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Drury, Michael David, The effect of prestressing on the inelastic (creep) behaviour of Australian made bare overhead conductors, Master of Engineering (Hons.) thesis, Department of Materials Engineering - Faculty of Engineering, University of Wollongong, 1993. <http://ro.uow.edu.au/theses/2501>

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THE EFFECT OF PRESTRESSING ON THE INELASTIC (CREEP) BEHAVIOUR OF  
AUSTRALIAN MADE BARE OVERHEAD CONDUCTORS

A thesis submitted in fulfilment of the requirements for the award of the degree

MASTERS OF ENGINEERING (HONOURS)

from

UNIVERSITY OF WOLLONGONG

by

MICHAEL DAVID DRURY, B. Met (HONS)

DEPARTMENT OF MATERIALS ENGINEERING  
1993

I hereby declare that I have not submitted this material either in whole or in part, for a degree at this or any other institution. Whilst this thesis has been prepared with the proper care, the information advice, opinion and recommendations contained herein are offered, I accept no responsibility for the use of the information in any particular application.

MICHAEL DRURY  
July 24, 1993

## ABSTRACT

The creep behaviour of Australian manufactured bare overhead conductors was examined. The CIGRE proposed relationship for prestressing behaviour was assessed. A comprehensive literature survey yielded alternative experimental models and extensive amounts of creep constants for many conductor constructions.

19, 37 and 61 strand ACSR and AAAC/1120 conductors were tested. 1000 hour creep tests were performed at tensile loads of 20, 30 and 40% of the NBL of the conductor at 20°C. Prestressing overloads of either 10 or 20% NBL were applied for periods of 1, 2 or 7 days.

It was found that prestressing removed a considerable portion of the total predicted creep of a conductor in a relatively short time, i.e. has the effect on creep, of "overaging" a conductor. Analysis of the tests revealed that prestressing will stabilise creep strains for a period of time after load reduction. The stabilised period is adequately described by the CIGRE equivalent time relationship.

$$t_{eq} = \left( \frac{\sigma_1}{\sigma_2} \right)^{\frac{\alpha}{\mu}} t_1$$

Creep constants determined by this work and revealed by the literature survey for Australian conductors, were compared with those published for comparable conductors manufactured overseas. It was shown that there are significant differences between the creep constants of Australian and overseas conductors. Creep constants therefore, for overseas conductors, are not applicable to Australian conductors.

## ACKNOWLEDGMENTS

The author wishes to thank the Department of Materials Engineering, and the Department of Mechanical Engineering, from the University of Wollongong, MM Cables and the Australian Electrical Supply Industry Research Board for providing the opportunity to contribute to this area of research, establishing a work place where it was a pleasure to work, and providing the on going funding and availability of research facilities essential to successfully carry out the work.

My thanks are directed to Mr. G. Brennan, Mr. A.C.G. Secrett, Dr. A. Basu and Dr. T. Chandra for their interest in the project and supervision.

I am indebted to Mr. F. Van Eimeren for many hours of discussions and the years of accumulated knowledge passed on to me so freely and cheerfully. For assistance in sample preparation and testing the author wishes to thank Dr. M. Apperley, Mr M. Boyle, Mr. J. Capri, Mr. R. Solanki, Mr L. Wallace and Ms. J. Wines. The wishes to thank Mr. F. Pedersen, and M. I. Fishburn for engineering support in modifying and constructing the test rig.

Lastly, I owe a very special debt of gratitude and thanks for the endless support, cheerful smiles, forbearance, encouragement and understanding during the course of these studies by my wife Belinda. To Sean my son many thanks for his smiles and happy face in trying times.

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## **CONDUCTOR TERMINOLOGY**

### **AAAC**

Abbreviation for all aluminium alloy conductor. A stranded conductor in which all the strands of wire are of aluminium alloy D6201-T81 or 1120.

### **AAC**

Abbreviation for all aluminium conductor. A stranded conductor in which all the strands of wire are of aluminium alloy 1350 (D1045).

### **AC**

Aluminium clad steel wire.

### **ACAR**

Abbreviation for aluminium conductor aluminium alloy re-enforced. A stranded conductor with a core of aluminium alloy 6201 (D6201-T81) wires surrounded by one or more layers of high conductivity aluminium wires 1350 (D1045).

### **ACSR**

Abbreviation for aluminium conductor steel re-enforced. A stranded conductor with a core of steel wires surrounded by one or more layers of high conductivity aluminium wires 1350 (D1045). Sometimes referred to as S.C.A. i.e. steel cored aluminium conductors.

**ALDREY**

An Al-Mg-Si heat treatable alloy similar in properties to 6201 or 6101A originating in Switzerland.

**ALMELAC**

An Al-Mg-Si heat treatable alloy similar in properties to 6201 or 6101A originating in France.

**ALUMINIUM-CLAD STEEL WIRE (AC)**

A wire used as an electrical conductor which is composed of a steel cored coated with a uniform continuous coating of aluminium. The coating is anodic to the core so they protect exposed areas of the core electrolytically during exposure to corrosive environments. Trade names are Natalum, Alumoweld and A.S. wire.

**ALUMINISED STEEL WIRE (AZ)**

A steel wire with a thin aluminium coating applied by a hot dipping process. Used as steel core wires for ACSR conductors.

**ARVIDAL**

An Al-Mg-Si heat treatable alloy similar in properties to 6201 OR 6101A.

**AS**

Abbreviation for Australian Standard. Used as a prefix to a standard specification number i.e. AS 3607.



## ASC

Aluminium Stranded Conductor (USA and Canada)

## ASTM

Abbreviation for American Society for Testing and Materials. Used as a prefix to Standard specifications i.e. ASTM B232.

## AWG

Abbreviation for American Wire Gauge. A system of gauge numbers widely used in the United States for designating the diameter of wire or thickness of sheet. Each successive number is a constant multiple of the preceding number. Also referred to as B. & S. (Brown and Sharpe) gauge.

## BIRD CAGING

A term used to describe an open lay in a stranded conductor, i.e. when the outer strands bulge outwards from the inner core wires.

## BREAKING LOAD

The maximum tensile load for either an individual wire or stranded conductor on the tensile testing machine.

## BSWG

See SWG.

## BS

Abbreviation for British Standard. Used as a prefix to standard specifications prepared by the British Standards Association i.e. BS 125.

## B. & S.Gauge

Brown and Sharpe Gauge - see AWG.

## CALCULATED EQUIVALENT ALUMINIUM AREA

This term denotes the area of solid aluminium rod which would have the same resistance as the conductor.

## CATENARY

The curve assumed by a conductor when strung between two towers or poles.

## C.B.L.

See M.C.B.L.

## CERL

Central Electricity Research Laboratory, of the Central Electricity Generating Board, England.

## CIRCULAR MILS

A unit of area used for electrical conductors. One circular mil is the area of a wire 1 mil in diameter (1 mil = 0.001 inches)

**COEFFICIENT OF THERMAL EXPANSION**

A number measuring the of change in dimensions per unit dimension, here length of a conductor caused by a change in temperature.

**COMPOSITE CONDUCTOR**

A conductor consisting of two or more strands of different metals, such as aluminium and steel or copper and steel, assembled and operated in parallel.

**COMPRESSION FITTING**

A metal sleeve which is compressed onto a conductor either for joining the ends of two conductors or connecting a conductor to a terminal.

**CONDUCTOR**

A term generally applied to a material designed to carry electric current.

**CREEP**

The permanent deformation of metals held for long periods of time at stresses lower than the normal yield stress. Creep is dependent on the material, conductor construction, applied stress, the time and the temperature.

**DEAD\_END FITTINGS**

A compression fitting used to terminate a length of overhead conductor at a tension tower.

## DIAMETER

The mean of two measurements of a conductor at right angles at a single cross section.

## DIRECTION OF LAY

The direction of lay is defined as right-hand or left-hand. With right-hand lay the slope of the wires is in the direction of the central part of the letter Z when the conductor is held vertically. With left-hand lay, the slope of the wires is in the direction of the central part of the letter S when the conductor is held vertically.

## DUCTILITY

The property that permits permanent deformation before fracture by stress in tension.

## EARTH WIRE

Any conductor which carries current to earth.

## E.C. ALUMINIUM

Electrical grade aluminium 1350

## EDS

Abbreviation for Every Day Stress. The normal operation stress in an overhead conductor and is usually 20-25% of the rated tensile strength.

## ELONGATION

Is the increase in gauge length of a tension test specimen, usually expressed as a percentage of the original gauge length. (The increase in gauge length maybe measured either at or after fracture.)

## EXTENSOMETER

A device usually mechanical, for indicating the deformation of metal while the metal is subjected to stress.

## FEEDER

An overhead or underground cable of large current carrying capacity.

## GALLING

The damaging of one or both metallic surfaces by removal of particles from localised areas during sliding friction.

## GALVANISING

A zinc coating applied to steel or iron generally by immersion in a bath of molten zinc. Steel core wires in ACSR are usually galvanised to improve corrosion resistance.

## GAUGE LENGTH

The original length of that portion of the specimen over which strain or change of length is determined.

## GZ

Steel wire with a zinc coating.

## IACS

Abbreviation for International Annealed Copper Standard. A comparative scale the relative conductivity of a material in relation to the conductivity of a fully annealed copper sample. Usually expressed as a percentage. i.e. 61% IACS.

## INITIAL CREEP

The early part of the time-elongation curve for creep, in which extension increases at a rapid rate.

## IWG

See SWG.

## JOINTING SLEEVES

Oval-shaped tubes used for joining together the ends of electrical conductors.

## KING WIRE

Is a larger central wire (king wire) in the finished conductor. The size of this wire in general is approximately 5% greater in diameter than that of the surrounding wires.

**KINK LENGTH**

See Lay Length.

**LAY RATIO**

The ratio of the axial length of a complete turn of the helix formed by an individual wire in a stranded conductor, to the external diameter of the helix.

**LENGTH OF LAY**

The axial length of one turn of the helix formed by a strand of the conductor.

**MCBL**

Abbreviation for Minimum Calculated Breaking Load.

**AAC/AAAC**

For a conductor containing not more than 37 wires, 95 % of the sum of the strength of the individual wires calculated from the minimum breaking load of each wire as set out in the standard.

For a conductor containing more than 37 wires, 90 % of the sum of the strength of the individual wires calculated from the minimum breaking load of each wire as set out in the standard.

**ACSR**

For a conductor 95 % of the sum of the strength of the individual wires calculated from the minimum breaking load of each wire as set out in the standard.

**EARTHWIRES****AC**

For a conductor containing not more than 3 wires, 95 % of the sum of the strength of the individual wires calculated from the minimum breaking load of each wire as set out in the standard.

For a conductor containing 7 or 19 wires, 90 % of the sum of the strength of the individual wires calculated from the minimum breaking load of each wire as set out in the standard.

**GZ**

For a conductor 95 % of the sum of the strength of the individual wires calculated from the minimum breaking load of each wire as set out in the standard.

**MCM**

Abbreviation for Milli-Circular mils.  $\text{MCM} = 10^{-3} \times \text{circular mils}$ .

See Circular Mils.



## MECHANICAL PROPERTIES

Those properties of a material that reveal the elastic and inelastic reaction when force is applied, or that involve the relationship between stress and strain; eg. the modulus of elasticity, tensile strength and fatigue limit.

## MICRON

A linear distance of 0.001 mm.

