depression has Passed

The sub-soil and road surface recover slowly to the original position.

The cable sheath is actioned by the road sub-soil upwards and forward.

The frictional contact between the slack core(s) and sheath is re-established.

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As the cable sheath moves slowly forward to its original position the cable core(s) will be pushed forward by the fictional force.

Figure 3 Sequence of events during the vehicular action on cable route.

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Figure 4 Deformation of Flexible Cables in Ducts Providing the cores have a significant stiffness the frictional force will compress the core(s) longitudinally otherwise the core(s) will take one of the forms shown in Fig.4.

Providing the cores have a significant stiffness the frictional force will compress the core(s) longitudinally otherwise the core(s) will take one of the forms shown in Figure 4.

The small depressions produced by the wheels of vehicles will be propagated along the cable route at an equal speed of the vehicle activating the cable movement. This phenomenon could be very much compared to a caterpillar crawling along the cable route with a resultant effect of core(s) movement measurable at cable joints.

2 Options and Devices Used to Prevent Cable Movement/Creepage in Ducts

The following solutions have been employed to reduce or eliminate cable movement/Creepage in ducts or of cable core(s) within their metallic sheath(s):

a) Damping

The damping system, as used in the early stages, consisted of a massive mould of concrete placed over, and in good contact with the cable duct(s). The system worked efficiently in several situations but because of its high cost and because of some failure cases due to poor sub-soil conditions and improper installation method it was abandoned.

b) Anchors

The devices used to anchor cables to cable ducts or of the cable core(s) to the cable sheath(s) varied and were adapted to match the cable type and its dimensions. One of the early devices was a lead collar wiped to the lead cable sheath near the duct-mouth and used in association with wooden blocks attached to cable between the duct-mouth and the lead collar.

When installed on cables with a high rate of movement the cable lead sheath was fractured near the plumbing area or, if the cable sheath withstood the strain then the cable core was moving inside the sheath.

Other developed devices and systems were as follows:

- Double-eyed cable grip mainly developed to anchor telecommunication (coaxial) cables.
- Sugar shovel cable anchor firmly attached to cable in front of the duct-mouth by copper wire bindings properly protected.
- Anchor type joints, specifically developed for gas and oil-filled cables, known as barrier joints. In this category are included any type of joint which would prevent cable core to move such as: reinforced joints, conductor fixing joints and stop joints.

c) Snaking

Snaking the cable along the cable route or on either side of the joint for a certain length of cable, say about 20 metres length was successfully used. This option requires a larger trench width, say 0.7 metres per cable circuit, while for the circuits consisting of three single core cables, the trench width would be designed by taking into account the outer diameter of cables and the spacing between them.

3 Observations and Conclusions

I. The mechanism of cable movement in ducts or, in the particular case of cable core(s) movement within their metallic sheath(s), do not follow invariably the same pattern in all cases. This phenomenon is very many dependents on cable mechanical characteristics, traffic particulars and road stiffness and its sub-soil conditions. In each particular case the cable movement is the product of a certain combination of factors.

II. The quality of road surface, factor which is responsible for the generation of road vibrations, has only a minor contribution to cable movement; contribution materialised by a reduction of the friction coefficient between ducts and cable or between cable core and cable sheath.

III. Cable movement could be reduced by a range of methods suitable for each type of cable and installation conditions. In case of heavy and rigid cables, consisting of metallic sheath and conductors of high cross sectional areas, longitudinal forces are significant and cable movement is proportional to these forces.

IV. The most efficient and economic method to eliminate the cable movement is by snaking it in a sequence of multiple cycles incorporated in troughs (flexible system) or embedded in sand /cement mixture of certain proportions (rigid snaking).

4 Influence of Temperature Variations on Cable Core Movement

Temperature variations are generated by the variable cable loading and by the ambient temperature.

The thermomechanical design of power cables installed in direct buried conditions is based on the principle that longitudinal and lateral movement of the complete cable is virtually eliminated, and the only possible movement is longitudinal displacement of the conductor and insulation within the sheath. This movement is resisted by friction between the core and the sheath and can be reduced or totally eliminated if the cable core is firmly held at the cable ends or if the cable sections are jointed by stop joints or other core movement restricted systems are employed.

