<u>OPTIONS AND EVALUATION FOR THE REFURBISHMENT OF VIBRATION DAMAGED SWER LINES IN CAPRICORNIA ELECTRICITY</u>

ABSTRACT: Capricornia Electricity has an extensive Single Wire Earth Return (SWER) rural distribution network. As this SWER network ages, service problems resulting from excessive uncontrolled aeolian vibration are becoming apparent. In some SWER schemes the failure of hand ties and associated hardware is widespread. In the worst affected areas, there is evidence of damage to the aluminium wires in the ACSR conductor. As the current accepted practice is to reconductor these damaged lines, Capricornia Electricity is faced with major refurbishment costs.

This thesis describes the investigative work undertaken to address the question of whether it is possible to reliably extend the service life of the vibration damaged lines without the need for reconductoring. In addition, the suitability of high tension line designs utilising small diameter conductors in terrain conducive to aeolian vibration is evaluated.

While aeolian vibration is a well recognised and researched problem on transmission lines, relatively little work has been carried out on highly tensioned small diameter conductors in the range 5-10mm. Furthermore, no specific work which addresses vibration problems in composite outer layer ACSR conductors could be located.

In this research project, the current knowledge on conductor vibration and fatigue in transmission line conductors was reviewed, and the applicability of this knowledge to small diameter conductors was examined. It was established that field data on vibration modes and duration needed to be collected to allow for a satisfactory analysis of the vibration problem.

Subsequent investigative work included the collection and analysis of a large volume of field data on the nature of the vibration problem, the establishment of the residual life of damaged conductors through laboratory testing, as well as experimental work to ascertain the effectiveness of various damping devices.

Based on the available data, it was concluded that the application of appropriate damping systems would ensure the mechanical integrity of lines even where fatigue damage has occurred.

OPTIONS AND EVALUATION FOR THE REFURBISHMENT OF VIBRATION DAMAGED SWER LINES IN CAPRICORNIA ELECTRICITY

TERRY EFFENEY B.Eng, B.Ec

Dissertation submitted in fulfilment of
the requirements for the degree of
Master of Engineering

UNIVERSITY OF CENTRAL QUEENSLAND

JAMES GOLDSTON SCHOOL OF ENGINEERING

Department of Electrical Engineering

February 1994

TABLE OF CONTENTS

LIST OF TABLES AND ILLUSTRATIONS

Page

ACKNOWLEDGMENTS

I wish to express my thanks to the staff of Capricornia Electricity for their support over the duration of this project. I wish to particularly acknowledge the guidance of my supervisor A/Prof. Ken Kwong of the Electrical Engineering Department at the University of Central Queensland and the assistance of Mr Roger Thomas of the Mechanical Engineering Department.

In addition, I would like to thank Dulmison Australia for the provision of test facilities and technical support.

DECLARATION

This thesis considers the options for the refurbishment of vibration damaged SWER lines in Capricornia Electricity. The achievements of this investigation are the establishment of conditions under which high tension designs utilising small diameter high steel content ACSR conductors can provide adequate service performance even in vibration prone terrain, and the experimental demonstration that even where vibration related damage has occurred to overhead conductors, the addition of adequate vibration protection devices can ensure the mechanical integrity of the line.

Fundamental to this research project is an understanding of the effect of static and dynamic stresses on the fatigue life of stranded overhead conductors, and how these considerations have led to the establishment of the existing line design rules.

Subsequent analysis led to the conclusion that these "rules" established for vibration design, which were based primarily on transmission line experience, were not directly applicable to the range of conductors under consideration in this project. Consequently a comprehensive field data collection and laboratory testing program was instigated.

The collected data, associated analysis, and conclusions presented in this thesis all represent a significant extension in the understanding of the vibration performance of highly tensioned small diameter ACSR conductors.

The work contained in this thesis has not been previously submitted for a degree or diploma at any tertiary education institution. To the best of my knowledge this thesis contains no material previously published by another person except where due reference in made.

T.J. Effeney

Terry Effeney

PUBLICATIONS

The following publications have been produced during the course of this research.

(i) Effeney, T.J. "Options and Evaluation for the Refurbishment of the Capricornia Electricity Rural Distribution Network - Preliminary Considerations", Electric Energy Conference, Brisbane, October 1992.

(ii) Effeney, T.J., Roughan, J.C., Thomas, R.H. "Options and Evaluation for the Refurbishment of Vibration Damaged SWER Lines", Distribution 2000 Conference, Melbourne, November 1993.

(iii) Capricornia Electricity, "Report on Acceptance Tests, VIBREC 300 Vibration Recorder", May 1992.

(iv) Capricornia Electricity, "Report on Vibration - Kensington SWER, Undamped", 1992.

(v) Capricornia Electricity, "Report on Vibration - Stormhill SWER, Undamped", 1992.

(vi) Capricornia Electricity, "Report on Vibration - Stonehenge SWER, Undamped", 1992.

(vii) Capricornia Electricity, "Report on Vibration - Waterloo SWER, Undamped", 1993.

(viii) Capricornia Electricity, "Report on Vibration - Waterloo SWER, One Damper, Preform Tie", 1993.

(ix) Capricornia Electricity, "Report on Vibration - Waterloo SWER, One Damper, Hand Tie", 1994.

(x) Capricornia Electricity, "Report on Vibration - Waterloo SWER, Two Dampers, Preform Tie", 1993.

(xi) Capricornia Electricity, "Report on Vibration - Waterloo SWER, Two Dampers, Hand Tie", 1993.

(x) Capricornia Electricity, "Laboratory Testing of Spiral Vibration Dampers", Report 1993.

1. BACKGROUND TO INVESTIGATION

1.1 SWER ELECTRICITY DISTRIBUTION SYSTEM

The Single Wire Earth Return (SWER) electricity distribution system uses a single high voltage conductor erected on poles, with the earth as a return path, to supply distribution transformers which have their primary windings connected between the single conductor and earth (1). Normally an isolating transformer is provided to separate the earth return system from the conventional single phase and three phase system as shown in Figure 1.1 below.

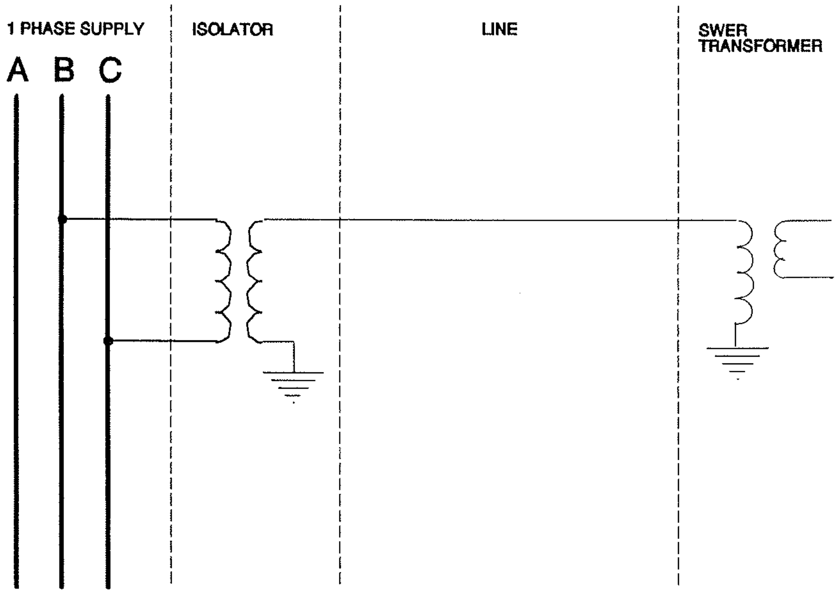


Figure 1.1 SWER Distribution Schematic

This type of SWER distribution system incorporating an isolating transformer was first developed in New Zealand in the early 1940's to provide a low cost means of supplying isolated rural customers (2).

SWER systems were trialled in Australia in the early 1950's (3), firstly by the State Electricity Commission of Victoria and then by the Cairns Regional Electricity Board.

These trials were closely monitored by the Postmaster-Generals Department (PMG) to ensure that the level of interference with communication lines was acceptable.

Following the monitored application of these trial SWER schemes, the Electricity Supply Association of Australia (ESAA) successfully sought permission from the PMG to allow for the introduction of SWER systems throughout Australia. A set of guidelines specifying separation from communication equipment, allowable load and fault currents, and exposure lengths were established to ensure good co-ordination between telephone and earth return power lines (4,5,6,7).

By the time SWER distribution was approved for general use, many authorities in Australia had introduced 22kV and 33kV as voltages for conventional rural distribution systems. As a consequence and in order to standardise on readily available materials, 12.7kV and 19kV, being the phase to ground voltages corresponding to three phase 22kV and 33kV systems respectively, were adopted as the standard SWER line voltages.

These early SWER schemes were so attractive on an initial capital cost basis, that many Supply Authorities adopted SWER with enthusiasm to supply isolated homesteads and small rural communities.

In locations with a benign climate and suitable topography, the reliability of the SWER distribution system has proven to be excellent as it has a very clean construction with only one active wire and utilises standard proven components.

1.2 SWER IN CAPRICORNIA ELECTRICITY

The supply region for which Capricornia Electricity is responsible covers an area of approximately 434 000 square kilometres in Central Queensland with 80 000 customers. A map of the supply area is provided in Appendix A. In this region there are in excess of 32 000 kilometres of distribution lines of which approximately 17 500 kilometres are

Single Wire Earth Return distribution lines servicing only some 5900 customers. These lines were installed to provide a relatively low cost means of servicing a sparsely spread rural community.

The first SWER scheme in the Central Queensland area was trialled at Bajool near Rockhampton in 1959. Following the successful operation of this scheme, SWER became the basis for many small distribution systems along the coastal belt, mainly operating at 12.7kV.

The development of SWER systems continued particularly when an extensive rural electrification program was initiated soon after the formation of the Central Western Regional Electricity Board based at Barcaldine in 1966 (now part of Capricornia Electricity). The SWER systems in the Central Western Region were structured around 22kV three phase and single phase distribution feeders which supplied the 12.7kV and 19kV SWER schemes via isolating transformers.

The early SWER schemes were relatively short, with the load current limited to 8 amperes by the PMG in an attempt to control interference with the then existing open wire telephone lines. However in 1977, based on the satisfactory performance of the SWER systems and the proven methods of interference calculations, the load limit was removed (7). While co-ordination with telephone systems still influenced the selection of line routes, the removal of the load limit allowed for a more rapid expansion of the SWER network through the use of larger isolating transformers leading to longer and more extensive SWER schemes to supply customers in the more remote areas.

The impetus for the present widespread SWER network came from the State Government Rural Electrification Subsidy Schemes which were offered in the late 1970s and throughout the 1980s, to encourage development of the rural economy. The last of the major SWER extensions in Capricornia Electricity were completed in the late 1980s, and now only the most remote customers do not have access to reticulated supply.

The growth of the SWER network in the Capricornia Electricity area of supply from 1959 through to 1991 is summarised in figure 1.2 below.

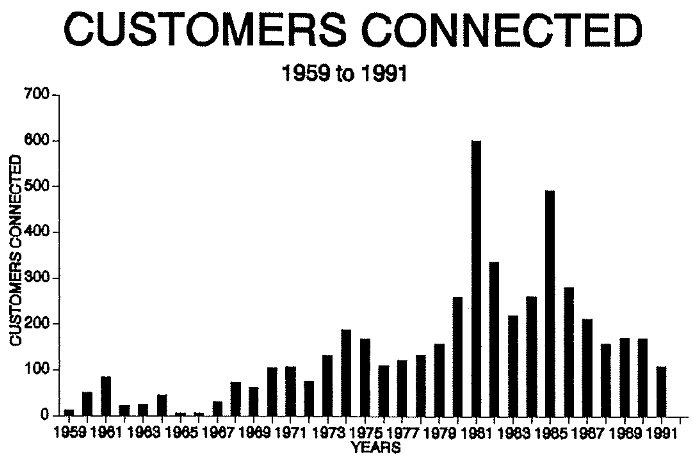


Figure 1.2 Growth of the SWER Network

A high percentage of the SWER distribution network is located in the Western Region of Capricornia Electricity (refer to Appendix A for a map of the area of supply) as indicated in Table 1.1 below.

Region	km of SWER Line (30/6/92)	
	3/2.75 SC/GZ	3/4/2.50 ACSR/GZ
Northern	1692	272
Southern	2347	255
Western	10866	2225

Table 1.1 Kilometres of SWER Line by Region

1.3 SERVICE EXPERIENCE

Early SWER schemes in the Capricornia Electricity distribution system were established along the coastal strip; an area where service experience with single phase and three phase lines was well established. Consequently the SWER line designs and pole top constructions were adopted from these existing lines. Over the years the designs used for these coastal SWER schemes have proven to be successful in providing a reliable supply.

In order to minimise the capital contribution by rural customers, the basis of the SWER line design was to use small diameter high strength conductor strung at high tension to achieve long individual spans with the minimum statutory ground clearance. The conductor was typically 3/4/2.50 ACSR/GZ (Aluminium Conductor Steel Reinforced, Galvanised) for the "backbone", with 3/2.75 SC/GZ (Steel Conductor, Galvanised) used for "tee-offs" and lightly loaded sections. It was standard practice, evolving from experience on the coast, to construct these lines using hand ties on armoured conductor. No additional vibration damping devices were initially installed. A detailed analysis of the line construction and conductor parameters, including the Standard Construction Drawings, is presented in Appendix B.

As the SWER systems spread into the more remote areas in Western Queensland, the coastal design and constructions were copied without any substantial modification for these western areas where there was a lack of awareness that the line designs and pole top constructions which had proven to be so successful on the coast may not be suitable for this new terrain, which was open and rolling with few obstacles to break up wind flows.

Within a couple of years of their construction however, it became apparent that the service life of the SWER lines in the open terrain areas was being severely impacted upon by aeolian vibration, a phenomenon which had previously been observed on transmission lines throughout the world in similar terrain (9-19).

Inspection of various lines in the open terrain areas, together with numerous reported vibration associated problems, gave a clear indication that excessive vibration was occurring. The vibration was present on both the SC and ACSR lines and it could be clearly heard as a hum or whistle and could be felt quite strongly through the wood poles. A common consequence of the conductor vibration was the loosening of line hardware and line clamps which results in a clearly audible rattle on the line.

An early indication of vibration on the ACSR lines can be seen in the appearance and accumulation of black aluminium oxide on the insulator skirt resulting from the fretting of the aluminium hand ties on the insulator and armour rods. The presence of the aluminium oxide which is considerably harder than the aluminium parent material and a well known abrasive (9), accelerates the process of fretting corrosion. Over time continued fretting can result in the total disintegration of the aluminium hand tie and in many areas tie failures are regular and recurrent. In Appendix C, photographs of typical damage highlight the vibration problem.

The consequence of the failure of hand ties has been the increased occurrence of conductor falling from the insulator and dropping to the ground, and presenting a serious danger to fauna, livestock and people in the vicinity of the line. This problem is particularly acute on SWER schemes because "line-down" conditions are difficult to detect particularly in areas where the soil moisture is low (high fault impedances),(8).

The fretting of the hand ties also results in severe pitting of the armour rods and the action of the tie and armour rods on the insulators wears away the insulator glaze marking them susceptible to puncture. Pole top fires have resulted from this failure of the primary insulation.

Problems are also becoming apparent with the conductor itself. In the worst affected areas fatigue failures of aluminium wires in ACSR conductors have occurred, and concerns have been raised by field staff about the mechanical integrity of the conductor.

The failure of aluminium wires has been observed exclusively at a point immediately under the inner turns of the hand tie adjacent to the insulator. This point is shown in Figure B.4 of Appendix B.

Tie failures have not become a major problem on the steel lines to this point and as a result the majority of this research work for this project has been concentrated on the ACSR lines with particular interest in the 3/4/2.50 ACSR/GZ lines.

1.4 THE INITIAL RESPONSE TO VIBRATION PROBLEMS

Field staff in the Western Region were well aware of vibration related problems on some of the early SWER lines, however because the lines were relatively short and only had a small proportion of ACSR conductor, the problems were fairly isolated and were not addressed in any systematic manner. The repairs generally consisted of replacing like with like.

It was not until about 1986, some years after the erection of extensive SWER systems in the more remote areas, that the vibration problems began to severely impact on the serviceability of some of these lines. Reports of loose hardware, tie failures, and conductor drops began to cause major concerns.

Preliminary investigations indicated that for line conductor vibration to occur for extended periods, the wind flow needs to be in the range 0.5 to 10 m/s (1.8 to 36 km/h) and be laminar in nature (19). While wind flow patterns in this velocity range are common on the coast, the presence of obstacles to laminar flow such as trees, buildings and terrain features, ensure that vibration cannot be sustained for extended periods of time on these lines. This is due to the fact that terrain features help to create turbulence in the wind acting on the conductor, and thus assist in reducing vibration problems. In the Western Region, much of the area over which the SWER lines traverse is rolling open terrain with few obstacles (refer to Appendix C for photographs). As a consequence there are few features to break up the laminar wind flows. This is particularly evident in the early mornings before the ground temperature causes convection turbulence. Although there is little information on relative wind turbulence factors, it is abundantly clear from current service experience, that the topographical conditions in the western areas are very conducive to wind flow patterns which pose a high risk of aeolian vibration in the SWER lines.

Lines which run normal to prevailing winds patterns will be exposed to greatest risk. However natural ground features can cause a degree of channelling of the wind and as a result, area reputation of "windiness" or even the direction of the line may not provide good guides to possible vibration problems.

In 1987, a detailed inspection of vibration problems on sections of line in open rolling terrain on the Stonehenge and Waterloo SWER schemes near Longreach (refer to Figure A.1 in Appendix A) was undertaken. The inspection revealed that the 3/4/2.50 ACSR/GZ lines which had only been in service for some four years, had suffered extensive vibration damage. Aluminium oxide was prevalent on all structures and many of the aluminium hand ties had completely disintegrated. Damage to the armour rods was extensive, and broken aluminium wires in the conductor were found at some locations. A detailed line condition report was prepared (50) confirming the need for major refurbishment work. Inspection of other SWER lines in open terrain areas confirmed a wide spread problem.

Advice on repair strategies was sought from Suppliers and other Electricity Authorities throughout Australia. The responses (51) however only provided information which was relevant to lines which were at lower tensions or in different terrain types. The general opinion was that the application of spiral dampers and preformed ties would provide a much improved vibration performance for the lines. These opinions were based primarily on observation and were not supported with detailed systematic data. Specific details were not available on the impact of damping systems on the service life of conductor which had sustained fatigue damage.

In 1988, a section of the Waterloo line, where the vibration damage had been most acute, was retied with preformed ties and spiral vibration dampers were added. This trial section of line has been closely monitored over the years and the results will be discussed later in this thesis. (Section 6)

In 1989, Capricornia Electricity engaged the services of a Consultant to prepare a report on possible solutions to the vibration problems (49). It was concluded that without a systematic study of the line vibration characteristics, it was not possible to accurately predict the remaining fatigue life of the conductor.

Discussions with other Electricity Authorities in Australia indicated that the tensions used by Capricornia Electricity were too high for lines in vibration risk areas (49). This notion was supported by drafts of the revised ESAA document "Guidelines for Design and Maintenance of Overhead Distribution and Transmission Lines" (22) which were being circulated for comment in 1989.

In 1990 Capricornia Electricity responded to the concerns raised about vibration damage and its relationship to the high tension designs by reducing the allowable conductor stringing tensions for a wide range of conductor types used in rural distribution and recommending the application of appropriate spiral vibration dampers. In addition the use of 3/4/2.50 ACSR conductor was reviewed. It was concluded that its susceptibility to vibration damage could be attributed in part to the small diameter of the individual aluminium wires. As a consequence the use of 4/3/3.00 ACSR was recommended. This new conductor type and the associated lower stringing tensions resulted in shorter average spans for the rural lines and as a consequence there was a significant increase in the associated line construction costs.

On going investigations and field inspections indicated that the vibration problem was fairly widespread and by 1990 Capricornia Electricity faced the possibility of having to reconductor and add vibration dampers to extensive areas of vibration damaged SWER lines. As shown in Table 1.1 above there are approximately 2200km of ACSR lines in SWER schemes in the Capricornia Electricity Western Region. A high percentage of these lines are at significant risk of sustaining vibration damage.

The cost of this type of major refurbishment work on rural lines cannot be readily justified. This is because the revenue received from the SWER customers provides only a small gross return on the investment made by Capricornia Electricity, and when all associated costs such as the cost of energy, system maintenance and distribution costs are considered, the net return on investment may very well be negative.

Thus more cost effective means of extending the mechanical service life of the SWER lines without the need for reconductoring was called for. The subsequent sections of this thesis will describe the research effort undertaken to identify the extent of the vibration problems and to resolve the issues surrounding the refurbishment of the vibration damaged SWER lines. In addition, the thesis will critically review the adequacy of the existing guidelines for the design of overhead lines in dealing with vibration problems on small diameter highly tensioned conductors.

An outline of the thesis is provided below.

Section 2 will review the impact of aeolian vibration on line design considerations, and discuss the appropriateness of current design "rules" to highly tensioned ACSR conductors used in SWER distribution.

Section 3 will report on the acquisition and analysis of data on modes and duration of vibration on undamped ACSR conductor.

Section 4 will analyse the implications of the vibration on the remaining conductor service life of the ACSR conductor.

Section 5 will consider the options for vibration control, including the experimental verification of damper effectiveness and the interpretation of comparative field results.

Section 6 will draw conclusions in two main areas.

1. The extension of the service life of the ACSR conductors even where fatigue failures of aluminium wires has occurred, and
2. The suitability of high tension designs in vibration prone areas.

2. AEOLIAN VIBRATION - THE IMPACT ON LINE DESIGN

2.1 HISTORICAL DEVELOPMENTS

The phenomenon of a tensioned string vibrating as a result of the passage of air perpendicular to the string has been well known for centuries. The ancient Greeks named the Aeolian or wind harp after Aeolus, the god of wind (9).

Aeolian vibration of a tensioned overhead conductor is characterised by relatively high frequencies and low amplitudes, rarely exceeding one conductor diameter (19), and occurs in the presence of low-velocity laminar wind. The flow of air creates alternate shedding of vortices from the top and bottom of the conductor resulting in a force perpendicular to the air flow inducing the conductor to move up and down. It is most noticeable in the early mornings or late in the evening when the airflows are laminar and have the least amount of turbulence.

Given these characteristics, aeolian vibrations are not always immediately obvious and it comes as no surprise that the earliest recordings of conductor vibrations were reported some years after the erection of the earliest transmission lines (10,11,12). It took until the late 1920s for the connection to be made between conductor vibration and failures of wires in overhead conductors recorded at the support points (12,13). It was established by Davidson and others (14), that failures were occurring as a result of metal fatigue arising from the accumulation of cyclic stresses due to line vibration.

The initial response to conductor damage was to reinforce the conductor at the support points by means of armour rods or tape (11). However it was not long before it was recognised that damping devices could be used to reduce the levels of vibration amplitude. The earliest stockbridge type damper dates from about 1924 (15), and over the years it has undergone extensive development and modification. Many other types of damping systems including impact dampers, torsional dampers, festoon type dampers were developed over time with varying success. A good review of the development of damping systems is provided in reference (9).

From 1930, papers (11,14,16) attempting to quantify risks of conductor vibration began to appear. Hazard factors such as conductor diameter, tension and mass were included in reports endeavouring to clarify why some lines suffered vibration damage while others did not. Work continued through the 1940s and 1950s, with many publications expanding the level of knowledge, but mostly only addressing part of the problem particular to certain line designs or terrain types. W. Bückner in reference (17) provides an adequate review of these early works with many valuable references.

2.2 STRESSES AND FATIGUE IN AERIAL CONDUCTORS

The factors influencing conductor fatigue are extremely complex, however a basic understanding of the impact of static and dynamic stresses on conductor fatigue is essential when designing overhead lines.

The fatigue failure of an individual wire within a conductor is the result of a large number of stress reversals which exhaust the endurance limit of the material (33). This type of failure is known to occur almost exclusively at points where the conductor motion is constrained (9). These points are typically at the structure support, damper locations or at line clamps. Inspection and analysis of fatigue failures of wires indicate that fatigue cracks always originate at points of contact. This contact may be with another wire in the conductor, with support hardware, or with the clamping device (28). The reason for this lies with the stress concentrations which arise from material fretting at these interfaces (33). Fretting is the form of damage that occurs when two surfaces in contact with each other experience relative motion. The forces which initiate fatigue damage at these locations are a combination of the static and dynamic stresses imposed on the conductor as detailed below.

<u>Static Stresses</u>: Static stresses are imposed on the conductor as a result of the line tension producing tensile stresses, and the support hardware and the bending angle of the conductor over the support point producing compressive and bending stresses. Line designers can control the levels of static stress in the conductor through the choice of

line hardware and line tension parameters.

Dynamic Stresses: Superimposed on the static stresses in the conductor are the alternating bending or dynamic stresses which result primarily from wind induced conductor vibration. These stresses can vary widely in amplitude, frequency and duration as a result of the climatic and topographic factors present at the service location. Line designers can reduce the dynamic stresses through the application of dampers which limit the amplitudes of the vibration. Unfortunately the selection of the appropriate damping system is not always a simple matter as many environmental factors can impact upon the risk of sustaining vibration damage.

A more detailed review of the current knowledge on conductor stresses and fatigue, presentation of the formulae used in analysing vibration and fatigue, together with some critical comment is provided in Appendix D.

2.3 ESTABLISHED DESIGN "RULES" FOR VIBRATION

The relative importance of static and dynamic stresses in overhead conductors has been the topic of considerable research over the last 50 years (9,17-35). Static stresses appear to be much easier to measure, control and model than dynamic stresses and as a result most of the early attempts to establish design "rules" for vibration centred around the control of static stress levels. Because of the ease of application, the static stress based "rules" remain today as the basis on which the majority of distribution lines are designed.

Attempts have been made to incorporate dynamic stress considerations into design "rules" (31,34), however their application requires extensive laboratory and field testing which may be difficult to justify for low cost distribution lines. It will be shown however, that the CIGRE "safe-border" dynamic stress analysis has a direct application when considering the residual fatigue life of vibration damaged conductors.

In this Section, design rules which have been established over the years by Power Transmission Engineers in an attempt to combat the effects of line vibration will be reviewed. The first three "rules" considered; EDS, OLS and T/m are primarily concerned with the static stress levels in the conductor. In Section 2.3.4, "rules" based on the dynamic stress levels in the conductor are considered. These dynamic stress based "rules" contend that total static stress in the conductor is only a secondary factor in the fatigue of conductors (33,34).

2.3.1 Everyday Stress, EDS Rule

In 1955, Study Committee No. 6 (later to become No. 22) of CIGRE established a panel with a task of investigating the influence of conductor tension on vibration related conductor problems. The panel introduced the term "Everyday Stress", EDS, which described the stress in the conductor at mean temperature with no superimposed wind loads.

A comprehensive world-wide survey was undertaken with the aim of establishing statistically the boundary between those existing transmission lines which had suffered conductor vibration failures and those which had not. The data received was based on experience with regard to the vibration performance of about 400 transmission lines with a total length in excess of 100000km.

The Panel's recommendation in 1960 (18), following the survey, was that conductors would not normally suffer wire failures if they were installed with everyday tensions (EDT) below a certain percentage of their calculated breaking load (CBL). The Panel clearly established conductor tension as the main parameter when evaluating the risk of vibration damage. The EDS proposal can be expressed as follows

$$\frac{EDT}{CBL} = \text{Constant} \tag{2.1}$$

The CIGRE database was collected from information about the vibration performance of multi-layer conductors on transmission lines and a large proportion of the data was referenced to medium content steel (10-20%) ACSR lines and hard-drawn copper lines which were in common use at the time. While there was only very limited data on conductors with small diameters, the EDS rule was extended to cover the full range of conductors used in the distribution system including ACSR conductors which had a significantly higher steel content. All ACSR conductors were treated as a single case regardless of their construction type.

While there was a great deal of apprehension surrounding these recommendations, they were generally adopted by Supply Authorities in Australia and became the basis for the revised "Code of Practice for Overhead Line Construction", established by ESAA in 1962 (20). Initially this code only addressed Hard Drawn Copper, Steel and ACSR conductors, however when it was revised in 1974, AAC and AAAC conductors were included.

In Queensland, Regulations establishing the allowable tensions in overhead lines followed the ESAA guidelines. The EDS proposal was incorporated into the "Uniform Practices Manual For The Mechanical Design Of Overhead Electric Lines - SEC(Q)M1-1977" (21), which was developed to provide the basis on which line design was to be carried out. The manual provides tables showing the allowable tensions in conductors with and without vibration control. These tables are still widely used in Queensland as the basis of distribution line design.

Quoting from SEC(Q)M1-1977, "*Where the conductor is not protected from the fatigue effects of prolonged vibration either by the surrounding terrain features or by effective vibration protection measures (e.g. dampers, armour rods) the percentage of the minimum calculated breaking load shall not exceed that shown in column (1) of Table 1; where the conductor is suitably protected the percentage shown in column (2) shall apply*

Table 1

Type of Conductor	*Percentage of Minimum Calculated Breaking Load*	
	Without Vibration Protection (1)	*With Vibration Protection (2)*
Hard-drawn copper, galvanised steel, aluminium clad and copper clad steel	*25*	*33⅓*
Hard-drawn cadmium copper, aluminium conductor steel-reinforced and all aluminium alloy conductor	*18*	*25*
All aluminium conductor	*18*	*22*

Table 2.1 Allowable Tensions from SEC(Q)-M1-1977

Although EDS design rule was easy to handle and had some logical basis, it was generally concluded, as early as 1970 (19), that the use of everyday stress as the single measure of vibration risk was not valid. Some of the criticisms of the EDS rule are:

(1) The conductor tension was referenced to the everyday temperature, whereas the mean winter temperature is far more relevant to the control of vibration,

(2) The EDS panel recommended a percentage of breaking load which is the same for all ACSR conductors regardless of the steel/aluminium ratio. Because the proportion of tensile stress carried by the aluminium wires is a function of the steel/aluminium ratio (refer Appendix D, Section D.1.1), a different percentage of breaking load should really apply for each ACSR steel/aluminium ratio. Although the correlation between EDS and vibration damage may be reasonable for the medium steel (10-20%) content ACSRs, the extension of this principle to the more recent high

steel (>20%) content ACSRs could not be substantiated as relatively little performance data was available.

(3) The main criticism however relates to EDS proposal's inability to incorporate factors such as climate and topography which are known to impact significantly on the fatigue life of the conductors (19).

2.3.2 Outer Layer Stress, OLS Rule

Up until the early 1980s support for the EDS Rule was still strong (23,24). However, with criticisms mounting and the introduction of new alloyed aluminium conductors (AAAC 1120), a review of the EDS Rule was undertaken by CIGRE. One of the many proposals considered by CIGRE Committee 22 Working Party 04 "Endurance Capabilities of Conductors" was the Outer Layer Stress Rule (62). This rule proposes that in order to achieve a given fatigue endurance, it is the stress in the outer layer wires which must be limited.

CIGRE has not published any recommendation with respect to the OLS Rule, and the draft documents reviewed in this research was provided by the Convener of the CIGRE Australian Panel 22, Mr Philip Dulhunty (62). The review indicates that the acceptable stress levels in the outer layer wires were most probably established based on the experience of the medium steel content ACSRs and other conductors under the EDS proposal. For example, a medium steel ACSR conductor at 18% of CBL has an outer layer stress in the aluminium of around 40MPa and at 25% of CBL a stress of around the 60MPa level. These figures correspond with the levels adopted under the OLS Rule.

As a result of mounting dissatisfaction with the EDS Rule and the need to include a range of new conductor types (AAAC, AACSR), the ESAA Committee 2.2 "Overhead Lines" considered the OLS Rule over a period from 1986-1990. It was finally adopted as the basis for the revised conductor tension recommendations published in ESAA Document C(b)1-1991 (22). The stress levels adopted by ESAA in the review of C(b)1-1991 are detailed below.

Conductor Type	Base Case Outer Layer Stress	Maximum Allowable Outer Layer Stress
Copper	100MPa	130MPa
AAC	30MPa	40MPa
AAAC	35MPa	50MPa
ACSR	40MPa	60MPa
Steel	300MPa	400MPa

Table 2.2 Allowable Outer Layer Stresses - C(b)1-1991

The base case OLS applies to a conductor at everyday temperature supported in a short bolted clamp with no armour rods or dampers in a terrain conducive to vibration. The maximum allowable OLS applies to a fully supported, fully damped conductor at everyday temperature in a terrain NOT conducive to vibration.

Stress levels in the outer layer wires of the conductor can vary between the base case and maximum allowable levels depending upon support/clamp type, terrain factors and damping systems used.

The OLS rule is still referenced to the everyday temperature. However, it does address the second criticism of the EDS proposal relating to the steel/aluminium ratio in ACSR conductors, by providing different recommendations for the various classes of ACSR construction. It is important to note that within C(b)1-1991 the recommendations made with respect to composite outer layer ACSR conductors of the 3/4 and 4/3 stranding are inconsistent with the allowable outer layer stress levels provided in Table 2.2. This point is demonstrated in Table 2.3 in Section 2.4. The composite outer layer conductors were only included at the tension levels shown in C(b)1-1991 at the request of Rural Distribution Authorities who had extensive experience with these conductor types.

2.3.3 Tension/Mass, T/m Rule

In the mid 1980s with the introduction of alloyed aluminium conductors, renewed interest was generated in the stress levels in aluminium based conductors. As a result of a review of the performance of aluminium based conductors on transmission lines, the T/m Rule was proposed.

It can be shown that the stress in the outer layer wires of an ACSR conductor is proportional to the installed tension/unit mass (T/m) ratio, irrespective of the steel/aluminium ratio, (refer to Appendix D, equation D.3). The T/m criterion (25,26), is similar to the OLS Rule in that it effectively limits the stress in the outer layer wires. The difference is that the T/m rule suggests that the same conductor fatigue endurance or vibration lifetime will be achieved for all ACSR, AAC, and AAAC conductors if the value of T/m is kept at a constant value, and that the value of this constant be made to vary dependent upon the support clamp type, armour rods and dampers used. Whereas the allowable stress levels for the different conductor types varies under the OLS Rule, under the T/m rule the stress levels are the same across all aluminium based conductor families (AAC, ACSR, AAAC, AACSR). A base case T/m value of 1500m is recommended for ACSR conductors with a best case recommendation of 2250m (27).

CIGRE 22 is currently considering the T/m criterion and indications are that it may become the basis for new recommendations.

2.3.4 Dynamic Stress Rules

As it became evident that the EDS Rule offered only limited reliability, designers of transmission lines in Germany, Canada and the USA moved away from the application of simple static tension or stress based rules, and placed greater emphasis on practical tests of conductor fatigue endurance. Tests conducted in the USA and Germany from about 1968 through to 1976 (27,31) proved that wire failures caused by vibration depended, not only on the EDS, but many other factors such as climatic and topographic features, clamp design and type of conductor.

As aeolian vibration causes primarily alternating bending stresses (31), extensive work (28,29,30) was carried out to measure the dynamic stress levels in conductors subjected to vibration and the associated impact on the fatigue life of the conductor.

Around 1970, as a result of tests on ACSR conductors, utilities in the USA adopted a maximum elongation (strain) rule. Quoting from a discussion point raised by A. S. Richardson in reference (64), "*Field experience suggests that strand damage is unlikely to occur if the dynamic strain, e, in the outer strands remains below a critical value, e_0, which is independent of frequency. This concept has gained general acceptance as has* (the figure of) ... *150 parts per million critical strain in ACSR conductors* ...". This strain level corresponds to a dynamic stress level of around 10MPa (peak to peak) in the aluminium wires. This recommendation was based on measured alternating bending stresses or alternating bending amplitudes at the critical points near the clamps.

The main problem with this recommendation is that it did not consider the number of cycles and thus the influence of climatic and topographic features which were becoming recognised as a major factor in conductor fatigue life (19).

The above mentioned tests in the USA and Germany were further developed within the scope of CIGRE Study Committee 22, Working Group 04. In 1979, after ten years of intensive work, the Committee produced a report titled "Recommendations for the evaluation of the lifetime of transmission line conductors" (34). The report outlined a methodology for determining the fatigue life of a conductor exposed to aeolian vibration.

The method involves:

(1) The determination of the number of vibrations up to fatigue failure of the conductor at stress levels similar to those experienced under service conditions. These measurements produce an S-N or Wölher curve.

(2) The measurement in the field of the alternating stresses in the conductor while in service, and

(3) The comparison of the recorded field stresses with the allowable stresses

in the conductor. From this a lifetime projection for the conductor can be estimated.

A detailed review of the CIGRE methodology is provided in Appendix D.

The significant advantage with this method is that it measures directly the vibrations and hence dynamic stresses in the line while it is still in its service location. In this way it accounts for the climatic and topographic factors as well as clamp, support and conductor factors. Providing an adequate sampling regime is undertaken, this method can provide a more systematic technically based approach to the problem of conductor vibration. Instruments for carrying out this type of assessment are now available and this allows for a quantitative analysis to be undertaken.

The main drawbacks with this type of analysis are: (1) the need for an S-N curve which is relevant to the conductor/support combination under consideration,and (2) the need to collect appropriate data which is representative of the likely service conditions. In considering the design of a distribution line where the initial capital is constrained, such testing and analysis could not normally be justified, and the need remains for a relativity simple "rule" which Distribution Engineers can apply with a degree of confidence.

This methodology however does provide a valuable analysis tool for determining the residual life of conductors which have experienced vibration damage, and for recommending what remedial action is necessary to ensure that further fatigue damage does not occur. The systematic testing and analysis can also provide information on which simple design rules for future line designs in similar terrain can be based.

2.4 APPLICATION OF "RULES" TO SWER CONDUCTORS

Capricornia Electricity has used the EDS rule as the criteria for the design of the rural distribution network. Based on the extensive and successful experience with armoured conductor along the coastal strip, it was considered that armour rods fulfilled the requirement for vibration protection specified in C(b)1 and later SEC(Q)M1. As a consequence many SWER lines were built over a variety of terrains with the maximum tensions indicated in column (2) of Table 2.2.