## MIDSPAN JOINT

A compression joint joining the two ends of lengths of overhead conductor between poles or towers.

## MODULUS OF ELASTICITY

The slope of the elastic portion of the stress-strain curve in mechanical testing (ratio of stress to strain within the elastic range). The stress is divided by the unit elongation. The tensile elastic modulus is called "Young's Modulus"

## NATALUM

Aluminium Clad Steel wire used as an electrical conductor. Trade name of National Standards Company.

## NECKING DOWN

Reduction in area concentrated at the subsequent fracture when a ductile metal is tested in tension.

## PHYSICAL TESTING

Those properties familiarly discussed in physics. eg density, electrical conductivity, co-efficient of thermal expansion.

## PLASTIC DEFORMATION

Permanent distortion of a material under the action of applied stresses.

## PLASTICITY

The ability of a metal to be deformed extensively without rupture.

## PREFORMING

A process in which each strand of a cable is correctly bent before stranding so as to produce a tight uniform lay which resists unravelling.

## PROOF STRESS

In a test stress that will cause a specified permanent deformation in a material, usually 0.01 or less.

## REDUCTION IN AREA

The difference between the original cross-sectional area and that of the smallest area at the point of rupture, usually stated as a percentage of the original area.

**RTS**

Abbreviation for rated tensile strength. Term is often used as an alternative for U.T.S. in overhead conductor terminology.

**RULING SPAN**

The length of a span which most nearly represents the behaviour of all spans in a section of an overhead transmission line.  $\text{Ruling span} = \text{average span} + \frac{2}{3}(\text{max. span} - \text{min. span})$ .

**SAG**

The vertical distance from the lowest point in the span from the line joining the supports at the ends of the span.

**SAG TENSION CHART**

A series of graphs which show the relationship between sag, tension and ruling span for a given conductor reacting under a given set of conditions.

**SDC**

Abbreviation for self damping conductor. A conductor which by virtue of its construction is able to prevent harmful vibrations being induced by steady cross winds.

**SECONDARY CREEP**

The second portion of the creep curve following the initial creep stage and in which the rate of creep has reached a rather constant value.

**SHAVED ROD**

Rod which has the rolled surface removed prior to drawing.

**SILMALEC**

An Al-Mg-Si heat treatable alloy similar in properties to 6201 or 6101A originating in Britain.

**SPAN**

The horizontal distance between supports of an overhead conductor.

**SMOOTH BODIED STRAND**

A stranded conductor in which the wires of the outer layer are shaped so as to produce a smooth outer surface.

**SSAC**

Abbreviation for Steel Supported Aluminium Conductor. Similar to ACSR. Annealed (0 Temper) 1350 alloy aluminium wires surrounding a steel core.

**STRAIN**

Deformation expressed as a pure number or ratio. Ordinarily expressed as  $\epsilon$ , equivalent to the change in length divided by the original length.

**STRAND**

One of the wires, or groups of wires, of any stranded conductor.

**STRANDED CONDUCTOR**

A term applied to wires stranded together to form a flexible larger capacity conductor.

**STRANDED STRAND**

A conductor produced by stranding together several previously stranded conductors. These conductors are very flexible.

**STRESS- CONDUCTOR**

The load per unit cross-sectional area, of a conductor.

**STRESS STRAIN GRAPH**

A graph showing the extensions produced in a material with increasing and decreasing stress. Stress-Strain graphs are used to construct sag-tension charts for overhead conductors.

**SUSPENSION CLAMP**

A fitting for attaching a conductor to a supporting structure.

**SWG**

Abbreviation for Standard Wire Gauge. A system of gauge numbers widely used for representing wire sizes or sheet thicknesses. Also called British Standard Wire Gauge and Imperial Wire Gauge.

**TENSILE STRENGTH- OF A CONDUCTOR**

The value obtained by dividing the maximum load observed during tensile straining by the specimen cross-sectional area before straining.

**UPRATING**

A term used to describe an increase in the rating of a power transmission line.

**UTS**

Abbreviation for Ultimate Tensile Strength. Defined as the maximum load divided by the original cross sectional area.

**YIELD STRENGTH**

The stress at which a material exhibits a specified limiting deviation from proportionality of stress to strain. An offset of 0.2% is used for many metals such as Aluminium-base alloys, while a 0.5% total elongation under load is frequently used for copper alloys.

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LIST OF SYMBOLS

$n$	= regression constant, is a fundamental property of the material at the test temperature considered.
$t$	= elapsed time at load
$\epsilon_{\text{tot}}$	= total permanent elongation
$\tau$	= average temperature of conductor °C
$T_{\text{max}}$	= maximum mechanical tension.
$T$	= mechanical tension of the conductor.
$H(x)$	= is a co-efficient that generally depends on the formation of the conductor.
$\gamma$	= a co-efficient that depends upon the internal factors.
$\sigma$	= average conductor stress (kg/mm <sup>2</sup> ).
$f(\tau)$	= function increasing with temperature
$\alpha, \mu(\sigma)$	= mechanical tension of the conductor.
$\epsilon_{\text{creep}}$	= creep strain
$\epsilon_p$	= creep strain $\mu\epsilon$ .
$H$	= regression constant.
$k$	= regression constant in mm/km.
$T$	= Tension kg.
$\beta$	= regression constant.
$\delta$	= regression constant.
$1/n$	= regression constant- slope of line.
$k_1$	= regression constant- y intercept.

$k_2$  = stress exponent

$h_1, h_2, h_3$  = temperature co-efficients

$\epsilon_{Kr}$  = creep strain

$k_1$  = regression constant- y intercept in  $h^{-1}$ .

$t_0$  = 1 hour (time unit)

$n_1$  = regression constant- slope of line.

$$0 < n_1 < 1$$

$\epsilon_{Kr}$  = creep strain rate

$k_2(\Theta)$  = regression constant in  $h^{-1}$ .

$\sigma_N$  = nominal stress

$\sigma_{N0}(\Theta)$  = stress that causes an almost constant creep rate.

$n_2(\Theta)$  = regression constant- slope of line.

$$0 < n_2$$

$e$  = creep strain  $\mu\epsilon$

$W$  = Steel in percent of total weight.

$T$  = Temperature  $^{\circ}C$ .

$P$  = Tension in % Nominal Breaking Load (Rated Strength).

$A$  = cross sectional area  $mm^2$ .

$\beta$  = regression constant.

$\phi$  = regression constant, experimentally shown to be load independent.

$\Theta$  = Temperature  $^{\circ}C$ .

UTS = Nominal Breaking Load.

$\epsilon_c$  = metallurgical creep strain  $\mu\epsilon$  mm/km

- $K$  = regression constant dependent on the material in mm/km.
- $\sigma$  = is the average stress on the conductor (kg/mm<sup>2</sup>)
- $\beta$  = is the average of the angles of the tangent at a point of the wires with the axis of the conductor.
- $\phi$  = experimentally determined regression co-efficient.
- $\alpha$  = experimentally determined regression co-efficient.
- $\mu$  = experimentally determined regression co-efficient.
- $E_a$  = elasticity modulus of aluminium or alloy (kg/mm)
- $E_{st}$  = elasticity modulus of steel (kg/mm)
- $\epsilon_s$  = geometrical settlement creep strain  $\mu\epsilon$  mm/km
- $\sigma_{ult}$  = is the ultimate tensile strength (kg/mm<sup>2</sup>).
- $d$  = is the average diameter of aluminium or alloy wires (mm).
- $m$  = the ratio of aluminium or alloy cross section to steel cross section.
- $\sigma_{ult a}$  = is the ultimate tensile strength of the aluminium or alloy (kg/mm<sup>2</sup>).
- $\sigma_{ult st}$  = is the ultimate tensile strength of the steel (kg/mm<sup>2</sup>).
- $\epsilon$  = creep strain  $\mu\epsilon$  mm/km
- $k_2, k_3$  = regression constant dependent on the material in mm/km.
- $c_1, c_2, c_3, c_4, c_5$  = experimentally determined regression co-efficient.
- $x_{cr}$  = creep strain
- $s$  = stress MPa
- $\sigma, \Delta, \beta$  = regression constants
- $x_{cra}$  = aluminium creep strain

$T_a$	= aluminium temperature in °C
$s_a$	= aluminium stress MPa
$\kappa_{crs}$	= steel creep strain
$T_s$	= steel temperature in °C
$s_s$	= steel stress MPa
UTS	= Ultimate Tensile Strength of the steel

## **CHAPTER 1 LITERATURE REVIEW**

### **1.0 INTRODUCTION**

Essential in any research program is a review and critique of the available literature about the subject to be investigated. Many research programs have been undertaken around the world in an attempt to understand the mechanical behaviour of conductors. Most of the "classical" research has been undertaken in either North America/ Canada or Europe.

A number of methods have evolved to measure the inelastic stretch of conductors and relationships developed to explain the experimental results obtained. For these reasons the review will be chronological in nature to allow the development of theory to be followed.

## 1.1 HISTORICAL REVIEW OF CONDUCTOR TESTING.

### 1.1.1 Stickley G.W. (1932) [68]

This paper although basically related to Stress-Strain testing illuminates some of the behaviour observed in creep tests. Stickley developed the now common procedure used to determine both the initial and final elastic moduli of stranded conductors.

Key observations include; " The application of stress to a cable increases the actual modulus of elasticity". "The modulus of a conductor will always be less than that of a single wire of the same material." This phenomena has also been shown to apply to creep rates. "The actual modulus of elasticity of a conductor depends upon the lay of the individual wires ie the longer the lay length the closer the modulus will be to that of a solid material of equal cross sectional area."

Stickley also observed that if after straining the conductor to obtain homogeneous repeatable conductor properties such as final elastic modulus, subsequent winding back onto a drum negates considerably any advantage obtained.

Hence any process designed to modify the behaviour of stranded conductors must occur in the field at the time of line erection and not at the factory stage.

### 1.1.2 Strum R.G. Dumont C. and Howell F.M. (1936) [70]

The authors discuss their observations of a large of creep curves for Alcoa products. They noted that for any material tested at a constant temperature (usually room temperature) with a constant stress and plotted on a logarithmic scale of creep versus elapsed time the slope "n" of the various creep curves at different stresses is practically constant. Hence they propose that n is a fundamental property of the material at the test temperature considered. "n" maybe considered as the susceptibility of a material to continue to creep after the process has started. Limited tests at higher temperatures suggest that, the linear relationship existing between elapsed time and creep strain at room temperature may also apply at higher temperatures.

The affect of increasing the test stress ( $\sigma$ ) upon creep ( $\epsilon$ ) is not linear but is greater than 1 on log-log scale.

Whilst the value of k ( creep at time  $t=1$ ) is a function of i/ the material; ii/ test temperature; iii/conductor history; iv/ the applied load and time unit used. Increasing the cold work of the test piece has the affect of increasing "k" ie the initial susceptibility of the material to creep is increased. To assist understanding "k" maybe considered as a measure of the initial susceptibility of the material to creep upon the application of a load.

1.1.3 Boyse C.O. and Simpson N.G. (1944) [10]

The authors proposed the procedures of overtensioning and pre-stressing as methods that could be applied to conductors which will sag significantly during their lifetime and contravene statutory ground clearance rules.