If it is assumed that no longitudinal movement occurs due to thermal variations, then the force developed in the conductor will be:

$$F=EA\alpha\Delta t$$

where: F = force in conductor (N or kgf)

E = effective modulus or elasticity of the conductor (kgf/mm^2 or N/m^2)

A = cross sectional area of the conductor (m^2)

α = Coefficient of expansion of the conductor (per deg.C at 20°)

Δt = Temperature variations (°C)

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Appendix 3
Cable Ageing

by Francis Mitchell and George Bucea
TransGrid

1 Introduction

Very often cable manufacturers have been asked whether they know the actual life of power cables operating under normal or emergency conditions. The manufacturers were asked to recommend the best methods and tools to investigate and check the intrinsic qualities of cable component parts.

Unfortunately, there is not a simple answer to the question on diagnostic techniques and the general phenomena controlling the life of a cable. There are too many factors which could affect the cable-operating conditions and consequently the cable life. The stresses acting on high voltage power cables may be classified as follows:

Thermal: due to the operating current under normal and emergency conditions. The maximum operating temperature depends on insulator materials and operating conditions. For traditional oil paper dielectric it is 85/90 C and for XLPE cable it is 90 C.

Electrical: due to operating voltage under normal and emergency conditions and due to impulse voltages following lightning and switching.

Environmental: due to environmental conditions acting on the external sheaths of the cable (polymer degradation, metal corrosion).

Mechanical: due to laying operations (bending), service conditions (load cycling or externally induced cyclic movements for submarine cables), or accidental damage.

The action of these factors on power cables is materialised by a degradation phenomenon that will cause the cable failure under service conditions.

2 Degradation Mechanisms Of Paper-Insulated Cables

2.1 General

Due to the similarities in the materials used, the long-term behaviours of oil-filled cables has often been compared to that of transformer insulation. Consequently, it is not surprising that many laboratory studies of the degradation phenomena have been based on the same investigations: the determination of gases dissolved in oil. Nevertheless, the operating conditions of cables are somewhat different from transformers, for instance a lower service temperature, so the degradation of cellulosic insulation is very slow. There are many utilities' networks with cables having useful lifetimes of 60 years or more.

Deterioration of paper oil dielectric due to thermal or electrical ageing (partial discharges) can result in failures.

A water free, well impregnated insulation is not reported to degrade under the application of an electrical stress alone. Common causes of electrical degradation are the presence of water oxidising agents or of gas bubbles and elevated temperatures.

These conditions may occur in operating of cables. Of particular importance is overloading of the cables and, therefore, heating of the cable. Elevated temperature will promote the degradation of the insulating materials and reduce the remaining service life of the cable. However, it is not clear by how much overheating can reduce cable life, of a certain type of cable.

According to American practice (NEMA/ICEA Publications), emergency overloads may last limited periods of time for a specific number of hours per year. Whilst it is recognised that such operations could have an effect on the cable life, the conditions are chosen to ensure that only limited ageing is likely to occur. It is anticipated that the International practice may follow this direction in the future.

Unfortunately, there is no simple answer to the question on what controls the life of a cable. There are many factors which can affect the cable temperature and, implicitly, the cable life. Precise data regarding the installation and operation conditions is seldom found. Consequently, for cases where cables have been designed on the basis of continuous loading at a maximum allowable conductor temperature, the manufacturers admit very little or no overload capacity. In addition, high voltage cable manufacturers do not specify any expected period of cable life. The often quoted period of 40 years is based on the fact that this is approximately the present experience of operated oil-filled cables.

In this paper, some factors which accelerate the decomposition of cable dielectric materials are considered. An excellent paper by Gazzana-Priaroggia *et al* [1] presented results of some experiments performed on cable insulating materials. Their results and findings are also outlined in the sections below.

2.2 Maximum Operating Temperature

The maximum rating of a high voltage cable is determined by the maximum temperature to which the insulation can be safely operated. In most types of pressure cables, the allowable conductor temperature has been limited for many years to 85ºC. This temperature depends on ageing characteristics of the dielectric. After extensive research and studies on the life and aging characteristics of dielectric materials, it was found that, with the high quality paper and synthetic oil used today, the temperature for continuous operation of oil-filled cables could be safely increased from the traditionally accepted value of 85ºC to 90ºC. Since the early 1970's the European manufacturers and users have adopted this temperature and the current carrying capacity is calculated accordingly.

With impregnated paper, MIND cables (19/33kV), it is unlikely that the maximum insulation temperature can be raised appreciably (maximum conductor temperature 65ºC) due to compound movement and metal sheath enlargement, which on cooling would give rise to the formation of excessively large voids and consequent destructive ionisation. With oil-filled cables, since void formation does not occur, the main problem is whether electrical insulation can withstand the elevated operating temperature for certain periods of time without affecting the life of the cable.