In Appendix B a critical analysis of the conductor parameters is presented together with the derivation of the allowable stress levels for the aluminium and steel wires in the conductors. The vibration response for typical spans is also determined.

Based on data presented in Appendix B and information from the appropriate Australian Standards (36,37), a comparison of the allowable tensions in conductors expressed as a percentage of their CBL based on the static stress "design rules" outlined in Sections 2.3.1 to 2.3.3 is provided in Table 2.3 below.

Conductor Name and Stranding	% Steel	% CBL					
		EDS Rule		OLS Rule		T/m Rule	
		Base Case	Best Case	Base Case	Best Case	Base Case	Best Case
Mango 54/7/3.00 ACSR	11.5	18	25	17.7	26.5	17.9	26.8
Lemon 30/7/3.00 ACSR	18.9	18	25	15.6	23.4	15.8	23.7
Apple 6/1/3.00	14.3	18	25	17.1	25.6	17.3	25.9
Raisin 3/4/2.50 ACSR	57.1	18	25	11.6	17.4	11.6	17.4

Table 2.3 Comparison of Allowable Tension for ACSR Conductors

It is clear from Table 2.3 that the EDS, OLS and T/m rules give reasonably consistent results for ACSR conductors with steel contents in the range 10-20% which is typical of transmission class conductors. However, the results for "Raisin" with a steel content of 57%, are not consistent. Using the stress levels established under the OLS rule (40MPa), the high steel content lines could only be strung at around 11-13% of their Calculated Breaking Load (CBL) in vibration prone areas and only up to about 18% under ideal conditions. Yet extensive experience in Capricornia Electricity and other Rural Electricity Authorities in Australia has shown that even in vibration prone areas, the use of adequate dampers allows lines to be strung to tensions as high as 20-25% of CBL without experiencing vibration damage.

Arguing along the same theme, it would also appear that the factors in the OLS and T/m criteria giving consideration to the use of dampers are overly conservative for small diameter conductors utilising spiral dampers. This is confirmed by reported work carried out by the Preformed Line Products Company (42) which compared conventional stockbridge damping systems to spiral dampers on a 9mm steel conductor.

It is the Author's opinion that the OLS and T/m rules over emphasises the relative importance of the static tensile stresses and underplays the importance of dynamic stresses in the ACSR conductor. It is contended that the base case values without dampers may be optimistic and that the topographic and climatic factors play a much more dominant role in the fatigue endurance. These contentions will be further substantiated in later Sections of this thesis.

2.5 GOALS OF THIS RESEARCH

While aeolian vibration is a well recognised problem, and has been extensively investigated for transmission line conductors, relatively little work has been carried out on rural distribution class conductors, typically in the range 5-10mm in diameter. No published work could be found which addressed fatigue problems in ACSR conductors with composite aluminium/steel outer layers although their usage is fairly widespread in Australia and other countries with low population densities and distributed rural communities.

It is clear from the information above that the high strength ACSR conductors require more careful consideration than they have currently been given. Based on the OLS and T/m rules, line designs could become overly conservative with unwarranted additional expenditure. With extensive rural electrification programs under way in developing countries such as China, India, Indonesia and Nepal, the need to keep capital expenditure as low as possible is paramount.

A goal of this research is to establish that where adequate precautions are taken for vibration, whether high steel content ACSR conductors can be safely tensioned to around 25% of CBL even in terrain which is conducive to vibration. A further goal is to show that even where fatigue failures of aluminium wires has occurred due to vibration, whether the addition of adequate vibration dampers will ensure the mechanical integrity of the line.

2.6 METHODOLOGY OF INVESTIGATION

Capricornia Electricity has many thousands of kilometres of Distribution lines with high content steel ACSR conductors strung in accordance with the EDS Rule. Only those lines in the critical terrain areas are providing inadequate service performance. It is the Author's intention to show whether the application of appropriate tie and damper systems to high tension designs in critical terrain areas will ensure adequate service even where the fatigue failure of aluminium wires has occurred. The methodology for the investigation is as follows

1. Collect and analyse data on undamped lines where significant damage from vibration has occurred,
2. Investigate the remaining fatigue life of the conductors and consider options for extending the service life
3. Consider options for vibration control and their impact on service life
4. Draw conclusions on highly tensioned damped designs.

3. ACQUISITION AND ANALYSIS OF VIBRATION DATA

3.1 THE NEED FOR DATA ON UNDAMPED CONDUCTOR

To allow for a satisfactory analysis of the extent of the vibration problem, the collection of accurate data on vibration amplitudes, frequencies and duration on undamped conductors at typical SWER sites is essential. This requires the availability of suitable vibration recording and analysing equipment.

3.2 VIBRATION RECORDING

After an extensive survey of the vibration recording instruments available on the market, a Sefag Vibrec 300 Vibration Recorder was purchased to perform the field measurements of vibration amplitudes and frequencies. The recorder measures bending amplitudes and frequencies at a point on the conductor 89mm from the last point of contact between the conductor and the support in accordance with the IEEE recommendations (29). Wind velocity and temperature are also recorded. Details of the recorder selection process, calibration checks, set-up and mounting arrangements are provided in Appendix E.

The technical specification for the recorder, Figure E.2 of Appendix E, indicates that it will record vibration frequencies up to 200Hz. The calibration checks carried out as part of this research project and detailed in Appendix E, only confirmed satisfactory frequency performance up to 167Hz. The results of frequency recordings in the 200Hz class are presented in this thesis, typically as shown in Figure 3.3 and Table 3.3, but they must be treated as being suspect. The number of recorded cycles could be low by as much as 50%. It will be shown in this and later sections however, that the impact of the higher frequencies is relatively insignificant in assessing the accumulated fatigue damage to the conductor. Thus the recorder's inability to log the higher frequencies does not invalidate the analysis and conclusions.

It is important to note that the amplitudes presented in the following field data are the values recorded at the 89mm point and not anti-node values. Where necessary, it is possible to convert the 89mm point values to anti-node values by assuming that the conductor standing wave loop is sinusoidal (45).

3.3 FIELD DATA COLLECTION AND ANALYSIS

3.3.1 Selected Sites for Measurement

Because of the risks to the aluminium wires and the fact that tie failures were happening almost exclusively on the hand tied ACSR lines, the initial investigations have centred around lines strung with 3/4/2.50 ACSR/GZ, "Raisin".

Based on the experience of the local field staff, the recorder was installed successively at four locations where vibration was known to be severe and continually causing problems with loosening of hardware and tie failures.

In these locations, refer to Table 3.1 below, the conductor was armoured and hand tied. There were no dampers fitted when the recordings were taken.

Location	Pole No.	Conductor	Span Length (m)	Year Erected	Recording Period (days)
Kensington SWER	122	3/4/2.50 ACSR/GZ "Raisin"	300	1982	31
Stormhill SWER	64		270	1984	22
Stonehenge SWER	81		250	1984	71
Waterloo SWER	19		250	1984	30

Table 3.1 Details of Vibration Recordings - No Dampers

3.3.2 Typical Results

The results of the field recordings are reported in Capricornia Electricity Field Reports, references (52-55). Recordings taken at two location are of particular interest in this research project.

(1) Stonehenge SWER Pole 81 - The conductor from this site was recovered from the field for residual fatigue life assessment, and

(2) Waterloo SWER Pole 19 - The comparative damper tests were carried out at this site.

The details of the recorder matrices from these locations are included in Appendix F, Tables F.1 and F.2. The results are summarised below.

3.3.3 Stonehenge Results

The following are results of a recording taken on the Stonehenge SWER scheme, located approximately 100km southwest of Longreach, over a 71 day period from 14 September to 24 November 1992. The section of line which was constructed in 1984, comprised 3/4/2.50 ACSR/GZ conductor strung at 25% of CBL and supported on standard line pins (SLP22/420). The line was armoured and hand tied. No dampers had been installed on this section of the line.

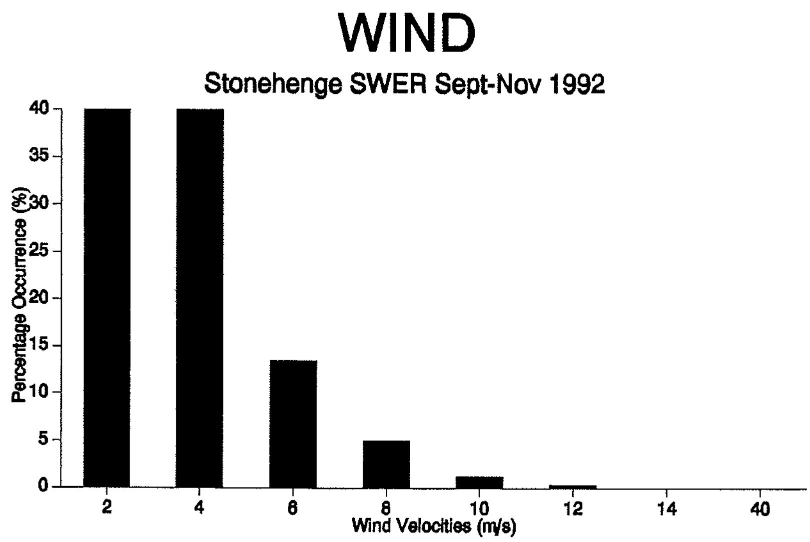


Figure 3.1 Summary of Wind Recordings, Stonehenge - No Dampers

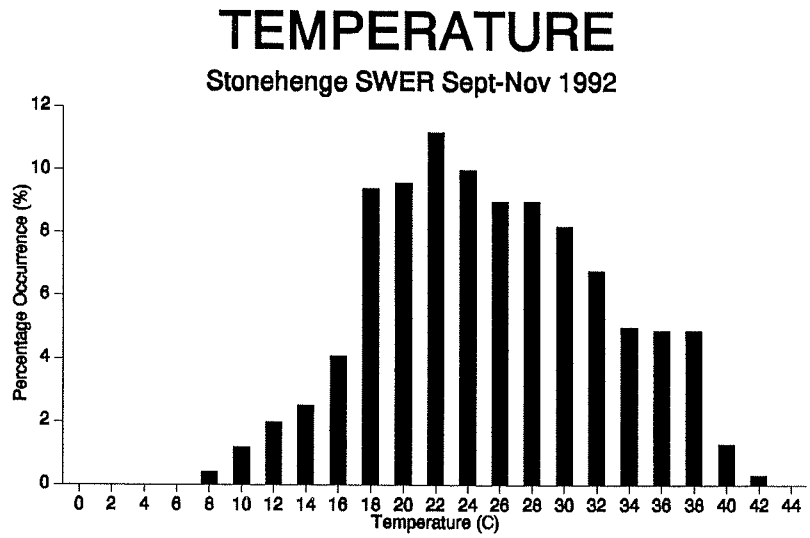


Figure 3.2 Summary of Temperature Recordings, Stonehenge - No Dampers

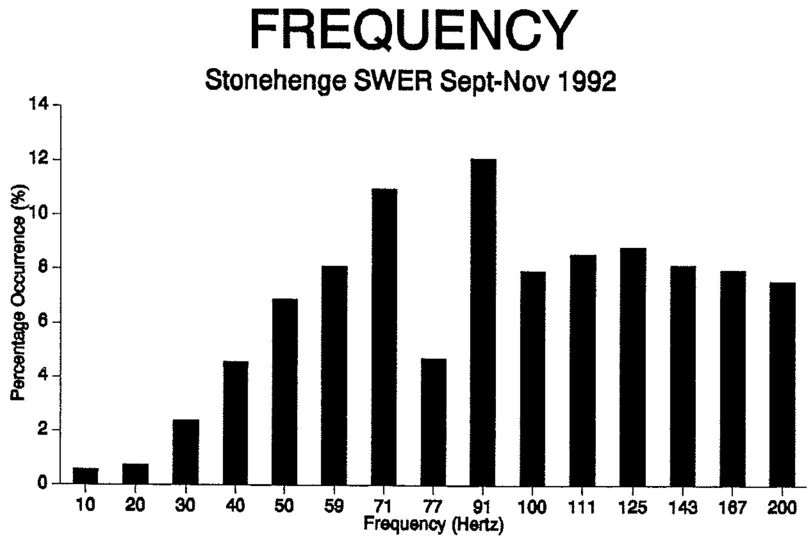


Figure 3.3 Summary of Frequency Recordings, Stonehenge - No Dampers

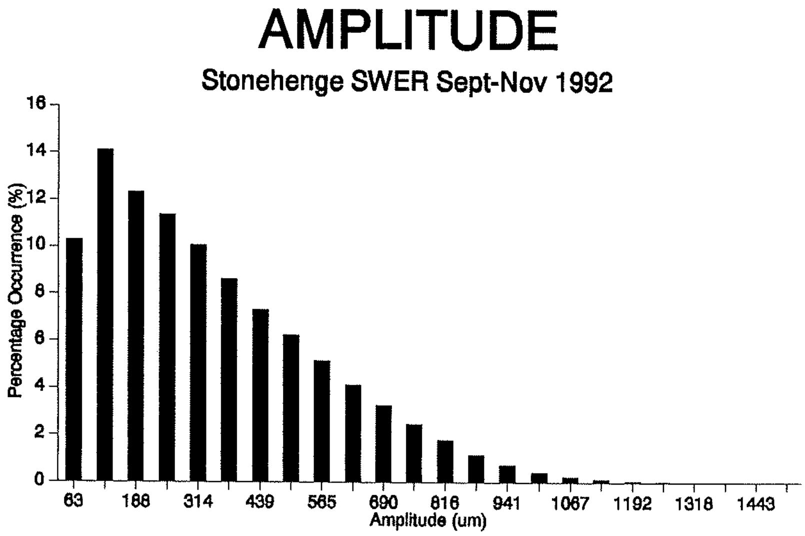


Figure 3.4 Summary of Amplitude Recordings, Stonehenge - No Dampers

This section of the line was decommissioned in December 1992 and the conductor recovered to allow for quantitative testing of the remaining fatigue life. The individual conductor wires were inspected and subjected to torsional ductility tests. The results of this testing is reported in Section 4.

Broken aluminium wires were found in some of recovered conductor, though not at the actual pole where the recorder was mounted.

Following the CIGRE methodology outlined in Section 2.3.4 and utilising Miner's cumulative damage hypothesis as outlined in Appendix D, and the S-N data curve provided in Appendix B, it is possible to consider the relative effects of the various frequency and amplitude classes on the conductor fatigue life. These relative effects are presented in Tables 3.2 and 3.3 below.

Amplitude (μm)	Stress (MPa)	N ($x10^6$) S-N Data	n No. of Cycles	n/N ($x10^{-6}$)	%
63	2.14	2773000	239039	0	
125	4.24	46957	327789	7	-
188	6.37	4136.70	286170	69	0.02
251	8.51	740.520	264063	356	0.12
314	10.64	195.260	233986	1198	0.40
376	12.75	66.810	200411	3000	1.00
439	14.88	26.560	170486	6419	2.14
502	17.02	12.930	144826	11200	3.73
565	19.15	7.160	119527	16694	5.56
627	21.26	4.250	96185	22632	7.54
690	23.39	2.640	75466	28586	9.52
753	25.53	1.700	57675	33926	11.29
816	27.66	1.140	41639	36525	12.16
878	29.76	0.790	27183	34408	11.46
941	31.90	0.559	16988	30335	10.10
1004	34.04	0.404	9960	24900	8.29
1067	36.17	0.298	5494	18313	6.10
1129	38.27	0.225	2924	13291	4.42
1192	40.41	0.171	1468	8635	2.87
1255	42.54	0.132	684	5261	1.75
1318	44.68	0.104	274	2740	0.91
1380	46.78	0.082	94	1175	0.39
1443	48.92	0.066	31	516	0.18
1506	51.05	0.053	7	140	0.05
			2322369	300326	100

Table 3.2 Cumulative Damage by Amplitude, Stonehenge - No Dampers

Frequency (Hertz)	Wind Velocity (m/s)	n No. of Cycles	$\Sigma(n/N)$ ($x10^{-6}$) per Class	%
10	0.40	13473	0	-
20	0.81	17369	2	-
30	1.22	55337	256	0.08
40	1.62	105891	2964	0.99
50	2.03	160113	12318	4.10
59	2.39	188333	23811	7.93
71	2.88	254913	47812	15.92
77	3.12	109075	37920	12.63
91	3.69	280868	77443	25.79
100	4.05	184088	41159	13.70
111	4.50	198806	25980	8.65
125	5.07	204662	17246	5.74
143	5.80	189423	8125	2.71
167	6.77	184584	4323	1.44
200	8.11	175434	967	0.32
		2322369	300326	100

Table 3.3 Cumulative Damage by Frequency, Stonehenge - No Dampers

The above results are based on 6808 ten second samples taken over a period of 71 days. The total recording time is therefore 68080 seconds. To equate the recordings to a period of one year a multiplying factor of 463 must be applied.

The total number of accumulated cycles in one year can now be estimated.

Total number of cycles/year $\approx$ $1x10^9$

By application of Miner's Rule the fatigue life of the aluminium wires in the 3/4/2.50 ACSR/GZ conductor can be estimated.

$$\text{Life} \quad = \quad 1 / (300326\text{x}10^{-6} \text{ x } 463) \quad = \quad 7.2\text{x}10^{-3} \text{ years}$$

3.3.4 Waterloo Results

The following are the results of recordings on the Waterloo SWER scheme, located approximately 110km southwest of Longreach, over a 30 day period from 22 February 1993 to 24 March 1993. This section of line which was constructed in 1984, comprised 3/4/2.50 ACSR/GZ conductor strung at 25% of CBL and supported on standard line pins (SLP22/420). When the line was constructed, the conductor was armoured and hand tied, however in 1989 this section of line was retied with preform ties and damped with spiral vibration dampers, two per span. During the inspection in 1989, two broken aluminium wires were found at the location where these recordings have been taken.

For purpose of recording the vibration levels without dampers, the dampers on the measured span and adjacent spans were removed and a standard hand tie applied.

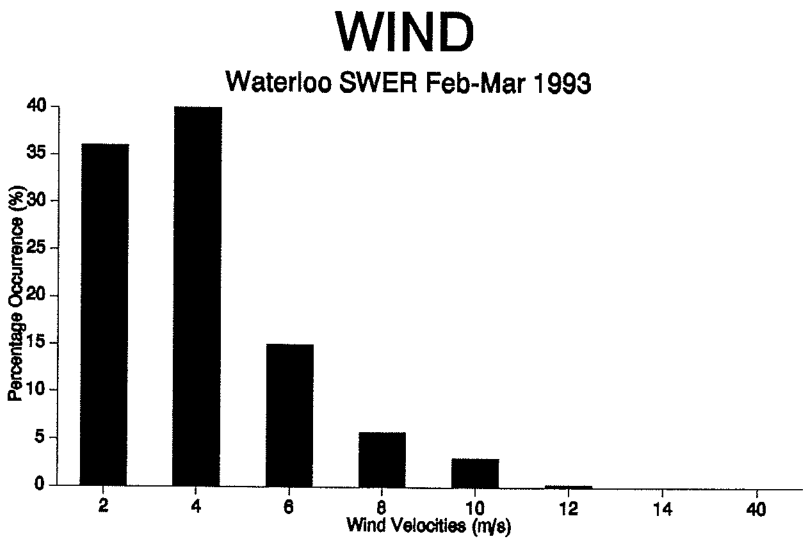


Figure 3.5 Summary of Wind Recordings, Waterloo - No Dampers

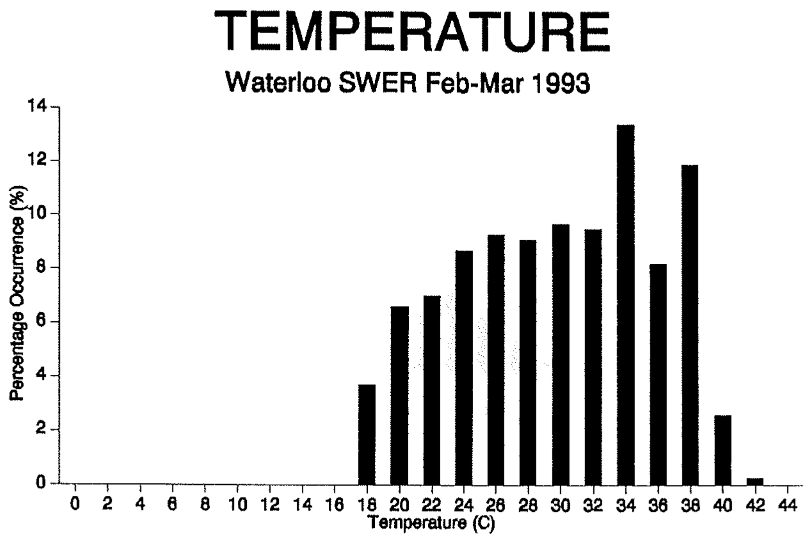


Figure 3.6 Summary of Temperature Recordings, Waterloo - No Dampers

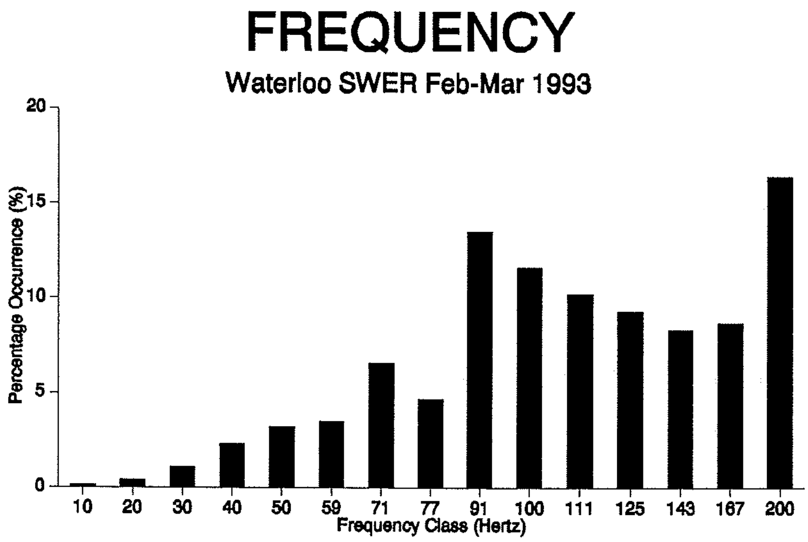


Figure 3.7 Summary of Frequency Recordings, Waterloo - No Dampers

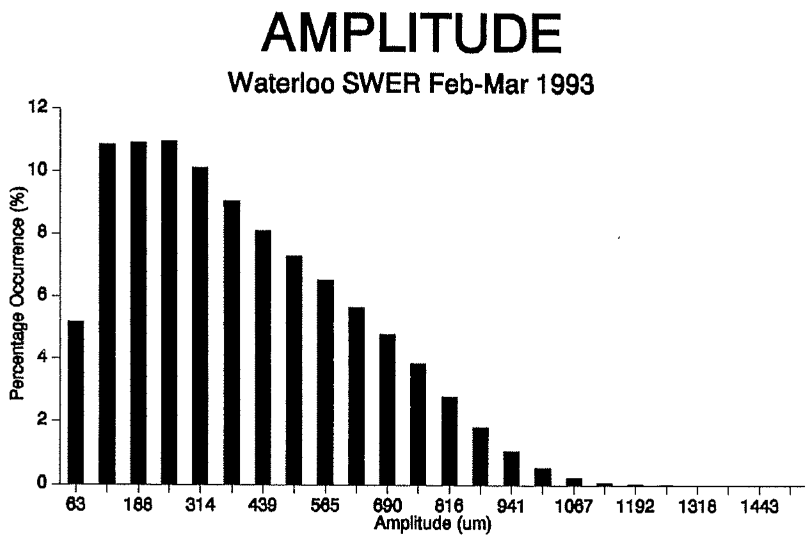


Figure 3.8 Summary of Amplitude Recordings, Waterloo - No Dampers

In the detailed report prepared on this line (50), it was concluded that the conductor in the section of line where this recording was taken, had suffered extensive vibration damage. Measurements of the conductor tension also indicated that the line had been over tensioned during construction. The line tension was measured at around 30% of CBL as opposed to the design level of 25% CBL.

In Appendix B it is shown that the line tension has only a minor impact on the life assessment analysis and that the use of the single S-N curve is appropriate for the analysis.

Following the CIGRE methodology outlined in Section 2.3.4 and utilising Miner's cumulative damage hypothesis as outlined in Appendix D, and the S-N data curve provided in Appendix B, it is possible to consider the relative effects of the various frequency and amplitude classes on the conductor fatigue life. These relative effects are presented in Tables 3.4 and 3.5 below.

Amplitude (μm)	Stress (MPa)	N ($x10^6$) S-N Data	n No. of Cycles	n/N ($x10^{-6}$)	%
63	2.14	2773000	114385	0	0
125	4.24	46957	239135	5	0
188	6.37	4136.70	240629	58	0.02
251	8.51	740.520	241706	326	0.09
314	10.64	195.260	223242	1143	0.31
376	12.75	66.810	199957	2993	0.81
439	14.88	26.560	178543	6722	1.81
502	17.02	12.930	160764	12433	3.36
565	19.15	7.160	143919	20100	5.43
627	21.26	4.250	124353	29260	7.90
690	23.39	2.640	105777	40067	10.81
753	25.53	1.700	84952	49972	13.49
816	27.66	1.140	61830	54237	14.64
878	29.76	0.790	40327	51047	13.77
941	31.90	0.559	23654	42239	11.40
1004	34.04	0.404	11806	29515	7.97
1067	36.17	0.298	5083	16943	4.57
1129	38.27	0.225	1852	8418	2.27
1192	40.41	0.171	538	3165	0.85
1255	42.54	0.132	164	1262	0.34
1318	44.68	0.104	51	510	0.14
1380	46.78	0.082	5	63	0.02
1443	48.92	0.066	-	-	-
1506	51.05	0.053	-	-	-
			2202672	370478	100

Table 3.4 Cumulative Damage by Amplitude, Waterloo - No Dampers

Frequency (Hertz)	Wind Velocity (m/s)	n No. of Cycles	$\Sigma(n/N)$ (x10^{-6}) per Class	%
10	0.40	3016	0	0
20	0.81	8547	7	0
30	1.22	23948	201	0.05
40	1.62	51843	1167	0.31
50	2.03	70779	3417	0.92
59	2.39	77895	6543	1.77
71	2.88	144611	18893	5.10
77	3.12	103349	15099	4.08
91	3.69	297752	73141	19.74
100	4.05	255996	91259	24.63
111	4.50	225081	69469	18.75
125	5.07	205239	43856	11.84
143	5.80	182877	22719	6.14
167	6.77	191376	13443	3.63
200	8.11	360363	11264	3.04
		2202672	370478	100

Table 3.5 Cumulative Damage by Frequency, Waterloo - No Dampers

The above results are based on 3288 ten second samples taken over a period of 30 days. The total recording time is therefore 32880 seconds. To equate the recordings to a period of one year a multiplying factor of 959 must be applied.

The total number of accumulated cycles in one year can now be estimated.

Total number of cycles/year $\approx$ $2\text{x}10^9$

By application of Miner's Rule the fatigue life of the aluminium wires can be estimated.

$$\text{Life} = 1 / (370478 \times 10^{-6} \times 959) = 2.8 \times 10^{-3} \text{ years}$$

3.3 COMPARISON OF RESULTS

In the following section the results from the two sites are compared and a conclusion drawn that the Waterloo site presents a higher risk of vibration damage.

A comparison of the wind functions for the two sites presented in Figure 3.9 below shows very similar wind patterns. This allows for a reasonable comparison of the two sets of results.

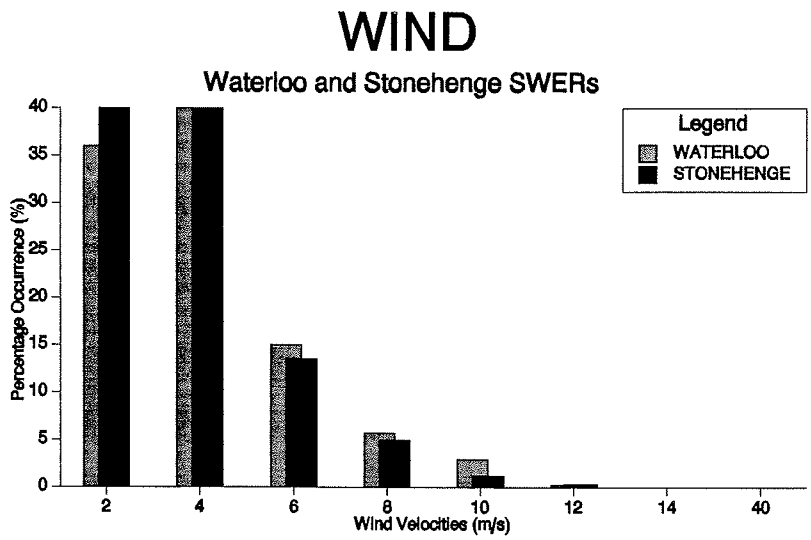


Figure 3.9 Comparison of Wind Recordings - No Dampers

In Figure 3.10 below the maximum amplitudes measured in the various frequency classes are compared for the Stonehenge and Waterloo recordings. The amplitudes shown are the values highlighted in Tables F.1 and F.2 of Appendix F and represent the levels where the cycle count has a minimum significance of 0.01% of the total number of cycles in the recorded matrix. All maximum amplitudes presented in this thesis are based on this significance criteria.

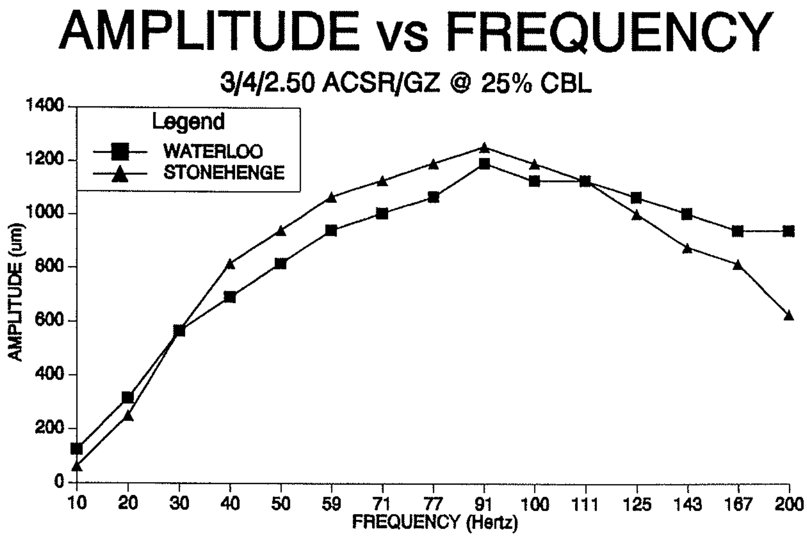


Figure 3.10 Comparison of Maximum Amplitudes Recorded - No Dampers

As pointed out in Section 3.2, the amplitudes presented above are the values recorded at the 89mm point. These amplitudes can be converted to anti-node values by assuming that the conductor standing wave is sinusoidal (45). In Figure 3.10 below this conversion has been carried out and the maximum calculated anti-node values for the various frequency classes are presented.

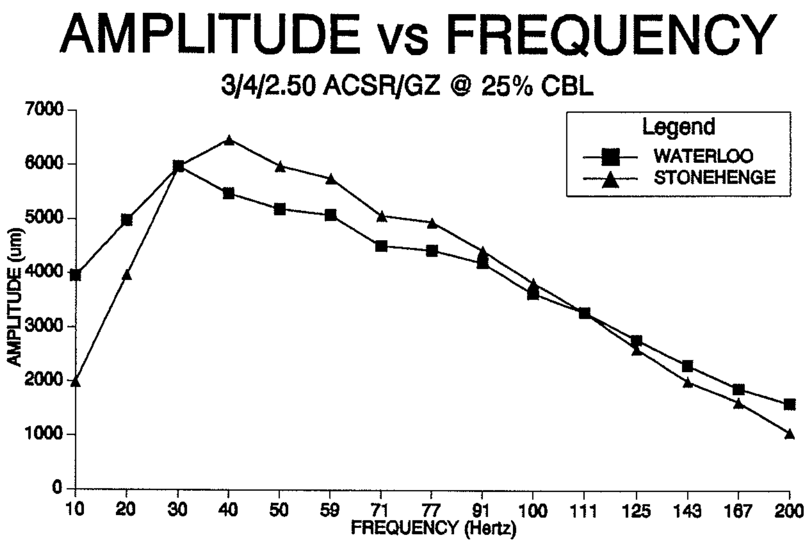


Figure 3.11 Comparison of Maximum Anti-node Values - No Dampers

The maximum calculated anti-node value of vibration gives a peak to peak level of around 6.5mm or 86% of the conductor diameter. The amplitudes tend to roll-off at the higher frequencies in a manner consistent with the explanations provided in Appendix D, Section D.2.3.

While there is only limited published data on the characteristics of vibration of small diameter conductors, work by Rawlins (62) and Preformed Line Products (63) on 9mm diameter steel earthwires shows that the maximum free loop (anti-node) amplitudes over a wide range of recordings never exceeded 90% of the conductor diameter and was more typically around the 50% level.

It is reasonable to assume therefore that the recordings taken are fairly representative of the maximum levels of vibration on lines where the terrain is conducive to laminar wind flows, and form a good basis on which comparative laboratory and field testing can be undertaken.

While the wind functions and maximum amplitudes are reasonably comparable, the accumulated damage for each frequency class varies considerably.

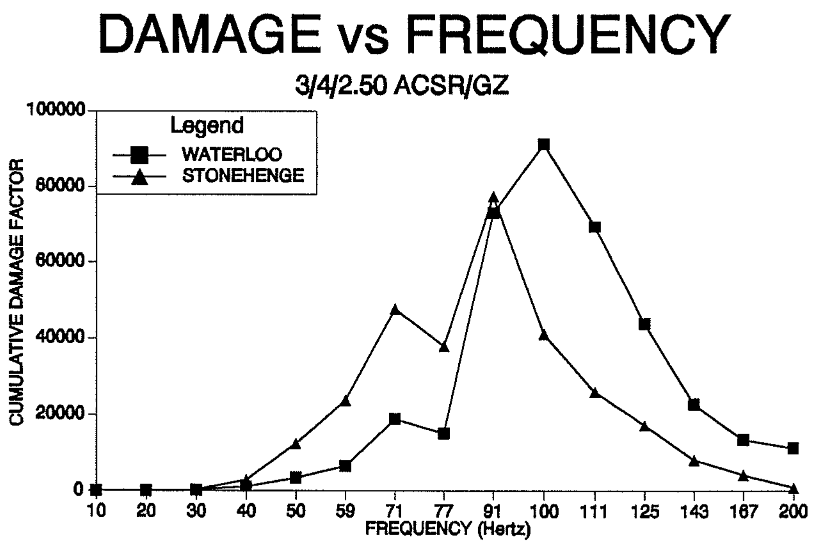


Figure 3.12 Comparison of Cumulative Damage - No Dampers

It is clear from the comparative life assessment results and the cumulative damage results shown above that while the two lines are located in sites with similar wind distributions, the Waterloo SWER site represents a higher risk site for vibration than the Stonehenge site. This is most probably due to the variation in terrain between the two sites (there being some isolated patches of trees near the Stonehenge line) and the fact that the two lines run at right angles to each other, perhaps causing different turbulence patterns.

The life assessment results carried out using the data collected at the two field sites (Stonehenge and Waterloo), predict that aluminium wire failure will have occurred very early in the conductor service life (about 10^{-3} years). This clearly was not the case and it is contended that the application of Miner's Rule using the S-N curve provided by the CIGRE safe border approach (32) is very conservative when applied to composite outer layer small diameter ACSR conductors. The reasons for this are as follows:

1. The CIGRE safe border S-N curve has been derived primarily from multi-layer transmission class conductors where aluminium wire failure normally occurs in the penultimate layer due to the fretting effects of the surrounding wires. In a 7 strand composite outer layer conductors there may be considerably less fretting due to the presence of the steel wires in the outer layer (refer to Appendix D for more information),and
2. The S-N curve derived in Appendix B assumes a worst case static stress with no allowance for conductor creep. In addition the maximum amplitudes from each recording class have been used to calculate the stress levels in the derivation S-N curve.

This contention that the life assessments will be conservative is supported by field investigations. Inspection of the worst section of the Waterloo SWER line, in combination with reports from line staff, indicate that the initial aluminium wire failures occurred in the vicinity of 3-5 years after construction. At the Stonehenge recording site, pole 81, the aluminium wires had not suffered fatigue failure even after a service period of around 8 years.

While a more accurate estimate of conductor service life may not be easily obtained, it will be shown in later Sections that it is the relative performance of the line with and without dampers which is of particular relevance and not the actual life assessment values in years.

It is also important to note the impact of the frequencies in the range 167-200 Hertz on the predicted fatigue life of the aluminium wires. Tables 3.3 and 3.5, which detail the cumulative damage by frequency class, clearly show that these higher frequencies have only a minor impact of the fatigue life. As a result, errors made in recording at these frequencies should not invalidate the findings of this research project.

4. ASSESSMENT OF CONDUCTOR LIFE

Inspection of vibration damaged lines indicated that the aluminium wires in the ACSR conductors are at significant risk of failure as a result of the accumulated stresses arising from the line vibration. These findings have been supported by the data recordings and analysis presented in Section 3. It is not clear however what impact these stress cycles have had on the steel wires in the ACSR conductors. It is a theme of this thesis that the residual fatigue life of the steel wires is of prime importance in the serviceability of vibration damaged SWER lines.

Prior to this investigation, as the remaining fatigue life of the damaged conductors was an unknown factor, the only acceptable option had been to re-conductor the affected sections of line and add vibration dampers. In view of costs associated with this practice, it is of benefit to consider whether it is possible to reliably extend the service life of the damaged lines without the need for re-conductoring. An assessment of the remaining electrical and mechanical properties of the damaged conductor was therefore essential in determining the level of refurbishment necessary to achieve a satisfactory service life.

Because of the high steel content in the ACSR conductors used on the SWER lines in Capricornia Electricity, the proportion of the total static tensile load carried by the aluminium wires is relatively small. In Appendix B it is shown that for 3/4/2.50 ACSR/GZ, the aluminium wires carry only around 20% of the total tensile load. Total failure of all aluminium wires will not result in a tensile overload in the steel wires and consequent total conductor failure and line drop. The failure of steel wires due to factors other than tensile load shift must occur for the initiation of a line drop condition.