1.1.4 Winkelman P.F. (1960) [76]

Winkelman describes a method of calculating sags and tensions in transmission lines conductors which has been adopted by the E.C.N.S.W. He also identified creep as a significant contributor to the change in length of the conductor and hence sag and tension. His observations of creep data supplied by manufacturers are:- a/ for a given time the conductor creep will increase, with increasing temperature and/or stress; b/ for a given stranding the creep rate decreases from AAC/AAAC to ACSR/AACSR to copper to steel conductors; c/ conductors exhibit logarithmic creep behaviour; d/ increasing the stress level results in a shift of the creep curve vertically up without a change in slope and strand settling contributes a considerable part of the total conductor elongation during the initial loading. Strand settlement where the wires "bind" together results in an increase in elongation far in excess of ordinary creep elongations.



Laboratory tests indicate that prestressing the conductor can result in marginal improvements in creep compensation in the early stages but sustained benefits may not be recognised as the slope of the creep curve is increased and the predictions will eventually converge. However, Bonneville Power Administration always pre stresses each conductor during stringing.

In the discussion H.H. Rodee of Alcoa states that in ACSR's the creep is primarily due the aluminium strands creeping progressively transferring load to the steel core and thus reducing the creep rate. He also states that creep will be greater for shorter spans because of the higher tensions involved in maintaining similar sags. Thus, the shorter spans will lower their tension at a quicker rate, hence, it is more important to consider creep in longer spans than shorter spans where the tension reduces quickly.

L.H.J. Cook describes two prestressing methods, they are: a/"the conductors are pulled up to 20% above the required stringing tension and left at this tension for a minimum of 15 minutes. The conductors were then slacked off, sagged and clipped in"; and b/"the conductors are pulled up to stringing tension and left in the sheaves' at this tension overnight. The following morning the conductor is checked, adjusted if necessary and then clipped in.

#### 1.1.5 Fritz E. (1960) [31]

Fritz considering only ACSR conductors included the influence of creep compensation into his analysis of transmission line costing. He stated that transmission line costs decrease with increased tensions. Fritz believes that for all ACSR's with a high percentage of aluminium ie 45/7 the effect of creep on ground clearance at normal temperatures and stringing tensions must be considered. The importance of creep considerations increases with increasing overall cable sizes or increasing aluminium wire diameters based on observations of tensile test elongation samples. However this relation is disputed by cable manufacturers, who deny having observed any relation.

Fritz believes that final sagging should contain an allowance for 10 years creep only, since the creep after 10 years is negligible.

Fritz cautions against using overtensioning as a method of creep compensation because of the deleterious fatigue damage and negation of vibration dampeners, due to a change in conductor vibration behaviour. Pretensioning is proposed as a superior alternative to overtensioning, however, it has the drawback of higher initial stringing costs with a closer to "normal" final working tension.

#### 1.1.6 Aldrich A.M. (1962) [1]

Aldrich reports on laboratory and field test designed to stabilise the conductor prior to final sagging. The aim was to stabilise a  $76/0.1463 \text{ in}^2$  Al +  $7/0.1138 \text{ in}^2$  steel conductor for 4 hours. The project was successful with the laboratory trials confirmed for three test spans.

#### 1.1.7 Giblin J.F.(1962) [34]

Giblin in an attempt to predict the behaviour of ACSR conductors nearing the end of their life or requiring an uprating, surveyed the literature. His findings were that very little work had been done on creep tests at normal operating temperatures (90-120°C).

His survey also indicates that in short time creep tests, annealing of the aluminium wires increases the creep rate and therefore, operation of transmission lines at temperatures above 100°C should be avoided as normal operating temperatures. Higher temperatures can be tolerated for shorter periods as required, provided the time is limited "to a few hours over many years".

#### 1.1.8 Bogardus K.O. et al (1963) [9]

They tried to reconcile the change in tensile strength due to creep at elevated temperatures with microstructural changes. Polygonisation, grain growth and a decrease in dislocation density appeared to be the main causes.

A prior claim that microvoids and incipient cracks contributed was not been proven, however a higher than normal density of voids after tensile tests near fracture points may support the claim.

Of greater significance to transmission line design are the following facts:- 1/ residual tensile strength after a known creep strain decreases with increasing elapsed time and/or temperature to achieve that creep strain; 2/ increasing the stress employed to achieve a set creep strain results in a decrease in the rate of tensile strength loss.

Application here would be to pre-tension at a "high" tension to remove the first few years of creep from a conductor prior to final sagging.

#### 1.1.9 Gaylard B. and Musgrave K.C. (1965) [33]

This report examines the short term ( $> 100$  hours) influence on creep of prestressing Zebra  $0.4 \text{ in}^2$  ACSR conductor for 1, 3, or 6 hours at 10, 20 or 30 percent over normal stringing tensions. From the results it can be generalised that a/ as the prestressing time is increased for constant prestressing tension the creep constant  $k$  increases whilst  $n$  decreases; b/ for any give time increasing the prestressing tension increases  $k$  whilst  $n$  decreases; c/ upon the removal of the prestressing tension, there is a period of time during which the strain (creep) shows little elongation or contraction.

The authors propose that this effect is due to interstrand friction. There is some delayed elastic recovery which for a certain time period more or less balances the continuing creep; and d/ prestressing affects the creep rate. Increasing the severity of the prestressing (either the time or tension) reduces the total creep normally observed during the first 6 weeks after final sagging, thus, reducing the overall creep sag.

However, only qualitative inferences can be made since no qualitative relationships between  $\sigma, \epsilon, k, n$  and time are evident with a high multiple regression correlation co-efficient, however no confidence limits. Using the creep predictor equation for the various prestressing conditions shows divergent predictions. The authors suggest that this is highly unlikely and instead proposed that at sometime in the future the predictions will converge.

#### 1.1.10 Musgrave K.C. and Hewitt E. (1965) [50]

They tested both ACSR and Aluminium alloy Aldrey conductors of the same wire sizes and stranding and found that 61/0.125 in<sup>2</sup> Aldrey creeps at a lower rate than 54/7/0.125 in<sup>2</sup> ACSR at tensions of 10, 20, 30, 40 or 50 percent of the Nominal Breaking load. Possibly due to the lower strength of the 1350 aluminium.

In order to gauge the affect of stranding on the creep rate of Al (1350) and Al alloy wires a comparison of individual wire tests before and after stranding was tried. They found using wires from the outer layer that stranding reduces the creep rate by about 50% of AL(1350) and Al alloy (Aldrey) wires compared to "the before stranding" wire tests. They proposed that when using individual wire tests to predict stranded conductor behaviour the wire, where possible, shall be destranded from the conductor in preference to testing "before stranding" wires.

#### 1.1.11 Dassetto G. (1967) [27]

The author investigated the influence of temperature and stress (load) upon creep rates in AAC (1350), AAAC (6201) and ACSR conductors and wires. For all wires and conductors the creep a/ at any given time increases with increasing temperature; b/ increases with increasing stress/tension at any time. When comparing wire to strand, the strand will exhibit the higher creep rate.

#### 1.1.12 Bradbury J. (1967) [11]

Laboratory and field tests on ACSR conductors for several short spans. He concluded that although the creep rate was a function of the span length, the effect of span length on the creep rate was negligible. When comparing laboratory test with field test data, he found it was necessary to subtract the first hours creep from the laboratory data thus, taking into account the effect of the initial stringing behaviour before landing.

This appears to be due to the difficulties associated with obtaining creep data due the initial stringing period.

Laboratory tests followed the familiar linear, log Elapsed Time versus Log Creep Strain, as did the field tests thus confirming that laboratory tests can successfully predict the in service creep. When a strung conductor is restrung a lower creep allowance is possible due to higher creep resistance resulting from the prior creep.

Bradbury suggests two ways for creep compensation using pretensioning; a/ loading with normal tension for a number of days before final tensioning; or b/ appreciably overloading the line components for a short time. He also references a Scandinavian paper in 1959 which suggests final sagging at a temperature below ambient in an attempt to compensate for creep but believes that the authors method under predicts the extent of creep involved.

When it is necessary to mix new conductors with old the author reinforces the belief that the new conductor must be stabilised to avoid potential problems due to differential sags.

When attempting to compensate for creep by overtensioning, 15% was found to be too low to sufficiently compensate for creep.

#### 1.1.13 Bradbury J. and Vaughan D.W (1968) [14]

The economic advantages driving the investigations into quantifying and compensating for in-elastic stretch are:- "If creep could be reduced there would be some amenity and economic advantages by allowing the towers to be shorter or further apart".

Observations include:- increasing the test temperature at constant tension increases the creep rate. It is possible to satisfactorily predict the creep behaviour in the field from laboratory tests, however, it is not cost effective to test each batch manufactured (type tests are therefore suggested).

In transmission lines increasing the temperature results in a change in conductor tension. For short spans there is a decrease in the tension whilst for spans in excess of 600 m there is an increase in tension. This change in tension affects the creep rate.

The authors preferred method of creep compensation is to provide an allowance based upon a lower than actual stringing temperature.

#### 1.1.14 Roche J.B. and Dziedzic E. (1968) [66]

The authors found that the method used to produce the wire (ie Properzi verses hot rolled billet) for use in a conductor affects the creep rate, with 1350 aluminium creeping at higher rate than 6201.



They tried to quantify the affect of variations in wire tensions during stranding using stress-strain (modulus) and creep tests. These tests showed that uneven tensioning of the wires during stranding increases the extension of the conductor over that of homogeneously tensioned wire conductors.

However they proposed that "stringing at higher tensions for a short time period (15 hours) followed by a reduction in tension during sagging is often used to stabilise a conductor" to facilitate accurate sagging of bundled conductors. The proposed method has been confirmed in laboratory tests.

In creep tests, the authors state that the affect of temperature on the creep rate is greater on AAC, ACAR and 5005 conductors than for ACSR conductors. When comparing conductors (AAAC, ACAR, ACSR) of similar construction for the same job the lower the mass/unit length of a conductor the lower the initial sag at stringing for equal tensions. Hence, either smaller towers or longer spans greater margins for creep allowances are bonus options to be considered.

#### 1.1.15 Harvey J.R. (1969) [36]

In an effort to describe the creep behaviour of conductors at higher operating temperatures (50-150 °C) a number of tests have been reported. Harvey's report is the first to try and quantify the influence of changing or elevated creep test temperatures upon the creep rates. Compressions fittings used on the test pieces may have influenced the results but it is hard to verify.

Where ACSR conductors were compared to AAC or AAAC/6201 conductors of similar stranding and size the creep rate was lower in all cases for the ACSR. It was proposed that since the majority of the creep is associated with the aluminium and not the cored, a more rigorous analysis of the stress distribution maybe needed to ascertain the true distribution of component loading.

Alcoa have confirmed that the creep predictions from 1000 hour tests are consistent with test predictions based on tests of 5 to 8 years duration.

#### 1.1.16 Roest C.A. (1969) [65]

Roest reported upon the results of aluminium wire creep tests for alloys such as 1360-H19, 5005-H19 and 6201-T81, at temperatures of 25-105°C, for tensions of 15-25 percent of NBL. Roest states the test temperature has a great effect upon the creep rate.

For any wire the total creep at any elapsed time  $t$  was proposed to be dependent on a/ the amount of prior total creep, b/ the stress level and c/ the test temperature. The creep was independent of the conditions resulting in the prior creep. Roest provides an example of how this conclusion was reached for a wire at constant tension but with changing test temperature. Kaiser Aluminum Co U.S. questioned the conclusion stating that, at the time, they had not seen the proposed behaviour.