An answer to this question is possible if the mechanical deterioration of the insulating paper is taken as a criterion of the state of used cables. It may be possible to fix, for both new and used cables, temperature limits for normal and emergency loading in relation to the desired life of the cable. In fact, paper insulation plays the most important role in this problem [1].

2.3 Ageing of Paper Insulation

The mechanical characteristics that, in order of decreasing sensitivity, permit evaluation of paper quality and degradation are: folding strength, tear strength, elongation, burst and tensile strength.

Deterioration of paper insulation can be caused by a number of factors, but the main agents are moisture and acids, elevated temperature and oxidising agents. Even atmospheric oxygen can oxidise paper. A wide range of products are formed by paper decomposition, including moisture, gases (especially carbon monoxide and dioxide) and organic acids. The production of moisture is a problem, because it further accelerates the rate of decomposition.

The curves in Figures 1 and 2 show, for Kraft paper, the deterioration of folding and tear strength with heating time in the range of 90 to 140ºC[1]. For conductor temperatures above 120ºC, all cable components and their environments are affected. The mechanical properties of the paper insulation deteriorate extremely rapidly.

It was found during ageing tests that the increase of acidity in the cable oil was due to degradation of the paper and not to the alternation of the oil and that acidic compounds formed from degradation of the paper dissolved in the cable oil, increasing the acidity of the oil.

Exposure of the oil to copper, either metallic or dissolved, can increase the rate of oxidation. Addition of a passivator to the oil prevents copper from reacting with the oil. The power factor of passivated oil, heated in the presence of copper, does not increase, in absence of air and humidity.

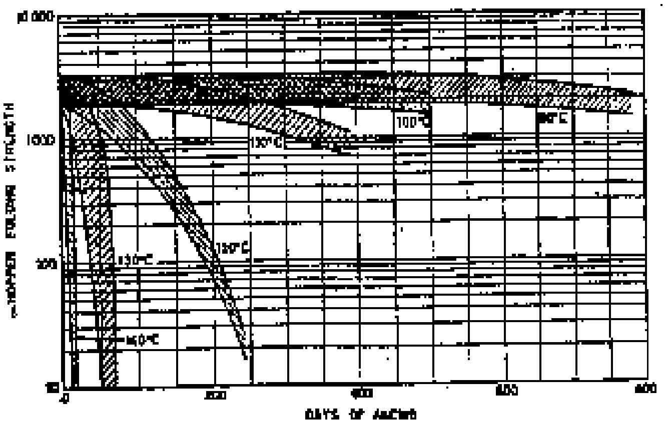

Figure 1 Schopper folding strength of cable oil-impregnated paper as affected by ageing in the absence of air and humidity [1].

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Figure 2 Elmendorf tear resistance of cable oil-impregnated paper as affected by ageing in the absence of air and humidity [1].

Assuming that there is little or no moisture and dissolved oxygen within the cable insulation, then the cable life is mainly affected by elevated temperature and the duration of exposure. Therefore, life may be increased by operating the cable system at lower temperature. Expected cable life can be estimated from the operating temperature using the "8ºC rule". This rule states that an increase of 8ºC in cable operating temperature doubles the rate of paper deterioration. (In the same way, a decrease of 8ºC halves the rate of deterioration).

The "8ºC Rule" is not quantitatively exact. In fact, in studies conducted by Clark [2], it was found that the temperature increase that doubles the ageing rate depends on the state of the paper and the actual temperature of operation, as found in Figure 3 [2]. For example, when oil-impregnated manilla paper, with 100% of its tensile strength, an increase of only 4.2ºC will double the ageing rate. This illustrates the complex nature of the degradation reactions involved.

The "8ºC Rule" (and other similar "rules", eg "10ºC Rule") should therefore only be used as generalisations. They do not accurately predict remaining life of insulating materials.

It is also important to note that the criteria selected as the end of useful life of the paper insulation may vary depending on the particular cable installation. Whether the cable can sustain the loss of 70% of the paper's mechanical properties, or high losses, depends to some extent on the mechanical forces that the cable will experience in service.

2.4 Influence of Temperature on Cable Installations

Operating a cable installation at elevated temperatures always implies a certain technical risk related to the loss of mechanical characteristics of the cable components, as well as the effect of the increased temperature on the medium in which the cable is laid.