4.1 ELECTRICAL CONSIDERATIONS

On high current ACSR lines, the fatigue failure of aluminium wires may result in a heating problem and the eventual failure of the steel wires (35). In SWER systems utilising isolating transformers, which is typical of the Capricornia Electricity system, the line current rarely exceeds 10 Amps under normal operating conditions, or more than 250 Amps under fault conditions (1,8). Considering that all SWER conductors in Capricornia Electricity have a high steel content and are armoured, the failure of aluminium wires is unlikely to cause a localised heating problem and hence the risk of an associated conductor failure due to heating is acceptably low.

4.2 MECHANICAL CONSIDERATIONS

Conductor vibrations arising from steady wind blowing across the line, and characterised by their relatively high frequency and low amplitudes, introduce cyclic variation in the longitudinal stresses of the conductor wires. At the support points, the superposition of static stresses caused by tensile loading, bending and compressive forces, when combined with the dynamic stresses due to vibration, can cause conductor wire failures as a result of fatigue. The problem is further aggravated where fretting of aluminium wires and hardware produces abraded particles which hasten the fatigue failures of the wires. A detailed consideration of conductor fatigue and life assessment is provided in Section 4 of Appendix D.

As indicated in Appendix D, ferrous materials exhibit a fatigue endurance limit. This is a stress level which the metal can withstand for an infinitely large number of cycles with a 50% probability of failure. In Appendix B, the critical stress level for steel wires in aerial conductors is considered and a figure 80 MPa is recommended. It is also shown that this stress level corresponds to a "bending amplitude, Y_b" of 0.75mm peak to peak. Bending amplitudes in excess of this level may result in accumulated fatigue damage in the steel wires.

Aluminium on the other hand does not exhibit a fatigue limit, and fatigue damage is accumulated even at very low stress levels. For Aluminium, instead of reporting a fatigue limit, it is necessary to report a fatigue strength, which is the stress to which the aluminium can be subjected for a specified number of cycles.

From the field data recordings on the Waterloo SWER scheme, it is clear that stress cycles in the aluminium are accumulating at around 2×10^9cycles per year. If the service life expectancy of the line is assumed to be around 30 years, then the fatigue strength needs to be referenced to 6×10^{10} cycles. In Appendix B, the allowable stress versus number of cycles (S-N Curve) for aluminium wires in aerial conductors is considered, and based on the CIGRE recommendations (34), a fatigue strength of 4 MPa corresponds to 6×10^{10} cycles. It can also shown that this stress level corresponds to a "bending amplitude, Y_b", of 0.120mm peak to peak.

It can be seen from the Stonehenge and Waterloo SWER scheme recordings that amplitudes well in excess of the considered safe vibration levels are occurring.

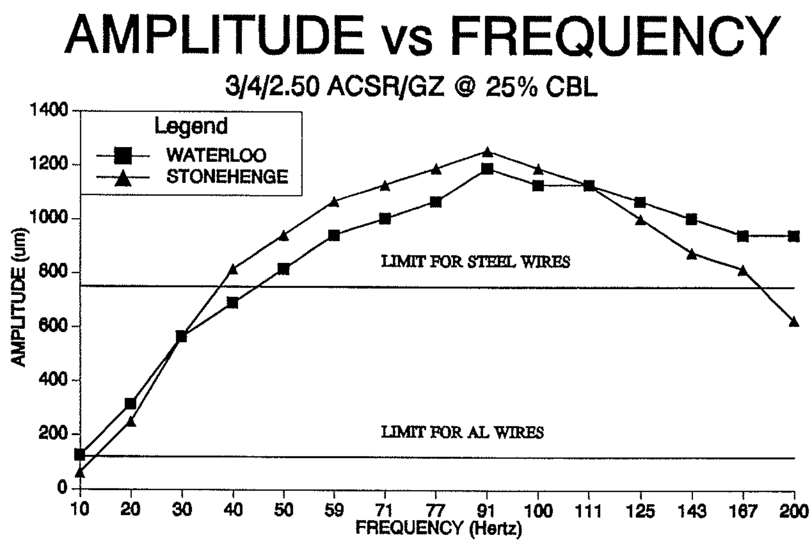


Figure 4.1 Comparison of Recorded and Allowable Vibration Amplitudes

In the worst affected areas the initial failure of aluminium wires in the ACSR conductors is occurring after around three-five years. Although the fatigue failure of aluminium wires is fairly widespread, no fatigue failures of steel wires in any conductor have been recorded. However as indicated in Figure 4.2 above, this does not mean that fatigue failures of steel wires could not happen within the anticipated life of the lines (30+ years).

The risk of failure of the steel wires in the ACSR/GZ conductors represents an unacceptable situation to Capricornia Electricity, and while no steel wire failures had been recorded, it was considered prudent to establish what the actual risk of steel wire failure was through quantitative testing of wires in conductors which had been exposed to significant vibration.

Using facilities at the University of Central Queensland, steel wires from a 3/4/2.50 ACSR/GZ line were recovered from the Stonehenge SWER scheme and subjected to torsional ductility tests in an attempt to establish the remaining fatigue life of the conductor. This work was carried out in accordance with the Standard Method for Torsional Testing of Wire ASTM E558-83 (60) and follows work carried out by Ontario Hydro in Canada (61).

The results of this testing are reported in reference (40), with the main conclusions being;

1. "*Ductility of the steel conductor strands was not significantly different from when the conductor was erected;*" and
2. "*Fatigue life of the steel strands has not been affected directly by aeolian vibration.*"

The significance of these findings cannot be understated, as it means that the risk of total failure of the ACSR/GZ conductors is acceptably low and that even in locations where aluminium wires were broken, the ductility of the steel had not been significantly affected (40).

While the risk to the mechanical integrity of the conductor appears to be low, the service period (vibration exposure) has been relatively short in terms of the required service life. Thus, the continued accumulation of high amplitude cycles is still highly undesirable. In addition, the high amplitude cycles impact significantly on the performance of the ties and support hardware. It is necessary therefore to consider a range of damping and tie options which limit the dynamic stresses to ensure the mechanical integrity of the conductor and address the problem of tie and hardware failures.

While the failure of the steel wires is the primary concern, the continued failure of aluminium wires is still not desirable. Thus the application of amplitude limiting devices to ensure the integrity of the steel wires must also improve the fatigue life of the aluminium wires. The effectiveness of the damping systems in limiting the vibration amplitudes will determine whether the failure of aluminium wires will continue to occur. In any case, some continuing aluminium wire failures are to be expected because of the already high cycle accumulation on some lines in service.

The requirements for the damping system can now be established as;

1. Ensure that the "bending amplitude, Y_b", is restricted to well below the critical level of 0.75mm for the full range of vibration frequencies to ensure the integrity of the steel wires;
2 Restrict amplitudes to levels which ensure the security of ties and support hardware; and
2. If possible, restrict the amplitudes to a level which ensures that failure of the aluminium wires in new conductor does not occur.

5. OPTIONS FOR VIBRATION CONTROL

5.1 WHY SPIRAL VIBRATION DAMPERS ?

Vibration dampers have been used since the early 1920s (9) to restrict the amplitudes of vibration on overhead lines. The stockbridge type damper (15) and its derivatives have been used extensively on transmission class conductors with great success, and as such have been the topic of extensive research work. Because of its popularity and effectiveness, this type of damper has become the standard to which other damper systems are compared.

Unfortunately, manufacturers have found it difficult to manufacture effective stockbridge type dampers for small diameter conductors (41). This is partly because the smaller conductors vibrate at proportionally higher frequencies, and partly because the energy levels in the conductors are relatively low compared with the transmission class conductors and there is generally a lower than required energy level to excite the damper.

The damper design is further complicated by the requirement to have a line clamp with small inertial mass relative to the conductor mass. For large heavy conductors, vibrating at relatively low frequency, the inertial mass of the standard clamp is not significant, however for small, light conductors vibrating at much higher frequencies, the inertial effect of the clamp becomes very significant and as a result the energy imparted to the damper is greatly reduced (42).

This comparative ineffectiveness of stockbridge type dampers on small diameter conductors has been recognised since the 1930s (9,42) and a variety of other damping systems that slap, shake, or rattle have been used to reduce the vibration amplitudes.

The most effective of these devices has been the spiral vibration damper (SVD), which was introduced in the 1950s (44) for use on overhead earthwires on transmission lines. Their use has been extended to small diameter distribution class conductors and have proven to be not only very effective but relatively inexpensive compared to stockbridge type dampers.

Spiral vibration dampers function in different manner to the stockbridge type damper systems. The stockbridge damper reduces the vibration amplitudes by absorbing and dissipating the vibration energy. SVDs on the other hand are an interference type damper as they upset the behaviour of the span termination, and prevent the formation of large amplitude standing waves. Spiral vibration dampers absorb energy from an incident travelling wave and store it as kinetic energy in the movement of the SVD. This movement results when the travelling wave impacts on the SVD causing it to lift away from the conductor. The SVD then continues to move until it strikes the conductor again, at which time the energy is transferred back into the conductor. This impact has the effect of imparting the energy to the conductor at a different frequency and phase angle relative to the incident wave, and in this way the SVD acts to confuse the span termination and so interferes with the resonant behaviour of the span. Thus, the resonant standing waves are suppressed and vibration amplitudes restricted (42,43,44).

Spiral vibration dampers cannot reduce vibration amplitudes to zero, since some vibration amplitude is required to cause the device to leave the conductor and so allow it to work. For the SVD to lift away from the conductor, the acceleration of the SVD must exceed $1g$. Tests have shown that this style of damper performs well for accelerations of about $2g$ and above (9).

The effectiveness of the damper can be considered be examining the relationship between vibration amplitude and frequency, and acceleration of the vibrating conductor. Reference (9) provides the following equation.

$$\text{Acceleration} = 2\,\pi^2\,f^2\,Y \qquad (5.1)$$

where f = Frequency of vibration (Hertz)

Y = Anti-node peak to peak amplitude (m)

For an acceleration of $2g$ ($2 \times 9.807 m/s^2$), the above equation can be expressed as;

$$Y = \frac{994}{f^2} \text{ mm} \tag{5.2}$$

This represents the minimum amplitude of vibration required to actuate the damper. Assuming that the mode shape of vibration is sinusoidal (45), the minimum amplitude may be referred to Y_b, the bending amplitude (refer to appendix D.3) measured at the 89mm point (29). The following table shows the critical amplitudes for damper effectiveness on a typical SWER line.

3/4/2.50 ACSR/GZ @ 25% CBL, SPAN = 250m			
Frequency (Hertz)	Anti-node p-p Amplitude, Y (mm)	Loop Length L (m)	Bending Amplitude Y_b (mm)
10	9.940	8.843	0.314
20	2.485	4.421	0.157
30	1.104	2.948	0.105
40	0.621	2.210	0.078
50	0.398	1.769	0.063
59	0.286	1.500	0.053
71	0.197	1.245	0.044
77	0.168	1.148	0.041
91	0.120	0.972	0.034
100	0.099	0.884	0.031
111	0.081	0.797	0.028
125	0.064	0.707	0.025
143	0.049	0.618	0.021
167	0.036	0.530	0.018
200	0.025	0.442	0.015

Table 5.1 Critical Amplitudes for Spiral Damper Actuation

Whapman and Champa (42), have published comparative field test results for stockbridge type dampers and spiral vibration dampers on a range of small diameter (9-11mm) steel overhead earthwires. The results clearly support the use of spiral vibration dampers in preference to stockbridge type dampers for small diameter conductors.

It has been standard industry practice in Australia to use spiral vibration dampers on conductors up to around 13mm diameter. Conductors above this diameter are recognised as having standing wave loop lengths and energy levels which are more effectively controlled by stockbridge type dampers. While the SVDs have been in common use for many years, very little published information is available on the effectiveness of the dampers on the range of conductors used in the Capricornia Electricity SWER network. No specific results could be found for composite outer layer ACSR/GZ conductors supported on line pins.

To consider the actual effectiveness of SVDs on typical SWER lines, it was considered necessary to undertake laboratory testing and comparative field testing. The remainder of this Section describes and analyses the results of the laboratory and subsequent field tests.

5.2 LABORATORY TESTING

The testing of the spiral vibration dampers was undertaken at Dulmison Australia's NATA registered laboratory at Wyong in New South Wales in June 1993. The results of the tests are reported in the Capricornia Electricity Report "Laboratory Testing of Spiral Vibration Dampers" (47).

The effectiveness of the dampers at limiting vibration amplitudes, based on the results of actual amplitudes and frequencies measured in the field, was the prime object of the testing. The vibration amplitudes and frequencies recorded in the field formed the basis for establishing the test amplitudes and frequencies.

5.2.1 Test Method

Early laboratory tests conducted to evaluate the effectiveness of SVDs used decay testing methods (43). Later testing used forced vibration conditions similar to those applied to the conventional stockbridge type dampers (46). However there is a great amount of difficulty in applying these methods, and it has been recognised that it is not practical to test spiral vibration dampers using the test methods for conventional dampers (41,43).

In view of these problems a frequency sweep test has been developed (41). In the test, the frequency is varied at a constant rate from the lowest to highest required frequency. The power input can be selected to achieve the required amplitudes of the standing wave vibrations. The test method does not yield absolute values of power dissipated, but does produce useful comparative results of amplitudes on damped and undamped spans. The test method attempts to simulate the behaviour of the spiral vibration damper on a real span.

For these tests, a test span as described in IEEE Standard 563 (48) is used. The conductor is supported at one end of the 28.98m span on the typical SWER intermediate insulator and a electro mechanical shaker is used to induce vibration at the other end. The tension in the conductor is held constant during each test by the application of a known load at the shaker end. The test frequency may then be varied to simulate vibration which models the field results (47).

5.2.2 Instrument Calibration

The Sefag Vibrec 300 recorder which has been used to collect the field data presented in Section 3 was also used as the prime recording instrument in the laboratory tests. To ensure accuracy of the readings the Vibrec 300 was calibrated for amplitude and frequency against the laboratory equipment. The following table provides a representative sample of the calibration tests (47). It shows that the Vibrec recorder was within the required accuracy tolerance limits.

Frequency (Hz)		Amplitude (μm)		
Function Generator (HP3325A)	Vibrec 300 Recorder	Laboratory LVDT	VScope	Vibrec 300 Recorder
48.8	40-50 class	720 1410	750 1400	690-753 class 1380-1443 class
100.7	100-111 class	373 685 1130	400 700 1200	314-376 class 627-690 class 1129-1192 class
151.5	143-167 class	380 500	400 500	376-439 class 439-502 class

Table 5.2 Sefag Vibrec VR300 Calibration Check

5.2.3 Replicating Field Results

The power input levels to the span were selected to produce amplitudes in undamped armoured 3/4/2.50 ACSR/GZ conductor @ 25% CBL at frequencies which corresponded as closely as possible to those collected in the field from the Stonehenge and Waterloo SWER sites as detailed in Section 3.

It was not possible to use a single power level for the full frequency range (25-200Hz) of the sweep test as the amplitudes tended to roll-off significantly as frequency was increased. As result, power input to the span was increased for the different frequency levels to as closely as possible replicate the field recordings..

A roll-off of amplitudes on the test span at the higher frequencies was unavoidable due to a power limitation of the electro mechanical shaker (47).

A summary of the power inputs, referenced as voltage inputs to the electro mechanical shaker are shown in Table 5.3 below.

Frequency Range (Hz)	Voltage Input (mV)
25-75	500
75-105	750
105-130	1000
130-150	1500
150-200	2000

Table 5.3 Voltage Input to the Electro mechanical Shaker

The comparison of amplitude vs frequency for the test span against the field results is shown in Figure 5.1 below.

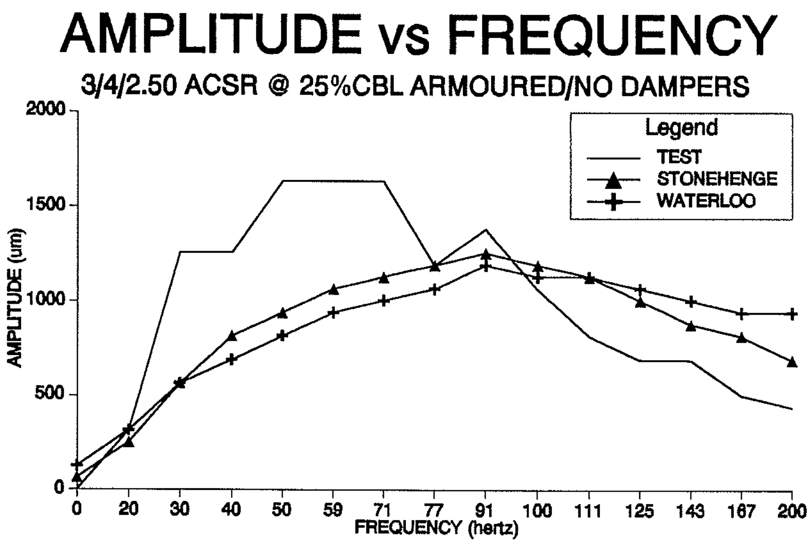


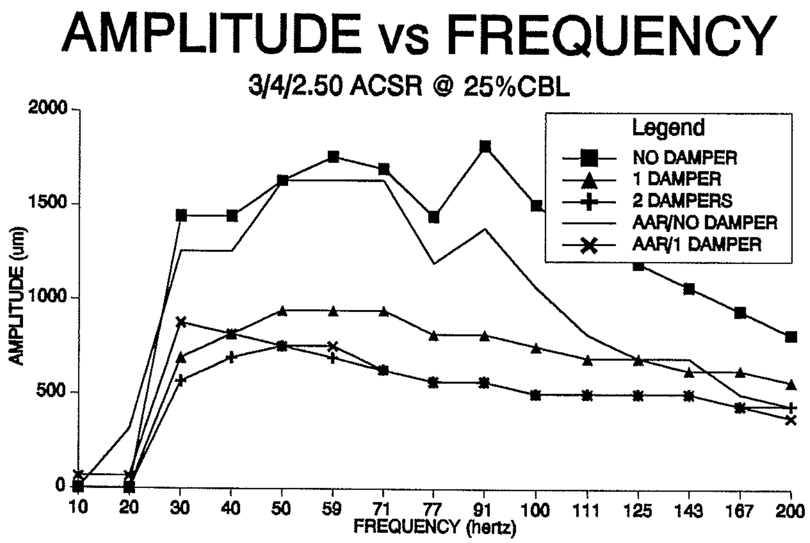
Figure 5.1 Comparison of Field and Test Amplitudes for Base Case

5.2.4 Test Results on 3/4/2.50 ACSR/GZ @ 25% CBL

With the conductor tensioned to 25% of its calculated breaking load, frequency sweep tests were then carried out for a number of different pole top configurations as detailed below using the power levels determined for the base case, (case 4) below.

1. Preformed Tie (AWT0750-1), no armour rods, no dampers
2. Preformed Tie (AWT0750-1), no armour rods, 1 damper (SVD0635)
3. Preformed Tie (AWT0750-1), no armour rods, 2 dampers (SVD0635)
4. Preformed Tie (AWT1430-1), armour rods (AAR0750), no damper
5. Preformed Tie (AWT1430-1), armour rods (AAR0750), 1 damper (SVD0635)

The effectiveness of each pole top configuration in limiting the amplitude of the vibration at the various frequency levels can be seen in Figure 5.2 below and is further indicated in Table 5.4.



<u>Figure 5.2 Comparison of Amplitudes for the Various Pole Top Configurations</u>

AMPLITUDE 1/1000mm	NUMBER OF CYCLES				
	NO ARMOUR NO DAMPER	NO ARMOUR 1 DAMPER	NO ARMOUR 2 DAMPERS	ARMOURED NO DAMPER	ARMOURED 1 DAMPER
63	1238	40128	192850	94634	350988
125	268050	523648	737398	1039478	716780
188	748708	546694	437478	267396	344040
251	227634	306204	193280	148716	146150
314	133452	159680	111244	108138	95042
376	104130	98764	62236	81008	59420
439	83518	74594	30172	53454	35398
502	57118	46888	20305	16891	17568
565	45212	32202	13332	22162	9628
627	36190	19984	6410	17644	5124
690	29706	12004	2282	16988	1704
753	26276	6228	422	11164	452
816	22436	2212	58	10584	166
878	19276	676	6	9528	244
941	18466	298		5172	90
1004	12888	254		3242	6
1067	13660	176		6190	
1129	10662	74		4196	
1192	9322	14		2826	
1255	7350			2402	
1318	6072			2206	
1380	5238			1692	
1443	5828			2566	
1506	3174			2036	
1569	2140			1992	
1631	2600			1008	
1694	1898				
1757	542				
1820	178				
1882	172				
1945	216				
2000					
	1904464	1870722	1807473	1933313	1782800

Table 5.4 Summary of Cycles Recorded During Frequency Sweep Tests

The frequency sweep test was used to produce a comparative result of each of the pole top arrangements tested. The equivalent lifetime for each test arrangement is estimated by considering the relative effectiveness of each pole top arrangement in reducing or increasing the number of cycles in the various amplitude classes compared with the base case. This comparison was used to adjust the field recordings and so attempt to predict impact of the different pole top constructions on the amplitudes of vibration under service type conditions. In the following the Waterloo results have been used as the comparative field results. The results of the adjustments to the field data are presented in Table 5.5 below.

AMPLITUDE 1/1000mm	S/N CURVE *10^6	NUMBER OF CYCLES				
		NO ARMOUR NO DAMPER	NO ARMOUR 1 DAMPER	NO ARMOUR 2 DAMPERS	ARMOURED NO DAMPER	ARMOURED 1 DAMPER
63	2773000				114385	
125	46957				239135	408593
188	4136.70			779989	240629	577224
251	740.520		528479	482094	241706	346919
314	195.260		408894	339013	223242	284495
376	66.810	126337	281757	221738	199957	214102
439	26.560	214312	302497	130443	178543	164750
502	12.930	473934	306514	131674	160764	114258
565	7.160	307967	177902	73164	143919	54009
627	4.250	273157	105715	32683	124353	26745
690	2.640	217403	55536	10082	105777	7996
753	1.700	212563	25382	1613	84952	2148
816	1.140	151761	7140	167	61830	750
878	0.790	101363	1833	12	40327	557
941	0.559	70413	680		23654	122
1004	0.404	33562	266		11806	4
1067	0.298	12882	66		5083	
1129	0.225	4959	11		1852	
1192	0.171	1490	1		538	
1255	0.132	430			164	
1318	0.104	127			51	
1380	0.082	12			5	
1443	0.066					
1506	0.053					
1569	0.043					
1631	0.036					
1694	0.030					
1757	0.025					
1820	0.021					
		2202672	2202672	2202672	2202672	2202672

Table 5.5 Summary of Adjusted Field Data Referred to the Base Case

A relative life assessment can now be carried out using Miner's rule.

COMPARATIVE LIFETIMES				
NO ARMOUR NO DAMPERS	NO ARMOUR 1 DAMPER	NO ARMOUR 2 DAMPERS	ARMOURED NO DAMPERS	ARMOURED 1 DAMPER
0.4	2.7	8.5	1	9.3

Table 5.6 Comparative Lifetimes Referred to the Base Case

5.2.4 Impact of Tension Changes

The influence of conductor tension on the vibration amplitudes was also investigated. Frequency sweep tests were carried out on unarmoured conductor with no dampers (case 1) at 15.5% and 35% of CBL to allow for comparison to the 25% tests. The results of these tests are summarised below.

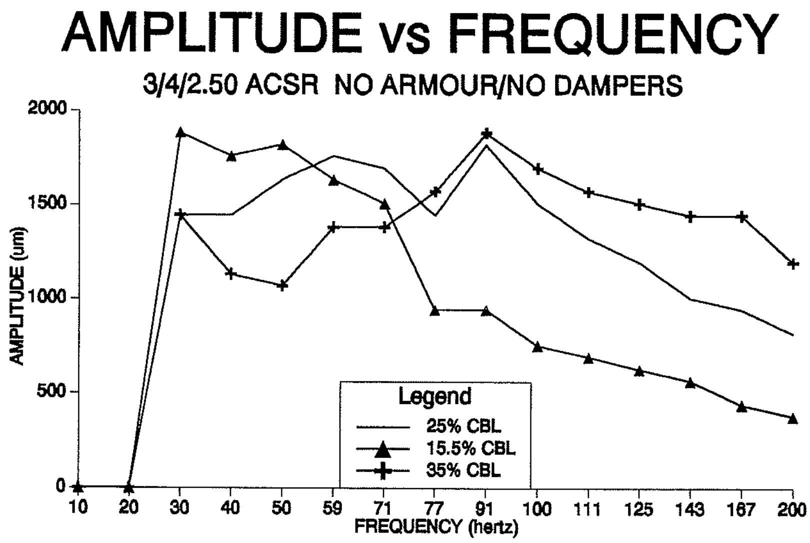


Figure 5.3 Comparison of Maximum Amplitudes for Different Tensions

AMPLITUDE 1/1000mm	NUMBER OF CYCLES		
	15.5% CBL	25% CBL	35% CBL
63	21558	1238	1132
125	284056	268050	473158
188	802174	748708	612896
251	275700	227634	186266
314	161062	133452	107326
376	94370	104130	90760
439	70218	83518	53474
502	49032	57118	41408
565	38510	45212	32572
627	21662	36190	28892
690	18986	29706	25004
753	16782	26276	23806
816	10268	22436	24112
878	7026	19276	22352
941	6062	18466	19220
1004	4818	12888	18918
1067	5878	13660	18094
1129	5568	10662	188848
1192	4878	9322	16610
1255	5088	7350	13224
1318	5524	6072	12408
1380	4004	6516	11326
1443	4784	5828	6656
1506	4474	3174	3958
1569	4794	2148	3096
1631	3796	2600	1872
1694	1788	1898	664
1757	990	542	190
1820	796	178	156
1882	980	216	750
1945			
2000			
	1935626	1904464	1869148

Table 5.7 Summary of Cycles Recorded During Comparative Tension Tests

The results shown in the above table are presented graphically in Figure 5.4 below. The ordinate axis has a Log scale to more clearly demonstrate the impacts of conductor tension changes.

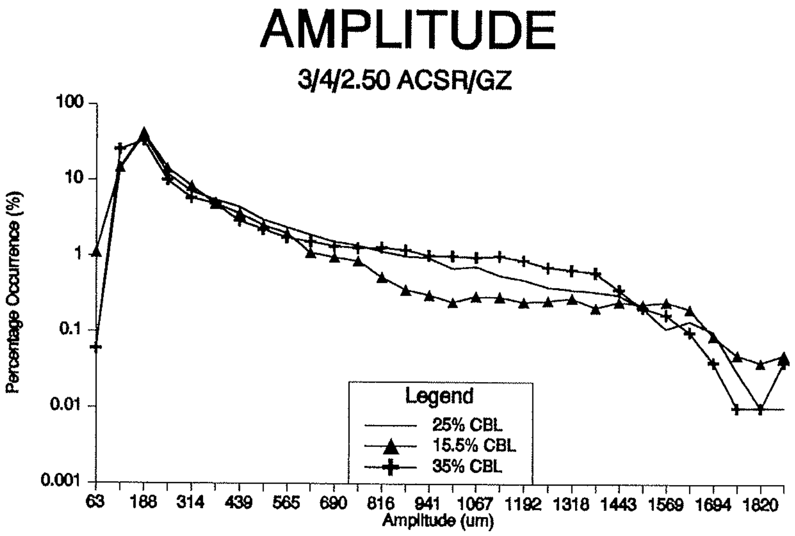


Figure 5.4 Comparison of Recorded Amplitudes Occurrences

The results are then adjusted with reference to the base case as detailed in Table 5.8 .

AMPLITUDE	15.5% CBL		35% CBL	
1/1000 mm	S-N CURVE (*10⁶)	No. OF CYCLES	S-N CURVE (*10⁶)	No. OF CYCLES
63	7954000		1280293	
125	134688		21680	
188	11865.00		1909.92	
251	2124.05	235062	341.90	4338
314	560.09	342992	90.16	97380
376	191.62	182738	30.84	99998
439	76.20	209946	13.21	62527
502	34.30	365331	6.75	407484
565	17.35	236717	3.74	262685
627	10.31	160094	2.22	267483
690	6.39	131381	1.38	229779
753	4.13	125778	0.90	251130
816	2.76	80783	0.59	197257
878	1.91	53939	0.41	139203
941	1.35	40598	0.29	99184
1004	0.98	22197	0.21	52574
1067	0.72	9203	0.16	20070
1129	0.54	4017	0.12	8257
1192	0.42	1311	0.09	2435
1255	0.32	430	0.07	682
1318	0.25	141	0.05	190
1380	0.20	14	0.04	16
		2202672		2202672

Table 5.8 Summary of Adjusted Tension Data

A comparative life assessment has been carried out using the Miner's rule.

COMPARATIVE LIFETIMES		
15.5% CBL	25% CBL	35% CBL
1.6	1	0.32

Table 5.9 Comparative Lifetimes for Different Tensions

5.2.6 Interpretation of Laboratory Test Results

In the comparative testing of dampers carried out for the alternative pole top arrangements, the results were generally in agreement with expectations. With one spiral damper installed there was a significant reduction in vibration amplitudes, and a consequent increase in conductor lifetime expectancy. A further decrease in vibration amplitude was evident when a second spiral damper was added. The response of the damper system to frequency is good and shows an increased effectiveness with frequency as predicted in Section 5.1 above.

It was also evident that the inclusion of armour rods resulted in a significant increase in expected lifetime, with a particularly notable reduction in vibration amplitudes at higher frequencies. This effect is probably related to the vibration loop lengths at the higher frequencies approaching the active length of the armour rods.

The result obtained for the test with armour rods and one damper was similar to that found for two spiral dampers. This result is encouraging as all of Capricornia Electricity's SWER lines have armour rods already fitted at the support points.

The application of a single damper to the armoured conductor system appears to restrict the vibration amplitudes to below the critical fatigue endurance limit of the steel wires (around the 0.75mm level) required to ensure the security of the steel wires. The results of the laboratory tests suggest however that the restriction of vibration amplitudes to levels required to ensure the integrity of the aluminium wires cannot be readily achieved by the application of a single spiral damper. While the addition of spiral dampers will significantly reduce the stress levels in the aluminium wires, these tests suggest that some fatigue failures will continue to occur. This does not represent a major risk to system security for the reasons detailed in Section 4.

The comparative tension tests confirmed that higher tensions would result in a shift in the frequency/amplitude response curve. The higher tensions result in longer loop lengths at the higher frequencies and this results in higher amplitudes at these frequencies. Some care must be exercised in interpreting the comparative lifetimes calculated for the different tension levels. These tests do not consider the effect that higher amplitudes at higher frequencies may have on accelerated fretting. The results however do tend to support the CIGRE findings (32) which concluded that in vibration prone areas, static line tension was not the dominant factor but rather the extent to which the dynamic stresses in the conductor were controlled.

Because the test span vibrates at discrete natural frequencies determined by the allowable loop lengths and the velocity of the travelling waves (Appendix D), it is also possible to examine the constant loop length vibration response of the conductor at the various tensions levels. If the results are compared over the range where the power input is held constant, and it is assumed that the energy is dissipated primarily through conductor self-damping, then the equation (D.10) in Appendix D can be rearranged to provide a power dissipation equation for a constant loop length.

$$P_{SD} = \text{Constant} \, . \, H \, . \, T^{1/2} . \, Y^2 \qquad (5.3)$$

where P_{SD} = Conductor Self-damping Power Dissipation

H = Damping Constant

T = Conductor Tension

Y = Anti-node Vibration Amplitude

The results shown in Table 5.10 below indicate that when a particular loop length is considered with a constant power input, the amplitude response tends to roll-off at the higher tensions. This could only be consistent with equation (D.10) if the variation of the conductor damping constant, which was reported to decrease as tension increases (19), was relatively small.

Number of Loops (n)	Loop Length (m)	15.5% CBL		25% CBL		35% CBL	
		Frequency (Hz)	Amplitude (um)	Frequency (Hz)	Amplitude (um)	Frequency (Hz)	Amplitude (um)
10	2.898	24.15	1882	30.70	1443	36.30	1129
15	1.932	36.25	1757	46.00	1631	54.45	1380
20	0.690	48.30	1820	61.35	1757	72.60	1569

Table 5.10 Comparison of Maximum Amplitudes for a Given Loop Length

A plot of the amplitude response versus frequency for the loop length of 1.932m recorded during the frequency sweep tests further illustrates this point.

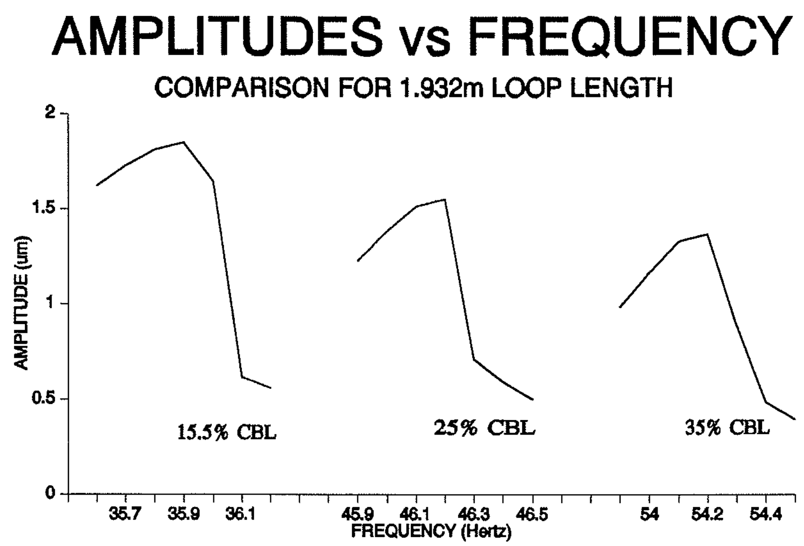


Figure 5.5 Comparison of Amplitude Response from Frequency Sweep Tests

The results above tend to indicate that the damping constant for the 3/4/2.50 ACSR/GZ conductor does not vary significantly with tension. This is in contrast with the results reported for multi-layer conductors reported in reference (19). Further specific self-damping tests would be required to confirm this finding.

5.3 FIELD TESTING

The laboratory testing can only provide a guide as to how the various damper/tie systems will perform relatively. The true effectiveness of the damper/tie system needs to be tested under service conditions to confirm the results from the laboratory tests.

5.3.1 Selected Site for Measurement

Field trials of the spiral vibration dampers was carried out on the Waterloo SWER line at pole 19. This site was selected as it represented the worst location for vibration of all the sites where recordings were taken. The results of the undamped vibration recordings are given in Section 3.3.4. There were two broken aluminium wires in the 3/4/2.50 ACSR/GZ conductor at this pole.

Sets of recordings, as detailed in Table 5.11 below, were taken over a seven month period from June 1993 to January 1994. The resulting recorder matrices are provided in Appendix F. Tests were carried out with preform and hand ties as indicated.

Dampers	Tie	Recording Period (days)
one per span (SVD0635)	hand tie	38
	preform tie (AWT1430-1)	58
two per span (SVD0635)	hand tie	47
	preform tie (AWT1430-1)	56

Table 5.11 Details of Vibration Recordings with Dampers

To allow for a reasonable comparison of recordings taken at different times, the recordings selected for comparison are those where the wind velocities recorded most closely match the undamped case.

The field recordings used for the comparative analysis correspond to the hand tied recording sets provided in Tables F.4 and F.6 in Appendix F. From the vibration amplitude and duration view points, the tie type will not be a significant factor. It will only become significant when considering the static stress distributions and fretting mechanisms operative at the support point and the consequential tie security. (Refer to Section 6)

5.3.2 Results with One Damper per Span

The results of the recordings taken with one damper per span are shown below. In Tables 5.12 and 5.13 the relative effects of amplitude and frequency on conductor fatigue life are presented.