From the Renyolds Metal Co. U.S. test results, Roest concluded that the creep rate of individual wires is higher than that of conductors made from the constituent wires. In all other papers the opposite has been proposed to date due to the initial strand tightening phenomena contributing large strains to the initial creep portion of the curve. Alcan stated that their tests show conductors creep at a greater rate than constituent wire regardless of whether the wires are sampled before or after stranding.

At this stage there is still no reliable method available based upon current experimental data to allow wire and conductor creep to be correlated.

All experimenters agree that the absence of a standard for creep wire testing has lead to the wide dispersion of experimental results from the major suppliers.

1.1.17 Bradbury J. (1969) [12]

This paper describes the results of resistance heating during elevated creep testing and proposes a method of predicting creep from laboratory tests for different temperatures and stresses.

At a set load, the creep strain increases with increased conductor temperature. The rate at which the creep increases is not constant and increases as the temperature increases.

When investigating the influence of grease on the creep rate a small difference was detected between conductor with only the core greased from those conductors where all internal layers were greased.

This method seems crude by today's standards, however, the results in producing reasonable predictions which were confirmed by field studies verify the technique.

1.1.18 Harvey J.R and Larson R.E. (1970) [38]

This paper is a logical extension of Harvey's earlier work on ACSR's in particular elevated creep tests. In the paper, he describes an equivalent relationship between stress changes and temperature changes which on comparison with other later relationships is conflicting rather than reinforcing.

The authors showed that stress changes in constant temperature tests could be related back to single stress creep tests. The conductor during a stress reduction was stabilised for a period of time and did not creep until an equivalent time to reach the original creep strain was achieved. Conversely, for stress increases, the increment when displaced to the left on the time axis back to the higher stress curve gave equivalent creep readings. Similarly a change in temperature up or down produces a comparable result. These relationships are based upon hot rolled billet aluminium strand, any relationship for Properzi rod had not yet been made.

#### 1.1.19 CIGRE SC 22 (1970) [17]

First draft of Electra 74. Of interest here, but dropped in latter versions of the draft, is the rationale behind the epoxy fittings used in Canada and by Kaiser Aluminium USA.

#### 1.1.20 Nakayama Y. and Kojima T. (1970) [51]

Comparison of 1000 hours laboratory tests at two tensions with field tests at three tensions of 4.5 year (40000 hours) duration provide an excellent correlation. This result assists in building confidence in the Winkelman approach of creep compensation. Further more, the approach of using a lower than actual sagging temperature to compensate for creep sag was validated for this conductor and different tensions.

#### 1.1.21 Dey. P et al (1970) [29]

When considering the cost of new transmission lines, the authors proposed that the effect of creep upon the overall cost of an overhead line was minimal, since, the cost of building taller towers to compensate for creep is relatively small.

However they neglected to consider the advantages in being able to eliminate even one tower, at a cost of \$70,000-\$80,000 each.

#### 1.1.22 CIGRE SC 22 (1971) [18]

Second draft of Electra containing tables of figures used in diagrams of subsequent publication.

#### 1.1.23 Comellini E. (1971) [26]

The author proposed that the creep of any all aluminium conductor (AAC) at a constant tension with constant temperature could be represented by a single equation (Equation 8). Alternatively for ACSR's once the creep constants for the component aluminium strands have been determined, the creep of the any ACSR is a function of the creep elongation of the component aluminium strands. Once the constants for the all aluminium conductor (AAC) equation are known the ACSR's creep depends only on the ratio  $m$  of the aluminium:steel strand cross sectional areas.

ACSR conductors creep initially at a higher rate than all aluminium conductor of similar construction. Comellini believes that ACSR's creep in two straight line parts governed by the transfer of load to the steel core and the ratio  $m$ . The creep of all ACSR's where the cross sectional area of aluminium to steel is  $>5$  and homogeneous conductors with  $n = 4,5$  converge between 20-50 years. It is proposed that ACSR's creep more at the start than corresponding homogeneous conductors, however, the rate decreases as the aluminium creeps and transfers load to the steel core, resulting in convergence between 20-50 years. Prestressing as a means of compensating is mentioned but it is a complex relation in determining the amount of creep removed from the aluminium and the percentage of load transferred to the steel core. I believe that more work needs to be done on this facet of prestressing as it was beyond this research.

#### 1.1.24 Helms, R. and Ziebs. J. (1971) [39]

When analysing the results of creep tests they found that it took up to 10 hours of "settling in time" before the log elapsed time verses log strain (creep) graph could be considered linear.

Prestressing at higher than normal stresses for limited times results in a reduced creep rate upon a stress reduction back to normal levels. However, the total extension will approach that of the non pre-stressed conductor at sometime in the future.

**NOTE** "Prestressing results in, an unavoidable load shifting and a decrease in the fracture elongation values."

Interesting observations made in this paper include: "The 0.2% Proof Stress, the nominal tensile strength and the modulus of elasticity of the cable vary more strongly in the region of the smaller cross section ratio  $area_{Al} : area_{St}$  than in the case of bigger ratios ( $area_{Al} : area_{St} > 3$ ). The characteristic values listed depend additionally on the lengths of the lay employed in the layers of wires, the number and level of preloads applied, the number of layers of wires, and less markedly on the number and diameter of the single wires and the method of manufacture."

At 6000 hours elapsed time for a stress of 25% of the rated strength the creep rate for steel cable: ACSR (Al:St 6:1 ....13:1) and All aluminium conductors (AAC) was stated to be in the ratio 1:5:10 ie after 6000 hours creep the creep rate of ACSR's had fallen to half that of All aluminium conductors (AAC). It was also noted that Aldrey has a creep rate between that of ACSR's and All aluminium conductors (AAC).

#### 1.1.25 Ramy, T. (1971) [63]

Using 12 AWG (2.05 mm Dia) aluminium wire the author tried to evaluate the influence of chemistry and processing on the creep rate of common aluminium alloys used in America. Testing at standard conditions of  $21^{\circ}\text{C} \pm 1$  at a tension of 50 lbs.



From the tests the authors concludes that; a/ Al-Fe alloys creep more than EC grade aluminium; b/ Al-Cu-Mg alloys creep less than EC grade aluminium; and c/ Al-Fe-Mg alloys creep less than EC grade aluminium but more than Al-Cu-Mg alloys. Item c is inconclusive when compared to other tests reported suppliers.

1.1.26 Schlosser. S., Snowman. A. and Ramy. T. (1971) [67]

Unlike the title of the article, the authors have not shown the influence of the individual aluminium wire creep rates used in ACSR to explain the cause of observed differences in ACSR creep rates. The authors following on from Ramy's previous work attempted to ascertain the influence of fabrication route on the creep of EC grade aluminium. They used the following test conditions; 14 AWG (1.63 mm Dia) EC grade aluminium wire at 21° C and at a stress level of 35% UTS.

Their work did show that the creep of EC grade wire is greatest for conventional hot rolled billet, lower for extruded wire and lowest for wire manufactured using the properzi method. This order they explain as a function of the grain size, with the properzi rod having the largest grain size and the hot rolled billet the smallest.

Due to the method of strain measurement employed using a microscope mounted upon a trolley, a wide dispersion of displacement measurements was predicted. Until further information about experimental data is found, confidence in this method of testing for creep must be discounted.

#### 1.1.27 CIGRE Wood, A.B. (1972) [77]

This paper brings together many years of work. It describes a 5 step graphical procedure to compensate/provide an allowance for the life time inelastic stretch (creep) of a conductor at final sagging.

Creep in a transmission line can be broken down into two basic parts. Part A occurs up to final sagging, whilst part B is the remaining creep over the life of the line.

The authors recommend prestressing to stabilise the conductor during the sagging operation and to provide a stable base upon which to predict future creep for the life of the line. Several examples of alternative practices are outlined all resulting in roughly three (3) hours of stable time in which to perform the final sagging operations. This paper was designed for practitioners who wanted answers as to how the affects of any conductors creep over its lifetime could be compensated at the time of stringing To this end, it is successful. However, more importantly, the authors have published creep data from around the world for a number of conductors.

This list although large is only a small fraction of all the conductors currently in use. Also the majority of the aluminium used in the construction of the conductors was from the now largely superseded method of hot rolled billet wire. More up to date creep information using aluminium produced by the Properzi method is needed to cross check the above relationships.

#### 1.1.28 Cahill. T. (1973) [15]

Following the initial success in straining steel wires at 4-500°C to improve creep resistance and mechanical properties, the author decided to try the technique on aluminium alloys. Straining aluminium wires to 1% plastic strain at 200°C reduced the creep rate by a factor of 2 in homogeneous conductors. ACSR's show this effect to a lesser degree.

The author suggests that by heating ACSR conductors, to say 200°C, and producing a 1% strain the conductor will upon cooling exhibit enhanced mechanical properties including creep resistance. No comparison between prestressed conductor to 1% strain and stabilised is given. However, 1% strain is well known as the point at which most conductors will rupture. Therefore, great care needs to be taken prior to trialing this method.

My analysis of the Lynx ACSR conductor 30/7/0.110 in a creep test graph at 40% NBL and at 20°C produced the following relations not stated in the paper:-

$$\text{Stabilised} \quad \epsilon_{\text{creep}} = 382xt^{0.3186}$$

$$\text{Unstabilised} \quad \epsilon_{\text{creep}} = 604xt^{0.1596}$$

Equating these shows that after 19 years the stabilised conductor will creep more than its unstabilised counterpart. This is of course well beyond the normal limits of good and reasonable extrapolation for creep tests of 700 hours duration.

If, however, the stabilised curve has been displaced down the Y-axis by  $100 \mu\epsilon$  and is consistent with another graph for Zebra conductor; then the new regression equation becomes:-

$$\text{Stabilised} \quad \epsilon_{\text{creep}} = 321xt^{0.0968}$$

Significant benefits can be achieved from stabilising if the lower predicted creep strains can be realised.

#### 1.1.29 Tilbury, C.O. and Bradbury, J. (1973) [73]

The authors describe a new computer program for sag tension calculations, however the limited number of creep tests available for allaying to the program mean that it is hard to evaluate the accuracy of the computer model.

Zebra conductor was studied from several British conductor manufacturers. State that the "creep strain rate depends upon the existing tension existing temperature and the creep strain that has occurred in the material". The relationship is termed the "strain hardening material law". The CERL empirical creep relationship has been compared to the Alcoa relationship.

Examples of sag-tension predictions using CERL "Computer Program for Long Term Creep Assessment" based upon these equations (19,21,22) are given in the appendices. Unfortunately, no direct comparisons can be drawn between CERL and Alcoa creep equations since examples are of dissimilar conductors thus, making it difficult to evaluate the influence of creep equations on sag-tension calculations.

#### 1.1.30 Bradbury, J. et al (1975) [13]

The authors compared their equation (19) and the Harvey & Larson equations (21,22) to creep field tests. A fit to  $\pm 5\%$  was obtained and termed "useably accurate".

Application of the CERL Sag-tension program was used to illustrate the influence of pre stress and over-tensioning as creep compensation methods. The possibility of failures in the new over-tensioned lines during the first winter in high ice/wind loading conditions in Britain is highlighted using the program.

In addition, the "strain hardening material law" was shown to be applicable to conductor creep predictions. However, it does not predict the observed phenomena of strain recovery after load reductions.