High voltage oil-filled cable outer serving (anti-corrosive sheath) may reach for a certain type of cable a steady state temperature of 100ºC when the cable is buried in a soil with thermal resistivity of 1.2ºC m/W and the conductor is operated at 120ºC.

It is well known that a continuous operating temperature above 50ºC at the cable surface will cause moisture migration from the cable, and will dry out the backfill. In this case, the cable could exceed the allowable temperature due to the thermal cumulative effect on thermal resistivity of the soil, which may rise to values above those normally used for rating calculations.

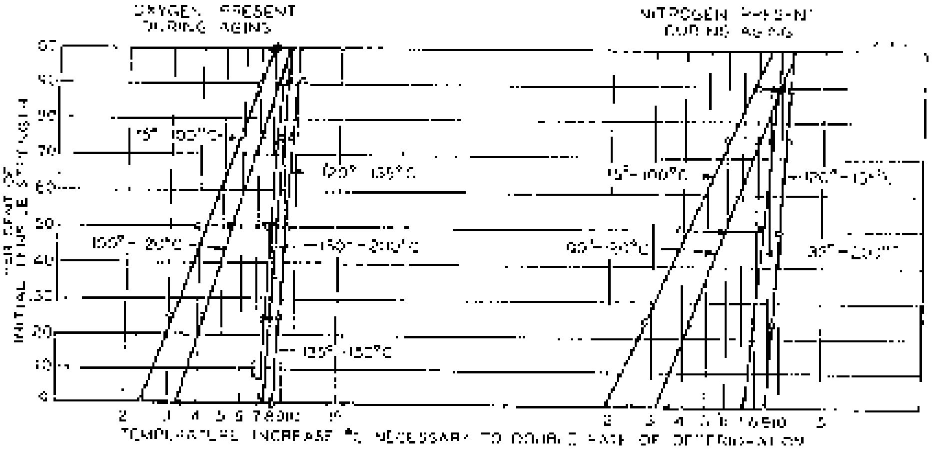

Figure 3 Rate of mechanical deterioration of vacuum dried and oil-impregnated 0/0003 inch Manilla paper becomes more sensitive to temperature increase as the deterioration progresses [2].

To avoid these conditions, one of a variety of stabilised backfills could be sued, such as sand/cement 14:1 or 20:1, as well as other backfilling sands available of suitable graded particle size to give an acceptable thermal resistivity even when quite dry. However, at temperatures higher than 100ºC, even these specialised backfills no longer have nay thermal stability. In addition, the cable metal sheath of lead or lead alloy is subjected to recrystallisation at temperatures above 100ºC.

In spite of the severe deterioration of paper insulation at elevated temperatures, its electric strength and impermeability are not significantly changed. Research has shown that severely degraded cable paper, where the number of double folds to facture were 100 or less (corresponding to about 3% of original folding strength), maintains it dielectric constant as well as its electric strength. However, dissipation factor can increase as a result of paper degradation. So, for cables directly buried in the ground, severe loss of mechanical properties could be sustained by the operating cable provided there is no movement of the cable. Where cables are free to move, by expansion and contraction, the paper may tear easily during the imposed load cycling.

Even when a cable is operated according to the manufacturer's instructions, thermal degradation of paper insulation does occur. This has been proved in practice, when, on a number of occasions, high voltage cables have been inspected on removal from service.

Based on the "8ºC Rule" it was produced a model (Figure 4) to estimate the loss of the folding strength as a function of temperature magnitude and its duration.