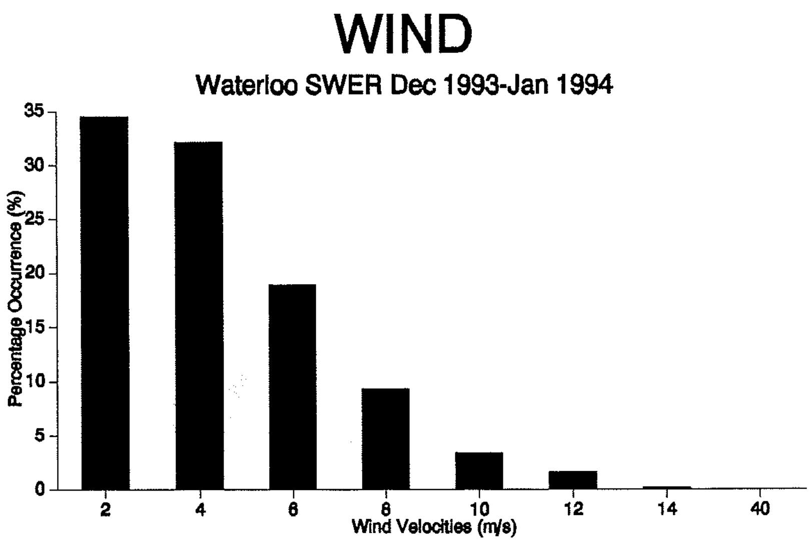


Figure 5.6 Summary of Wind Recordings - 1 Damper

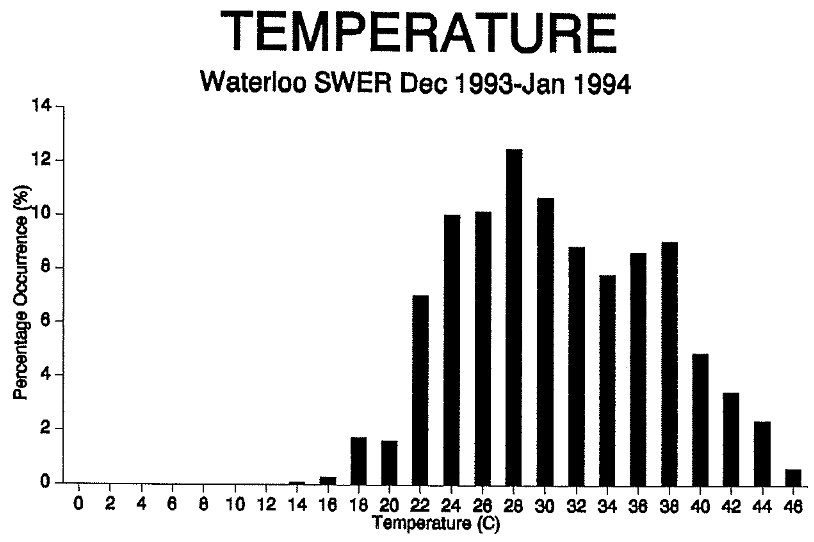


Figure 5.7 Summary of Temperature Recordings - 1 Damper

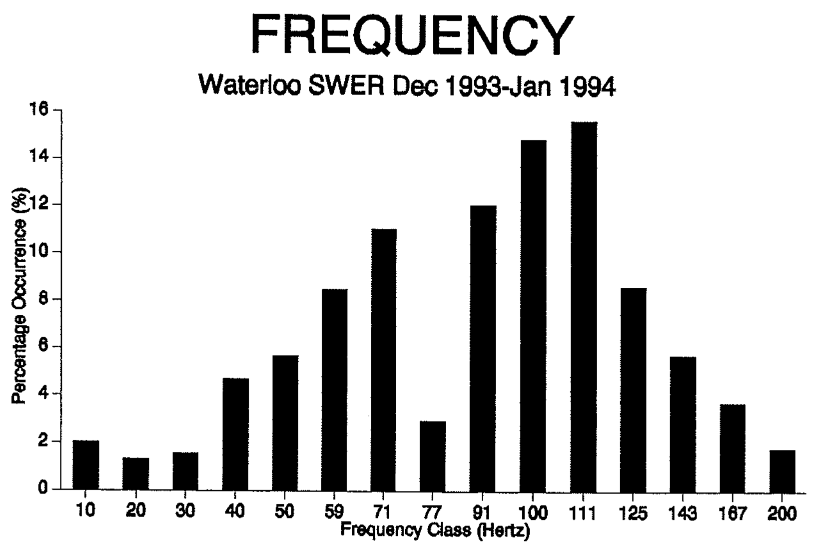


Figure 5.8 Summary of Frequency Recordings - 1 Damper

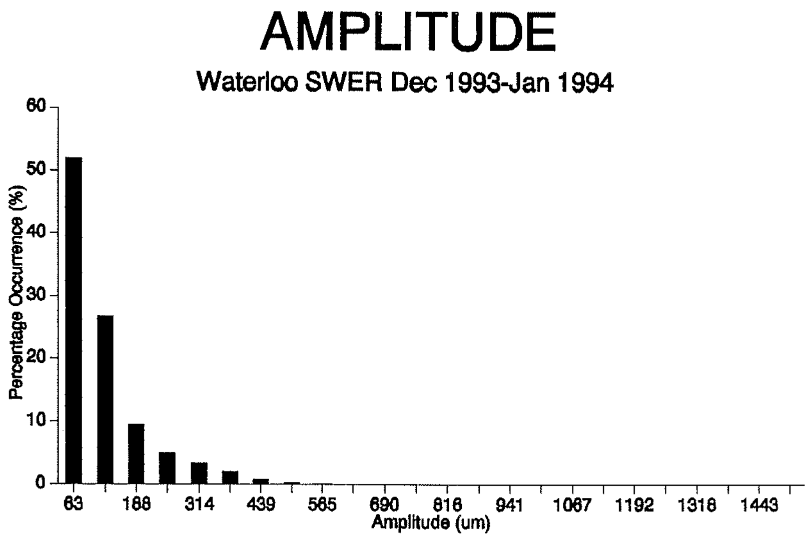


Figure 5.9 Summary of Amplitude Recordings - 1 Damper

Amplitude (μm)	Stress (MPa)	N ($x10^6$) S-N Data	n No. of Cycles	n/N ($x10^{-6}$)	%
63	2.14	2773000	564571	0	-
125	4.24	46957	290352	6	0.40
188	6.37	4136.70	103413	25	1.67
251	8.51	740.520	54844	74	4.94
314	10.64	195.260	36736	188	12.54
376	12.75	66.810	22476	336	22.41
439	14.88	26.560	9785	368	24.55
502	17.02	12.930	3770	292	19.48
565	19.15	7.160	1079	152	10.14
627	21.26	4.250	234	55	3.67
690	23.39	2.640	8	3	0.20
			1087268	1499	100

Table 5.12 Cumulative Damage by Amplitude - 1 Damper

Frequency (Hertz)	Wind Velocity (m/s)	n No. of Cycles	$\Sigma(n/N)$ $(x10^{-6})$ per Class	%
10	0.40	22042	0.02	-
20	0.81	14392	0.01	-
30	1.22	17196	0.42	0.03
40	1.62	51060	17.94	1.20
50	2.03	61575	330.64	22.06
59	2.39	92169	842.72	56.22
71	2.88	119784	281.53	18.76
77	3.12	32083	6.58	0.44
91	3.69	131107	4.69	0.33
100	4.05	161093	2.04	0.14
111	4.50	169959	3.70	0.25
125	5.07	93355	5.13	0.34
143	5.80	61780	3.02	0.20
167	6.77	40255	0.52	0.03
200	8.11	19418	0.04	-
		1087268	1499	100

Table 5.13 Cumulative Damage by Frequency - 1 Damper

The above results are based on 3653 ten second samples taken over a period of 38 days. The total recording time is therefore 36530 seconds. To equate the recordings to a period of one year a multiplying factor of 863 must be applied. By application of Miner's rule the fatigue life of the aluminium wires can be estimated.

$$\text{Life} \quad = \quad 1 \,/\, (1499\text{x}10^{-6} \text{ x } 863) \quad = \quad 0.77 \text{ years}$$

$$\text{Total number of cycles/year} \quad \approx \quad 9.4 \text{ x } 10^{8}$$

5.3.3 Results with Two Dampers per Span

The results of the recordings taken with two dampers per span, one each end, are shown below. In Tables 5.14 and 5.15 the relative effects of amplitude and frequency on conductor fatigue life are presented.

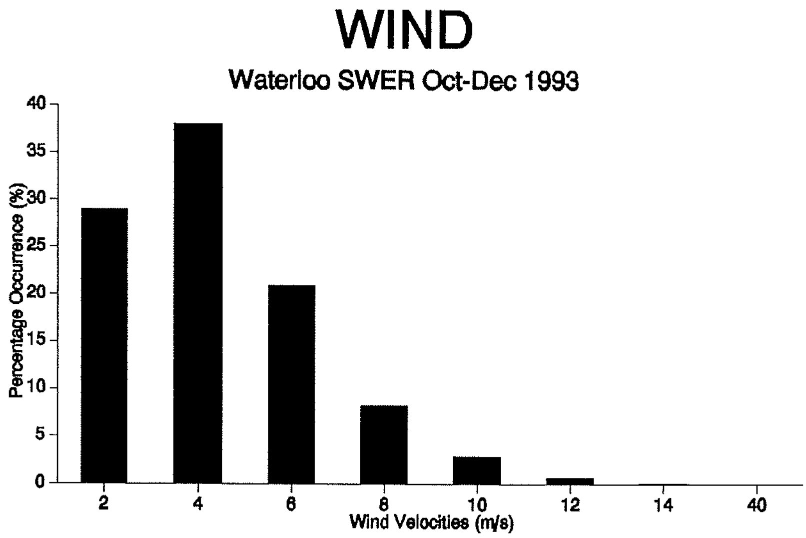


Figure 5.10 Summary of Wind Recordings - 2 Dampers

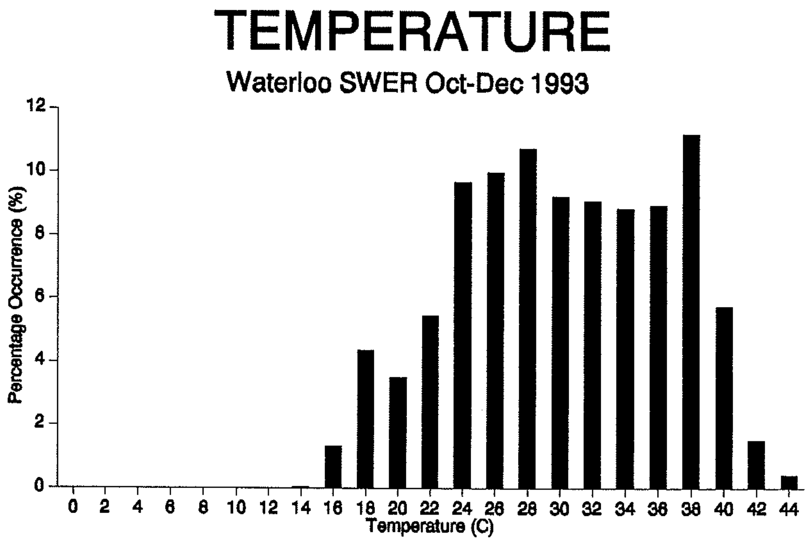


Figure 5.11 Summary of Temperature Recordings - 2 dampers

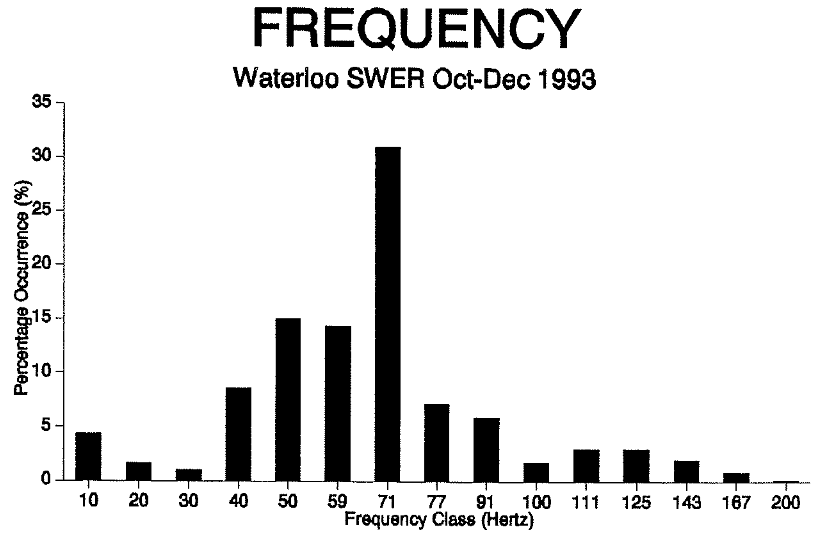


Figure 5.12 Summary of Frequency Recordings - 2 Dampers

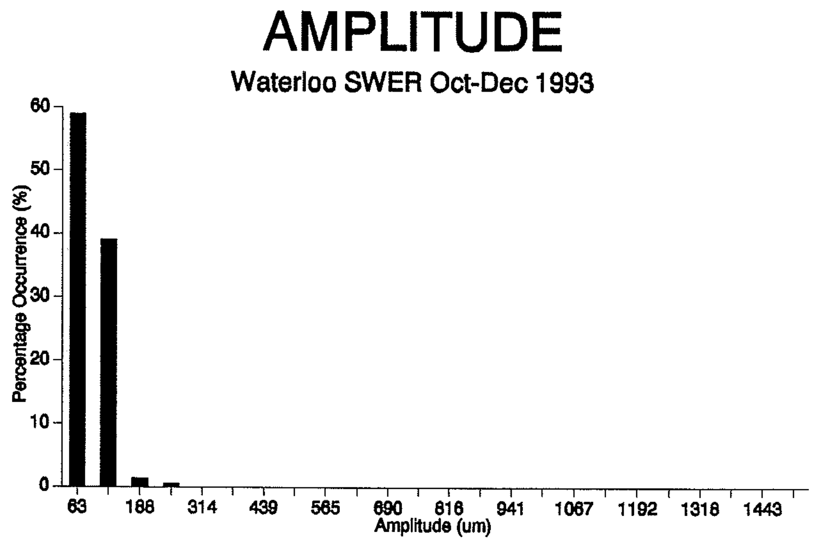


Figure 5.13 Summary of Amplitude Recordings - 2 Dampers

Amplitude (μm)	Stress (MPa)	N ($x10^6$) S-N Data	n No. of Cycles	n/N ($x10^{-6}$)	%
63	2.14	2773000	199072	0.07	1.68
125	4.24	46957	132918	2.83	67.87
188	6.37	4136.70	4855	1.17	28.06
251	8.51	740.520	101	0.10	2.39
			336946	4.17	100

Table 5.14 Cumulative Damage by Amplitude - 2 Dampers

Frequency (Hertz)	Wind Velocity (m/s)	n No. of Cycles	Σ(n/N) ($x10^{-6}$) per Class	%
10	0.40	14734	0.01	0.24
20	0.81	5506	0	-
30	1.22	3584	0.01	0.24
40	1.62	28968	0.68	16.30
50	2.03	50724	1.09	26.14
59	2.39	48461	0.71	17.03
71	2.88	104708	0.99	23.74
77	3.12	24053	0.24	5.75
91	3.69	19812	0.18	4.32
100	4.05	5952	0.05	1.20
111	4.50	10080	0.08	1.92
125	5.07	10139	0.07	1.68
143	5.80	6669	0.04	0.96
167	6.77	2989	0.02	0.48
200	8.11	567	0	-
		336946	4.17	100

Table 5.15 Cumulative Damage by Frequency - 2 Dampers

The above results are based on 4507 ten second samples taken over a period of 58 days. The total recording time is therefore 45070 seconds. To equate the recordings to a period of one year a multiplying factor of 700 must be applied. By application of Miner's rule the fatigue life of the aluminium wires can be estimated.

$$\text{Life} = 1 / (4.17\text{x}10^{-6} \text{ x } 700) = 343 \text{ years}$$

$$\text{Total number of cycles/year} \approx 2.4 \text{ x } 10^{8}$$

5.3.3 Interpretation of Field Test Results

It is clear from the field results that the spiral vibration dampers are very effective in reducing the vibration amplitudes on the SWER lines.

The results of the recordings with one and two dampers show a significant increase in anticipated conductor lifetime. The results of the lifetime calculations are summarised in Table 5.16 below. A comparative assessment against the undamped base case condition is also provided as a factor shown below in parenthesis.

COMPARATIVE	LIFETIMES	
Armoured No Dampers	Armoured One Damper Per Span	Armoured Two Dampers per Span
$2.8\text{x}10^{-3}$ Years (1)	0.77 Years (275)	343 Years (122500)

Table 5.16 Comparative Lifetimes from Field Recordings

The results are significantly better than predicted from the laboratory tests. The laboratory tests with armouring and one damper predicted only a 10 fold increase in conductor life; whereas the field results give an increase in conductor life by a factor of 275.

As pointed out earlier, the laboratory tests can only approximate the service field conditions, and observations of the modes of vibration on the laboratory test span and the field span showed some marked differences.

On the field span, when the line had significant vibration, the application of a single damper reduced the vibration to a level at which it was barely noticeable. This was not the case on the test span however, where with the damper applied the vibration amplitudes were still clearly observable.

It can be seen from Table 5.4 that the application of the dampers during the laboratory testing did not have a marked affect on the number of recorded cycles even though a $31\mu m$ filter was used in the recorder (refer Appendix E). In the field tests however the application of the dampers does appear to have significantly affected the accumulated cycles.

The difference in vibration amplitudes and duration could be the result of a number of factors:

1. The test span is attached to a much more rigid support than the line supported on poles. It is probable that the poles will provide an addition damping mechanism which will translate energy away from the conductor and effectively reduce the amplitudes of vibration. As a result the pole line will have more inherent self-damping than the test span and less energy will be required to excite the span in the laboratory than in the field. The use of a constant power input for the comparative laboratory tests may over estimate the amplitude response of the conductor because of this additional damping factor.
2. The forced type vibration on the test span may not replicate the conditions in the field where the energy build up in the line is restricted by the action of the dampers.

A problem with the interpretation of the field recordings centres around the inability to control the environmental conditions. It is difficult from a statistical point of view to directly compare sets of field recordings because they have been subjected to different wind conditions.

The recordings used for these comparisons are of a reasonably long duration and the recorded wind velocities and percentage occurrences are comparable. The recorded wind velocities for the three cases used in the comparison are provided in Figure 5.14 below.

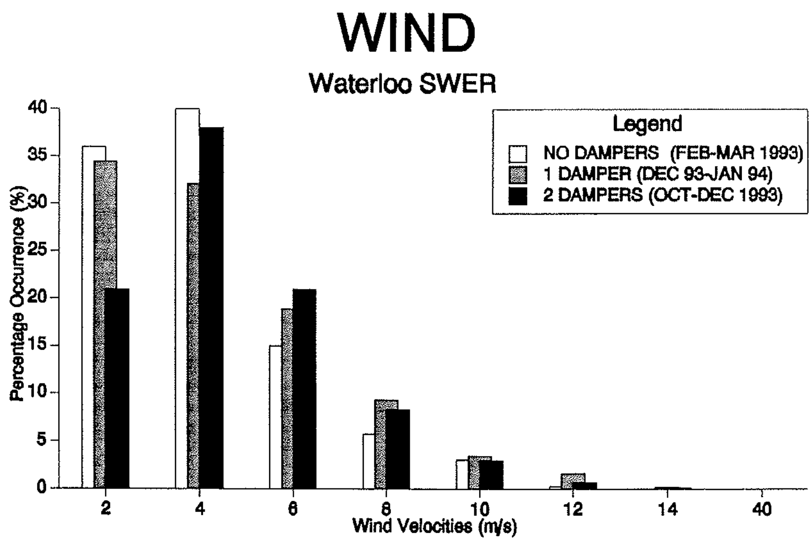


Figure 5.14 Comparison of Wind Velocities For Field Recordings

It is the Author's contention that the frequency sweep tests provide a worst case scenario, and that in service the damper performance will be considerably better than predicted from the laboratory testing. The laboratory testing does however provide a valuable insight into the performance of the dampers and although the results do appear to be somewhat conservative, they provide an assurance which can only be obtained under controlled environmental conditions or through exhaustive field testing.

As pointed out above the application of two dampers appears to reduce to number of recorded cycles. This allows for a review of the allowable fatigue strength level in the aluminium wires. The cycles are now accumulating at around 2.4×10^8 cycles per year. So for a service life of 30 years, the fatigue strength of the aluminium can now be referenced to 7.2×10^9 cycles. This provides for a fatigue strength of 5.8MPa and a corresponding"bending amplitude, Y_b" of 0.170mm peak to peak. This is reflected in Figure 6.1 by a shift in the critical stress level for aluminium wires to a higher level than indicated in Figure 4.1 of Section 4.2.

6. CONCLUSIONS AND RECOMMENDATIONS

The work carried out by the University of Central Queensland on the remaining fatigue life of the steel wires in the recovered ACSR, confirms that the probability of total mechanical failure of the 3/4/2.50 ACSR/GZ conductor is acceptably small even where the fatigue failure of aluminium wires has occurred. With this consideration, the work done in this research project has focused on the following areas:

1. Eliminating the possibility of further damage to the steel wires in the ACSR conductors and thus ensuring the mechanical integrity of the lines;
2. Limiting the accumulated damage to the aluminium wires in the ACSR conductors to a level where fatigue failures are not prevalent;
3. Controlling the vibration amplitudes to levels where the integrity of the ties and line support hardware is assured; and
4. Investigating the impact of conductor tension on fatigue life, so that realistic stringing tensions can be used for future lines.

6.1 RECOMMENDATION ON DAMPING

The results of the field tests on spiral vibration dampers is summarised below in Figure 6.1.

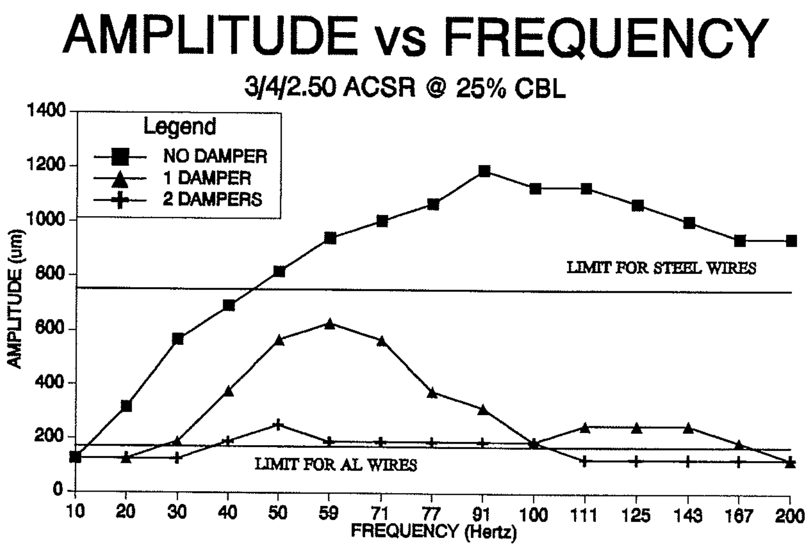


Figure 6.1 Comparison of Field Damper Tests

A comparison of the accumulated fatigue damage to the conductor with the various damper arrangements is summarised in Figure 6.2 below. The ordinate axis has a log scale to more clearly demonstrate what impact the adding of successive dampers has on the cumulative damage by frequency class.

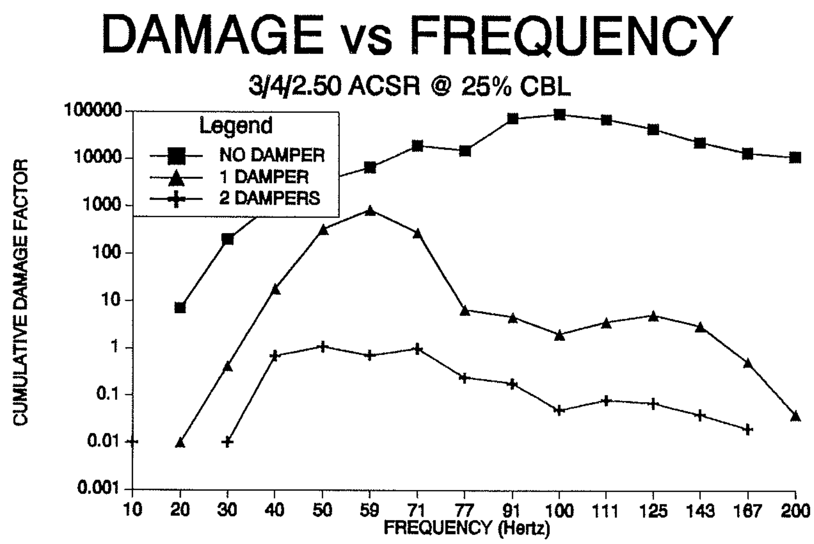


Figure 6.2 Comparison of Accumulated Damage from Field Damper Tests

It is predicted in Section 5.1 that the effectiveness of spiral vibration dampers will increase with frequency. This prediction is supported by the field results summarised in Figures 6.1 and 6.2 above where the application of successive dampers results in a shift of the peak amplitude responses and accumulated damage to the lower frequency levels.

During the comparative field trials the condition of the ties and support hardware was closely monitored. In addition, the impact of the recorder probe on the armour rods was observed.

These results lead to the evaluation of the following options for damping the ACSR conductor.

Option 1. No Dampers

While the tests carried out by the UCQ could not find statistically significant accumulated fatigue damage in the steel wires, the conductor had only been in service since 1984. Figure 6.1 confirms that where no dampers are fitted to the line, amplitudes above the considered safe level for the steel wires is occurring and this will result in a finite life for the conductor. It is difficult to predict an actual service life, however any risk of total mechanical failure of the conductor is unacceptable.

An inspection of the hand tie and support hardware on undamped ACSR lines after the recording period with no dampers indicated that fretting was a problem even after such a short period of service. Aluminium oxide had appeared at most interfaces and some damage to the tie was already obvious. The recorder probe had worn a significant mark in the armour rod to a depth of 2.5mm.

When the consideration of mechanical integrity is coupled with the prospect of on going problems with the ties and support hardware as a result of fretting arising from the large relative movements at the structure, it is clear that leaving the conductors undamped is not a reasonable option.

Option 2. One Damper per Span

The application of one damper per span will probably suffice to ensure the mechanical security of the conductor as the vibration amplitudes are restricted to well below the critical level for the steel wires. Significant damage however may still accumulate in the aluminium wires leading to possible fatigue failures. A more important consideration is whether the risk of continued fretting damage to the ties and support hardware has been averted.

The inspection of the ties and support hardware after each recording period revealed that only minor fretting had taken place, but some small amounts of aluminium oxide were beginning to appear particularly at the interface between the armour rods and the insulator. The recorder probe had marked the armour rod though the indentation was less significant.

Extensive field monitoring of spans with only one damper has not be carried out. However, from the limited recording and inspection undertaken, there appears to be a risk of on going damage to the ties and support hardware as a result of fretting.

While these results are not conclusive, the cost of an additional damper (around $10) and the significant performance improvement gained by another damper tend to support the use of two dampers per span as discussed below.

Option 3. Two Dampers per Span (one at either end)

The application of two dampers per span (one at either end) appears to offer the best option for controlling the amplitude of the vibrations. It can be seen that this option ensures the mechanical security of the lines by restricting the amplitudes to around 25% of the critical level for the steel wires. In addition the critical level for the aluminium wires (to achieve a service life of 30 years) is very close to being achieved. Given the conservative nature of the analysis, this level will in all probability be adequate to ensure that integrity of the aluminium wires in any new lines and reduce the likelihood of fatigue failures in existing lines.

No evidence of fretting or any accumulation of aluminium oxide could be found during the inspection of the ties and support hardware after each recording interval. The recorder probe had not left any discernible mark on the armour rod.

As indicated in Section 1, a trial section of the Waterloo SWER scheme was retied with preform ties and two spiral dampers per span added in 1988. This section of line has since been regularly monitored and no vibration related problems are evident. No fretting or accumulation of aluminium oxide is apparent and vibrations are not discernible on the line. No problems with insulators, clamps or loose hardware have been reported or have been found during inspections.

The results of the laboratory testing, field testing and the five year trial all support the use of two spiral vibration dampers per span on the 3/4/2.50 ACSR/GZ conductor to provide mechanical security for the lines.

6.2 RECOMMENDATION ON TIES AND ARMOURING

It can be seen from the photographs provided in Appendix C, that the aluminium hand ties used to secure the conductor to the support are a source of aggravated fretting on the insulator and armour rods in the presence of aeolian vibration. Furthermore, as pointed out in Section 1.3, fatigue failures of aluminium wires have occurred exclusively at a point under the first tie support immediately adjacent to the insulator. This is generally to be expected as the hand tie and insulator will cause an increase in localised static stresses at this conductor/insulator interface, and when this is coupled with the high dynamic stresses and fretting problems present at this location, the risk of fatigue failures is higher at this location than at any other point on the conductor.

Even with the addition of the recommended damping system, broken or loose hand ties still need to be replaced. The use of preformed ties is recommended as they are specifically designed for the insulator/conductor combination, result in lower static stress concentrations and result in better uniformity of installation. They are not prone to becoming loose as a result of vibration (63) and the neoprene pad eliminates the possibility of fretting of the armour rods on the insulator.

Hand ties which are still secure and not showing signs of fretting (the accumulation of the black aluminium oxide) need not be replaced. The application of damper will be suffice to ensure their security. However where ties need to be replaced, the appropriate preformed tie should be installed.

Where extensive damage has occurred to the armour rods as a result of fretting on the ties and insulators, these armour rods must be replaced. However, even if broken aluminium wires are found under the armour rods, the application of new armour rods will suffice in restoring the mechanical integrity of the conductor. The Author does not consider that the application of repair splices is warranted.

6.3 RECOMMENDATION ON CONDUCTOR TENSIONS

The results of the laboratory tests, comparative damper tests and the monitored five year trial, all indicate that where adequate precautions are taken to limit the impact of aeolian vibration, designs which utilise small diameter ACSR conductors strung at high tensions will provide adequate service.

It can also be concluded that the performance will not be particularly sensitive to small changes in tension. As a result, lines which are considered to be "over tensioned" will still provide adequate service if the appropriate damping system is employed.

The extensive work carried out on 3/4/2.50 ACSR/GZ conductor strung at 25% of CBL, provides clear data that lines at this tension which are armoured and have two spiral vibration dampers per span will not suffer vibration problems even in terrain which is conducive to the establishment of extended periods of line vibration.

This research work clearly shows that the extension of design "rules" derived from the experience with transmission conductors is not appropriate. This is particularly the case when considering ACSR conductors with a high steel content and composite outer layer.

6.4 CONCLUSIONS

From the data collection, analysis and testing carried out, it is concluded that the application of two spiral vibration dampers per span to highly tensioned small diameter ACSR conductor will result in reductions in vibration amplitudes to levels which do not pose a risk to the mechanical integrity of the line.

While some failures of aluminium wires in existing ACSR conductors may continue to occur as a result of the stress cycles already accumulated, the installation of spiral vibration dampers on new lines will suffice to ensure the security of the aluminium wires at those installations.

Field testing has verified the laboratory testing, and it can be concluded that for SWER lines similar to those installed in Capricornia Electricity, the application of spiral dampers will ensure that the full design service life of the conductor can be achieved even on lines with broken aluminium wires.

The results clearly support the continued use of highly tensioned designs for rural applications.

REFERENCES

(1) The Electricity Authority of New South Wales, "High Voltage Earth Return Distribution for Rural Areas", Fourth Edition , June 1978.

(2) Mandeno, L. "Rural Power Supply, especially in Back-Country Areas", Proceedings, Institution of Engineers, New Zealand, Vol. 33, 1947.

(3) Harvey, J.L.W., Richardson, B.C.E., Montgomery, I.B. "Single Wire Earth Return High Voltage Distribution for Victorian Rural Areas", Elec. and Mech. Engineering Transactions, May, 1959.

(4) Robertson, E. "Rural Electrification by Means of High Voltage Earth Return Power Lines", Electrical Engineering Transactions, March, 1965.

(5) Harvey, J.W.L., Davis, H.T. "Co-ordination of Power and Telecommunication Systems in Australia", CIGRE, 19th Convention, Vol. 3, May 1962.

(6) MacIntosh, M.E. "The Limits of the Single Wire Earth Return System of High Voltage Distribution, as Affected by Telecommunication Co-ordination Problems", Electrical Engineering Transactions, March, 1966.

(7) "Code of Practice for Earth Return High Voltage Power Lines", ESAA, 1969. (Reprint 1977). (Supersedes the Conditions for Single Wire Earth Return High Voltage Lines, 1962.)

(8) Taylor, J. Effeney, T. "Service Experience with Single Wire Earth Return Distribution Systems in Central Queensland", 7th CEPSI, 1988.

(9) "Transmission Line Reference Book, Wind-Induced Conductor Motion", Electric Power Research Institute, 1979.

(10) Varney, T. "Notes on the Vibration of Transmission Line Conductors", AIEE Transactions, 1926.

(11) Holts, J.G. "Vibration of Conductors", CIGRE Proceedings, Bd ll, page 582, 1931.

(12) Bate, E. "The Vibration of Transmission Line Conductors", Journal of Institution of Engineers, Vol. 2, No. 8, 1930.

(13) Ryle, P.J. "Some Transmission Line Vibration Observations", CIGRE Report No. 214, 1935.

(14) Davidson, A.E., Inglis, A., Martinoff, V.M. "Vibration and Fatigue in Electrical Conductors", Transactions AIEE-USA, 1932.

(15) Stockbridge, G.H. "Overcoming Vibration in Transmission Cables", Electrical World, Vol. 86, 1925.

(16) Carroll, J.S. "Laboratory Studies of Conductor Vibration", CIGRE Report No. 233, May 1936.

(17) Bückner, W. "Retrospective View at the Efforts Made to Solve the Problem of Aeolian Conductor Vibration on Overhead Transmission Lines", Electra, No.120, 1985.

(18) Zetterholm, O.D. "Report on the Work of the CIGRE Committee No.6: Bare Conductors and Mechanical Calculation of Overhead Lines", CIGRE Proceedings, 1960.

(19) CIGRE Working Group 22.01. "Aeolian Vibration on Overhead Lines", CIGRE Report 22-11, 1970.

(20) Electricity Supply Association of Australia. "Code of Practice for Overhead Line Construction", ESAA, C(b)1-1962.

(21) "Uniform Practice Manual for the Mechanical Design of Overhead Electric Lines - SEC(Q)M1-1977", Queensland Government Gazette, July 1977.

(22) Electricity Supply Association of Australia. "Guidelines for Design and Maintenance of Overhead Distribution and Transmission Lines", ESAA C(b)1-1991.

(23) Alt, K., Bauer, K.H., Boos, K.V., Jürdens, C., Paschen, R. "Dynamic Effects on Transmission Lines", CIGRE 22-08, 1984.

(24) Fusheng, Jia., Zhonghua, Pan., Naiguang, Xiu, "Aeolian Vibration and Ice Problems on Transmission Lines in China", CIGRE 112-04, 1981.

(25) Barber, K.W., Callaghan, K.J. "New Aluminium Alloy Overhead Line Conductors in Australia ", 7th CEPSI Conference, Paper 3-34, 1988.

(26) Pettersson, A.R., Bronnvall, W. "A Swedish Standard for Overhead Aluminium Alloy Conductors with 59% Conductivity (IACS)", IEE, Overhead Line Design and Construction, 1988.

(27) White, H.B. "Limits of Conductor Use", Presentation to the Task Force on Safe Design Tensions, IEEE/PES Winter Meeting, New Orleans, 1987.

(28) Bückner, W., Kerner, H., Philipps, W. "Stresses in Transmission Line Conductors Near the Suspension Clamp", CIGRE Report No. 23-07, 1986.

(29) IEEE Committee Report. "Standardisation of Conductor Vibration Measurements", IEEE Transactions, Vol. PAS-85, 1966.

(30) Komenda, R.A., Swart, R.L. "Interpretation of Field Vibration Data", IEEE Paper, 1968.

(31) Poffenberger, J.C., Swart, R.L. "Long-Term Vibration Study with the Live Line Recorder", IEEE Conference Paper, C71/159, 1971.

(32) Philipps, W., Carlshem, W., Bückner, W. "The Endurance Capability of Single and Bundle Transmission Line - Conductors and its Evaluation", CIGRE Report No. 22-05, 1972.

(33) Bückner, W.F., Helms, R., Papailiou, O. "Determination of the Lifetime of Transmission Conductors on the Basis of Vibration Measurements and Fatigue Tests", 1985.

(34) CIGRE Working Group 22.04. "Recommendations for the Evaluation of the Lifetime of Transmission Line Conductors", Extract from Electra No. 63, 1979.

(35) EPRI EL-1946, "Conductor Fatigue-Life Research", Final Report, Research Project 1278-1, July 1981.

(36) Australian Standard AS 3607. "Conductors - Bare Overhead, Aluminium and Aluminium Alloy - Steel Reinforced", 1989.

(37) Australian Standard AS 1222.1. " Steel Conductors and Stays - Bare Overhead, Part 1 - Galvanised (SC/GZ)", 1992.

(38) Australian Standard AS1442. "Carbon Steel and Carbon-Manganese Steels - Hot-Rolled Bars and Semifinished Products", 1992.

(39) Australian Standard AS 2848.1. "Aluminium and Aluminium Alloys - Compositions and Designations, Part 1 - Wrought Products", 1986.

(40) Thomas, R.H. "Determination of Fatigue Damage to 3/4/2.50 ACSR/GZ Conductor", University of Central Queensland, 1993.

(41) Dulmison Australia, "Spiral Vibration Dampers", Technical Brochure, QAFPG18-01/2 Issue 1, 1983.

(42) Whapman, R., Champa, R.J. "Wind Induced Vibrations of Overhead Shield Wires", Preformed Line Products Company, March 1983.

(43) Hard, A.R., Holben, R.D. "Application of the Vibration Decay Test to Transmission Line Conductors", IEEE, Vol. PAS-86, 1967.

(44) Preformed Line Products Company, "Spiral Vibration Dampers", Technical Brochure, 8-200, 1962.

(45) Simmons, J.M., Cleary, P.M.G. "Measurement of Aerodynamic Power Associated with Vortex-Induced Vibration of Electrical Transmission Lines", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 1 Jan/Feb, 1980.

(46) IEEE, "Guide on the Measurement of the Performance of Aeolian Vibration Dampers for Single Conductors", IEEE Standard 664, 1980.

(47) Capricornia Electricity, "Laboratory Testing of Spiral Vibration Dampers", Report 1993.

(48) IEEE, "Guide on Conductor Self-Damping Measurements", IEEE Standard 563, 1978.

(49) Mackness, C.R. "Mechanical Damage to SWER Conductors as a Result of Aeolian Vibration", Report for Capricornia Electricity, 1989.

(50) Capricornia Electricity, "Report on Condition of Stonehenge SWER Scheme and Recommended Refurbishment", 1992.

(51) Geelan, G.T. "Repair and Maintenance of Vibration Damage on Rural Lines", ESEA Regional Conference, April 1990.

(52) Capricornia Electricity, "Report on Vibration - Kensington SWER, Undamped", 1992.

(53) Capricornia Electricity, "Report on Vibration - Stormhill SWER, Undamped", 1992.

(54) Capricornia Electricity, "Report on Vibration - Stonehenge SWER, Undamped", 1992.

(55) Capricornia Electricity, "Report on Vibration - Waterloo SWER, Undamped", 1993.

(56) Capricornia Electricity, "Report on Vibration - Waterloo SWER, One Damper, Preform Tie", 1993.

(57) Capricornia Electricity, "Report on Vibration - Waterloo SWER, One Damper, Hand Tie", 1994.

(58) Capricornia Electricity, "Report on Vibration - Waterloo SWER, Two Dampers, Preform Tie", 1993.

(59) Capricornia Electricity, "Report on Vibration - Waterloo SWER, Two Dampers, Hand Tie", 1993.

(60) American Society for Testing and Materials. "Standard Method for Torsional Testing of Wire", Designation E558-83.