1.1.31 Boal, G.R. (1977) [8]

Describes of a computer program for T(ransmission) L(ine) D(esign) using the Catenary equation in sag-tension calculations. The program is designed to handle creep data as either Larson-Miller charts or creep prediction equations, with allowances for reduced breaking strength as the conductor aged. The author notes that as a result of differences in the coefficient of thermal expansion, when the temperature of a conductor rises the aluminium transfers load to the steel core, as it expands. The study concluded that the creep rate should become that of the steel core when the aluminium unloads. Later authors show this to be a special case.

1.1.32 Mattock, A.F.L. (1978) [45]

For a number of commercially available British aluminium alloys the author compared wire tensile test results with wire creep tests (1000 hours at 20°C, at 56 MPa). The wires were tested in the H19 Fully Hard to 0 Fully Annealed temper states.

He concluded that "A relationship has been established creep rate and elongation in the tensile test, the lowest creep rates being exhibited by wire with the lowest elongation". Note that the highest tensile strength wires did not always exhibit the lowest elongation. Small additions of copper can have a marked affect on the creep rate.

#### 1.1.33 Metal Manufacturers (1970's) [80]

Early creep test work sheets by this company indicate that: a/ the creep rate for ACSR's increases with increasing temperature.(k or n not specified); b/ the creep rate at higher temperatures is greater even though the tension is substantially reduced from 22 to 14 % NBL; c/ overtensioning for a period during a creep test results in a reduction in the creep rate when the load is returned to the original value; and d/ approximately 90% of the elastic strain produced on overtensioning is recovered when the load is reduced to the original value.

#### 1.1.34 CIGRE (1981) [20]

This paper follows on from the earlier CIGRE paper [77] and concentrates more on the mechanics of creep and how to use the equations presented by the testing facility. The paper covers these topics:- a/ "Analysis of permanent elongation"; b/ "The means used in experimental research to determine the creep laws"; c/ "Proposed predictor equations"; and d/ "Calculation methods for evaluation of permanent elongation during the life of lines.

Topics affecting creep, but still under review, include the use of Heat Resisting Conductors or alternatively the use of conventional conductors at relatively high temperature. The report cites creep as constituting of two sources; the metallurgical which is dependent on how long the load is applied; and the geometrical settlement, where the dependence is upon both the elongation for the applied load and the elongation resulting from the stress at the wire cross-over points. Geometrical settlement is considered by the authors, to be time independent and will be evident only in the initial hours of the creep curve.

Next and arguably the most important section of the paper is that of a standard test method for stranded conductors and wires. The former has been adopted for this project and is now standard for all testing in Australia for many years, but it is still the cause of some concern due to the poor repeatability of some testing facilities. Probably due to the use of compression terminations [54]. Unfortunately the document omits any reference to the effect of cable rotation and methods to restrain the cable.

The last part of the paper deals with how to predict the conditions and times in which the conductor will serve during its lifetime. Unfortunately, very little is stated about the significance of each of the co-efficients. No information is supplied about the reliability or confidence interval around each of the co-efficients nor, on how many observations they were based.



## 1.1.35 Nigol. O and Barrett. J.S. (1981) [53]

Four important observations are aired in this paper. They are: 1/ that the aluminium wires in an ACSR are capable of supporting a compressive load; 2/ in a broad range of conductor tensions the compressive loading on the aluminium wires remains a differentially constant; 3/ when measuring temperatures, it was found that there is a wide temperature profile across the conductor, 40 °C being quoted; and 4/ the thermal gradient permits the aluminium to support a higher than expected compressive load.

This paper presents a rationale for the greater observed sag of ACSR conductors at higher operating temperatures over the sag predicted from calculations traditionally used in transmission line design. The ability of aluminium wires in ACSR conductors to support a compressive load (6-12 MPa measured) is proposed, as a balance to the tensile load on the steel reinforcing wires resulting in an increased conductor length. Prestressing may decrease the permanent sag due to heavy loading e.g. ice, wind, however, the high temperature sag will still be greater than the theoretical.

With regard to thermal expansion, ACSRs are considered to have two CTE relationships or one composite. The first below the birdcaging temperature and the other above the birdcaging temperature.

They represent this with a non-linear function taking into account the conductor tension at which the temperature is measured. Observations include: a/ increasing the conductor tension will increase the bird caging temperature; or b/ alternatively a conductor with greater permanent aluminium strain will bird cage at a lower temperature.

#### 1.1.36 Barrett. J.S., Ralston. P. and Nigol. O. (1982) [6]

The authors describe a model to account for the radial and longitudinal behaviour of aluminium strands in ACSRs as well the relative contributions of Al and Steel to ACSR stress and strain behaviour.

Next, the authors discuss the growing body of knowledge in the US and Canada discrediting the current method of calculating the NBL (Nominal Breaking Load) for a conductor based upon individual wire tests and rating factors for different strandings.

Further, a modified method of stress-strain testing is outlined where emphasis is placed upon the judicious crimping of compression sleeves onto the steel sleeve and aluminium wires to prevent the extrusion of any wires (usually from the outer aluminium layer) into the test length between the two terminations. The authors recommend that stress-strain curves be obtained for each production batch to be installed into a line for accurate sag tension modelling.

Next, the authors describe again their experimentally backed hypothesis for the larger than expected sags seen in ACSR's at elevated temperatures due to a compressive loading in the aluminium wires.

Lastly, they introduce an outline of a new sag-tension computer program called S(ag and) T(ension) E(valuation by) S(train) S(ummation) STESS, which is reviewed later.

#### 1.1.37 Toth. T. (1982) [74]

Toth re-iterates the recommendation that conductor life be broken into discrete time intervals of uniform temperature and conductor stress to evaluate creep over the life of that conductor. He recognised that conductor creep is greater than (more than twice) the individual wire creep for the component wires for the same test conditions. Other authors have also reported this behaviour. Toth noted that shorter lay lengths result in greater creep.

A good correlation between 1000 hour creep test predictions with the 3 year creep tests of Holms (not reviewed), the 5 & 8 year creep predictions of J.R. Harvey, and an IEEE report with tests lasting 9 years allow the  $\epsilon = kt^n$  equation to be used with a high degree of confidence when predicting creep strains.

1.1.38 Barrett, J.S., Dutta, S. and Nigol, O. (1983) [5]

Since Varney's 1927 graphical method of sag-tension calculations, all subsequent computer programs have been designed to replace the time consuming iterative process of using these charts. This computer program however, is the first departure from that method.

Stess was designed to provide a better model of the elevated temperature behaviour of ACSR conductors which can be extended to other composite and homogeneous conductors. The program examines potential sags and tensions by summation of all recognised contributing strain mechanisms. It works forward from sagging instead of the traditional method of working backwards from the maximum allowable sag.

The strain summation method uses the following equation to measure

$$\text{strain:- TOTAL ALUMINIUM STRAIN} = \text{THERMAL STRAIN} + \text{SLACK STRAIN} + \text{ELASTIC STRAIN} + \text{SETTLING STRAIN} + \text{CREEP STRAIN}$$

These are:-

Thermal strain which is considered to consist of a linear and a quadratic term including the effect of change of elastic moduli with temperature.

Slack which is any inherent looseness in the strand as a result of the manufacturing process.

Elastic Strain which is that described by the final curves of the stress-strain conductor curves.

Creep Strain which is based upon observations that the aluminium strain is the important factor, since the aluminium fails before the steel core. Both aluminium and steel creep curves are calculated. To account for the history of the conductor creep and changing conditions the authors have applied the "material strain hardening law". Any future creep is based upon the current stress, temperature and prior creep strain, but not on the order of the stress and temperature intervals contributing to the current creep values.

Settling Strain are the radial and tangential strains of the metal wires resulting from the initial loading. Both the elastic and 1 hour creep strains are subtracted from the initial modulus curves to give the settling strain.

Stess proposes that during pre-stressing the aluminium is elongated more than the aluminium in its non pre-stressed cable counterpart. Thus, a high percentage of the load is taken by the steel core resulting in a lower creep rate. However, at some time in the future their respective creep rates shall co-incide.

One drawback with the program is that it is unable to take into account the effect of annealing on the aluminium wires in service.

#### 1.1.39 CIGRE (1983) [22]

This paper is a shortened form of [20] and [77].

## 1.1.40 CIGRE (1983) [24]

This paper suggests that progressive annealing of aluminium wires due to operating temperatures results in the creep rate becoming increasingly larger in relation to the as manufactured creep rate.

## 1.1.41 Chapman W.G. (Post 1983) [16]

This paper deals with the classical ruling span and sag-tension calculations. It proposes a method of including creep into the change of state equation based upon Bradbury's and Barrett's papers on strain hardening material law by breaking down the life of a transmission line conductor into intervals of uniform stress(tension) and temperature.

## 1.1.42 Galland, J. Nicoud, J.C., Moreau, M. and Vieille, J. (1983) [32]

The authors tested Almelec of TS, TC and TR23 at 60°C and 100°C at 60 MPa ( $\approx$  EDS). These variations of Almelec 6201 alloy were tested to assess the thermal stability of the alloy and processing route to extended elevated temperatures. The results suggest that two versions show superior creep resistance, whilst the third would require lower EDS and thus are inappropriate to be used in transmission lines.

## 1.1.43 Northwood. D.O. and Smith. I.O. (1984) [58]

The authors attempt to determine the rate controlling process(es) in creep by changes in stress  $\pm$ . They claim that stress decreases are not as sensitive as stress increases for process determination .

Based upon their criteria for the large stress decrease a type I transient rate controlling process is evident in conductors. I type transients are viscous glide rate controlled. Increases in stress will result in the following types of behaviour:- for 1120 and 1350 alloys an N type recovery rate controlling creep factor is predicted whilst 6201 should be I type viscous glide rate controlling creep factor.

#### 1.1.44 Barrett, J.S. (1986) [4]

This class of paper will become more important in Australia as increasing power demands focus on new lines, and replacement or higher loadings on existing lines. It looks at the alternatives available when ACSR transmission lines must be uprated. The paper details, using STESS and field measurements, the affects of uprating existing lines, thus increasing both the normal operating temperatures and emergency temperatures for a line. Changes in the creep contributions resulting from higher operating temperatures, hence annealing the aluminium wires are unknown. Almost all published reports are based on as manufactured conductors with unannealed aluminium wires for initial design purposes. The author identifies a lack of information about the effects of partial annealing on the short and long term creep behaviour of conductors. This, has yet to be investigated in order to assist line engineers in their future decisions to uprate lines.

#### 1.1.45 CIGRE (1976) [81]

This paper is a preliminary to Electra 75 [77]. The paper states the CIGRE WG 22 preferred method of creep testing for component wires prior to stranding. Comparison between creep co-efficients of wires tested before and after stranding show a high correlation with the after stranding wire having a higher  $k$  value.

No approved relationship for evaluating the effects of geometrical settlement on the conductor creep equation are given. However, work was initiated on a probabilistic method of co-efficient determination. A deterministic approach to the creep of a conductor based on the creep of the aluminium wires is given.

#### 1.1.46 Nord. E. (1986) [57]

58 wire tests and 12 stranded conductor creep tests are reviewed from three separate testing facilities. A great dispersion is observed in Al59 test results. For an aluminium conductor alloy termed Al59 (59% IACS) there are no chemical specifications or recommended fabrication methods. Thus, allowing wide ranges of properties since only resistance, tensile strength and creep are specified.