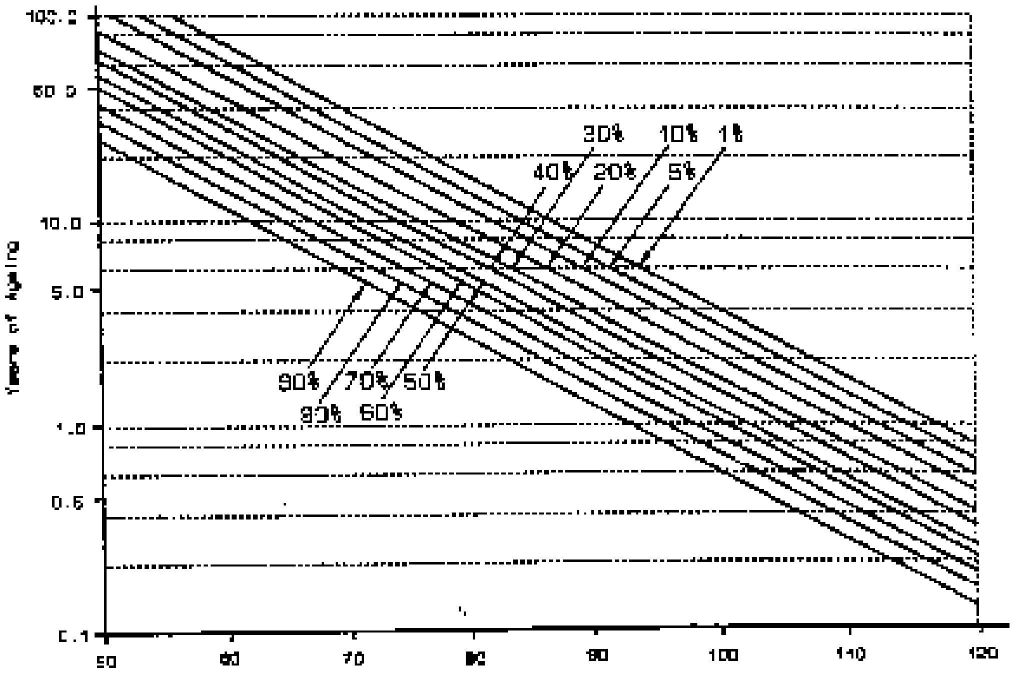

Figure 4 Time required to reduce the folding strength of cable paper to various percentages of the original value as a function of temperature.

Instead of using mechanical tests to determine the ageing level of paper tapes it is more and more used a chemical test which measures the average number of glucose molecules per cellulose molecules. The longer the chain of molecule the better. This test is name “The Average Viscosimetric Degree of Polymerisation”. Figure 5 shows the variation of DPv and tensile strength for a specific type of insulating paper, and in Figure 6 is given the chemical representation of glucose and cellulose.

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Figure 5   Tensile strength and DP
of papers from model transformers

? free breathing units
? nitrogen blanketed units

(Ref: Shroff and Stannett, Proc. I.E.E.,
Vol 132 (Part C), 312-319, 1985.)

Structure of Glucose

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Haworth formula (2-D representation)

Structure of Cellulose

Figure is not able to be loaded

Glycosidic bond

Figure 6 Structure of Glucose and Cellulose

2.5 Assessing Paper Ageing by Oil Analysis

Methods using oil analysis to monitor the degradation of paper insulation in transformers are being developed. It may be possible to develop analogous techniques for cable paper.

Under service conditions, transformer paper degrades producing furfurals. the main product is 2-Furfuraldehyde, which is highly soluble in the oil and may be detected readily at concentrations down to 0.1ppm. Furfuraldehyde may be detected with this sensitivity by high performance liquid chromatography (HPLC).

It may be possible to apply the techniques used for transformer oil to cable oil analysis, but there are significant differences between the two systems.

In general, no part of a cable system would normally operate at the temperatures required to degrade cellulose to furfuraldehyde (typically > 100°C). In addition, the cable is less chemically reactive environment than a transformer, largely because of the low concentration of oxygen in a cable.

As a consequence this method is not used in case of SCOF (Self contained oil-filled) cables.

However by investigating the cable oil in regard of gas content (Dissolved Gas Analysis – DGA) it could be evaluated the paper ageing by measuring the amount and type of gases present in oil.

The thermal ageing of paper produces CO_2, CO and traces of water. The quantity of these gases found in service cables is normally 2 or 3 orders of magnitude less than the solubility limit. The CO_2/CO ratio is normally about 3. Lower figures indicate a higher than normal service temperature.

Hydrogen and hydrocarbons are mainly produced by oil electric degradation and their content can rise beyond the very low value of a few (ppm) usually found in practice only in presence of discharge phenomena or anomalous heating. When measuring the content, caution is required since the content is biased by contributions other than dielectric degradation (degassing of metal surfaces, oil mechanical cracking).

Interpretation of the DGA results help not only to estimate the natural ageing level under normal operation conditions but it can be used as a diagnostic tool and identify if the cable system undergoes abnormal operation condition.

They typical causes behind the generation of any gas identified in cable oil are summarised in Table 1.