(61) Havard, D.G., Bissada, M.K., Fajardo, C.G., Horrocks, D.J., Meale, J.R., Motlis, J., Tabatabai, M., and Yoshiki-Gravelsins, K,S. "Aged ACSR Conductors Part II - Prediction of Remaining Life", IEEE Transaction on Power Delivery, Vol. 7, No. 2, April 1992.

(62) Private Correspondence with the Convener of the CIGRE Australian Panel 22, Mr Philip Dulhunty.

(63) Zastawnik, J.E., Champa, R.J. "Conductor Vibration Protection, Field Inspection and Repair Techniques", Preformed Line Products, 1980.

(64) Bruniar, R.M., Ramey, G., Duncan, R.R. "An Experimental Evaluation of S-N Curves and Validity of Miner's Cumulative Damage Hypothesis for an ACSR Conductor", IEEE Transaction on Power Delivery, Vol 3, No. 3, July 1988.

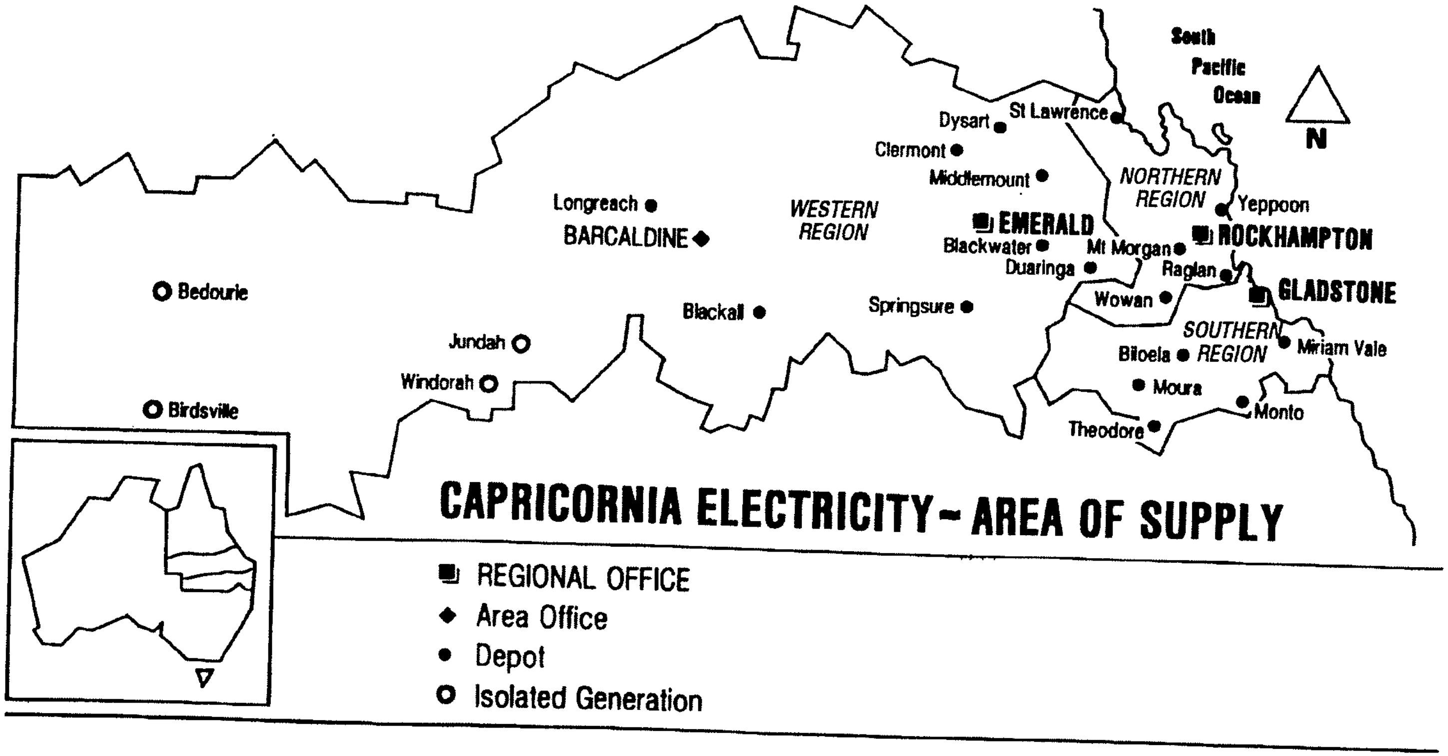


Figure A.1 Capricornia Electricity - Area of Supply

APPENDIX B

LINE CONSTRUCTION PARAMETERS

In this Appendix a detailed analysis of the conductor and line construction parameters for typical SWER lines in Capricornia Electricity is presented. In addition the allowable stress levels to achieve an adequate fatigue life is derived for the range of conductors used in the SWER Distribution.

B.1 CONDUCTOR PROPERTIES

B.1.1 Range of Conductors

The basis of the SWER line design was to utilise high strength conductors so that long individual spans could be achieved. The range of conductors most commonly used for SWER construction are summarised in Table B.1 below. The conductors are manufactured in accordance with the relevant Australian Standards (1,2).

Name	Stranding		Nominal Diameter (mm)	Cross-Sectional Area (mm^2)	Approx. Mass (kg/km)	Breaking Load (kN)
	Aluminium	Steel				
3/2.75 SC/GZ	-	3/2.75	5.93	17.82	139	22.2
Raisin 3/4/2.50 ACSR/GZ	3/2.50	4/2.50	7.50	34.36	195	24.4
Sultana 4/3/3.00 ACSR/GZ	4/3.00	3/3.00	9.00	49.48	243	28.3

Table B.1 Conductor Properties

B.1.2 Steel Wire Properties

The steel wire use in the conductors shown above is a galvanised (GZ) fully-killed steel in accordance with Australian Standard AS1442 (3). The steel has a minimum ultimate tensile strength of 1310MPa and a modulus of elasticity of 193GPa. The steel is fully-killed to allow for cold drawing of the wire. While the Australian Standard allows for a wide range of steels to be used, BHP Australia has advised that the steel wire is generally drawn from K1068, K1072 or K1077 steel (10).

As pointed out in Section 4 of Appendix D, ferrous materials typically exhibit a fatigue endurance limit. This is the critical (50% probability) stress level which the metal can withstand for an infinitely large number of cycles. BHP could not provide any information on the specific fatigue properties of the steel when included in a stranded conductor, but indicated that a fatigue endurance limit of around 6% of the material tensile strength would be conservative (10).

The EPRI Transmission Line Reference Book (5) gives a fatigue endurance limit of 192MPa for EHS (Extra High Strength) steel based on actual fatigue tests. This EHS steel is very similar to the 1310MPa steel used in Australia. However due to the variability in the steel types used in ACSR and SC conductors in Australia and the need to ensure an adequate safety margin, the critical level of dynamic stress for steel in a stranded conductor has been selected as 80MPa. This is not a published figure but one which has been arrived at based on the Author's conservative review of the available materials information (5,6,9,10).

B.1.3 Aluminium Wire Properties

The Aluminium wires used in the above conductors are alloy 1350 in accordance with Australian Standard AS2848.1 (4). The Aluminium has a minimum ultimate tensile strength of 175MPa and a modulus of elasticity of 68GPA.

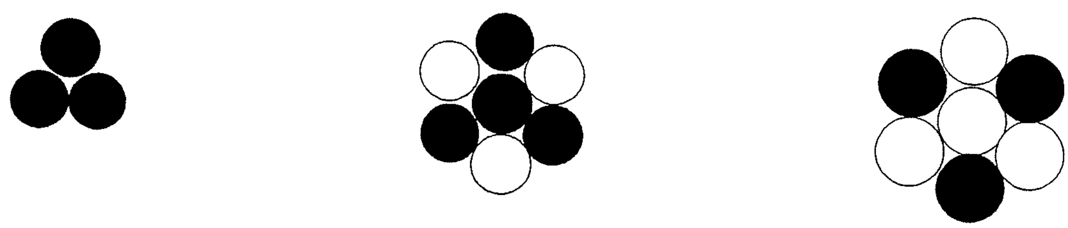
As pointed out in Section 4 of Appendix D, aluminium does not exhibit a fatigue endurance limit and continues to accumulate damage even at very low cyclic stress levels. For aluminium, instead of reporting a fatigue endurance limit, it is necessary to consider the allowable stress levels referenced to the number of cycles. An S-N curve (9) is used to present fatigue test results and forms the basis, using Miner's rule (9), on which conductor life assessments are carried out.

Advice from conductor manufacturers has confirmed the conclusion from the Author's own investigations, that a specific S-N curve for the range of conductors under consideration is not available.

To determine an actual S-N curve for the aluminium wires in a stranded conductor is an exhaustive and time consuming process (5,9). To assist with assessment of conductor fatigue life, CIGRE have provided a "safe border" S-N curve which is recommended for use when an actual S-N curve is not available (9). The S-N curve used for the life assessments in this research is derived in Section B.5 of this Appendix.

B.1.4 Conductor Construction

The layout of the wires in the stranded conductors is as shown in the diagram below.



3/2.75 SC   3/4/2.50 ACSR/GZ   4/3/3.00 ACSR/GZ

Figure B.1 Conductor Construction Details

The conductors are constructed with a right-hand lay in the outerlayer, with a lay ratio of between 12-18. The core of the ACSR conductors is greased.

B.2 TYPICAL LINE CONSTRUCTION PARAMETERS

B.2.1 Stringing Tensions

While the stringing tensions have changed over the years, the vast majority of the SWER lines were constructed utilising the tension shown below. These tensions were the maximum allowable tensions permitted under the Regulations in the Electricity Act, SEC(Q)M1 (7), for conductors with vibration protection. The allowable tensions are expressed in terms of a percentage of the minimum Calculated Breaking Load (CBL) of the conductor and calculated at an ambient temperature of 15°C, no wind.

Conductor Type	%CBL
SC/GZ	33⅓
ACSR	25

Table B.2 Allowable Conductor Tensions

B.2.2 Support and Hardware

For the majority of the SWER lines, the conductors are armoured and hand tied on Standard Line Pins (typically SLP22/420) in accordance with the Capricornia Electricity Standard Construction Drawings V2-S4-P1 and V2-S9-P11 shown as part of this Appendix. The armouring was included as vibration protection and to provide some electrical protection for the conductor in the event of a lightning flash-over.

No additional damping devices were included on any of the lines when they were first erected.

B.3 STATIC TENSILE STRESSES

When considering the static tensile stress levels in conductors subjected to vibration, it is considered to be good practice to use a reference temperature equivalent to the mean of the winter season temperatures (8). Information provided by the Bureau of Meteorology in Longreach indicates that the mean winter temperature for Central Queensland is around 15°C. This temperature is equivalent to the base stringing tensions outlined in Section B.2.1 above. The static tensile stresses in the individual conductor wires are shown in Table B.3 below. These were calculated using the formula (D.1) presented in Appendix D, Section D.1.1.

Conductor Name	Tension in Conductor at 15°C, no wind (N)	Stress in Outer Layer Steel Wires (MPa)	Stress in Outer Layer Aluminium Wires (MPa)
3/2.75 SC/GZ	7400	415.0	-
3/4/2.50 ACSR/GZ	6100	245.8	86.6
4/3/3.00 ACSR/GZ	7075	227.0	80.0

Table B.3 Static Tensile Stresses in SWER Conductors

Based on the stress levels in the ACSR wires it is possible to calculate the proportion of static line tension carried by the steel and aluminium wires as shown in Table B.4 below.

Conductor Name	% of Tensile Load carried by Steel Wires	% of Tensile Load carried by Aluminium Wires
3/4/2.50 ACSR/GZ	79	21
4/3/3.00 ACSR?GZ	68	32

Table B.4 Percentage of Tensile Load carried by Aluminium and Steel

While the percentage of tensile load carried by the aluminium wires is relatively low, the stress levels in the aluminium wires is very high when compared to a conductor that does not have a composite outer layer. Typically the stress levels in homogeneous outer layer ACSR conductors are of the order of 30-40MPa (6). The fact that the aluminium stresses are not in the normal range was one of the primary reasons for undertaking this research project. No published data could be found on fatigue properties of conductors with composite outer layers or where the outer layer aluminium stresses were so high.

The model presented in Appendix D and used to calculate the material stress assumes that both the aluminium and steel are acting elastically. Also no allowance is made for the creep related load transfer from the aluminium to the steel. Published data indicates that the load transfer could be as high as 15MPa (9) for transmission conductors.

Because of the uncertainties associated with the stress distribution within composite outer layer conductors, a span of 3/4/2.50 ACSR conductor was erected and tests were carried out by the Mechanical Engineering Department from the University of Central Queensland. Miniature strain gauges were attached to each outer layer wire and readings taken over a range of tension settings. The results of this work are reported in reference (11) with the general conclusion that Aluminium and Steel are both acting elasticity and sharing the load in accordance with the classical proportional areas model.

In the life assessment analysis presented in the Thesis, a stress level in the aluminium wires of 86.6MPa has been used. This is considered to be a necessarily conservative approach with no allowance made for creep and with the static tensile stress based on the mean winter temperature of 15°C.

B.4 DYNAMIC STRESSES

By using the Poffenberger-Swart formula (D.11) presented in Appendix D, Section D.3, it is possible to relate the dynamic bending stress (σ) in the outer layer wires to the bending amplitude (Y_b) measured 89mm from the last point of contact of the conductor with the support.

$$\sigma = K\ Y_b \tag{B.1}$$

The equation above is derived based on the assumption that the conductor acts like a homogeneous beam (5). The ACSR conductors used in SWER lines have a very high steel content compared with those used in normal distribution and transmission lines. The SWER conductors are very stiff with little interlayer slippage capacity and are likely to conform more closely with the theoretical model than large multi-layer conductors.

To calculate K, the Flexural Rigidity (EI) of the conductors must first be calculated. The flexural rigidity of a stranded conductor can vary quite markedly depending upon whether it is assumed that all wires act independently or act together as a single unit. When considering the stresses in the outer layer wires, it is normal to assume (5) that all wires are acting independently, with minimum rigidity, as this gives the worst case stress relationship. Reference (5) provides the following formula for estimating the minimum flexural rigidity of a stranded conductor.

$$EI_{min} = n_s\, E_s\, (\,\pi\, d_s^{\,4} / 64\,) + n_a\, E_a\, (\,\pi\, d_a^{\,4} / 64\,) \tag{B.2}$$

where EI_{min} = Minimum Flexural Rigidity (Nm^2)

n_s = Number of Steel Wires

n_a = Number of Aluminium Wires

E_s = Modulus of Elasticity of Steel (MPa)

E_a = Modulus of Elasticity of Aluminium (MPa)

d_s = Diameter of Steel Wires (m)

d_a = Diameter of Aluminium Wires (m)

In the Table B.5 below the factors which relate bending amplitude to dynamic stress in the outer layer wires have been calculated. For the composite outerlayer ACSR conductors, factors for both the Aluminium and Steel wires are presented.

Conductor Name	Flexural Rigidity EI_{min} (Nm^2)	Aluminium Factor K (MPa / mm)	Steel Factor K (MPa / mm)
3/2.75 SC/GZ	1.625	-	120.64
3/4/2.50 ACSR/GZ	1.871	33.90	96.20
4/3/3.00 ACSR/GZ	3.384	34.54	98.05

Table B.5 Dynamic Stress Factors for SWER Conductors

It can be shown that in the event of total fatigue failure of all aluminium wires in the ACSR conductors above, that Factor K for the steel would only rise by around 10 - 15%. The actual calculated figures are shown below.

Conductor Name	Steel Factor K (MPa / mm)
3/4/2.50 ACSR/GZ	105.40
4/3/3.00 ACSR/GZ	112.87

Table B.6 Worst Case Dynamic Stress Factors

Where fatigue damage to the aluminium wires in the ACSR conductors has occurred, the factors shown in Table B.6 should be used in assessing the fatigue endurance limits for the steel wires in those conductors. The above factors assume that the full tensile load is taken by the steel and this results in the most conservative fatigue rating for the damaged conductor.

B.5 S-N CURVE FOR ALUMINIUM WIRES

From the factors calculated above, it is now possible to express the CIGRE "safe border" S-N curve in terms of the amplitude classes used in recording the field data. The details of the relevant data recording classes are provided in Section E.6 of Appendix E.

Class No.	Upper Limit (μm)	Number of Cycles, n (x10^6)	Class No.	Upper Limit (μm)	Number of Cycles, n (x10^6)
1:	63	2773000	17:	1067	0.298
2:	125	46957	18:	1129	0.225
3:	188	4136.70	19:	1192	0.171
4:	251	740.520	20:	1255	0.132
5:	314	195.260	21:	1318	0.104
6:	376	66.810	22:	1380	0.082
7:	439	26.560	23:	1443	0.066
8:	502	12.930	24:	1506	0.053
9:	565	7.160	25:	1569	0.043
10:	627	4.250	26:	1631	0.036
11:	690	2.640	27:	1694	0.030
12:	753	1.700	28:	1757	0.025
13:	816	1.140	29:	1820	0.021
14:	878	0.790	30:	1882	0.017
15:	941	0.559	31:	1945	0.015
16:	1004	0.404	32:	2000	0.013

Table B.7 S-N Curve Values for 3/4/2.50 ACSR/GZ @25% CBL

For 3/4/2.50 ACSR/GZ conductor strung at 25% of CBL, the "safe border" S-N curve can be expressed in terms of the bending amplitude through the revised Appendix D equations (D.12) below

$$Y_b = 13.274\ N^{-0.200} \text{ for the range } N \leq 2x10^7 \qquad (B.3)$$
$$Y_b = 7.758\ N^{-0.168} \text{ for the range } N \geq 2x10^7$$

where Y_b = Bending Amplitude, peak to peak (mm)

N = Number of Cycles

The allowable number of cycles referenced to the recorder bending amplitude classes are shown in Table B.7 above.

It is normal to present the results in a graphical form as shown in Figure B.2 below.

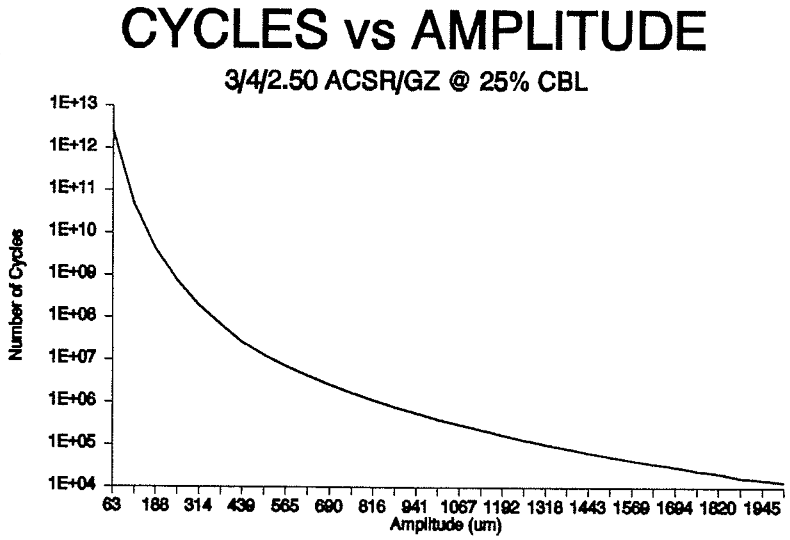


Figure B.2 Summary of Cycles vs Amplitude for 3/4/2.50 ACSR/GZ

As pointed out in Appendix D the use of the "safe border" S-N curve will produce a very conservative assessment of conductor fatigue life when it is applied to single layer ACSR conductors of the construction type being considered here. In addition to this, a number of other factors used in the derivation of the above curve will also ensure a very conservative result. These factors are as follows:

1. The worst case static stress for the conductor at 25% CBL has been used

in the derivation by assuming an operating temperature of 15°C and making no allowance for creep; and

2. The maximum amplitude in each recording class has been used to calculate the allowable cycles, whereas the actual amplitudes in service will be spread over the recording range.

B.6 IMPACT OF TENSION CHANGES

As described in Appendix D, Section 4, changes in conductor tension impact upon the velocity of the travelling wave and the associated loop length. A tension increase will thus impact upon the dynamic stress in the conductor through the Poffenberger-Swart formula which includes as a factor the conductor horizontal tension. Calculations have been carried out for 3/4/2.50 ACSR/GZ conductor at 15.5% and 35% of CBL to allow for comparison with the 25% CBL values above. The results are given in the Table B.8 below.

3/4/2.50 ACSR/GZ							
Wind Velocity (m/s)	Frequency (Hertz)	Loop Length (m)			Aluminium Factor K (MPa/m)		
		15%	25%	35%	15%	25%	35%
0.53	17.70	3.87	5.00	5.91	28.1	33.9	38.6
1.06	35.40	1.93	2.50	2.95			
2.11	70.80	0.97	1.25	1.48			
5.28	177.00	0.39	0.50	0.59			
10.56	354.00	0.19	0.25	0.29			

Table B.8 Impact of Tension Changes

The impact of significant tension changes on the dynamic stress levels is relatively small when compared to the impact of vibration amplitude changes. This further supports the position that, while static tensile loads are a contributing factor, it is the level of dynamic stress in the conductor outer layer which is most closely related to the conductor fatigue life.

Ambient temperature changes due to seasonal variations will also impact on the conductor tensions and hence the static stress levels. However these variations will be relatively small compared to the tension changes considered above.

Considering the relatively small impact of tension change and the large margin of safety provided by the safe-border analysis, the Author has chosen to use the one S-N curve for the analysis of the 3/4/2.50 ACSR/GZ conductor even where there is a measured difference between design (25% CBL) and actual installed tension.

B.7 SPAN LENGTHS AND NATURAL FREQUENCIES

A typical span for the ACSR conductors used in SWER schemes is 250m whereas the Steel is typically spanned to 350m. The following tables present the natural vibration frequencies for the various conductors for the range of wind speeds 0.5 - 10 m/s based on the typical spans above. The formulae used have been presented in Appendix D.

3/2.75 SC/GZ @ 33⅓% CBL, SPAN = 350			
No. of Loops, n	Loop Length, l (m)	Frequency = 0.329 n (Hertz)	Wind Velocity = 3.21×10^{-2} f (m/s)
50	7.00	16.45	0.53
100	3.50	32.90	1.06
200	1.75	65.80	2.11
500	0.70	164.50	5.28
1000	0.35	329.00	10.56

Table B.9 Natural Frequencies 3/2.75 SC/GZ

3/4/2.50 ACSR/GZ @ 25% CBL, SPAN = 250m			
No. of Loops, n	Loop Length, l (m)	Frequency = 0.354 n (Hertz)	Wind Velocity = 4.05×10^{-2} f (m/s)
50	5.00	17.70	0.72
100	2.50	35.40	1.43
200	1.25	70.80	2.87
500	0.50	177.00	7.17
1000	0.25	354.00	14.35

Table B.10 Natural Frequencies for 3/4/2.50 ACSR

4/3/3.00 ACSR/GZ @ 25% CBL, SPAN = 250m			
No. of Loops	Loop Length, l (m)	Frequency = 0.341 n (Hertz)	Wind Velocity = 4.86×10^{-2} f (m/s)
50	5.00	17.05	0.83
100	2.50	34.10	1.66
200	1.25	68.20	3.32
500	0.50	170.50	8.29
1000	0.25	341.00	16.59

Table B.11 Natural Frequencies for 4/3/3.00 ACSR/GZ

APPENDIX B - REFERENCES

(1) Australian Standard AS 3607. "Conductors - Bare Overhead, Aluminium and Aluminium Alloy - Steel Reinforced", 1989.

(2) Australian Standard AS 1222.1. " Steel Conductors and Stays - Bare Overhead, Part 1 - Galvanised (SC/GZ)", 1992.

(3) Australian Standard AS1442. "Carbon Steel and Carbon-Manganese Steels - Hot-Rolled Bars and Semifinished Products", 1992.

(4) Australian Standard AS 2848.1. "Aluminium and Aluminium Alloys - Compositions and Designations, Part 1 - Wrought Products", 1986.

(5) "Transmission Line Reference Book, Wind-Induced Conductor Motion", Electric Power Research Institute, 1979.

(6) Electricity Supply Association of Australia. "Guidelines for Design and Maintenance of Overhead Distribution and Transmission Lines", ESAA C(b)1-1991.

(7) "Uniform Practice Manual for the Mechanical Design of Overhead Electric Lines - SEC(Q)-M1-1977", Queensland Government Gazette, July 1977.

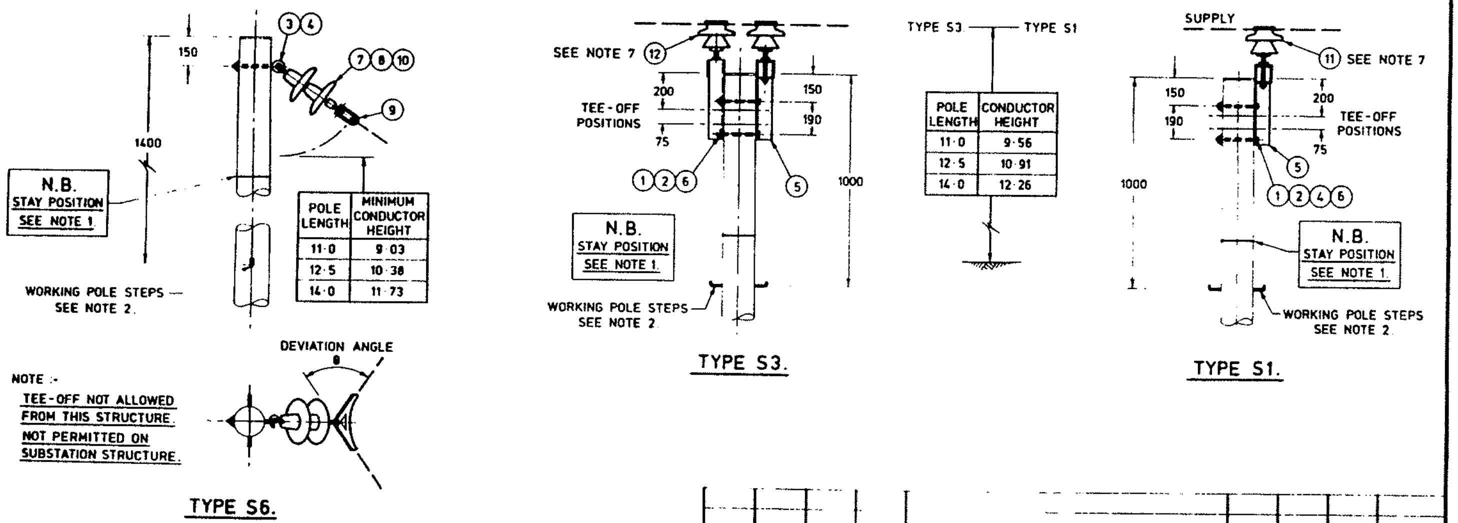
(8) Gibson, B. St C. "A Design Criterion for Conductor Fatigue Endurance on Overhead Transmission Lines", TLINE Consultants, 1991.

(9) CIGRE Working Group 22.04. "Recommendations for the Evaluation of the Lifetime of Transmission Line Conductors", Extract from Electra No. 63, 1979.

(10) Private Correspondence with Mr John Barrett, Technical Sales Metallurgist, BHP Australia, July 1992.

(11) Thomas, R.H. "Determination of Stresses in 3/4/2.50 ACSR/GZ Conductor", University of Central Queensland, 1993.

Figure B.3 Standard Construction Drawing - SWER



NOTE :-
TEE-OFF NOT ALLOWED FROM THIS STRUCTURE.
NOT PERMITTED ON SUBSTATION STRUCTURE.

NOTES:

1. STAY POSITIONS: 12·7 kV - 450mm CLEAR OF ALL METAL
   19·0 kV 600mm CLEAR OF ALL METAL.
2. POLE STEPS: REMAINING POLE STEPS TO BE FITTED AT 450mm CENTRES ON ALTERNATE SIDES OF THE POLE.
3. EYEBOLTS: THREADS TO BE BURRED TO PREVENT LOOSENING.
4. TIMBER PRESERVATIVE: ALL DRILLED POLE HOLES TO BE COATED WITH PETROLEUM BASED TIMBER PRESERVATIVE.
5. ALLOWABLE DEVIATION ANGLES: FOR DEVIATION ANGLES REFER TO H.V LINE SCHEDULES.
6. MINIMUM CONDUCTOR HEIGHT: CALCULATED USING STANDARD SETTING DEPTH FOR THE POLE. MINIMUM CONDUCTOR HEIGHT FOR TYPE S6 STRUCTURE IS CALCULATED ASSUMING A MINIMUM CONDUCTOR SWING ANGLE OF 17°
7. WASHERS: SPRING WASHERS NOT REQUIRED ON INSULATOR PINS

ITEM	QUANTITY TS6	QUANTITY TS3	QUANTITY TS1	DESCRIPTION	DRAWING VOL	DRAWING SECT	DRAWING PAGE	BIN Nº
12		2		INSULATOR ASSEMBLY TYPE 3	2	5	1	
11			1	INSULATOR ASSEMBLY TYPE 1	2	5	1	
				DISC INSULATOR, 250mm, MUNSEL GREY				5 5109 8
10	2			DISC INSULATOR, 250mm., BROWN				5 5106 3
				DISC INSULATOR, 250mm., GLASS				5 5100 4
9	1			ANGLE CLAMP, AC4.				4 1386 3
8	1			HOOK, BALL, SHORT SHANK, 16mm.	1	1	10	4 3506 8
7	1			SOCKET TONGUE, 16mm.	1	1	11	4 7645 7
6		2	2	WASHER ROUND 20 ϕ	1	1	4	17 7757 7
5		2	1	BRACKET POLE TOP	1	1	28	4 0599 1
4	1		2	WASHER SQUARE 75 × 75 × 6 × 20 ϕ	1	1	4	17 8059 4
3	1			EYEBOLT M20 × 300	1	1	5	17 1300 5
2		2	2	SPRING WASHER 20 ϕ	1	1	62	17 7810 7
				BOLT H H AND NUT, M20 × 300 - HEAVY POLE	1	1	3	17 0459 6
1		2	2	BOLT H H AND NUT, M20 × 260 - MEDIUM POLE	1	1	3	17 0454 5
				BOLT H.H. AND NUT, M20 × 220 - LIGHT POLE	1	1	3	17 0452 9

THE CAPRICORNIA ELECTRICITY BOARD

12·7kV AND 19kV S.W.E.R.
INTERMEDIATE AND ANGLE TYPES

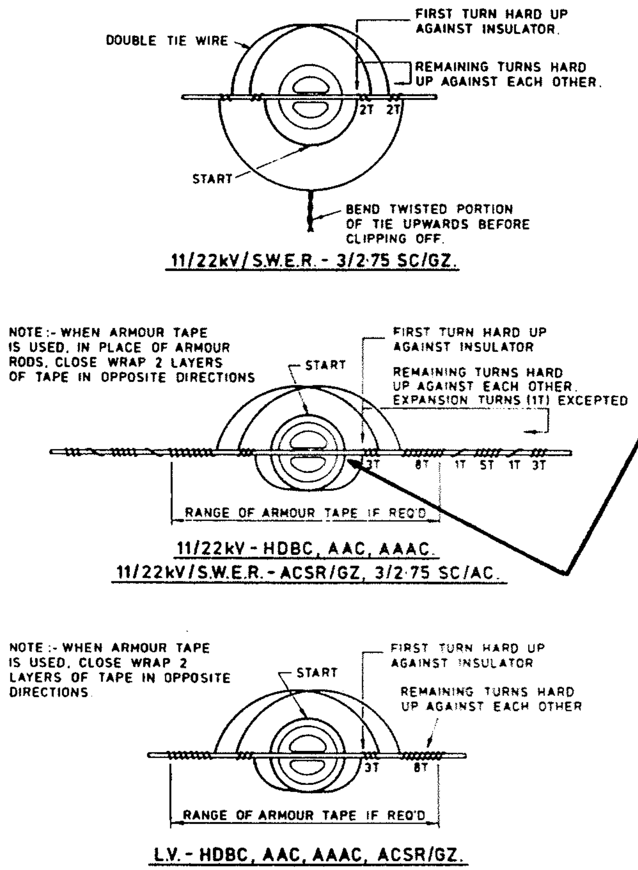
SCALE - DO NOT SCALE.

VOLUME 2 SECTION 4 PAGE 1

DRAWING No. 22 - A2 - 53 A B C D E

DRAWN N.A.R. SUBMITTED PASSED APPROVED DATE CHECKED

REFERENCE DRAWINGS



FATIGUE FAILURES OF ALUMINIUM WIRES AT THIS POINT

✱ TIE LENGTHS FOR SLACK STRINGING AS FOR ARMOUR TAPE

CONDUCTOR	✱ TIE LENGTH: ARMOUR TAPE L.V.	✱ TIE LENGTH: ARMOUR TAPE 11kV	✱ TIE LENGTH: ARMOUR ROD 11kV	✱ TIE LENGTH: ARMOUR ROD 22kV/S.W.E.R	TIE MATERIAL: HAND TIE
6/4·75 - 7/1·7 ACSR	2m	3m	4m	4m	ANNEALED AL 5·18mm
6/1/3·75 ACSR	2m	3m	4m	4m	
6/1/3·00 ACSR	2m	3m	3·5m	4m	
3/4/2·5 ACSR	2m	3m	3·5m	4m	
7/4·75 AAAC	2m	3m	4m	4m	ANNEALED AL 5·18mm
7/3·75 AAAC	2m	3m	4m	4m	
7/4·75 AAC	2m	3m	4m	4m	ANNEALED AL 5·18mm
7/3·75 AAC	2m	3m	4m	4m	
7/3·00 AAC	2m	3m	3·5m	4m	
3/2·75 SC/AC			2m	2m	ANNEALED AL 5·18mm
3/2·75 SC/GZ			2m	2m	GALV STEEL 1·70mm OR 2·00mm
COPPER	2m	3m	3·5m	4m	ANNEALED CU 2·75mm

THE CAPRICORNIA ELECTRICITY BOARD

CONDUCTOR HAND TIES FOR DISTRIBUTION PIN INSULATORS - STRAIGHT LINE TIES (TOP TIES)