Individual wire creep test results conform to the standard  $\epsilon = kt^n$  format. However, two composite equations ( $\sigma, T, t$ ) one for each testing facility, with a third for AlMgSi Type B alloys are required but not included.



Variables  $k$  and  $n$  in the equations are functions of tensile strength, creep strength, temperature and time. Variations in regression co-efficients I believe are due to alloy/processing paths and/or test method variations. Stranded conductors also fit the standard  $\epsilon = kt^n$  format.

An attempt was made to relate wire and conductor co-efficients.  $k$  and  $n$  for wire to  $k$  and  $n$  for a stranded conductor are equated by using the wire modulus of elasticity to the initial and final moduli of the conductor. Conductor creep predictions using the wire corrected co-efficients are of the same order of magnitude as those by conductor co-efficients.

Useful observations include: a/ when using the co-efficients due to the variations in equipment and test methods used the results "exhibit a great dispersion", whilst "very great uncertainty" must be attached to the temperature co-efficients for the same reason; b/ the authors believe that the creep elongation after a creep test at 40% NBL for 1500 hours will have the same order of magnitude as the conductor creep after 30-40 years in service; and c/ avoid as far as possible manual operations . Recording instruments should be used for load and elongation measurements.

## 1.1.47 Popczyk. J. et al (1986) [61]

Investigating the effects of fault current loading on sags using probabilistic techniques, they predicted that the effect of temperature upon the creep of ACSR conductors with relation to the expected decrease in tensile strength due to annealing. The expected increase in creep rate is considered only to a minor effect on sag when compared to the effect of the co-efficient of thermal expansion.

## 1.1.48 Hughes. D.T. (1988) [40]

Hughes looked at the influence of changing manufacturing processes upon the mechanical and physical properties of aluminium conductor alloys. 6201 AlMgSi AAAC age/precipitation hardening alloys produced by the Properzi method maybe unstable mechanically over long periods. Inferior creep behaviour being one of the noted drawback with the standard 55% IACS alloy manufacturing route.

## 1.1.49 Barber K.W. and Callaghan. K.J. (1988) [3]

The authors give an historical view of the development of 1120 (Aldrey) and its uses in Australia. Comparison creep tests at 120°C and 40% NBL for various conductors is given to illustrate the effect of alloy upon creep rates. Then, they compared the calculated creep for Grape conductor using the Harvey & Larson equation (21) with creep predicted by tests for various 1120 conductors, showing that up to 30 years for all conductor presented, 1120 conductors creep less than Grape.

Lastly they compared Grape with Grape/1120, again up to 30 years and found that the 1120 alloy conductor has a lower creep rate.

#### 1.1.50 Kremer. D. (1989) [79]

Kremer realises that the use of data on permanent elongation from foreign practices and literature is unreliable and a sort of rough approximation only, since conductors are not identical with regard to manufacturing processes and metallurgical structure. Common practice is to pre-tension conductors for several hours at tensions of 10-20% (or even 30%) over final sagging tension and, before reduction to normal stringing tensions for final sagging.

The paper describes testing methods and equipment at a new test facility. Based upon laboratory test results the greatest part of total elongation has been measured to occur during the initial stringing process of stretching ( and pre-stringing or tensioning)) of the conductor. Thus, the use of prestressing to remove the permanent elongation is fully justified to reduce the final sag of the conductor.

Many layered and wired conductors have been noticed to exhibit, percentage wise, more non-metallurgical creep in addition to larger overall elongation values. Manufacturers are to be encouraged to supply conductor test results with orders as per overseas practices.

## CHAPTER 2          CREEP OF CONDUCTORS

### 2.0                  INTRODUCTION

All conductors, begin to creep during run out, through stringing, final sagging and lastly throughout the life of the conductor, only stopping when the conductor is let down at the end of its life. When a new conductor is strung out and a tensile load (tension) applied it immediately creeps initially at a high rate for a number of hours (called Primary creep), followed by a period in which the creep rate slows until it attains a "constant" creep rate ( known as Secondary creep).

Conductor creep would in general only be a nuisance if it was not for certain rules and regulations. These require minimum clearances under the conductor to be maintained throughout the life of the conductor and under all conditions. Thus, the Transmission Line Design Engineer needs to not only consider creep, but must know how much a conductor will creep under a given set or history of conditions. Knowing how much a conductor will creep with time allows the engineer to calculate the sag at any given time and hence the initial stringing criteria to avoid contravening ground clearance resulting in expensive corrective actions. In addition, over allowing for creep and hence sag can result in higher than necessary establishment costs in transmission line construction.

Creep data from "The Aluminum Association of America" are in contradiction with all other reports in that they predict a linear relationship between stress and creep strain.

The benefits of accurately predicting the creep and hence the sag of conductors during their lifetime include: a/ larger spans with fewer towers per line, for the same tower height; or b/ alternatively in areas prone to lightning strikes or wind induced movement problems, reduced tower heights.

This chapter details the factors contributing to creep. Methods used to test and predict creep behaviour. The equations are used to model the experimental test data. Other relationships with variables not present in the current predictor equations, maybe incorporated as the phenomena of conductor creep is better understood.

Appendices 2 through 8 contain the various creep prediction equations with tabulated co-efficients for conductors and wires both in Australia and around the world.

## 2.1 CAUSES AND CONTRIBUTING FACTORS

Analysis of creep elongation curves has lead to the generally accepted idea that three main causes are involved [20]. These are metallurgical creep:- the elongation which results from a load being applied for a given time; and geometrical settlement (creep) from two sources, the elastic elongation which is directly related to the stress(load ) applied, plus the elongation produced as a result of deformation at the wire cross over points.

Metallurgical creep results directly from the effect of the applied stress upon the internal structure of the material. The grain size, sub-grain size, annealed/hard drawn condition of the wires and alloy all contribute to the creep rate.

Geometrical settlement is a function of the applied load, and generally considered to be independent of time, although it generally occurs for a limited period of following a change in the tensile stress (load) level. Even when a load is applied for short time only, the permanent elongation is considerable. Stranding is insufficient to tighten the wires, thus when a load is applied to the conductor the wires settle as the strand extends. Many researchers [4,5,6,11,13, 20,26,53,54,55,56,57,66,76] site the observation of wire tightening upon the application of a tensile load. Thus, as the wires are extended they bed in to the layer below, providing a further extension of the conductor.

This is hard to quantify and is usually only measured empirically. However, STESS [54,55,56] has tried to derive the amount of extension resulting from the bedding in of wires under a tensile load.

$$\varepsilon_{tot} = \varepsilon_s (T_{max}) + \varepsilon_c [T(t), t, \tau]$$

EQUATION No.(1) General equation for the creep (elongation) of stranded conductors [20].

where,  $\varepsilon_{tot}$  = total permanent elongation  
 $\varepsilon_s$  = geometrical settlement  
 $\varepsilon_c$  = metallurgical creep  
 $\tau$  = temperature in °C  
 $t$  = elapsed time at load  
 $T_{max}$  = maximum mechanical tension.  
 $T$  = mechanical tension of the conductor.

Factors contributing to conductor creep

These have been catalogued into two types a/ those related directly to the conductor and b/ those related to the surrounding conditions in which the conductor is located.

Major internal factors (a) influencing creep are 1/ the conductor manufacturing process eg Properzi vs hot-rolled vs extruded or type of stranding machinery, degree of work hardening and number of drawing passes [66,70,20],

2/ type of conductor including homogeneous vs composite, conductor construction eg 54/7, percent steel, or geometrical factors such as lay length, number and size of wires, degree of preforming, number of passes through stranding machine, back tension on individual bobbins in stranding machine [66] (uniform tension reduces creep rate), 3/ alloy type and metallurgical structure eg grain size, dislocation density, sub cell size.

Empirically these factors maybe shown to influence creep through the geometrical settlement in the following manner:-

$$\epsilon_s = H(x)\sigma^\gamma$$

EQUATION No.(2) Influence of internal factors on the creep of stranded conductors [20].

where,  $\epsilon_s$  = geometrical settlement creep

$H(x)$  = is a co-efficient that generally depends on the formation of the conductor, here conventionally indicted by the symbol x.

$\gamma$  = co-efficient that depends upon the internal factors.

$\sigma$  = average conductor stress (kg/mm<sup>2</sup>).

Major external factors (b) influencing creep are 1/ the mean temperature of the conductor, mean ambient temperature, maximum ambient temperature for x days,



2/ all loading on the conductor which will affect the tensile load, 3/ how and with what equipment/care the conductor is original run out and sagging procedures, 4/ working stresses at landing, 5/ span length, 6/ required lifetime, mean temperature resulting from resistance heating, and 7/ any conditioning such as pre-stressing its load and its application time.

Empirically these factors maybe shown to influence creep in the following manner:-

$$\epsilon_c = Kf(\tau)\sigma^\alpha t^{\mu(\sigma)}$$

EQUATION No.(3) Influence of external factors on the creep of stranded conductors [20].

where,  $\epsilon_c$  = metallurgical creep

$K$  = material constant.

$f(\tau)$  = function increasing with temperature

$\tau$  = temperature of conductor °C

$t$  = elapsed time at load hours

$\sigma$  = average conductor stress (kg/mm<sup>2</sup>).

$\alpha, \mu(\sigma)$  = experimentally determined co-efficients.

In reference [15], the author states that increasing the conductor size and decreasing the conductor design loading, normally increases the EDS. Therefore, reduce the ratio between maximum design and bare conductor tension. Hence, on a percentage basis increasing the tensile load on the conductor.

In reference [66] the authors cite American experience with conductor stating that at high temperatures AAC, ACAR, 5005 conductors exhibit considerably high creep rates than most equivalent ACSR conductors. Like ACSR's, ACAR's also show a shift in the load distribution as would be expected, however, very little has been written about this behaviour. Since very little ACAR conductor is made or used in Australia, it may not be necessary to follow up this point. The authors lobby for the use of aluminium stress data ([54 also]) to used in conductor design instead of mean stress or percentage of total conductor stress for load limitations/creep loads.

In reference [65] the author states that his work shows that at any elapsed time the creep rate was dependent on the amount of prior creep, the current stress and temperature, but was independent of the historical order of stress and temperature. This is known as the material strain hardening law.

Sturm et al [36] believe that  $n$  (EQUATION 4) is constant for a material being independent of stress and possibly temperature, whilst  $k$  is dependent not only on the material and its condition/history but also upon the stress and temperature. An observation that the effect of stress is greater than 1 was also made. Thus, the power law relationship was proposed.

In reference [11] the authors experimental results on ACSR conductors support the STESS proposal that it is the aluminium creep that governs ACSR creep behaviour. He lists the important factors affecting the creep rate as: a/ the residual stress in the conductor due to the manufacturing process - varies with process and plant; b/ span length - which is small for spans of 60-260 m; c/ the line temperature -increased temperatures result in increased creep in long spans but creep recovery due to reduced stress on short spans; d/ the extensional stiffness  $E.A$  -which varies with span length but invariant is with time, and e/ conductor type. An old conductor removed from service and restrung shows a lower creep rate than new conductor.