Table 1

DGA – Typical Gases in Cable Oil and the Causes of their Generation	
Hydrogen (H_2)	PD, Arcing, Water & Steel/Degasing of Metals/Mechanical Cracking
Oxygen (O2) Nitrogen (N2)	Installation conditions/trapped air
Carbon Monoxide (CO) Carbon Dioxide (CO2)	Thermal ageing of paper
Methane (CH4)	PD, Overheated oil (low 120ºC to 150ºC)
Ethane (C2H6) Ethylene (C2H4)	Overheated oil (moderate 150ºC to 200ºC)
Acetylene (C2H2)	High Temperature (>700ºC) - arcing

The use of synthetic oils of the type dodecylbenzene (d.d.b.) has improved the performance of oil-filled cables considerably. Dodecylbenzene reduces the rate of ageing, mainly because it is a pure compound whose ageing characteristics are well known. Mineral oil is a mixture of many thousands of compounds, whose ageing behaviour is complex and difficult to define.

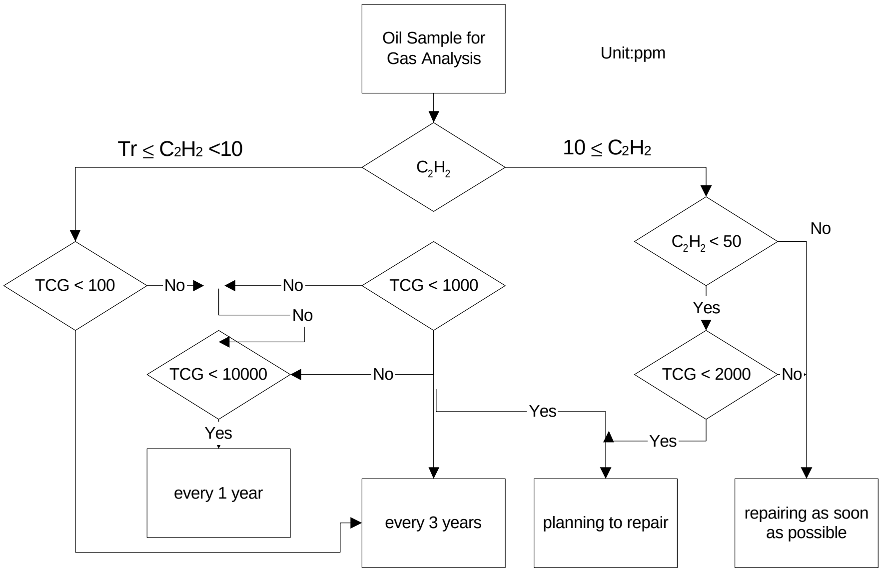

Figure 7 Flowchart of Inspection by Gas Analysis

There is not a consensus among cable manufacturers and cable users in regard of maximum permissible amount of gases in cable oil. Each utility in each country might have its own limits correlated with the technical conditions, operation and maintenance experience, etc.

In Figure 7 is presented the Japanese view in this regard highlighting the action to be taken when gas content level increases beyond acceptable limits.

This model was developed by Tokyo Electric Power Company (TEPCO) and represents a practical approach to DGA results.

3 Conclusion

So, overall, the materials used as dielectrics in cables are susceptible to degradation, which is usually a complex series of reactions and difficult to predict. Oils and paper are manufactured to minimise these reactions as much as possible, while still retaining good electrical properties. It is also important that service conditions are not too sever: most important is to prevent access of oxygen and moisture and to limit operating temperature as much as practical, to ensure long service life of the materials.

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Appendix 4
Supplementary Information from BICC

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Appendix 5
Supplementary Information from Pirelli

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Appendix 6
Listing of Cable Expertise within Mercury Energy

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Appendix 7
Soil Resistivity – AEPB Comment 1966

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Appendix 8
Document References

Mercury Energy Documents

Document	Description	References
MEL 7	Auckland Electric Power Board Engineering Instruction Manual No 10 – Volume 2	
MEL 63	Letter to Municipal Electricity Department 14 June 1966	
MEL 78	Quay No 2 Archival Material Relating to 110 kV Cables	
MEL 79	Auckland Electric Power Board 110kV Cable Penrose State Hydro Electric Department Substation Auckland Electric Power Board Quay Substation	
MEL 89	British Insulated Calenders Cables Limited Operating and Maintenance Instructions – Penrose – Quay	
MEL 113	Mercury Energy Limited Factual Report on Cables to the Ministerial Inquiry into the Auckland CBD Power Supply Failure, 17 April 1998.	