DRAWN G.J.B. DATE 24.11.83

SCALE DO NOT SCALE

VOLUME 2 SECTION 9 PAGE 11

DRAWING Nº 22-A2-222 A

SUPERCEDES DWG E30/2/1-8/1 & 2

REFERENCE DRAWINGS

Figure B.4 Standard Construction Drawing - Hand Ties

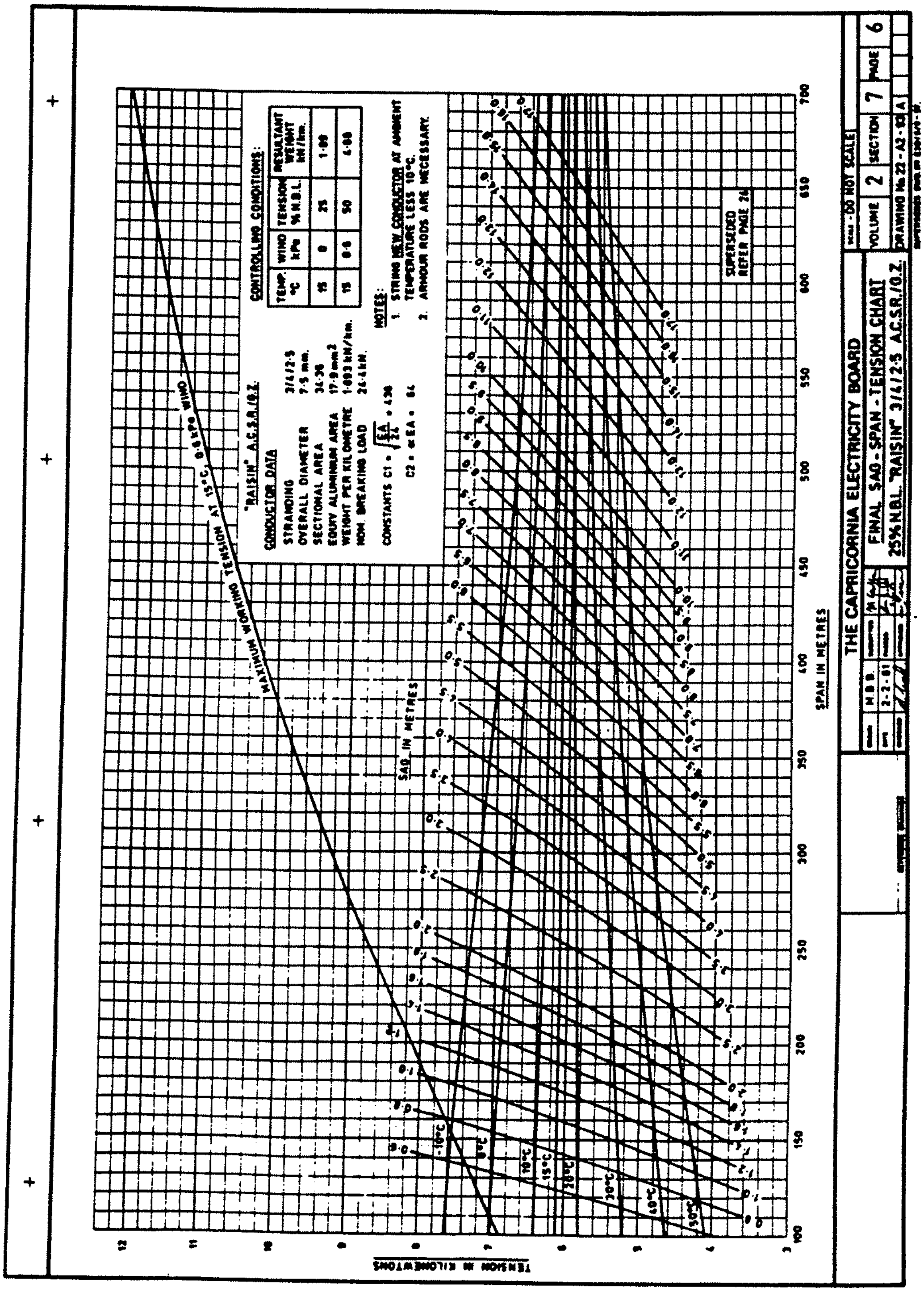


Figure B.5 Standard Construction Drawing - Stringing Chart

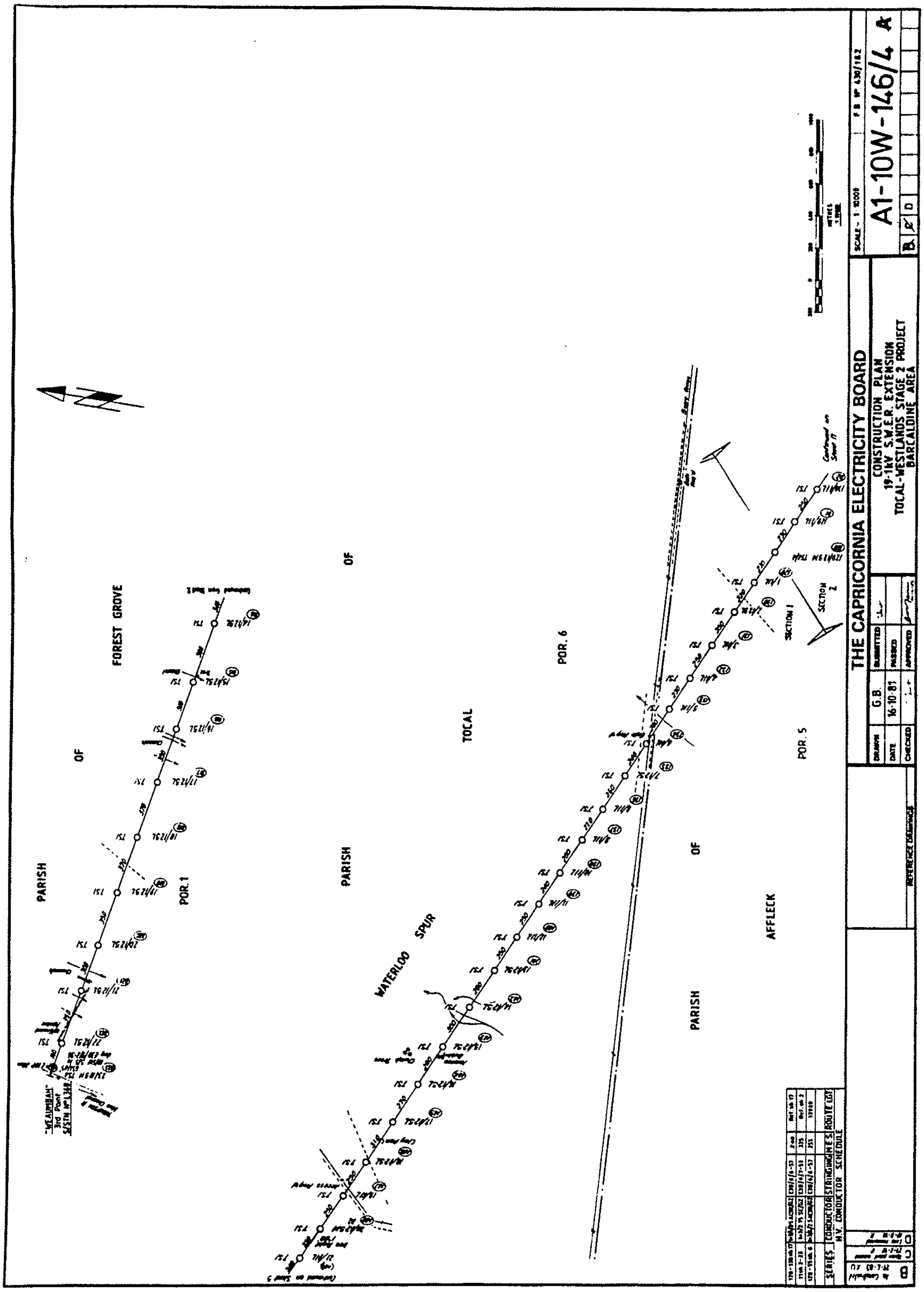
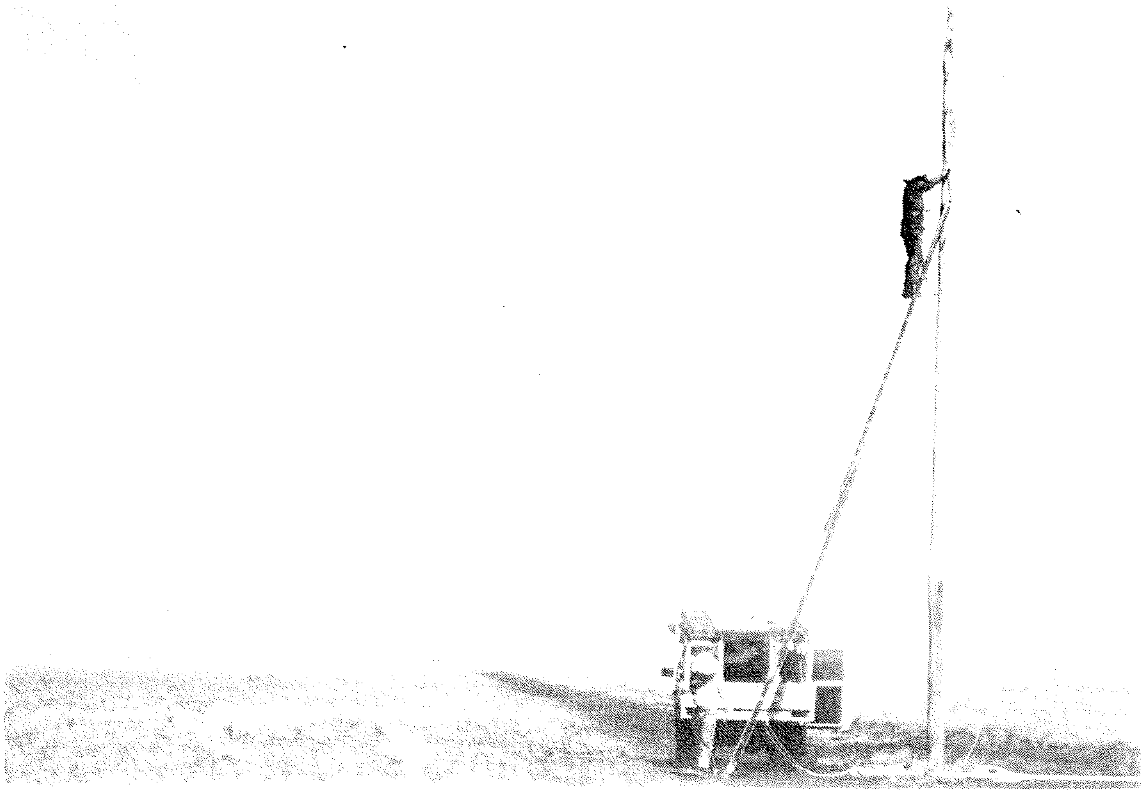
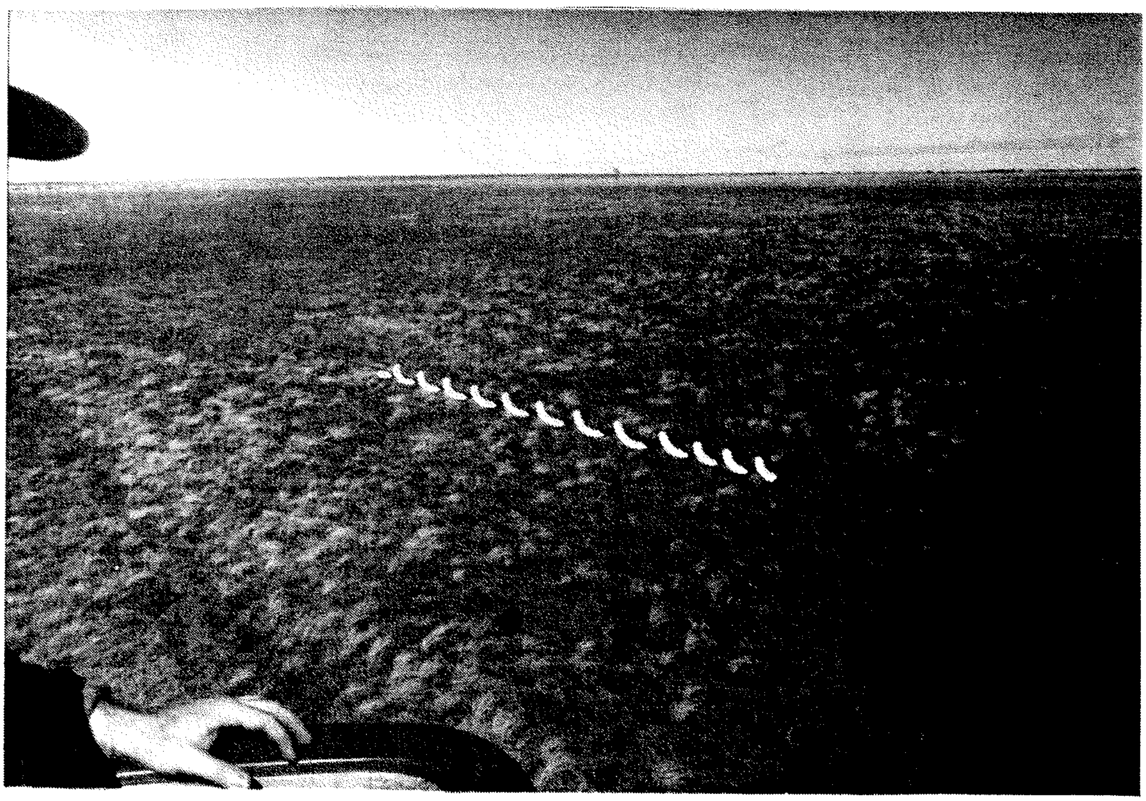


Figure B.6 Construction Plan - Waterloo SWER Scheme

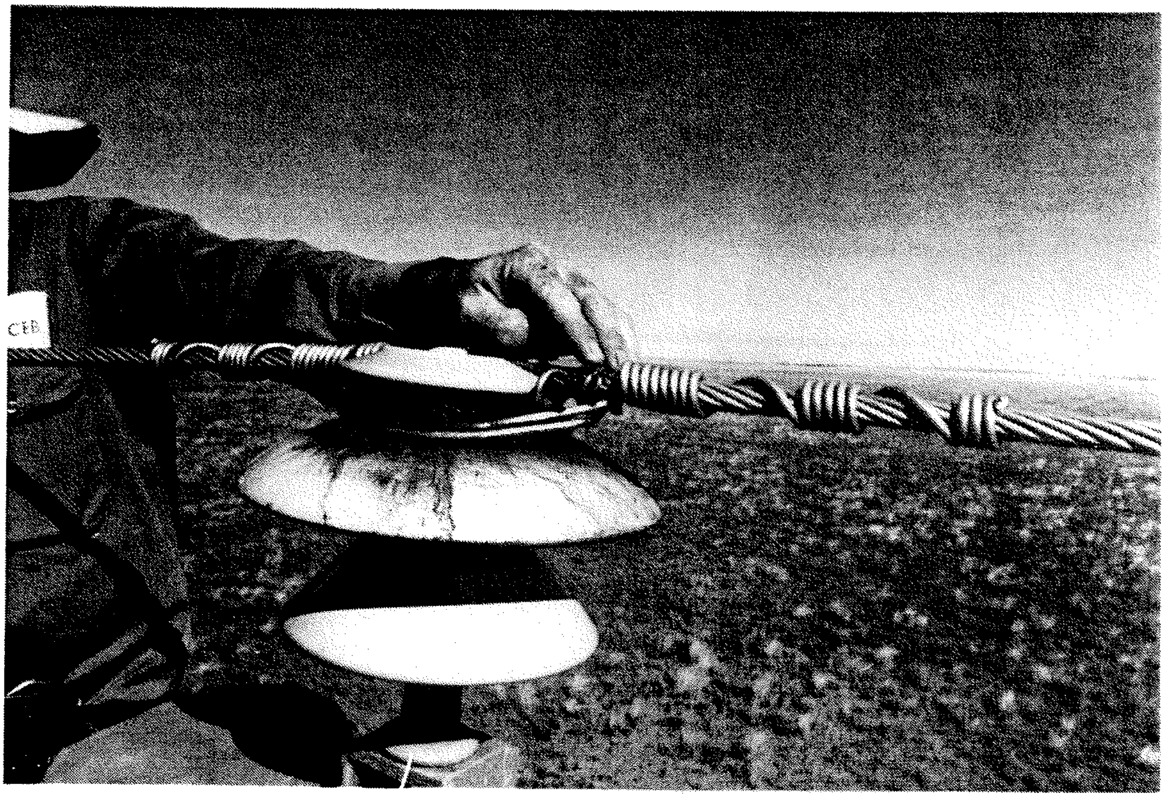
APPENDIX C



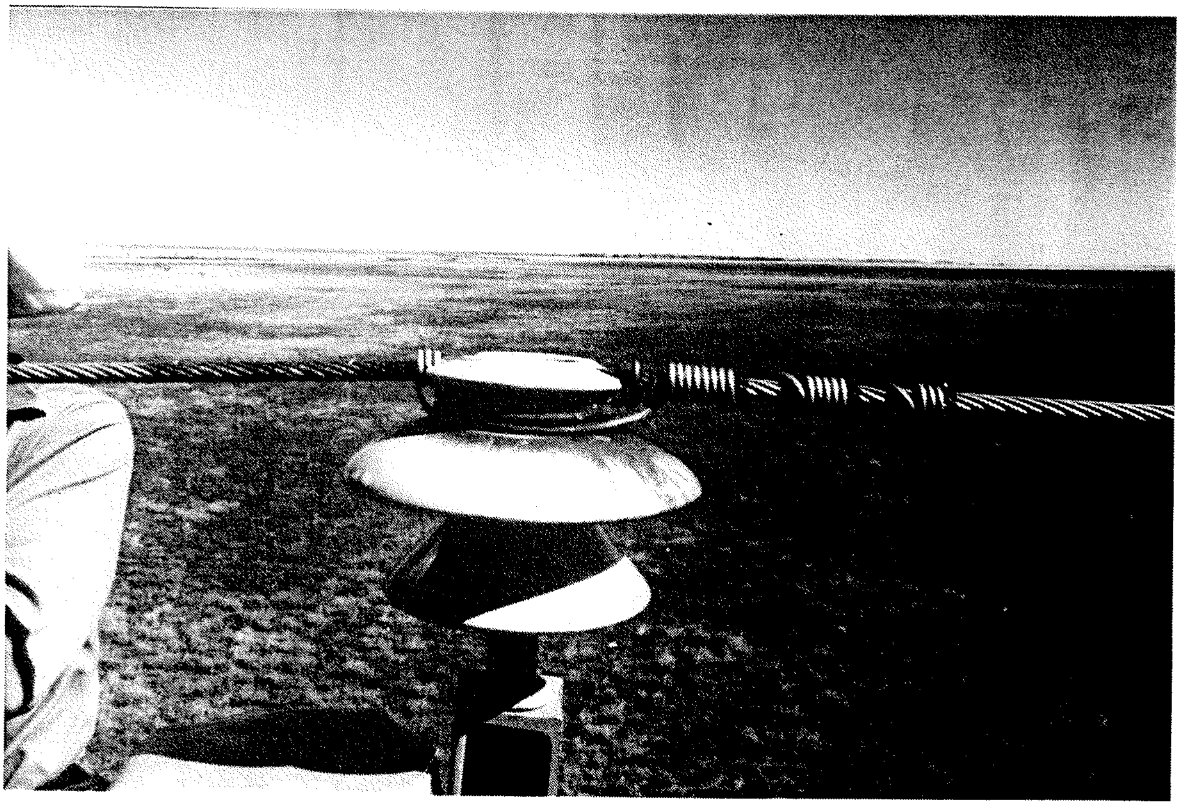
Photograph 1 Open Terrain on Stonehenge SWER



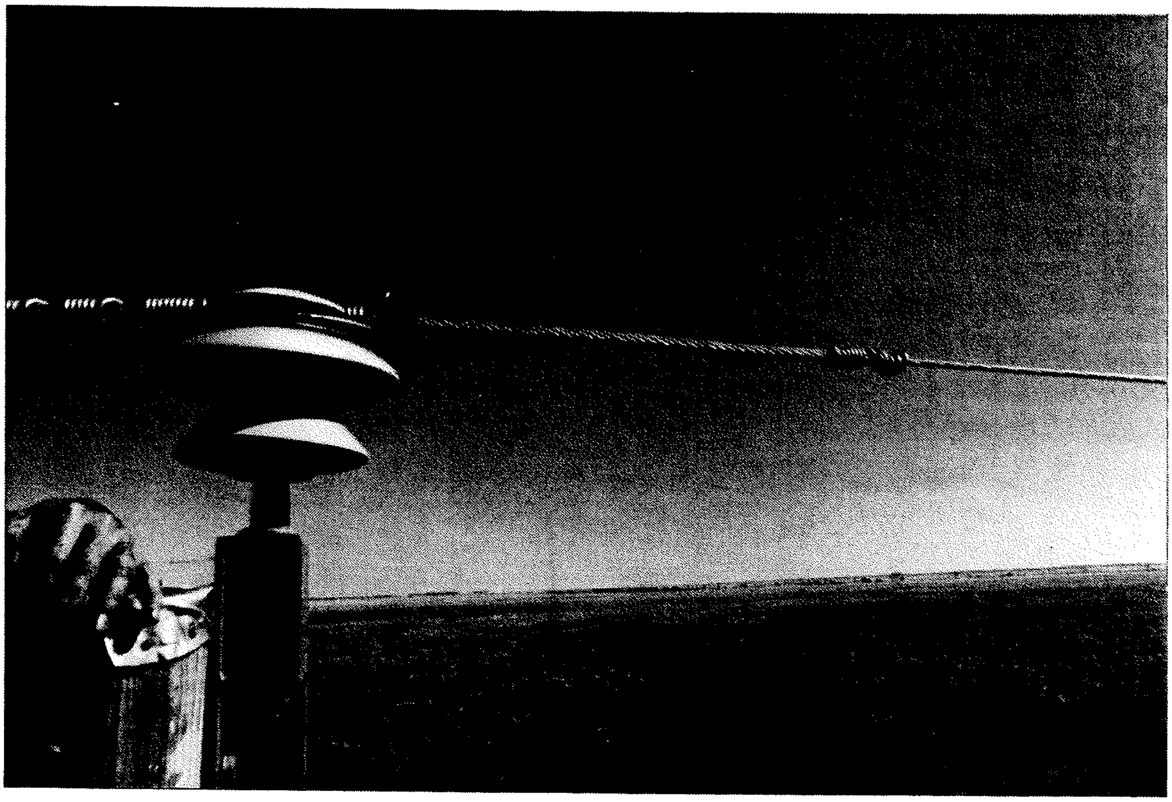
Photograph 2 Open Terrain on Waterloo SWER



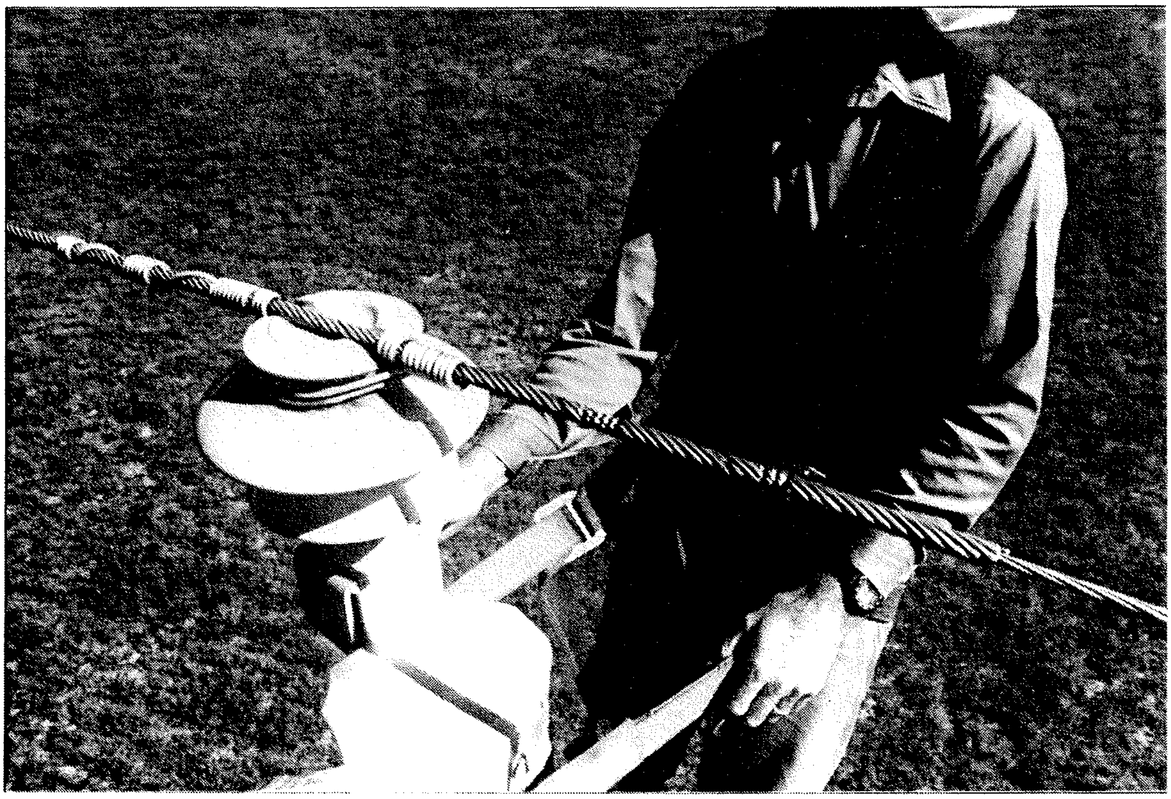
Photograph 3 Fretting of Hand Tie on Insulator



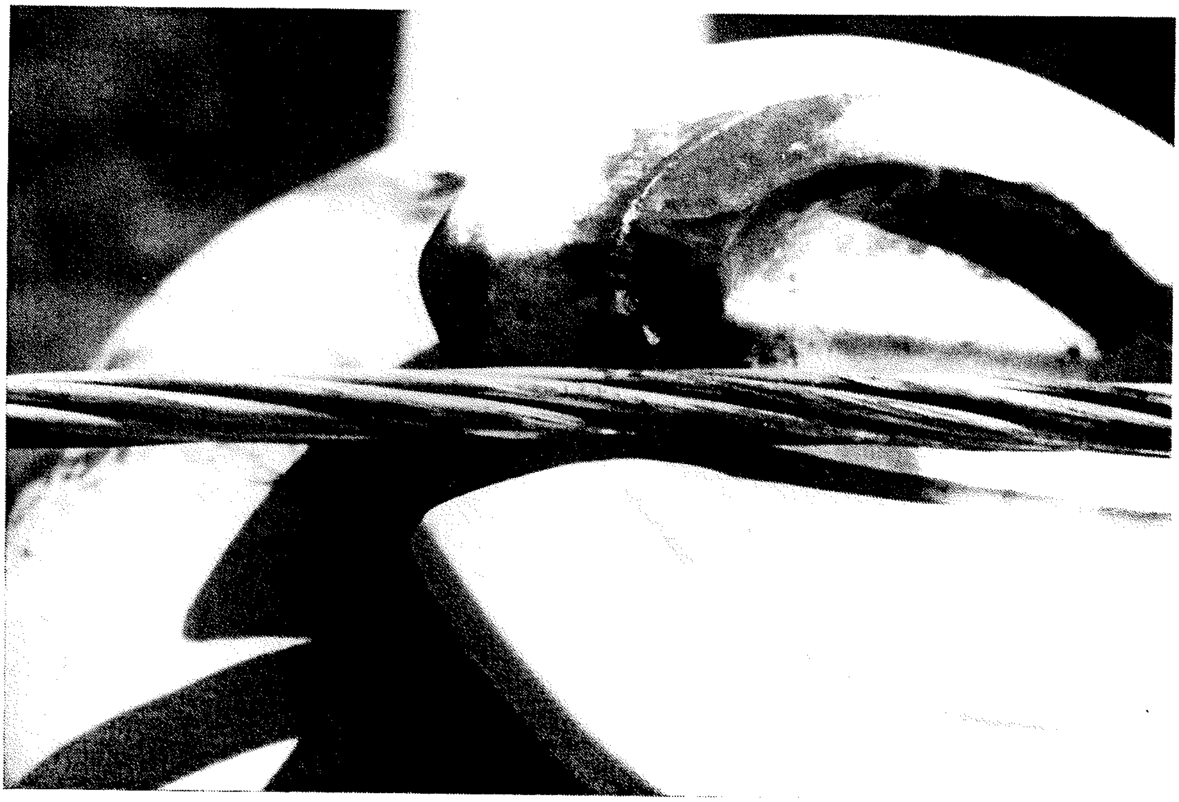
Photograph 4 Fretting of Hand Tie on Armour Rods



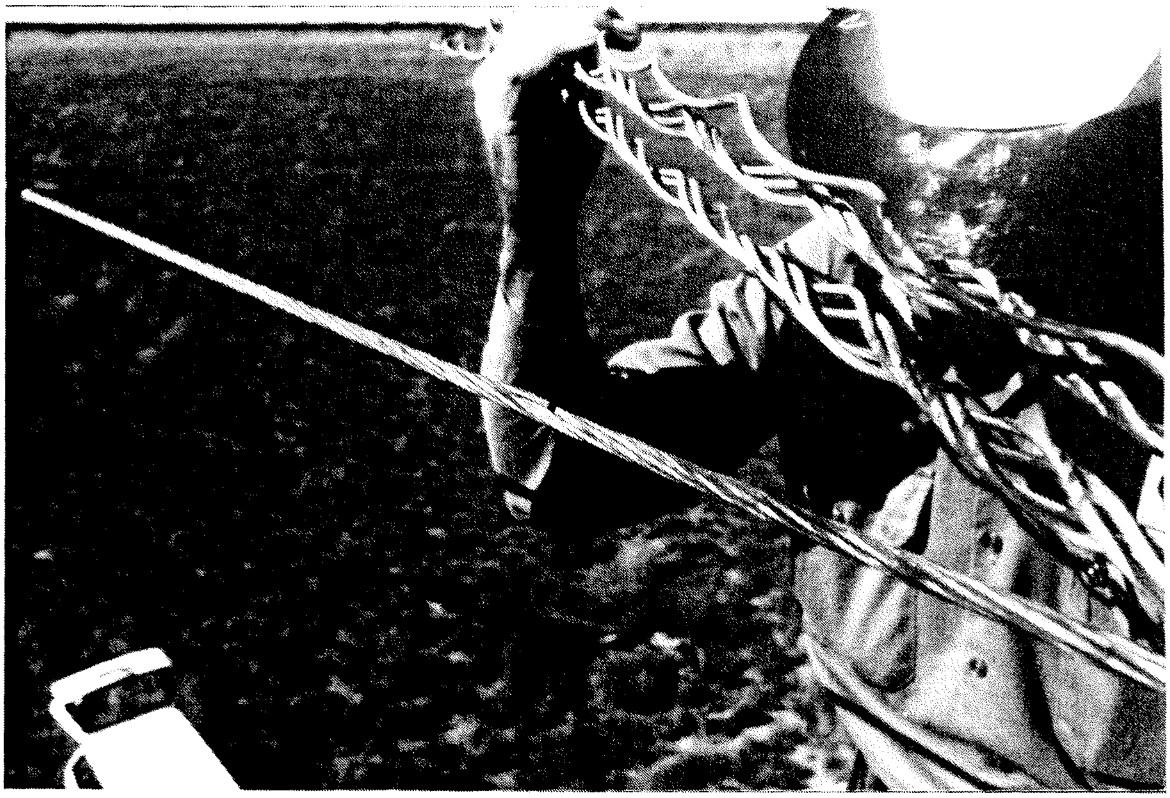
Photograph 5 Broken Hand Tie



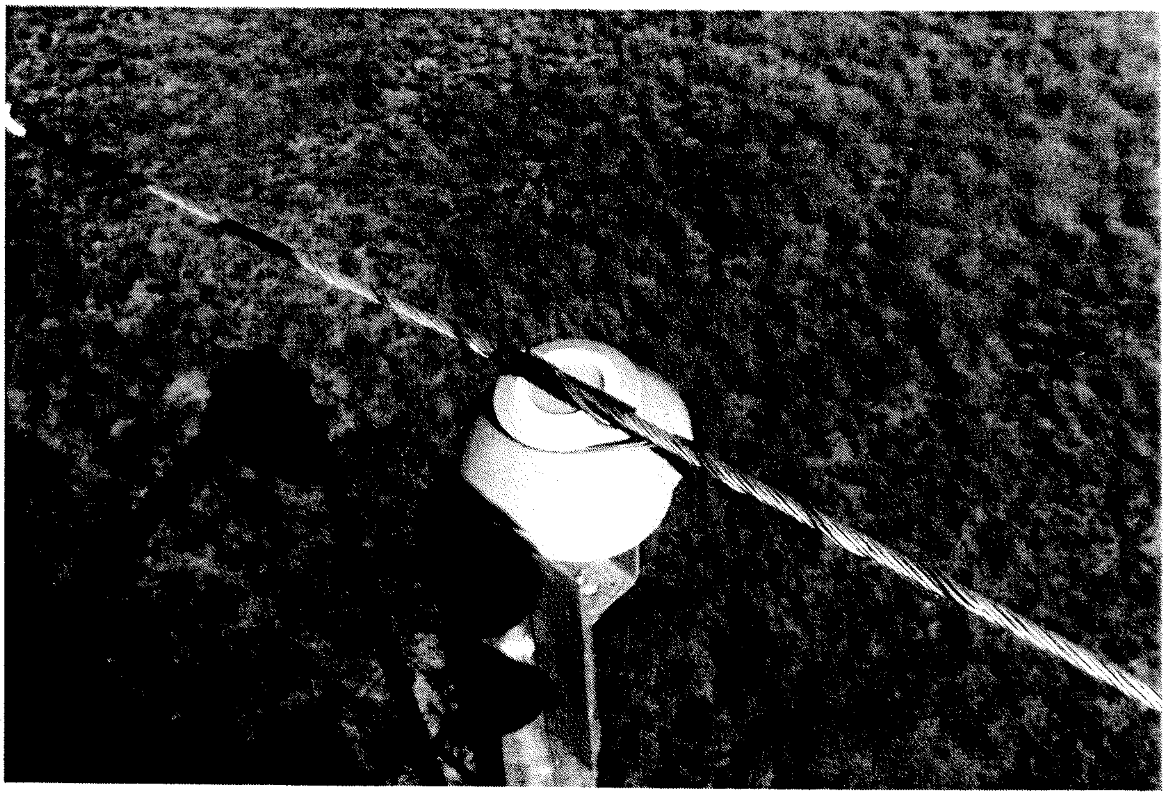
Photograph 6 Damage to Armour Rods



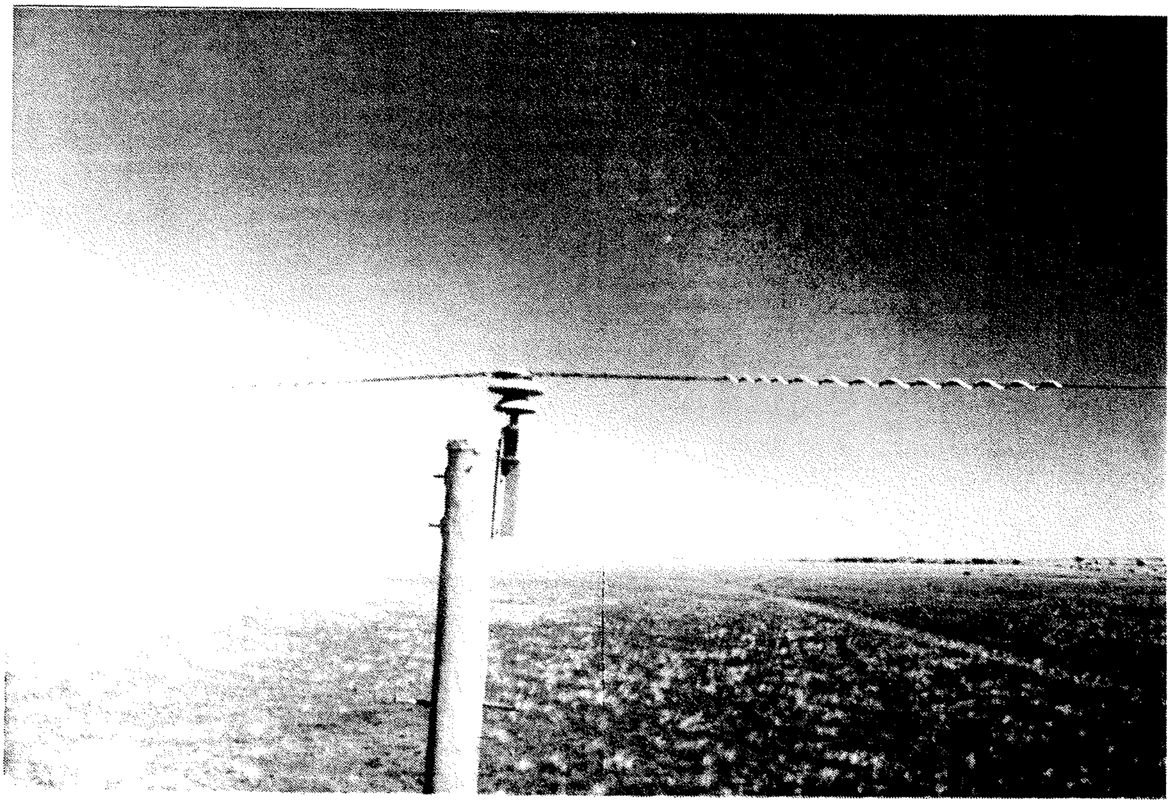
Photograph 7 Damage to Insulator



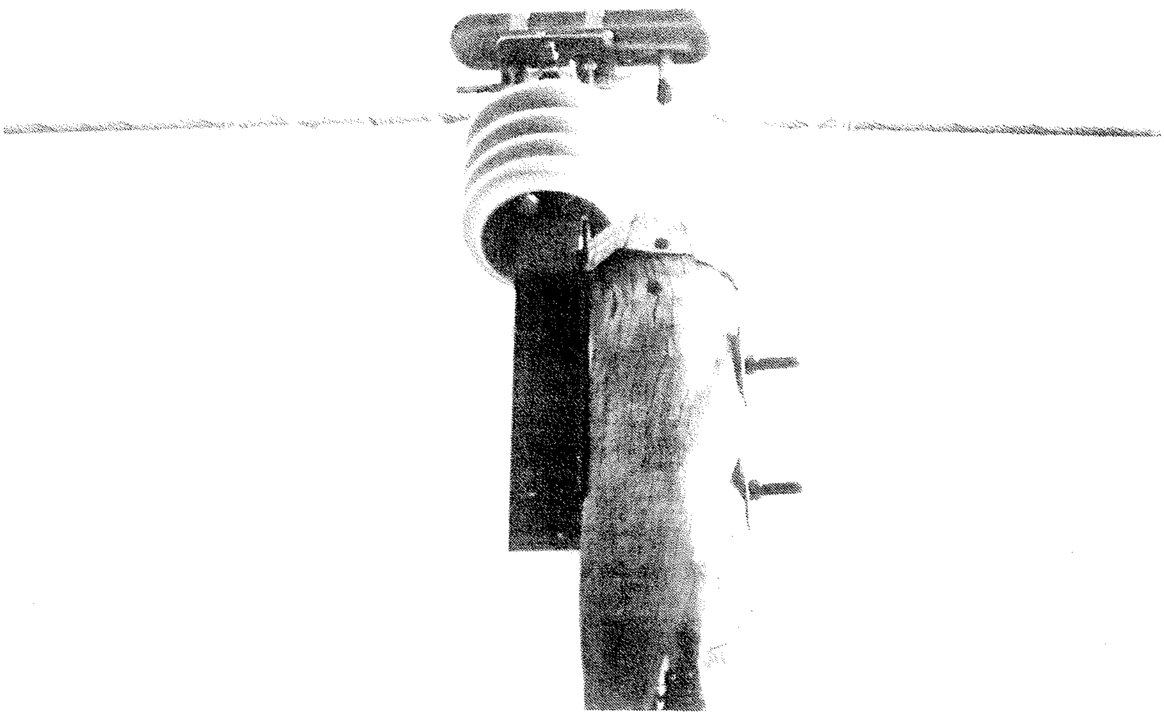
Photograph 8 Broken Aluminium Wire in 3/4/2.50 ACSR/GZ Conductor



Photograph 9 Preform Tie on Armoured Conductor



Photograph 10 Preformed Tie and Dampers Fitted



Photograph 11 Vibration Recorder Mounting

APPENDIX D

STRESSES AND FATIGUE IN AERIAL CONDUCTORS

The fatigue failure of wires in overhead line conductors is known to occur almost exclusively at points where the conductor motion is constrained (1). These points are typically at the structure support, damper locations or at line clamps. The fatigue failures are due to a combination of static and dynamic stresses. To achieve a satisfactory design life, it is necessary therefore to consider both the static and dynamic stresses which the conductor may experience during its service life. Conductor fatigue is an extremely complex mechanism, however a basic understanding of the impact of static and dynamic stresses on conductor fatigue is essential when designing overhead lines.

In this Appendix the static and dynamic stresses in overhead conductors are considered and a review of the current knowledge regarding the major factors operative in conductor fatigue is presented.

D.1 STATIC STRESSES

Static stresses are imposed on the conductor as a result of the line tension producing tensile stresses, and the support hardware and the bending angle of the conductor over the support point producing compressive and bending stresses as detailed below. The static stress levels in the conductor must be controlled to ensure that localised stress raisers are not created at the support points. Line designers can control the levels of static stress in the conductor through the choice of line hardware and line tension parameters.

D.1.1 Static Tensile Stress

The line tension produces static tensile stresses in the individual conductor wires. In the case of ACSR conductors, the stress in the aluminium wires decreases with time due to a creep induced load shift from the aluminium wires to the steel wires (2). Thus over time, the aluminium wire which creeps more than the steel wire, relieves its stress by increasing the stress levels in the steel wire.