In reference [50] 6XXX series aluminium alloys were shown to creep less than their ACSR counterparts of similar construction. Stranding appears to remove a significant portion of the individual wire creep, in both aluminium and aluminium alloy wires. Stress has the affect of increasing the amount of creep in any given time. However, increasing the stress level results in an increased creep rate, yet when the tension is reduced to the original, the creep strain tends to even out as there is a period in which no creep occurs. The net result is that the total creep strain is consistent with a cable which is not subjected to the higher stress level during the period.

## 2.2 METHODS OF TEST

### 2.2.1 WIRE TESTING

All investigators report using similar test methods, however significant differences in predictor equations are evident. In discussion, the authors believe that these are a result of differences in the handling of start up procedures. Electra 75 [20] by CIGRE is now the recognised world standard for individual wire testing, with the Swedish Standard SS 11 23 17 Aluminium-Wire-Non-Interrupted creep testing being based upon the CIGRE document but creating further qualifications to reduce experimental scatter observed when tests from separate laboratories are compared.

### 2.2.2 CONDUCTOR TESTING

Not much is known about the test methods of ALCAN, ALCOA, KAISER, and many other testing authorities overseas, most of which started testing conductors in the early 1900's. However, it is known that much of the earlier information has now been discarded due to the widely acknowledged influence of end effects resulting from the application of compression fittings onto short length test pieces. Most test methods and principle authors today cite the use of an epoxy resin to make terminations which ensure an even distribution of stress over all the wires in a conductor. A notable exception is the Bonneville Power Administration which believe that with judicious care no aluminium is extruded into the test piece during sample preparation.

What does become obvious from the reports is the paramount importance of the initial start up recordings coupled with the sample preparation method which determine the repeatability of any single test. Again the CIGRE ELECTRA 75 [20] document is used as the yard stick for conductor test methods and data analysis strategy. Sweden has again created their standard to further restrict the test method, (Swedish Standard AA 11 23 18 Aluminium-Steel-Stranded Conductors for Overhead Lines - Non-Interrupted-Creep Testing). The Aluminium Association in America is reported to have a test method but it is uncited.

### 2.3 PREDICTOR EQUATIONS USED TO EXPLAIN CREEP

In 1932 reference [70] the following creep equation was derived:-

$$\varepsilon_{creep} = k \times t^n$$

EQUATION No.(4) Relationship between the Logarithm of Creep and the Logarithm of Elapsed Time [70].

Where,  $\varepsilon_{creep}$  = creep strain  
 $k$  = regression constant- y intercept.  
 $t$  = elapsed time in hours  
 $n$  = regression constant- slope of line.

This equation is still acknowledged for single temperature and single constant load tests today.

In 1968 reference [14] a composite equation based upon Equation No. 4 to predict the influence of load (stress) and time at constant temperature was proposed, this had the form:-

$$\varepsilon_p = \eta T^\beta t^{\gamma/T^\delta}$$

EQUATION No(5) Experimental regression equation for ACSR/GZ 54/7/0.125 in Zebra conductor [14].

$$\text{where} \quad n = \gamma/T^\delta$$

EQUATION No.(6) Time exponent  $n$  from Equation 4 which appears to increase with decreasing conductor tension (stress), but is independent of temperature [14].

$$\text{with } k = \eta T^\beta$$

EQUATION No.(7) Load dependence of k from Equation 4 at constant temperature [14].

Where,	$\varepsilon_p$	= creep strain $\mu\varepsilon$ .
	H	= regression constant.
	k	= regression constant in mm/km.
	T	= Tension in kg.
	$\beta$	= regression constant.
	$\gamma$	= regression constant.
	$\delta$	= regression constant.
	t	= Elapsed Time in Hours.

In 1971 reference [26] the author proposed that the creep of any all aluminium conductor at a constant tension with constant temperature could be represented by an equation with the following form:-

$$\varepsilon_{creep} = k \times t^{1/n}$$

EQUATION No(8) Relationship between the Creep and Elapsed Time at constant tension and temperature [26].

Where,	$\varepsilon_{creep}$	= creep strain
	k	= regression constant- y intercept.
	t	= elapsed time in hours
	1/n	= regression constant- slope of line.

When an expression for changing stress ( conductor tensions) is included the above expression becomes:-

$$\varepsilon_{creep} = k_1 \times \sigma^{k_2} \times t^{1/n}$$

EQUATION No(9) Relationship between the Creep and Elapsed Time at constant temperature with changing stress( conductor tensions) [26].

Where,  $\varepsilon_{creep}$  = creep strain.  
 $k_1$  = regression constant- y intercept.  
 $\sigma$  = conductor stress in MPa.  
 $k_2$  = stress exponent.  
 $t$  = elapsed time in hours.  
 $1/n$  = regression constant- slope of line.

When both the stress and temperature are allowed to vary the expression becomes:-

$$\varepsilon_{creep} = k_1 \times \sigma^{k_2} \times t^{1/n}$$

EQUATION No(10) Relationship between the Creep and Elapsed Time with changing stress ( conductor tensions), and temperature [26].

$$k_1 = h_1 \times \tau^2 - h_2 \times \tau + h_3$$

EQUATION No(11) Relationship between the Creep and Elapsed Time with changing stress ( conductor tensions), and temperature [26].



Where,	$\epsilon_{creep}$	= creep strain.
	$k_1$	= regression constant- y intercept.
	$\sigma$	= conductor stress in MPa.
	$k_2$	= stress exponent.
	$t$	= elapsed time in hours.
	$1/n$	= regression constant- slope of line.
	$h_1, h_2, h_3$	= temperature co-efficients

Co-efficients in the above equations are dependent upon the type of material and manufacturing process employed to produce the aluminium strand.

In 1971 a creep strains power function reference [39] was described as

$$\epsilon_{Kr} = K_1 \times (t/t_0)^{n_1}$$

EQUATION No(12) Helms and Ziebs creep strain power function for single stress tests at constant temperature [39].

Where,	$\epsilon_{Kr}$	= creep strain
	$K_1$	= regression constant- y intercept in $h^{-1}$ .
	$t$	= elapsed time in hours
	$t_0$	= 1 hour (time unit)
	$n_1$	= regression constant- slope of line.
	$0 < n_1 < 1$	

The determination of the creep rate as defined by secondary creep at any elapsed time can be described by:

$$\dot{\epsilon}_{Kr} = K_2(\theta) \times (\sigma_N / \sigma_{NO})^{n_2(\theta)}$$

EQUATION No(13) NORTON's relationship between creep rate and stress [39].

Where,  $\epsilon_{Kr}$  = creep strain rate.

$K_2(\theta)$  = regression constant in  $h^{-1}$ .

$\sigma_N$  = nominal stress.

$\sigma_{NO}$  = stress that causes an almost constant creep rate.

$n_2(\theta)$  = regression constant- slope of line.

$$0 < n_2$$

$k_2(\theta)$ ,  $n_2(\theta)$  as well as  $\sigma_{NO}(\theta)$  are temperature dependent,

which are attributed to the work of Norton which has not been reviewed in this thesis.

In 1972 reference [77] CIGRE presented the following equations stating that they are applicable to all conductors where the basic creep equation  $\epsilon = kt^n$  has been determined at 20% NBL and at 20°C.

Simplified universal creep equations are:-

Using the basic creep equation provided for an 84/19 strand ACSR cable the following equations apply:-

% steel	Tension	Temperature	Basic creep equation
adjustment	adjustment	adjustment	20% steel, 20% NBL, 20°C

$$e = (1.212 - 1.06W/100)(0.0319 \times P^{1.15})(0.842 + 0.0079 \times t) = (28.2 \times T^{0.263})$$

EQUATION No(14) Universal creep Equation for ACSR's as proposed by CIGRE WG22 [77].

Simplifying,

$$e = (1.212 - 1.06W/100) (0.757 \times P^{1.15} + 0.0071 \times P^{1.15} \times t) \times T^{0.263}$$

EQUATION No(15) Universal creep Equation for ACSR's as proposed by CIGRE WG22 [77].

For 20% steel,

$$e = 1 \times (0.757 \times P^{1.15} + 0.0071 \times P^{1.15} \times t) \times T^{0.263} = kT^{0.263}$$

EQUATION No(16) Universal creep Equation for ACSR's with 20% steel as proposed by CIGRE WG22 [77].

Using the basic creep equation provided for a 61 strand AAC cable the following equations apply:-

Tension adjustment

Temperature adjustment

Basic creep equation

20%steel,20%NBL,20°C

$$e = (0.0319 \times P^{1.15}) (0.0319 \times t^{1.15}) = (26.0 \times T^{0.285})$$

EQUATION No(17) Universal creep Equation for AAC's (All Aluminium Conductors) as proposed by CIGRE WG22 [77].

Simplifying,

$$e = 0.0265 \times (P \times t)^{1.15} \times T^{0.285} = kT^{0.285}$$

EQUATION No(18) Universal creep Equation for AAC's (All Aluminium Conductors) as proposed by CIGRE WG22 [77].

- Where,
- e

= creep strain  $\mu\epsilon$ .
- k

= regression constant in mm/km.
- W

= Steel in percent of total weight.
- T

= Temperature in °C.
- P

= Tension in % Nominal Breaking Load (Rated Strength).
- t

= Elapsed Time in Hours.

In 1973 reference [73] the CERL UK proposed the following empirical creep relationship based principally on the laboratory and field tests on Zebra conductor. This predictor equation is an extension of EQUATION No.5 combining with Equation 20, where:-

$$\epsilon_p = k T^\beta e^{\phi \theta} t^\gamma / T^\delta$$

EQUATION No(19) CERL creep relationship for ACSR conductors in the temperature range 15-85°C [73].

$$k = \lambda e^{\phi \theta}$$

EQUATION No.(20) Temperature dependence of k in Equation 4 [14].

where;  $(\lambda \text{ and } \phi)$  = regression constants in mm/km.

Cited in this paper for comparison, from a paper by Harvey and Larson but not reviewed are the following predictor equations:-

$$\epsilon_p = k \left( \frac{T}{A} \right)^\beta \theta^\phi t^\gamma$$

EQUATION No(21) ALCOA creep regression for all conductors except ACSR [73].

$$\epsilon_p = k \left( \frac{T}{UTS} \times 100 \right)^\beta \theta^\phi t^\gamma$$

EQUATION No(22) ALCOA creep regression for ACSR conductors only [73].

Where,	$\varepsilon_p$	= creep strain $\mu\varepsilon$ .
	k	= regression constant in mm/km.
	T	= Tension in kg.
	A	= cross sectional area in mm <sup>2</sup> .
	$\beta$	= regression constant.
	$\phi$	= regression constant, experimentally shown to be load independent.
	$\Theta$	= Temperature in °C.
	$\gamma$	= regression constant of conductor.
	$\delta$	= regression constant of conductor.
	t	= Elapsed Time in Hours.
	UTS	= Nominal Breaking Load in kN.

In 1981 reference [20] CIGRE added a set of relationships designed to allow individual wire creep tests to be compared to predictor equations from conductor tests. Equations predicting conductor metallurgical creep from individual wire tests vary somewhat from those of stranded conductors and have the form:

$$\varepsilon_c = \frac{1}{\cos^{2+\alpha}\beta} K e^{\phi\tau} \sigma^\alpha t^\mu$$

EQUATION No.(23) Metallurgical Creep of Monometallic Conductors [20].

$$\varepsilon_c = \frac{m(m+1)^\alpha}{\left(\frac{mE_a + E_{st}}{E_a}\right)^\alpha} \times \frac{E_a}{mE_a \cos^{2+\alpha}\beta + E_{st} \cos^{\alpha-1}\beta} K e^{\phi\theta} \sigma^\alpha t^\mu$$

EQUATION No.(24) Metallurgical Creep of Bimetallic Conductors [20].