The static tensile stress in the aluminium wires of an ACSR conductor can be estimated using the well established transformation of areas stress analysis (3).

$$\sigma_{Al} = \frac{T}{A_{Al} + n\,A_{St}} \qquad (D.1)$$

where σ_{Al} = Stress in Aluminium Wires (MPa)

T = Conductor Tension (N)

A_{Al} = Area of Aluminium (mm^2)

A_{St} = Area of Steel (mm^2)

n = $\frac{\text{Modulus of Elasticity of Steel}}{\text{Modulus of Elasticity of Aluminium}}$

Recognising that the ratio of the density of the steel to aluminium is approximately the same as the moduli ratio n, (2.88 vs 2.84), the equation above can be rewritten as

$$\sigma_{Al} \propto \frac{T}{m_{Al} + m_{St}} \qquad (D.2)$$

where m_{Al} = mass of aluminium in conductor per metre (kg/m)

m_{St} = mass of steel in conductor per metre (kg/m)

Thus the stress in the aluminium can be expressed as

$$\sigma_{Al} \propto T/m \qquad (D.3)$$

where m = mass of conductor per metre (N/m)

In the case of a homogeneous aluminium conductor, the stress in the outer layer wires can be calculated from equation D.1 above by setting $n = 0$.

D.1.2 Static Bending and Compressive Stresses

Static bending stress results from the bending of the conductor at the support point and is a function of the span length, tension, self weight and flexural rigidity of the conductor, and the radius of the support clamp (4,5,6).

Static compressive stresses arise as a result of tensile and bending forces in the individual wires of the conductor as well as by the conductor's own weight and by external clamping forces (4,5,6). While the stresses are of a primarily bearing (radial) nature with very small associated longitudinal stress, they are a source of aggravated fretting problems (see Section D.4.2) which can significantly reduce the fatigue life of the conductor.

A good review of the static stress in aerial conductors is provided in references (4,5,6).

D.1.3 Impact of Static Stresses on Conductor Life

Failures caused by static overload are possible (4), however the use of modern clamp and support designs together with realistic stringing tensions have all but eradicated this type of conductor failure. It is now considered that the total static stress in the aluminium wires, while still important, is only a secondary factor in the fatigue life of conductors (2).

D.2 DYNAMIC STRESSES

Dynamic stresses are alternating stresses caused by wind induced vibration in the conductor. The stresses can vary widely in amplitude, frequency and duration. The fatigue failure of an individual wire within a conductor is the result of a large number of stress reversals which exhaust the endurance limit of the material (5).

Before considering how the dynamic stresses in conductors are estimated, it is instructive to consider the origin and nature of the vibration.

D.2.1 The Mechanics of Conductor Vibration

Aeolian vibration is one of a number of wind induced conductor motions which can damage overhead electrical lines. Typically the wind velocities for which vibration is a problem are is the range 0.5 to 10 m/s (1). Wind velocities above this range are usually of a short-term nature and not conducive to the establishment of conductor vibration for extended periods.

When a conductor is positioned in a laminar flow of air, the alternate shedding of vortices from the top and bottom of the conductor creates a force perpendicular to the air flow inducing the conductor to move up and down. Drag forces also occur on the conductor but are an order of magnitude smaller than the alternating lift force. Consequently, it is normal to only consider aeolian vibration in the vertical direction (8).

The mechanics of the vortex shedding is a function of the conductor diameter, air velocity and the kinematic viscosity of the air, and is generally expressed in terms of the Reynolds number, R.

$$R = v\,d\,/\,\nu \qquad \text{(D.4)}$$

where v = Velocity of air flow (m/s)
d = Diameter (m)
ν = Kinematic viscosity

For the typical wind range of 0.5 to 10 m/s in which conductor vibration has been observed, the Reynolds numbers for a 7.5mm diameter conductor will vary from 277 to 5550. Reference (1) provides a good summary of the effects of Reynolds numbers upon patterns of airflow around a cylinder and shows that conductor vibration falls in range of Reynolds numbers where vortex action is predicted though with some turbulence.

As a first approximation, the frequency of vortex shedding (Strouhal frequency) of a cylinder oscillating in a steady airflow is similar to that associated with a stationary cylinder. Hence the frequency of vibration in an overhead line can be approximately related to the conductor diameter and the wind velocity through a dimensionless entity called the Strouhal number (1,7,15).

$$f_s = S\, v / d \qquad \text{(D.5)}$$

where S = Strouhal Number

f_s = Strouhal Frequency (hertz)

While the Strouhal number shows moderate variation over the range of Reynolds numbers encountered in conductor vibration, a value of 0.185 is considered a good average and sufficiently accurate for design purposes (1,11). It is important to note that the frequency at which a span vibrates is independent of tension, and is a function only of the wind velocity and the conductor diameter. The conductor tension only impacts on conductor vibration by way of the wave velocity and associated loop length as will be shown in Sections D.2.2 and D.2.5.

When a conductor vibrates at amplitudes above about one tenth of its diameter, the mechanics of the vortex shedding differs from the Stationary cylinder model. Koopmann (15) showed that when the incident wind velocity is in the range where the vortex shedding frequency (f_s) is within 10 to 20% (depending upon the amplitude of vibration) of a natural frequency (f) of the span, the vortex shedding tends to be parallel with the conductor and the two frequencies become synchronised or "lock-in". The vortices are no longer shed at the Strouhal frequency (f_s) but are governed by the natural oscillating frequency (f) of the conductor. An important implication of this "lock-in" phenomenon is that vibration can be sustained on a line even though the wind condition may have changed. If the relationship given in equation D.5 were strictly followed, a span would only vibrate at very selective wind velocities when the Strouhal frequency corresponded to a natural frequency condition.

It is shown in reference (28) that the natural frequencies of a span are only separated by a fraction of a hertz, and hence a conductor will always be sufficiently close to a natural frequency to allow vibration to be initiated in the presence of any laminar wind flow.

D.2.2 Travelling Waves

The alternating forces on the conductor initiate travelling waves which propagate in both directions along the span. The wave is reflected at the span support points and this results in the possible formation of standing waves along the span. In Figure D.1 below the characteristics of standing wave vibrations are shown.

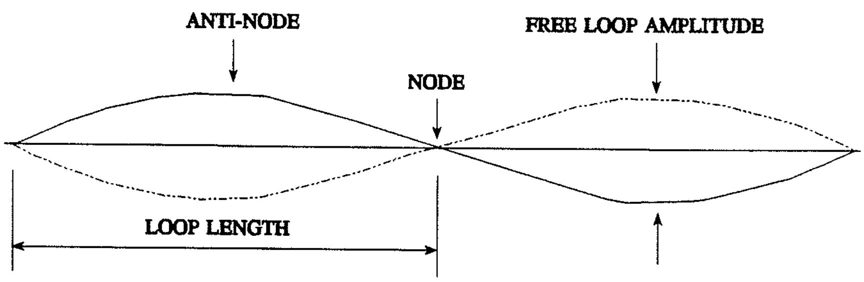


Figure D.1 Loop Geometry of Vibration

The velocity at which the wave moves along the span is a function of the conductor mass and tension. It is also a function of the natural frequency and loop length (half of a wave length), (1).

$$V_t = (T / m)^{1/2} = 2 f L \qquad \text{(D.6)}$$

where V_t = Velocity (m/s)
T = Tension (N)
m = Mass per unit Length (kg/m)
L = Loop Length (m).
f = Natural Frequency (Hz)

The natural frequencies for a span can now be calculated, as the number of standing wave loops is just the span length S_L divided by the loop length L.

$$n = S_L / L \qquad \text{(D.7)}$$

where n = Number of Loops
S_L = Span Length (m)

By substituting for L from equation (D.7) into (D.6) above, the natural frequencies can be expressed as

$$f = n V_t / (2 S_L) \qquad \text{(D.8)}$$

The fundamental frequency of the span is calculated by setting $n = 1$. For typical conductors and spans used in rural applications, the natural frequencies will only be separated by less than 0.4 hertz (Refer to Tables B.8, B.9 and B.10 in Appendix B).

D.2.3 Vibration Amplitudes

In this Section, methods for predicting the amplitudes of conductor vibration are reviewed. It will be shown that while these methods are well established for transmission class conductors, there is insufficient data available to allow for prediction of amplitudes on the range of conductors used in the SWER network. It will be concluded in Section D.2.4 that field measurement offers the more accurate means of determining the vibration amplitudes.

When the vibration frequency is close to a natural frequency of the line, small energy inputs can result in very high vibration amplitudes. When this is coupled with the "lock in" phenomenon described above, amplitudes which could cause damage to the conductor may occur at practically any wind velocity.

The amplitude of vibration can be determined by considering the system energy balance equations. Since a vibrating conductor receives its energy from the wind, and dissipates it only through the damping present in the conductor system, the vibration amplitudes levels will be such that the conductor energy dissipation will equal the energy input from the wind.

To simplify the analysis, "ideal conditions" are normally considered (28) in which the following assumptions are made: the wind is steady and uniform over the length of the span; the vibrations are as sinusoidal; and all energy dissipation is attributed to conductor self-damping. Using these simplifying assumptions the energy balance equations now consist of only the wind input and the conductor self-damping.

Reference (16) provides an equation for the power input transferred from the wind to a vibrating conductor.

$$P_w = k \,.\, f^3 \,.\, d^4 \tag{D.9}$$

where P_w = Wind Power Input

k = A Function of (Y / d)

Y = Free Loop Peak/Peak Amplitude

d = Conductor Diameter

f = Vibration Frequency

As the vibration frequency is a function of 1/d as described in equation (D.5), for a given wind, the power received by a conductor is approximately proportional to its diameter.

All conductors exhibit some self damping due to interstrand friction and metallic damping. Reference (16) again provides an equation in terms of frequency and amplitude.

$$P_{SD} = \frac{\pi}{2} \frac{H}{(T / m)^{1.5}} f^4 (Y / 4)^2 \qquad (D.10)$$

where P_{SD} = Conductor Self-Damping Power Dissipation
H = Damping Constant (from experiment)
T = Conductor Tension
m = Conductor Mass / Unit Length

Available data on the experimental damping constants for conductors is relatively scarce. Unfortunately no data appears to be available on the damping constant for the small diameter conductors used in the SWER systems, and as a consequence it is not possible to predict the amplitudes of vibration for these conductors from the energy balance method.

In the traditional energy balance method described above it is necessary to know the wind power input (Equation D.9). According to Rawlins, "*There is considerable uncertainty about wind power supplied even under conditions of steady or so-called laminar wind.* " (10).

An alternative approach has been proposed to calculate the response of a single conductor so that the uncertainty of the wind energy input can be circumvented, (8). This alternative approach recognises two fundamental difficulties pertaining to vortex-induced vibration:

(1) The lack of knowledge of the flow field around a cylinder in laminar flow, and

(2) The problem with the coupling between the oscillating cylinder and its surrounding air flow.

Rather than use the energy balance method, several analytical models (8,29,30,31,32) have been proposed which an attempt to model the experimental results.

The best known of these is the Iwan and Blevins model (8,31) which is used to predict the resonant amplitude of elastic structures of circular cross-section in the subcritical Reynolds Number range (300-300000). The equation is expressed as follows;

$$\frac{Y_{max}}{d} = \frac{0.07\,\gamma}{(\delta + 1.9)\,S^2} \left\{ 0.30 + \frac{0.72}{(\delta + 1.9)\,S} \right\}^{1/2} \qquad \text{(D.11)}$$

where Y_{max} = Antinode Peak to Peak Amplitude (m)

d = Conductor Diameter (m)

S = Strouhal Number

γ = Form Factor

δ = Conductor Damping Factor

Unfortunately the work carried out in formulating the above relationship and others like it has always been referenced to transmission class conductors. No data could be found for small diameter ACSR conductors or any conductors with composite outer layer constructions.

Work carried out by Rawlins has shown that ACSR and SC conductors suffer a loss of self-damping capacity with service, making them more vulnerable to vibration damage as time passes. The reason for this increased vulnerability lies with the fact that the individual wires tend to bed into each other over time making relative movement more difficult. This results in a decrease in self-damping and causes a marked increase in vibration amplitude particularly at frequencies above 50Hz (10).

While Rawlins points out that his results are not comprehensive enough to provide a basis for designing against vibration, he does conclude that "*the results emphasis the importance of field testing and long-term experience in deciding upon the need for, and the required level of vibration protection*", and further that "*decisions based upon the properties of new conductor can lead to future trouble*" (10).

The work by Rawlins also indicates that vibration amplitudes tend to roll-off at the higher frequencies. This could be attributed to the following reasons:

(1) The power input to the span is a function of f^3 while the conductor damping is function of f^4. This results in a relative increase in damping with frequency;

(2) As the frequency increases the loop length decreases. The shorter loop lengths effectively reduces the allowable amplitudes of vibration; and

(3) The higher frequencies require higher wind velocities to be sustained. Strong gusts of wind are relatively rare, and the duration of these stronger winds may not be sufficient to allow for a build up of power in the vibrating conductor.

D.2.4 Need for Data Collection

The difficulty with accurately predicting the amplitude of vibration for the various wind speeds tends to support the use of measured field data as being the more accurate means of determining the vibration amplitudes for the range of small diameter high strength conductors used in the SWER schemes.

The use of measured results rather than a mathematical determination is also supported by a manufacturer of line hardware. The Preform Line Products Company in California while carrying out investigations into the vibration of overhead steel earthwires, reported , "*Mathematical determination of the expected vibration levels on a proposed or existing line is a formidable task*" and "*because of the difficulty in determining expected vibration levels analytically, it is often advantageous to draw on the operating experience of a line of similar design in a similar geographical area, or to measure the vibration activity in the field firsthand.*" (21).

Based on extensive field data on transmission class conductors, it is generally considered (1), that free loop peak to peak conductor vibrations rarely exceed one conductor diameter. On the smaller diameter conductors there is only limited published data. However work by Rawlins (10) and Preformed Line Products (25) on 9mm diameter steel earthwires demonstrated that the maximum free loop amplitudes over a wide range of recordings did not exceed 90% of the conductor diameter. Typical results show the maximum amplitudes at around 50% of the conductor diameter. The work also shows the maximum amplitudes occurring at the lower frequencies and rolling off as the frequency increases.

D.2.5 Impact of Line Tension

Increased line tension does not impact on the frequency of vibration as demonstrated by in equation (D.5) above, however it does impact on the velocity of the travelling wave and the loop length given in equation (D.6). So for a given wind velocity, increases in tension will result in the same frequency of vibration but with a higher travelling wave velocity and a longer loop length.

In accordance with equation (D.10), an increase in the static line tension directly reduces the conductor self-damping characteristics (28). The increased line tension also impacts on the conductor self-damping constant H in equation (D.10) further reducing the overall self-damping. Consequently the higher tensions result in larger peak to peak amplitudes of vibration. The impact of these increased dynamic bending stress levels at the support point will be partly offset by a reduction in the static bending stresses due to the reduced take-off angle of the conductor..

The overall impact of an increase in line tension is to increase the severity of vibration (1). It will be shown later that line tension is a contributing factor to fatigue failures, but not to the same extent as the level of dynamic stress.

D.3 CALCULATION OF DYNAMIC STRESSES

The stresses in multi-layer overhead conductors are quite complex and difficult to analyse using mathematical techniques. However a simplified analysis, which considers the conductor as a tension loaded homogeneous beam with a constant flexural rigidity, is provided in reference (1). The EPRI analysis relates vibration intensity to a dynamic stress level in the conductor. The dynamic stress of the outer layer wires in the conductor is shown to be proportional to the bending amplitude and to the square root of the quotient of the tensile force and the flexural rigidity. In practice however, it was found that the level of dynamic stress is also a function of many other factors such as the conductor and clamp type.

Considering the complexity of the system, the EPRI model has correlated quite well to a range of conductor sizes and supports and has been found to be adequate for design purposes (1). An outline of the EPRI model is provided below.

The industry standard (25), for measuring vibration amplitudes has been established at a point 89mm from the last point of contact of the conductor with the support. When measuring at this position, the peak-peak value is called the "bending amplitude", Y_b.

According to the EPRI model, the alternating stress in the outer layer wires of a conductor can be related to the bending amplitude by the following equation called the Poffenberger-Swart formula (1,20).

$$\sigma = \frac{d\,E\,p^2 / 4}{e^{(-px)} - 1 + p\,x}\,Y_b \qquad \text{(D.12)}$$

where d	=	Diameter of Outer Layer Wires (mm)	
E	=	Young's Modulus of Material (MPa)	
p	=	$(H / EI)^{1/2}$ (m^{-1})	
H	=	Horizontal Tension (N)	
EI	=	Flexural Rigidity (Nm^2)	
x	=	Measurement Location (m) =	89×10^{-3} m
Y_b	=	Bending Amplitude (m)	
σ	=	Stress in Outer Layer Wires (Mpa)	

In Section B.5 of Appendix B, the impact on dynamic stress levels resulting from changes in tension in 3/4/25.0 ACSR/GZ conductor are considered. It is shown that the impact of tension changes on the dynamic stress levels is relatively small when compared to the impact of vibration amplitude changes.

D.4 CONDUCTOR FATIGUE AND FATIGUE LIFE

D.4.1 Mechanics of Fatigue

Fatigue is the progressive localised permanent structural change which occurs in a material that has been subjected to repeated or fluctuating stresses of a value less than the tensile strength of the material (27). Fatigue may culminate in cracks or fractures after a sufficient number of cycles (1).

The prediction of fatigue life of a material is complicated because it is very sensitive to small changes in loading conditions, local stresses and local characteristics of the material. Because it is difficult to account for these minor changes in either the dynamic stress-prediction techniques or in fatigue failure criteria, there is a large uncertainty inherent in analytical predictions of fatigue life (27).

Traditionally, fatigue life has been expressed as the total number of cycles required at a particular level of stress for a fatigue crack to be initiated and then grow large enough to produce catastrophic failure. The results of fatigue tests are usually plotted as maximum stress verses number of cycles as shown in Figure D.2 below. The resulting curve of data points is called an S-N or Wohler curve (1,2,11).

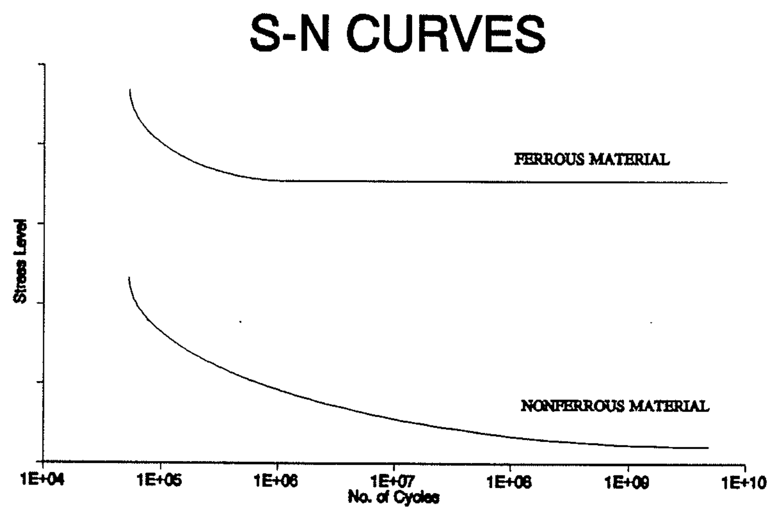


Figure D.2 Typical S-N Curves for Ferrous and Nonferrous Materials

Typically ferrous materials exhibit a fatigue (endurance) limit (27). This is a stress level which the metal can withstand for an infinitely large number of cycles with a 50% probability of failure. Most nonferrous materials do not exhibit a fatigue limit, instead their S-N curves continue to drop at a slow rate even at high numbers of cycles. Aluminium is a material which exhibits this property. For these metals, instead of reporting the fatigue limit, it is necessary to report the fatigue strength, which is the stress to which the metal can be subjected for a specified number of cycles. Care must be exercised when considering fatigue strengths as sometimes it is erroneously called the fatigue limit for a prescribed number of cycles, eg 5×10^8.

D.4.2 Fatigue in Conductors

The fatigue failure of an individual wire within a conductor is the result of a large number of stress reversals which exhaust the endurance limit of the material (5). This type of failure is known to occur almost exclusively at points where the conductor motion is constrained (1). These points are typically at the structure support, damper locations or at line clamps. Inspection and analysis of fatigue failures of wires indicate that fatigue cracks always originate at points of contact with another wire in the conductor, with support hardware, or with the clamping device (28). The reason for this lies with stress concentrations which arise from material fretting at these interfaces (33). Fretting is the form of damage that occurs when two surfaces in contact with each other experience relative motion. The fretting produces abraded particles and in the case of aluminium, the product consists of a black aluminium oxide. Fretting initiates fatigue cracking at a much earlier stage than is the case in the absence of this mechanism. The overall fatigue life of the conductor is drastically reduced when fretting occurs.

Because of this fretting behaviour the fatigue life of multi-layer conductors cannot be simply calculated from the fatigue characteristics of the materials used in their construction. Rawlins (1), summaries this, "*The fatigue characteristics of conductors must be determined by fatigue tests on the conductors themselves*".

As stated above there is no direct relationship between the S-N curve of the base material and the fatigue characteristics of the completed conductor. Tests must be carried out on sufficient number of sample conductors to establish the necessary S-N curve.

Work carried out by CIGRE, (2), in establishing the S-N curves for a range of conductors, has led to "safe border" S-N curve for aluminium wires. The curve can be expressed in the following terms

$$\sigma_a = 450\ N^{-0.200} \quad \text{for the range } N \leq 2x10^7 \qquad (D.13)$$

$$\sigma_a = 263\ N^{-0.168} \quad \text{for the range } N \geq 2x10^7$$

where σ_a = Stress in Aluminium Outer Layer Wires (MPa)

N = Number of Cycles.

The intention of the CIGRE curve is "*that this safe border line may be applied for a conservative estimation of life time of a conductor if an actual S-N curve (Wohler curve) is not available.*"

The "safe border" S-N curve above derived from fatigue tests carried out on multi-layer ACSR transmission conductors where aluminium wire failures generally occur in the penultimate layer due to fretting effects with the adjacent wires. Where there is aluminium only in a single outer layer, the magnitude of the fretting will be reduced. In the work carried out by CIGRE (2) in determining the safe border, an S-N curve for a single layer conductor is presented. It shows allowable cycles well in excess of the values determined by the safe-border curve. With only one set of results however the curve does not present a practical design option, but rather indicates that the results provided by the safe-border analysis will be very conservative for the range of small diameter conductors being considered here.

D.4.3 Assessment of Conductor Fatigue Life

During its service life an overhead line conductor will be subjected to a wide range of dynamic stress levels resulting from vibrations superimposed on the static stresses. The number of cycles experienced at the various stress levels will depend upon the topographic and climate factors at the service location. It is generally accepted that the best way to handle this kind of stress and cycle variability is to use a cumulative damage theory which describes the gradual deterioration of the conductor over time as cycles are accumulated.

The Miner's Hypothesis (2,13,14) is the simplest and most commonly used theory of cumulative damage. The proportion of damage at a given stress level is determined from the ratio of the number of cycles expected at this level during one year of service life (n_i) to the number of cycles up to failure (N_i) from the appropriate S-N curve. It is proposed that the damage accumulation is linear and not influenced by the order in which the different stresses occur.

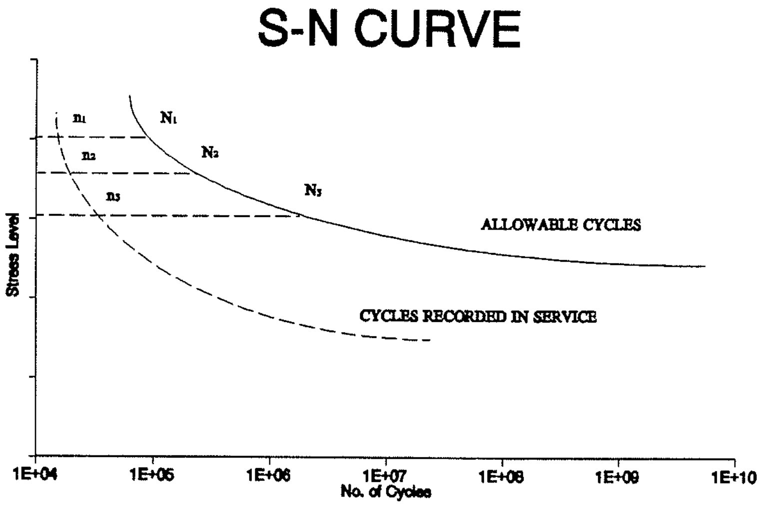


Figure D.3 Derivation of Miner's Analysis

The Miner's hypothesis at failure yields the following

$$n_1 / N_1 + n_2 / N_2 + n_3 / N_3 + ... + n_i / N_i = 1 \qquad (D.14)$$

The total damage for one year can now be represented as follows.

$$A = \Sigma^{i}_{1} \; n_i / N_i \qquad \text{(D.15)}$$

The actual lifetime (L) of the conductor can then be calculated:

$$L = 1 / A \text{ years} \qquad \text{(D.16)}$$

Whether the Miner's sum should be exactly one is a question which has been debated for many years. Reference (2) concludes that value is likely to be between 0.50 and 1.49.

Reference (11) reported the experimental validity of the Miner's hypothesis. It was concluded that, for the conductor tested (Drake 26/7 ACSR), the Miner's hypothesis was somewhat conservative; but could be assumed to be valid for design purposes. It was also concluded that other more complex cumulative damage theories would be difficult to validate experimentally and often would not yield a significant improvement in failure prediction over the simpler linear damage rule.

APPENDIX D - REFERENCES

(1) "Transmission Line Reference Book, Wind-Induced Conductor Motion", Electric Power Research Institute, 1979.

(2) CIGRE Working Group 22.04. "Recommendations for the Evaluation of the Lifetime of Transmission Line Conductors", Extract from Electra No. 63, 1979.

(3) EPRI EL-1946, "Conductor Fatigue-Life Research", Final Report, Research Project 1278-1, July 1981.

(4) Gopalan, T.V., Girish, S., Ramachandran, N. "Reduction of static strain for Increased Life of Transmission Line Conductors", Central Power Research Institute, "Strain", August 1983.

(5) Bückner, W.F., Helms, R., Papailiou, O. "Determination of the Lifetime of Transmission Conductors on the Basis of Vibration Measurements and Fatigue Tests", 1985

(6) Dulhunty, P.W., Lamprecht, A., Roughan, J.C. "The Fatigue Life of Overhead Line Conductors", Submission to CIGRE Working Group 22, 1984.

(7) Simmons, J.M., Cleary, P.M.G. "Measurement of Aerodynamic Power Associated with Vortex-Induced Vibration of Electrical Transmission Lines", IEEE Transactions on power Apparatus and Systems, Vol. PAS-99, No. 1 Jan/Feb, 1980.

(8) Tsui, Y.T. "Modern Developments in Aeolian Vibration", EPRI, Vol. 15, Pages 173-179, 1988.

(9) Simmons, J.M. "Introduction and Aerodynamic Aspects of Aeolian Vibration", Symposium on Wind-Induced Vibrations of Electric Transmission Lines, University of Queensland, Dept. of Mechanical Engineering, 1978.

(10) Rawlins, C.B. "Research on Vibration of Overhead Ground Wires", IEEE Transactions on Power Delivery, Vol 3, No. 2, April 1988.

(11) Bruniar, R.M., Ramey, G., Duncan, R.R. "An Experimental Evaluation of S-N Curves and Validity of Miner's Cumulative Damage Hypothesis for an ACSR Conductor", IEEE Transaction on Power Delivery, Vol 3, No. 3, July 1988.

(12) Richardson, A.S., Smith, F.S. "Some Effects of Tension on Static Wire Fatigue in New England", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 2, Feb 1981.

(13) Miner, M.A. "Cumulative Damage in Fatigue", Journal of Applied Mechanics, September 1945.

(14) Bückner, W.F. "Safety Determination of Transmission Conductors during Aeolian Vibrations", Transmission and Distribution International, June 1992.

(15) Koopman G.H. "The Vortex Wakes of Vibrating Cylinders at Low Reynolds Numbers", Journal of Fluid Mechanics, Vol. 28, 1967.

(16) Roughan, J. "Estimation of Conductor Vibration Amplitudes Caused by Aeolian Excitation", Journal of Wind Engineering and Industrial Aerodynamics, No. 14, 1983.

(17) Diana, G. Falco, M. "On the Forces Transmitted to a Vibrating Cylinder by a Flowing Fluid", Meccanica No. 1, Vol. VI, 1971.

(18) Claren, R., Diana, G. "Mathematical Analysis of Transmission Line Vibration" IEEE Transactions on Power Apparatus and Systems, Vol. 88, No. 12, December 1969.

(19) Kraus, M., Hagedorn, P. "Aeolian Vibrations: Wind Energy Input Evaluated from Measurements on an Energised Transmission Line", IEEE Transactions on Power Delivery, Vol. 6, No. 3, July 1991.

(20) Poffenberger, J.C., Swart, R.L. "Differential Displacement and Dynamic Conductor Strain", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-84, 1965.

(21) Whapman, R., Champa, R.J. "Wind Induced Vibrations of Overhead Shield Wires", Preformed Line Products Company, March 1983.

(22) CIGRE Working Group 22.08. "Dynamic Effects on Transmission Lines", 1984

(23) CIGRE Working Group 22.04. "Guide for Endurance Tests of Conductors inside of Clamps", Report No. 22-83(WG04)01

(24) Rawlins, C.B. "Wind Tunnel Measurements of the Power Imparted to a Model of a Vibrating Conductor", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 4, April 1984.

(25) IEEE Committee Report. "Standardisation of Conductor Vibration Measurements", IEEE Transactions, Vol. PAS-85, 1966.

(26) CIGRE Working Group 22.11. "Field Measurement and Field Data Processing on Conductor Vibration (Comparison Between Experimental and Analytical Results", 1982.

(27) American Society for Metals, "Properties and Selection of Metals", Metals Handbook, 8th Edition, 1961

(28) CIGRE Working Group 22.01. "Aeolian Vibration on Overhead Lines", CIGRE Report 22-11, 1970.

(29) Hartlen, R.T., Currie, I.G. "Lift-Oscillator Model of Vortex-Induced Shedding", Proceedings, American Society of Civil Engineers, 96-1970.

(30) Griffin, O.M., Skop, R.A., Ramberg, S.E. "The Resonant Vortex-Excited Vibrations of Structures and Cable Systems", Offshore Technology Conference, May 1975.

(31) Iwans, W.D., Blevins, R.D. "A Model for Vortex-Induced Oscillations of Structures", Journal of Applied Mechanics, 41-1974.

(32) Sarpkaya, T. "Fluid Forces on Oscillating Cylinders", Proceedings, American Society of Civil Engineers, 104-1978.

APPENDIX E - VIBRATION RECORDING

E.1 IEEE STANDARD

Although the bending stress in the conductor is considered to be the factor most closely related to fatigue, it was recognised that under field conditions the direct long-term measurement of stress was impractical (1). In 1966, the IEEE proposed a "Standardisation of Conductor Measurements" (1), in which the bending amplitude was established as the measurable parameter for vibration fatigue recordings. The bending amplitude is defined in (1) as "*The total excursion or displacement of the conductor, in mils peak-to-peak, measured relative to the suspension clamp and at a point 3½ inches out from the last point of contact between the clamp and the conductor.*"

As shown in Appendix D, Section D.3, the bending amplitude Y_b measured at the 89mm (3½ inch) point, has essentially a linear relationship with the bending stress.

The IEEE Report summarises the results of a study which concluded that the "bending amplitude method" is suitable for measuring vibration under all service conditions. The report recommends that samples be taken four times an hour with a duration of not less than one second. The duration of the test period is recommended as being a minimum of 14 days.

The longer the test period the greater is the probability of recording the maximum bending amplitudes. While the IEEE Report shows very high probabilities of recording maximum amplitudes for test periods of 2 weeks, it is now generally accepted that test periods in the vicinity of 4-6 weeks are required to provide sufficient data on which life predictions can be made (2).

E.2 THE EVOLUTION OF RECORDERS

The first recordings of conductor vibration were made around 1928 by attaching a string to the conductor and tracing the locus of its travel on a moving sheet of paper (3). The observations were very short-term and provided only limited information. These early studies did not attempt to determine the stresses adjacent to the support point.

By 1954, short-term vibration measurements of stress/strain on conductors were made using strain gauges (4). However as the equipment was very expensive and difficult to install, little field work was carried out and the results provided only a limited perspective on the problem.

About 1963, the first long-term vibration recorders were developed by Ontario Hydro in Canada (5). The devices recorded the vertical conductor movements at a distance of 89mm (3½ inches) from the last point of support. Unfortunately the recorders were heavy and significantly influenced the vibration behaviour. They were also very expensive and the data required a very time consuming manual analysis.

The Ontario Hydro recorders did however establish the basis for the IEEE "Standardisation of Conductor Measurements" (1) for line mounted vibration recording, and by the early 1980s, electronic recorders with storage capacity adequate for several months of data sampling became available. The recorders weighed less than 1kg and were cumulative data collecting devices. Evaluation software allowed for ease of data transfer and analysis.

E.3 THE SEFAG VIBREC 300 RECORDER

The requirements of a recorder for use on SWER lines were established as

(1) Meets IEEE requirements,
(2) Pole top mounting for security,
(3) Frequency range 0-300Hz,
(4) Amplitude range 0-2mm at 89mm point, and
(5) Weather station capabilities

All the recorders available on the market were designed specifically with transmission class conductors in mind (diameters > 20mm) and as a result the maximum frequency able to be recorded was limited to around 200Hz. This is quite satisfactory for large conductors where the frequency rarely exceeds 100Hz, however on SWER conductors the vibration frequencies could be as high as 300Hz for wind velocities of around 10m/s.

Wind data provided by the Bureau of Meteorology in Longreach, indicated that wind velocities in excess of 8m/s were only occurring less than 3% of the time. It is also most probable that these winds act on the conductor for only short periods. It was considered therefore that the impact of these wind velocities on the fatigue life of the line would be minimal. The vibration frequencies which could be expected on the range of SWER conductors for wind velocities of 8m/s are shown below.

Conductor Name	Frequency of Vibration @ 8m/s wind
3/2.75 SC/GZ	250
3/4/2.50 ACSR/GZ	197
4/3/3.00 ACSR/GZ	164

Table E.1 Vibration Frequencies at 8m/s Wind Velocity

Considering that the majority of the fatigue problems were associated with aluminium wires in ACSR conductors, the minimum acceptable frequency range for the recorder was established as 0-200Hz.

The Sefag Vibrec 300 recorder was selected as offering the best package for measuring the vibration. The recorder measures bending amplitudes and associated frequencies in accordance with the IEEE recommendation. Wind velocities and ambient temperature is also recorded. The recorder can do continuous measuring, however to conserve battery life the recorder can be set sample the data. The default sample cycle time is 10 seconds in every fifteen minutes in which the vibration amplitude and frequency, wind velocity normal to the line, and ambient temperature are sampled at 2kHz. The lowest temperature and wind velocity only are recorded once in each sample period. Using the default cycle time the recorder can be installed for periods in excess of three months.

The actual recorder specifications are provided at the rear of this Appendix.

E.4 RECORDER TESTING

The recorder was subjected to extensive acceptance testing as it was the first of this model of recorder to be used in Australia. The work was carried out at the University of Central Queensland under the Author's direct supervision, and is reported in reference (9).

The recorder performed within specification except in the range of frequencies 167-200Hz. The results of the testing on the frequency response is presented in the graph below.

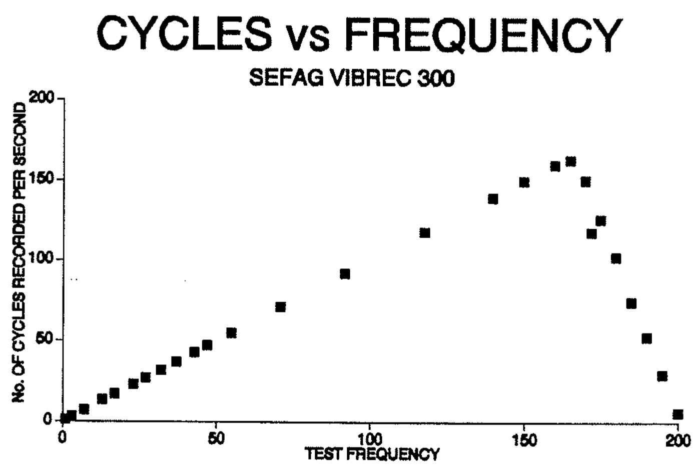


Figure E.1 Recorder Frequency Tests

It is clear that the recorder is unreliable at frequencies in excess of 167Hz. While the recorder was successful in distinguishing the correct frequency, it was not capable of accurately counting the number of cycles in that frequency range. A consequence of these recording anomalies, is that care needed to be taken in analysing the results, however it will be shown that the impact of the higher frequencies is negligible when adequate conductor dampers are applied.

Also of interest, and not documented in the recorder manuals, is the restriction on the range of frequency class boundaries allowable. Only the following numbers would be accepted by the recorder as legitimate class boundaries:- any number between 1 and 34, 36, 37, 38, 40, 42, 43, 45, 50, 53, 56, 63, 67, 71, 77, 83, 91, 100, 111, 125, 143, 167 and 200. If any other number was written to the recorder, it would choose the closest number from the list shown. This unfortunately limited the range of classes which could be used for the higher frequency recordings.

E.5 MOUNTING

The recorder is designed to be mounted underneath the conductor support clamp on a suspension structure. The mounting arrangement had to be significantly modified to allow for fixing on SWER pole top structures. A seizing clamp allows for mounting of the recorder directly on top of the line insulator without disrupting any of the conductor support or tie hardware. The mounting arrangement is shown in the photographs included in Appendix C.

This mounting arrangement addresses the concerns raised by A.S. Richardson in reference (7), where he concludes that "*electromechanical recorders suspended below the suspension clamp for the purpose of measuring aeolian vibration to the IEEE standard may be subject to large error owing to the dynamic reaction of the offset inertial mass of the recorder itself.*"

E.6 RECORDER SET-UP

The classes used for recording the wind velocities, temperatures, and vibration amplitudes and frequencies are detailed below. These have been written to the recorder using the set-up function.

Wind Classes: (8 classes, lowest value 0)

Class No.	Upper Limit (m/s)	Class No.	Upper Limit (m/s)	Class No.	Upper Limit (m/s)	Class No.	Upper Limit (m/s)
1:	2	2:	4	3:	6	4:	8
5:	10	6:	12	7:	14	8:	40

Table E.2 Recorder Wind Classes

Temperature Classes: (32 classes, lowest value -10°C)

Class No	Upper Limit (°C)	Class No	Upper Limit (°C)	Class No	Upper Limit (°C)	Class No	Upper Limit (°C)
1:	-8	2:	-6	3:	-4	4:	-2
5:	0	6:	2	7:	4	8:	6
9:	8	10:	10	11:	12	12:	14
13:	16	14:	18	15:	20	16:	22
17:	24	18:	26	19:	28	20:	30
21:	32	22:	34	23:	36	24:	38
25:	40	26:	42	27:	44	28:	46
29:	48	30:	50	31:	52	32:	54

Table E.3 Recorder Temperature Classes

Frequency Classes: (15 classes, lowest value 0)

Class No.	Upper Limit (Hertz)	Class No.	Upper Limit (Hertz)	Class No.	Upper Limit (Hertz)	Class No.	Upper Limit (Hertz)
1:	10	2:	20	3:	30	4:	40
5:	50	6:	59	7:	71	8:	77
9:	91	10:	100	11:	111	12:	125
13:	143	14:	167	15:	200		

Table E.4 Recorder Frequency Classes

Amplitude Classes: (32 classes, lowest value 32μm)

Class No.	Upper Limit (μm)	Class No	Upper Limit (μm)	Class No	Upper Limit (μm)	Class No	Upper Limit (μm)
1:	63	2:	125	3:	188	4:	251
5:	314	6:	376	7:	439	8:	502
9:	565	10:	627	11:	690	12:	753
13:	816	14:	878	15:	941	16:	1004
17:	1067	18:	1129	19:	1192	20:	1255
21:	1318	22:	1380	23:	1443	24:	1506
25:	1569	26:	1631	27:	1694	28:	1757
29:	1820	30:	1882	31:	1945	32:	2000

Table E.5 Recorder Amplitude Classes

An amplitude filter is used to suppress small variations of the signal amplitude which could otherwise falsify the counting and classification. The amplitude filter has been set at 31μm.

Measurement Cycle Time:	Duration of one measurement (s):	10
	Measurement cycle time (s):	900

E.7 RECORDING

The recorder uses a displacement transducer (LVDT) to measure the conductor vibration. As mentioned above, the signal is sampled at 2kHz during the sample period. A microprocessor compares every sample with the previous one and checks the signal for slope change. If a slope change has been detected (eg rising to falling), then the previous sample is considered as a maximum. However this is only recorded as a peak if the signal drops below the value of this maximum by the extent of the "amplitude filter". The valleys are treated in similar manner.

The amplitude (peak to peak) of a half cycle is determined by the vertical displacement between peaks and subsequent valleys. The frequency of the half cycle is defined from the time (T) between a peak and the subsequent valley. The frequency = 1/T.

During each recording interval, for each half cycle, the frequency and amplitude are determined, the wind velocity normal to the line is measured and the ambient temperature is measured. Once the frequency, amplitude and wind velocity are determined the appropriate element of a three dimensional FAV array (frequency F, amplitude A, velocity V) is incremented.

The matrix consists of columns of amplitude classes, rows of frequency classes, and layers of velocity classes. The 3 dimensional FAV matrix can store up to 1×10^9 half cycles.

At the conclusion of each recording interval, the lowest measured wind velocity and lowest measured temperature are determined and the appropriate elements of two dimensional arrays incremented.

E.8 DATA ANALYSIS

The Sefag recorder is supplied with a data analysis package for use on a personal computer. The analysis is based on the CIGRE recommendations (10), and by using the safe border S-N line and the Miner's hypothesis, an endurance capability or fatigue life expectancy for the conductor can be determined.

APPENDIX E - REFERENCES

(1) IEEE Committee Report. "Standardisation of Conductor Vibration Measurements", IEEE Transactions, Vol. PAS-85, 1966.

(2) Bückner, W.F. "Safety Determination of Transmission Conductors During Aeolian Vibrations", Transmission & Distribution International, June 1992.

(3) Varney, T. "Notes on the Vibration of Transmission Line Conductors", AIEE Transactions, 1926.

(4) Ruhlman, J.R., Poffenberger, J.C., Grosshandler, S. "A Modile Vibration Laboratory Unit for Monitoring Dynamic Characteristics of Overhead Transmission Lines", AIEE Transactions, Vol. PAS-78, 1959.

(5) Edwards, A.T., Boyd, M. "Ontario Hydro Live-Line Vibration Recorder for Transmission Conductors", IEEE Transactions, Vol. PAS-84, 1963.

(6) CIGRE Working Group 22.11. "Field Measurement and Field Data Processing on Conductor Vibration (Comparison Between Experimental and Analytical Results", 1982.

(7) Richardson , A.S. "Paradox Unresolved", Journal of Engineering Mechanics, Vol 115, No. 5, May 1989.

(8) Jacobs, M.L., Vaselaar, G.A. "A Ground -Based Sensor for the Detection of Transmission Line Conductor Motion", IEEE Transaction on Power Delivery, Vol. 5, No. 2, April 1990.

(9) Capricornia Electricity, "Report on Acceptance Tests, VIBREC 300 Vibration Recorder", May 1992.

(10) CIGRE Working Group 22.04. "Recommendations for the Evaluation of the Lifetime of Transmission Line Conductors", Extract from Electra No. 63, 1979.

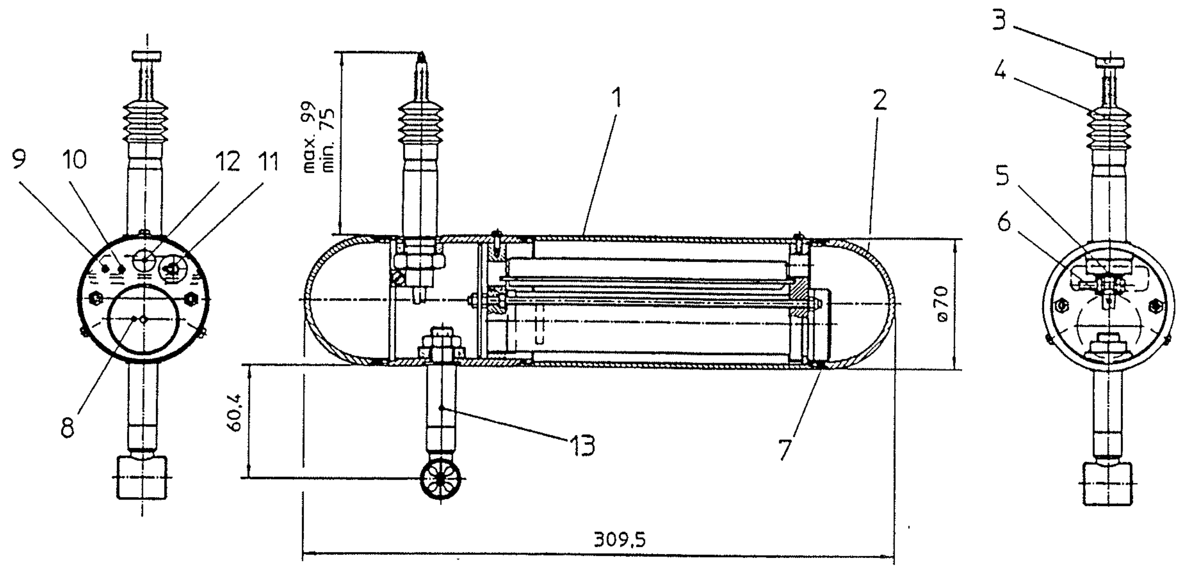
Specifications

VIBREC 300

Measurable variables	Vibration bending amplitude (peak to peak) and vibration frequency wind velocity perpendicular to line temperature (ambient or conductor)
Sensors	Standard: LVDT displacement transducer (± 1 mm) Optional: propeller anemometer (0 to 40 m/sec.) Silicon temperature sensor (−40 to + 140 °C) separate LVDT for remote measurements at spacer/damper locations strain gauges for stress assessment
Frequency range	0.1–200 Hz, allows measurement of subspan oscillations
Signal detection	Sampling of signal with 2 kHz Amplitude: peak – valley detection from two subsequent extrema Frequency: inversion of time lag between two subsequent extrema
Filtering	Programmable amplitude filter
Data classification	Events counting and storage in user selectable classes in a matrix with max. 32 amplitudes and max. 16 frequencies. With optional wind sensor data storage in cubic matrix with user selectable 8 wind classes; correlation of wind data to vibration amplitude/frequency data Temperature classification in max. 64 classes Default values as for VR 100
Storage memory	Max. 10^9 events per matrix elements (half cycles)
Reading interval	15 min. default, can be preset from quasicontinuous measurement to 8 hours intervals

Sample period	10 sec. default, can be preset from 0 to 65 sec. intervals
Electronics	Electronic circuits in SMD-technology Powerful microprocessor allows implementation of user defined firmware and evaluation algorithms Function control by LED
Real-time clock	Built-in real-time clock allows user selectable presetting of beginning and end of measurements
Communication	Built-in serial interface (RS 232) allows direct connection to PC at 9'600 baud rate Field kit with laptop and printer available
Utility Software	Utility program VIBREAD for parameter set-up and data read out via PC included; can also be used with VR 100
Data evaluation	Optional program LIFETIME allows evaluation and graphical presentation of data and lifetime estimation
Power supply	3 Lithium batteries (3.6 Volt) size C, separate battery for memory backup; six months battery lifetime at default settings
Temperature range	−40 to +80 °C (−30 to +65 °C with wind sensor)
Degree of protection	IP 67 (DIN)
Dimensions	Aluminium Alloy tube, length 306 mm, dia. 70 mm
Weight	Approx. 1'000 g incl. batteries
Tests	Extensive type and routine tests

Figure E.2 Vibrec 300 Recorder Specifications



LOCATION OF PARTS

ITEM NO.	DESCRIPTION	PART NO.
1	vibration recorder body	
2	end cap	125 005-401
3	sensor head	125 014-001
4	rubber cover	125 060-003
5	sensor clamping bolt	
6	LVDT sensor	125 061-001
7	cap seal ring	195 436-001
8	battery compartement	
9	red LED (lights up duringat the measurement)	
10	green LED (lights up if the power switch is in the reset position)	
11	power switch (has 3 positions: OFF-ON-RESET)	
12	serial connector (if connected the recorder is in communication mode, measuring is not possible)	
13	wind/temperature measuring device	125 062-001

Table E.3 Vibrec 300 Details and Dimensions

APPENDIX F

The tables detailed below and provided as part of this Appendix are summaries of recordings taken with the Vibrec 300 Vibration Recorder.

Table F.1	Field Recording Matrix - Stonehenge, Pole 81, Undamped
Table F.2	Field Recording Matrix - Waterloo, Pole 19, Undamped
Table F.3	Field Recording Matrix - Waterloo, Pole 19, One Damper, Preform Tie
Table F.4	Field Recording Matrix - Waterloo, Pole 19, One Damper, Hand Tie
Table F.5	Field Recording Matrix - Waterloo, Pole 19, 2 Dampers, Preform Tie
Table F.6	Field Recording Matrix - Waterloo, Pole 19, 2 Dampers, Hand Tie
Table F.7	Laboratory Test Recording Matrix - Case 1
Table F.8	Laboratory Test Recording Matrix - Case 2
Table F.9	Laboratory Test Recording Matrix - Case 3
Table F.10	Laboratory Test Recording Matrix - Case 4
Table F.11	Laboratory Test Recording Matrix - Case 5
Table F.12	Laboratory Recording Matrix - 35% CBL
Table F.13	Laboratory Recording Matrix - 15.5% CBL

The highlighted number in each frequency class in the Tables represents the 0.01% of population level used for determination of the maximum recorded amplitude. The recorded cycles at amplitudes above these points are too few in number to be considered as being significant.

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTALS
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	13301	171	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13473
20	11538	3641	1493	550	115	29	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17369
30	14435	13663	9661	7109	4876	3000	1595	627	270	79	18	2	2	-	-	-	-	-	-	-	-	-	-	-	55337
40	13742	18137	16762	14866	12536	9991	7258	5143	3374	2125	1128	507	209	71	30	10	2	-	-	-	-	-	-	-	105891
50	10999	15761	18587	20512	19407	17877	15919	13048	10009	7127	4810	3049	1655	818	354	144	32	5	2	-	-	-	-	-	160113
59	9472	14528	18517	21099	20974	20371	19027	17342	14594	11482	8291	5544	3356	1875	947	477	227	116	51	29	6	2	2	2	188333
71	12495	21409	24019	27170	25973	23602	22331	20853	18625	15802	13110	10896	7991	4937	3021	1558	699	284	92	30	9	4	2	1	254913
77	6509	9449	9134	9148	8643	8449	8251	7809	7483	6959	6323	5614	4796	3730	2749	1820	1075	606	315	140	51	20	2	-	109075
91	23229	29673	24767	24729	24394	21635	20422	19501	18010	16771	14926	12689	10190	7555	5102	3132	1920	1109	608	298	139	49	17	3	280868
100	18279	23063	17141	17419	16354	14335	12887	11897	10734	9789	8803	7441	5975	3903	2500	1563	958	534	285	142	60	18	7	1	184088
111	21214	29145	21721	20232	19171	17116	14923	12962	11220	9145	7266	5487	3763	2375	1424	853	443	207	94	36	7	1	1	-	198806
125	20831	29552	25031	23863	21555	19036	16050	13678	11162	8691	6116	4019	2466	1380	678	337	125	60	21	9	2	-	-	-	204662
143	20034	33459	27853	24359	21504	18333	14169	10635	7544	4991	3150	1752	962	447	156	59	13	3	-	-	-	-	-	-	189423
167	20239	36854	28643	25370	22237	18061	13457	9174	5422	2785	1360	611	253	84	27	7	-	-	-	-	-	-	-	-	184584
200	22722	49284	42840	27637	16247	8576	4194	2157	1080	439	165	64	21	8	-	-	-	-	-	-	-	-	-	-	175434
TOTAL	239039	327789	286170	264063	233986	200411	170486	144826	119527	96185	75466	57675	41639	27183	16988	9960	5494	2924	1468	684	274	94	31	7	2322369

Recording Period: 14/9/92 - 24/11/92 - 71 days   No. of Measurement: 6808   Total No. of Cycles in Matrix: 2 322 369

Table F.1 Field Recording Matrix - Stonehenge SWER, Pole 81, Undamped

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTALS
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	2739	191	59	22	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3016
20	4378	2029	1048	612	306	113	46	12	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8547
30	4916	5389	4043	3349	2483	1667	1137	561	266	99	29	8	1	-	-	-	-	-	-	-	-	-	-	-	23948
40	5280	7628	8293	7959	6910	5735	4488	2820	1548	696	296	114	46	24	7	1	-	-	-	-	-	-	-	-	51843
50	5320	8553	9267	9966	8718	7736	6831	5567	3958	2454	1367	578	251	123	60	24	5	1	-	-	-	-	-	-	70779
59	5453	10257	9993	10457	7961	6917	6002	5711	4836	3896	2932	1911	913	380	168	69	26	6	3	-	-	-	-	-	77895
71	8622	17318	16089	17362	14976	12456	10819	10190	9495	8482	7122	5355	3158	1653	935	370	150	51	8	-	-	-	-	-	144611
77	4725	8646	8416	10456	11143	10869	10242	9636	8556	6921	5131	3585	2398	1435	661	286	129	69	34	7	3	1	-	-	103349
91	11058	20769	20938	25021	27067	27438	27096	26655	25305	22626	19318	15582	11701	7735	4714	2539	1191	630	250	85	30	4	-	-	297752
100	6855	13062	14634	17403	19125	19188	19980	21090	22152	21702	20802	19482	15366	11061	7332	4089	1911	606	120	27	9	-	-	-	255996
111	6468	13461	15522	17529	18837	18618	18441	18228	18321	17493	16548	14526	11925	8901	5712	2916	1188	321	84	33	9	-	-	-	225081
125	6129	13809	17487	19239	19461	19446	18552	17181	16134	14913	13518	11217	8520	5295	2652	1110	387	138	39	12	-	-	-	-	205239
143	6684	16368	20298	22590	21555	18666	15603	13977	12489	10968	9327	6801	4302	2145	798	231	54	21	-	-	-	-	-	-	182877
167	8661	23883	28146	27459	23904	19689	16302	13218	10368	7503	5157	3471	2094	1014	384	99	21	3	-	-	-	-	-	-	191376
200	27093	77772	66396	52284	40791	31419	23004	15918	10488	6600	4230	2322	1155	561	231	72	21	6	-	-	-	-	-	-	360363
TOTALS	114385	239135	240629	241706	223242	199957	178543	160764	143919	124353	105777	84952	61830	40327	23654	11806	5083	1852	538	164	51	5	-	-	2202672

Recording Period: 22/2/93 to 24/3/93 - 30 days   No. of Measurements: 3288   Total No. of Cycles in Matrix: 2 202 672

Table F.2 Field Recording Matrix - Waterloo SWER, Pole 19, Undamped

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	15923	52	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15976
20	13161	1328	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14491
30	39183	53611	1404	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	94215
40	52367	152492	62229	6331	159	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	273581
50	27094	59265	53568	22297	5092	932	79	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	168330
59	12739	21594	33239	29528	17008	3092	464	37	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	117703
71	5206	11555	13304	13366	6808	1580	583	203	56	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	52671
77	1259	669	520	361	247	188	141	68	22	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3478
91	5427	1514	314	244	223	173	125	53	17	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8092
100	5369	2643	72	50	34	20	8	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8197
111	5489	3651	39	17	8	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9207
125	3411	1711	16	3	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5142
143	1352	454	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1810
167	444	90	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	535
200	142	14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	156
TOTALS	188566	310643	164713	72214	29580	5991	1400	365	97	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	773584

Recording Period: 18/8/93 to 15/10/93 - 58 days   No. of Measurements: 5569   Total No. of Cycles in Matrix: 773584

Table F.3 Field Recording Matrix - Waterloo SWER, Pole 19, One Damper, Preform Tie

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	21420	619	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	22042
20	14114	267	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14392
30	12012	4113	1019	48	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17196
40	11012	18677	15734	4468	1027	128	14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	51060
50	8527	11065	14842	11385	7499	4800	2285	863	254	55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	61575
59	7516	12868	15155	18571	17072	11891	5718	2499	713	158	8	-	-	-	-	-	-	-	-	-	-	-	-	-	92169
71	28020	36560	18071	18416	10954	5564	1705	375	98	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	119784
77	18496	12390	757	219	97	56	35	23	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	32083
91	89950	38669	2278	83	49	36	28	10	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	131107
100	113147	43999	3880	61	5	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	161093
111	110563	50082	9018	291	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	169959
125	41318	37714	13593	720	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	93355
143	35172	18305	7799	491	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	61780
167	34533	4429	1205	87	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40255
200	18771	595	48	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	19418
TOTALS	564571	290352	103413	54844	36736	22476	9785	3770	1079	234	8	-	-	-	-	-	-	-	-	-	-	-	-	-	1087268

Recording Period: 9/12/93 to 14/1/94 - 38 days No. of Measurements: 3653 Total No. of Cycles in Matrix: 1087268

Table F.4 Field Recording Matrix - Waterloo SWER, Pole 19, One Damper, Hand Tie

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	14974	182	5	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15163
20	10927	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10940
30	7964	171	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8135
40	63816	6611	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	70428
50	91084	24568	132	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	115784
59	39124	16307	101	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	55532
71	17568	2521	44	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20133
77	2206	171	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2386
91	2027	139	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2173
100	314	20	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	335
111	141	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	147
125	56	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	58
143	33	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	34
167	62	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	63
200	87	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	87
TOTALS	250383	50713	300	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	301398

Recording Period: 9/6/93 to 4/8/93 - 56 days No. of Measurements: 5380 Total No. of Cycles in Matrix: 301398

Table F.5 Field Recording Matrix - Waterloo SWER, Pole 19, Two Dampers, Preform Tie

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	14386.	339	8	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14734
20	5466	40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5506
30	3339	244	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3584
40	13484	13997	1471	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	28968
50	22610	26093	1983	38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50724
59	22109	25746	601	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	48461
71	65467	38689	541	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	104708
77	14077	9879	92	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24053
91	13602	6079	114	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	19812
100	4196	1717	33	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5952
111	6246	3823	9	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10080
125	6782	3355	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10139
143	4622	2047	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6669
167	2182	807	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2989
200	504	63	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	567
TOTALS	199072	132918	4855	101	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	336946

Recording Period: 21/10/93 to 7/12/93 - 47 days   No. of Measurements: 4507   Total No. of Cycles in Matrix: 336946

Table F.6 Field Recording Matrix - Waterloo SWER, Pole 19, Two Dampers, Hand Tie

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																														TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	1569	1631	1694	1757	1820	1882	
10	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20
20	6	-	-	-	-	-	56	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	62
30	10	-	-	-	1744	4944	2410	1332	1040	1142	468	322	254	160	140	136	218	212	264	176	214	306	464	182	-	-	-	-	-	-	16138
40	2	-	-	-	100	5860	5918	6258	4264	2896	2132	1708	1760	1330	1072	1464	1910	986	736	1210	612	528	838	30	-	-	-	-	-	-	41614
50	2	6	96	978	6478	9908	7044	6784	3852	2460	1950	1602	1058	656	792	700	696	420	556	458	442	614	798	448	714	584	92	-	-	-	50188
59	10	26	5692	17242	9748	4830	2406	1520	1102	930	888	774	696	838	600	724	778	884	708	806	860	1034	1066	1086	1022	1566	1310	326	-	-	59472
71	36	6802	32510	14770	7122	4176	2826	2436	2200	1738	1442	1294	1912	1456	486	664	806	812	704	554	614	592	656	1128	252	292	332	44	-	-	88656
77	74	11996	14966	5674	2298	974	768	674	798	596	442	384	378	450	426	640	820	602	730	558	228	364	238	2	2	8	4	4	4	4	45106
91	144	7546	56314	21590	8036	4434	3342	2598	2478	1830	2032	1692	1608	1900	1726	1582	1612	2242	1738	1566	1070	1800	1288	220	150	128	1422	140	144	186	131278
100	60	16824	40562	11064	4404	2828	1984	1704	1270	1318	1330	1108	1162	1236	1488	1182	1590	1504	1774	1630	1806	1278	480	78	8	22	18	28	30	26	99796
111	132	35948	38660	13422	7174	5406	2630	2118	1700	1698	1622	1708	2260	1630	1750	2258	2052	862	1118	392	226	-	-	-	-	-	-	-	-	-	124766
125	98	26100	104116	21896	13536	10134	5016	3142	2258	2470	2546	2266	2700	2640	2760	2824	2722	2090	994	-	-	-	-	-	-	-	-	-	-	-	210308
143	246	34876	70138	24776	16058	9018	8140	4824	3450	3028	3126	2942	3748	4286	5442	714	456	48	-	-	-	-	-	-	-	-	-	-	-	-	195316
167	236	6622	164328	44770	24598	18000	18906	9316	7140	6992	7396	7936	4370	2694	1784	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	325088
200	162	121304	221326	51452	32156	23618	22072	14412	13660	9092	4332	2540	530	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	516656
TOTALS	1238	268050	748708	227634	133452	104130	83518	57118	45212	36190	29706	26276	22436	19276	18466	12888	13660	10662	9322	7350	6072	6516	5828	3174	2148	2600	1898	542	178	216	1904464

Recording Period: 58 minutes No. of Measurements: 1 continuous Total No. of Cycles in Matrix: 1 904 464

Table F.7 Laboratory Test Recording Matrix - Case 1 (Hellically Formed Tie, No Armour, No Damper)

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTALS
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12
20	22	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24
30	16	24	58	4	2	16	60	118	164	156	82	36	28	22	18	10	4	2	2	-	-	-	-	-	822
40	50	198	220	438	424	786	1672	1994	2044	1828	1322	696	208	76	32	18	10	2	-	-	-	-	-	-	12018
50	174	1668	2826	4796	6048	6588	6514	5356	4442	3858	3134	1932	730	202	82	56	48	40	2	-	-	-	-	-	48496
59	236	3206	6378	9648	9410	6890	6542	5592	4116	2860	1934	1002	386	114	58	66	48	14	8	-	-	-	-	-	58508
71	3236	10860	19940	17370	13434	10422	8944	6024	4864	3128	2006	1236	478	172	78	84	44	12	2	-	-	-	-	-	102334
77	822	7454	14406	9572	5974	4788	3950	3014	2038	1356	724	376	128	54	22	14	12	2	-	-	-	-	-	-	54706
91	1036	29174	45314	24684	14336	11016	9136	5970	4700	2822	1382	582	184	34	8	6	12	2	-	-	-	-	-	-	150384
100	958	28436	29766	14270	8910	6772	5568	3000	2456	1308	572	152	34	2	-	-	-	-	-	-	-	-	-	-	102204
111	1382	48622	34184	15456	10116	7988	6450	4464	2672	1182	412	112	12	-	-	-	-	-	-	-	-	-	-	-	133052
125	1434	45314	41494	20374	12760	10608	7796	4104	2124	788	246	52	8	-	-	-	-	-	-	-	-	-	-	-	146402
143	2272	54342	74372	42966	21702	15194	10494	3816	1628	452	126	34	10	-	-	-	-	-	-	-	-	-	-	-	227408
167	6850	68162	117066	70850	24426	10296	6418	2994	806	216	56	18	4	-	-	-	-	-	-	-	-	-	-	-	308162
200	21638	226186	160670	75776	32138	7400	1050	442	148	30	8	-	2	2	-	-	-	-	-	-	-	-	-	-	525490
TOTALS	40128	523648	546694	306204	159680	98764	74594	46888	32202	19984	12004	6228	2212	676	298	254	176	74	14	-	-	-	-	-	1870722

Recording Period: 58 minutes　　No. of Measurements: 1 continuous　　Total No. of Cycles in Matrix: 1 870 722

Table F.8 Laboratory Test Recording Matrix - Case 2 (Hellically Formed Tie, No Armour, One Damper)

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTALS
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	38
20	58	4	-	-	2	-	2	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	68
30	174	350	144	70	142	168	288	334	180	58	10	4	-	-	-	-	-	-	-	-	-	-	-	-	1922
40	506	1216	1206	1022	1534	1618	2302	3378	3174	1900	692	142	22	2	-	-	-	-	-	-	-	-	-	-	18714
50	1254	5790	7138	5776	6176	7002	6462	6644	5574	3034	1212	234	34	4	-	-	-	-	-	-	-	-	-	-	56334
59	928	8672	11154	8654	8046	7526	5396	3940	2382	890	266	34	2	-	-	-	-	-	-	-	-	-	-	-	57890
71	5132	18236	24468	15556	11680	8808	5184	2706	1134	344	76	8	-	-	-	-	-	-	-	-	-	-	-	-	93332
77	1086	12484	16944	8972	5552	3654	1810	708	218	50	6	-	-	-	-	-	-	-	-	-	-	-	-	-	51484
91	3846	50854	51256	24522	14336	7636	3154	1044	302	60	12	-	-	-	-	-	-	-	-	-	-	-	-	-	157022
100	4632	44286	30724	14702	8582	4094	1424	426	74	12	2	-	-	-	-	-	-	-	-	-	-	-	-	-	108958
111	7214	49832	30034	14506	8102	3830	1302	398	92	22	4	-	-	-	-	-	-	-	-	-	-	-	-	-	115336
125	10350	66622	38148	18906	9488	3894	1142	332	108	28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	149018
143	15338	97360	67042	33504	17628	6826	898	220	62	6	2	-	-	-	-	-	-	-	-	-	-	-	-	-	238886
167	29372	130816	88196	30314	14958	5994	568	120	22	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	300366
200	112922	250876	71024	16776	5018	1186	240	50	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	458105
TOTALS	192850	737398	437478	193280	111244	62236	30172	20303	13334	6410	2282	422	58	6	-	-	-	-	-	-	-	-	-	-	1807473

Recording Period: 58 minutes   No. of Measurements: 1 continuous   Total No. of Cycles in Matrix: 1 807 473

Table F.9 Laboratory Test Recording Matrix - Case 3 (Hellically Formed Tie, No Armour, 2 Dampers)

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																										TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	1569	1631	
10	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	16
20	20	-	-	38	218	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	278
30	14	-	18	4256	1948	1510	658	385	1262	696	280	236	276	206	98	102	316	416	88	206	10	-	-	-	-	-	12981
40	24	-	-	2630	5790	9006	5282	1772	2752	2126	1536	1350	1378	1264	937	480	1084	732	548	282	154	-	-	-	-	-	39127
50	46	124	1172	5724	13008	9332	4046	1650	1988	1896	1262	1658	1310	1132	645	576	766	978	868	356	530	566	684	320	232	310	51179
59	22	694	10730	14768	8354	4430	2488	811	1224	1014	1206	948	656	582	434	175	708	764	308	728	792	550	922	1018	1210	458	55994
71	34	10138	33260	16060	7030	5798	1766	698	990	866	840	868	1000	1196	524	452	1452	532	230	584	592	436	858	698	550	240	87692
77	90	18132	9766	5148	2586	1900	986	298	400	416	514	412	530	480	107	178	110	160	168	20	-	-	-	-	-	-	42401
91	250	42602	41310	10356	7864	4668	3120	1226	2276	2096	2108	2242	2578	2830	1684	1157	1504	614	616	226	128	140	102	-	-	-	131697
100	3032	54408	15594	5080	2754	1872	1494	798	1680	1692	1886	2186	2218	1754	722	122	250	-	-	-	-	-	-	-	-	-	97542
111	6674	72052	12244	5070	3372	2350	2356	1407	3498	2706	3050	1160	638	84	21	-	-	-	-	-	-	-	-	-	-	-	116682
125	13558	133892	22178	10352	5422	3398	4112	2562	4780	3944	4000	88	-	-	-	-	-	-	-	-	-	-	-	-	-	-	208286
143	9260	154660	26092	13238	9318	5780	7634	3754	1230	192	306	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	231480
167	3350	214698	39738	17228	22174	16648	10460	1417	82	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	325795
200	58244	338078	55294	38768	18300	14314	9052	113	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	532163
TOTALS	94634	1039478	267396	148716	108138	81008	53454	16891	22162	17644	16988	11164	10584	9528	5172	3242	6190	4196	2826	2402	2206	1692	2566	2036	1992	2036	1933313

Recording Period: 58 minutes   No. of Measurements: 1 continuous   Total No. of Cycles in Matrix: 1 933 313

Table F.10 Laboratory Test Recording Matrix - Case 4 (Hellically Formed Tie, Armoured, No Damper)

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																								TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	
10	350	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	350
20	746	-	-	6	6	4	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	764
30	1344	12	18	100	496	1004	656	328	158	74	64	62	46	114	60	6	-	-	-	-	-	-	-	-	4542
40	1394	392	922	1682	4190	5012	3804	2670	1938	1002	212	46	54	116	30	-	-	-	-	-	-	-	-	-	23464
50	1790	3482	7596	7180	9348	8170	6694	4654	3496	2232	804	166	22	8	-	-	-	-	-	-	-	-	-	-	55642
59	6630	13358	15482	9498	7640	6106	4920	3316	2168	1218	478	152	40	6	-	-	-	-	-	-	-	-	-	-	71012
71	21798	25978	27140	14674	10052	6922	5220	2598	1168	492	140	26	4	-	-	-	-	-	-	-	-	-	-	-	116212
77	7790	16574	15244	6786	4964	3276	2044	760	220	48	4	-	-	-	-	-	-	-	-	-	-	-	-	-	57710
91	8858	53558	49074	20336	13174	7502	3878	1350	298	42	2	-	-	-	-	-	-	-	-	-	-	-	-	-	158072
100	6146	39996	30506	10804	5968	3300	1368	394	56	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	98546
111	13420	55234	30822	12314	6628	3302	1434	358	44	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	123562
125	33056	90526	38520	18152	10208	5898	2908	722	56	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	200048
143	48890	118404	43326	20800	12386	5996	2040	378	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	252240
167	60866	120684	40482	17382	8336	2634	390	36	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	250816
200	137910	178582	44908	6436	1646	294	40	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	369820
TOTALS	350988	716780	344040	146150	95042	59420	35398	17568	9628	5124	1704	452	166	244	90	6	-	-	-	-	-	-	-	-	1782800

Recording Period: 58 minutes No. of Measurements: 1 continuous Total No. of Cycles in Matrix: 1 782 800

Table F.11 Laboratory Test Recording Matrix - Case 5 (Hellically Formed Tie, Armoured, 1 Damper)

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (µm)																													TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	1569	1631	1694	1757	1820	1882	
10	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6
20	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12
30	16	162	290	3110	2578	3174	1130	662	520	450	258	424	100	76	152	152	210	240	32	44	46	104	398	-	-	-	-	-	-	-	14328
40	10	156	202	1164	1864	12988	6542	4324	3136	2080	2052	2262	2002	2340	702	1088	262	206	-	-	-	-	-	-	-	-	-	-	-	-	43380
50	6	-	132	5300	8328	12512	5184	4274	2590	2912	2854	1128	1558	1404	646	782	104	74	72	-	-	-	-	-	-	-	-	-	-	-	49860
59	8	318	7888	18722	7538	4398	3344	2212	1706	1204	1022	904	690	752	848	986	952	920	1592	986	318	452	120	-	-	-	-	-	-	-	57880
71	26	14110	36496	14600	8052	4382	2694	2062	1468	1450	1386	1166	1498	1668	1048	406	480	346	454	398	548	788	174	-	-	-	-	-	-	-	95700
77	48	16814	10834	3462	1504	1374	1150	822	734	620	458	500	520	376	322	216	204	164	168	168	202	232	208	234	274	18	-	-	-	-	41626
91	126	40074	34858	14588	5204	3638	3094	2198	1938	1992	1710	1794	2008	2144	1396	1502	1366	1188	982	1102	1324	1324	1056	1108	1522	1422	432	172	148	646	132056
100	50	42774	16352	5808	3126	2246	1738	1224	1338	1304	1058	1134	1096	1310	1190	1170	1180	1222	1236	1386	1390	1390	990	1000	936	406	232	18	8	104	94416
111	150	61704	23752	8058	3506	2230	1732	1430	1466	1236	1042	1094	1212	1474	1218	1354	1440	1734	1776	1984	1910	2024	776	1052	364	26	-	-	-	-	125744
125	166	69480	44316	13000	6344	4436	3034	2566	2428	2050	1436	2002	1648	1494	1642	2124	1854	2194	2296	2558	2072	2862	1606	500	-	-	-	-	-	-	174108
143	180	66554	60930	16630	7548	5988	3644	2884	2668	2500	2094	1896	2006	2342	1926	2034	2576	2998	3098	2692	2750	1442	850	56	-	-	-	-	-	-	198286
167	236	35238	162044	35502	17998	14794	7192	6030	4436	4064	3482	3288	3504	3658	4206	4054	4760	5336	4052	1832	1824	704	478	8	-	-	-	-	-	-	328720
200	92	125774	214802	46322	33736	18600	12996	10720	8144	7030	6152	6214	6270	3314	3924	3050	2706	2226	852	74	24	4	-	-	-	-	-	-	-	-	513026
TOTALS	1132	473158	612896	186266	107326	90760	53474	41408	32572	28892	25004	23806	24112	22352	19220	18918	18094	18848	16610	13224	12408	11326	6656	3958	3096	1872	664	190	156	750	1869148

Recoding period: 58 minutes   No. of Measurements: 1 continuous   Total No. of Cycles in Matrix: 1 869 148

Table F.12 Laboratory Test Recording Matrix - 35% CBL

163

FREQUENCY (Hertz)	UPPER LIMIT OF AMPLITUDE CLASS (μm)																														TOTAL
	63	125	188	251	314	376	439	502	565	627	690	753	816	878	941	1004	1067	1129	1192	1255	1318	1380	1443	1506	1569	1631	1694	1757	1820	1882	
10	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24
20	16	-	-	-	10	6	6	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40
30	18	-	-	2	88	2154	634	2334	1186	610	778	1496	356	86	48	80	96	152	126	210	174	172	270	248	410	394	410	356	452	870	14210
40	12	2	2	2	88	1624	2786	7020	6802	3434	2532	1728	1254	1448	1144	1194	1188	1068	1122	982	1196	1028	1390	1336	1840	1410	604	26	58	110	44430
50	28	12	58	424	2790	7966	4770	4260	3116	2328	1554	1376	1638	1786	1756	1502	1614	1474	1462	1734	2400	1238	1358	1282	1570	1754	750	608	286	-	52894
59	24	314	726	11994	10882	3496	2972	2084	1666	1788	2098	1282	1182	1142	1360	1202	1636	1632	1626	1548	1428	1324	1494	1372	974	238	24	-	-	-	57508
71	72	6236	14260	26928	8836	3662	2890	2648	2216	2122	1938	1664	1286	668	754	840	1344	1242	542	614	326	242	272	236	-	-	-	-	-	-	81838
77	88	3344	24306	10220	3746	1998	1250	968	1176	1180	1600	1192	1600	562	384	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	53614
91	148	2202	45150	25224	13178	7850	5940	3974	3396	3330	4250	6246	2882	1264	616	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	125650
100	38	1846	44616	16166	8610	5504	4570	3542	3542	4258	3954	1790	70	70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	98576
111	96	8582	57988	19530	11046	7236	6186	7036	5916	2166	282	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	126072
125	172	4888	114044	30864	17968	12656	10526	11216	8164	412	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	210890
143	186	18030	85274	33686	23532	14730	16584	3766	1330	34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	197152
167	368	15364	[illegible]	54290	[illegible]	22752	[illegible]	182	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	326568
200	20268	223236	230482	46370	20046	2758	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	546160
TOTALS	21558	284056	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	49032	38510	21662	18986	16782	10268	7026	6062	4818	5878	5568	4878	5088	5524	4004	4784	4474	4794	3796	1788	990	796	980	1935626

Recoding period: 58 minutes   No. of Measurements: 1 continuous   Total No. of Cycles in Matrix: 1 935 626

Table F.13 Laboratory Test Recording Matrix - 15.5% CBL