- Where
- $\varepsilon_c$  = metallurgical creep strain  $\mu\varepsilon$  mm/km.
  - K = regression constant dependent on the material in mm/km.
  - $\sigma$  = is the average stress on the conductor (kg/mm<sup>2</sup>).
  - $\beta$  = is the average of the angles of the tangent at a point of the wires with the axis of the conductor.
  - $\phi$  = experimentally determined regression co-efficient.
  - $\tau$  = Temperature °C.
  - $\alpha$  = experimentally determined regression co-efficient.
  - t = Elapsed Time in Hours.
  - $\mu$  = experimentally determined regression co-efficient.
  - m = the ratio of aluminium or alloy cross section to steel cross section.
  - $E_a$  = elasticity modulus of aluminium or alloy (kg/mm)
  - $E_{st}$  = elasticity modulus of steel (kg/mm)

The geometrical settlement term is given as:-

$$\epsilon_s = 750 \times (d-1) \times (1 - e^{-\frac{m}{10}}) \times \left( \frac{\sigma}{\sigma_{ult}} \right)^{2.33}$$

EQUATION No.(25) Geometrical Settlement Creep for all Conductors [20].

Where,  $\epsilon_s$  = geometrical settlement creep strain  $\mu\epsilon$  in mm/km.

$d$  = is the average diameter of aluminium or alloy wires (mm).

$m$  = the ratio of aluminium or alloy cross section to steel cross section..

$\sigma$  = is the average stress on the conductor (kg/mm<sup>2</sup>).

$\sigma_{ult}$  = is the ultimate tensile strength (kg/mm<sup>2</sup>).

Or alternatively, expressed only in  $m$  and  $\sigma$

$$\epsilon_s = 750 \times (d-1) \times (1 - e^{-\frac{m}{10}}) \times \left( \frac{m+1}{m \sigma_{ult_s} + \sigma_{ult_{st}}} \right)^{2.33} \sigma^{2.33}$$

EQUATION No.(26) Geometrical Settlement Creep for all Conductors, expressed as a function of  $m$  and  $\sigma$  only [20].



- Where,
- $\epsilon_s$  = geometrical settlement creep strain  $\mu\epsilon$  (mm/km).
  - $d$  = is the average diameter of aluminium or alloy wires (mm).
  - $m$  = the ratio of aluminium or alloy cross section to steel cross section.
  - $\sigma$  = is the average stress on the conductor (kg/mm
  - $\sigma_{ult\ a}$  = is the ultimate tensile strength of the aluminium or alloy (kg/mm<sup>2</sup>).
  - $\sigma_{ult\ st}$  = is the ultimate tensile strength of the steel (kg/mm<sup>2</sup>).

Comparisons between the three creep equations for ACSR stranded conductors and individual wire tests lead the group to conclude that there is no basis for favouring one method over the other.

In reference [65] it is stated that wires creep more than cables, perhaps because the cables had received some creep during manufacture. This is in contrast to other work where the wire creep is less than the cable, with a geometrical settlement factor required to equate the strain measurements.

In reference [45] a relationship was identified between the elongation in a tensile test and the creep rate. Wires with a low elongation exhibit a lower creep rate. However, these wires did not exhibit the highest strength. They were partially annealed.

In addition to EQUATION No.4, the following equations are used to describe the creep phenomena for all conductors at MM Cables and were used to evaluate the behaviour of stress upon creep strain of conductors in this research project.

$$\varepsilon_{creep} = k_2 \times \sigma^{c_2} \times t^{c_1}$$

EQUATION No(27) Relationship between the Creep and Elapsed Time with changing stress ( conductor tensions) at constant temperature [MM].

$$\varepsilon_{creep} = k_3 \times e^{\delta(\theta-20)} \sigma^{c_3} \times t^{c_4}$$

EQUATION No(28) Relationship between the Creep and Elapsed Time with changing stress ( conductor tensions), and temperature [MM].

- Where
- $\varepsilon$  = creep strain  $\mu\varepsilon$  mm/km.
  - $k_2, k_3$  = regression constant dependent on the material in mm/km.
  - $\sigma$  = is the average stress on the conductor (kg/mm<sup>2</sup>).
  - $\theta$  = Temperature °C.
  - $c_1, c_2, c_3, c_4, c_5$  = experimentally determined regression co-efficient.
  - $t$  = Elapsed Time in Years.

STESS [54,55,56] in contrast is based upon the creep of aluminium.

Like The Aluminum Association the authors are confident that a linear relationship exists between stress and creep strain. The aluminium creep relationships are derived from the composite conductor equation. To achieve this, the authors follow standard procedure and subtract the initial reduced steel curve (Modulus test) from the composite creep curve.

Removing the elastic and settling strains the long term creep strain is fairly well described by:-

$$x_{cr} = \alpha f(T) s^{\Delta} t^{\beta}$$

EQUATION No.(29) Form of the Aluminium Creep Equation [54,55,56].

where  $x_{cr}$  = creep strain

$T$  = temperature in °C

$s$  = stress MPa

$t$  = time in years

$\alpha, \Delta, \beta$  = regression constants

The authors claim "A reasonably good description of the creep strain for any conductor is obtained with:-  $\alpha=7.8 \times 10^{-6}$ ,  $\Delta = 1.3$ ,  $\beta=0.3$ " so that the creep equation for aluminium becomes:-

$$x_{cra} = 7.8 \times 10^{-6} e^{0.03(T_a - 20)} s^{1.3} t^{0.3}$$

EQUATION No.(30) Form of the Aluminium Creep Equation [54,55,56].

where  $x_{cra}$  = aluminium creep strain  
 $T_a$  = aluminium temperature in °C  
 $s_a$  = aluminium stress in MPa  
 $t$  = time in years

Harvey and Larson, Bradbury and Electra 75 all support a stress power of 1.3. A temperature relation of  $e^{0.2-0.3T}$  is common in the literature and is supported by Harvey and Larson  $e^{0.2T}$  (or  $T^{1.4}$ ) for EC grade aluminium), Bradbury  $e^{0.2T}$  (or  $T^{1.4}$ ) and Electra 75[20]  $e^{0.3T}$  (or  $T^{1.4}$ ). Time powers  $\beta$  ranging from 0.16-.036 reference [20, Harvey and Larson, Bradbury] have been reported however, the bulk of the values fall within the 0.2-0.3 range.

Similarly, for the steel core the creep equation in the same form as the above equation is:-

$$x_{crs} = 0.003 e^{0.02(T_s - 20)} \left( \frac{s_s}{UTS} \right)^{4.7} t^{0.13}$$

EQUATION No.(31) Form of the Steel Creep Equation [54,55,56].

where  $x_{crs}$  = steel creep strain  
 $T_s$  = steel temperature in °C  
 $s_s$  = steel stress in MPa  
 $t$  = time in years  
 $UTS$  = Ultimate Tensile Strength of the steel core.

## 2.4 RELATIONSHIPS

In reference [11] the relationship between laboratory and field tests are in reasonable agreement if the first hours creep is neglected in the creep test. In reference [51] the authors acknowledge the problems associated with comparing laboratory predictions with field test results due to wide variations in temperature in the field. They do, however, say that the use of temperature corrections based upon a laboratory predictor equation provides reasonably accurate prediction of sag with time.

In reference [50] wire tests the creep strain is approximately 50% less after stranding compared to those measured before stranding. Measurement on plastic strain during stranding on 0.125 in<sup>2</sup> wire show 0.0003 in or 4800 micro strain some of which must be permanently removed creep strain. Any relationship between wire and conductor creep seems "very difficult" to quantify.

#### 2.4.1 INFLUENCE OF TEMPERATURE UPON CREEP RELATIONSHIPS.

CIGRE in ELECTRA 24 [77] on a limited number of creep tests predict that the influence of temperature in °C on the creep after 30 years at 20% NBL could be described by:-

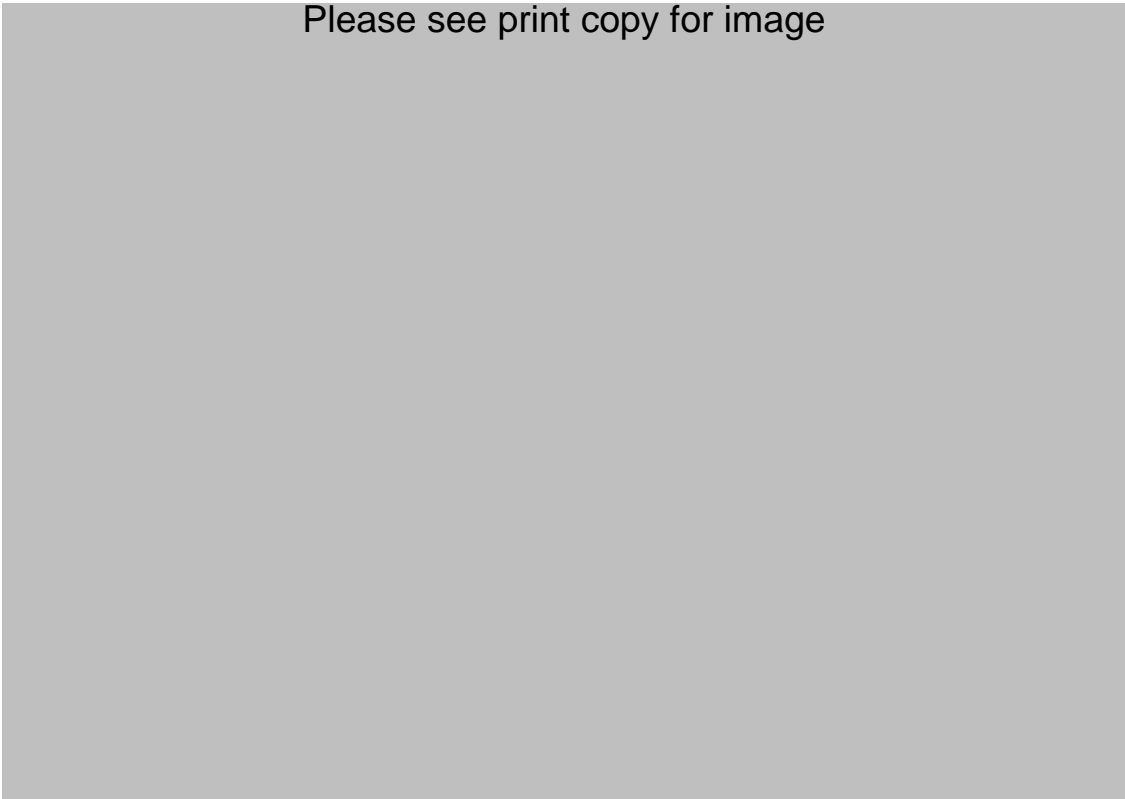
$$\text{ACSR Creep Factor} = 0.842 + 0.0079 \text{Temperature}$$

(Tested for 11.5-14% Steel)

$$\text{All Aluminium Creep Factor} = -0.2 + 6 * (\text{Temperature}/100) + (\text{Temperature}/100)^4$$

$$\text{All Aluminium Approx Equation} = 0.0319 * \text{Temperature}^{1.15}$$

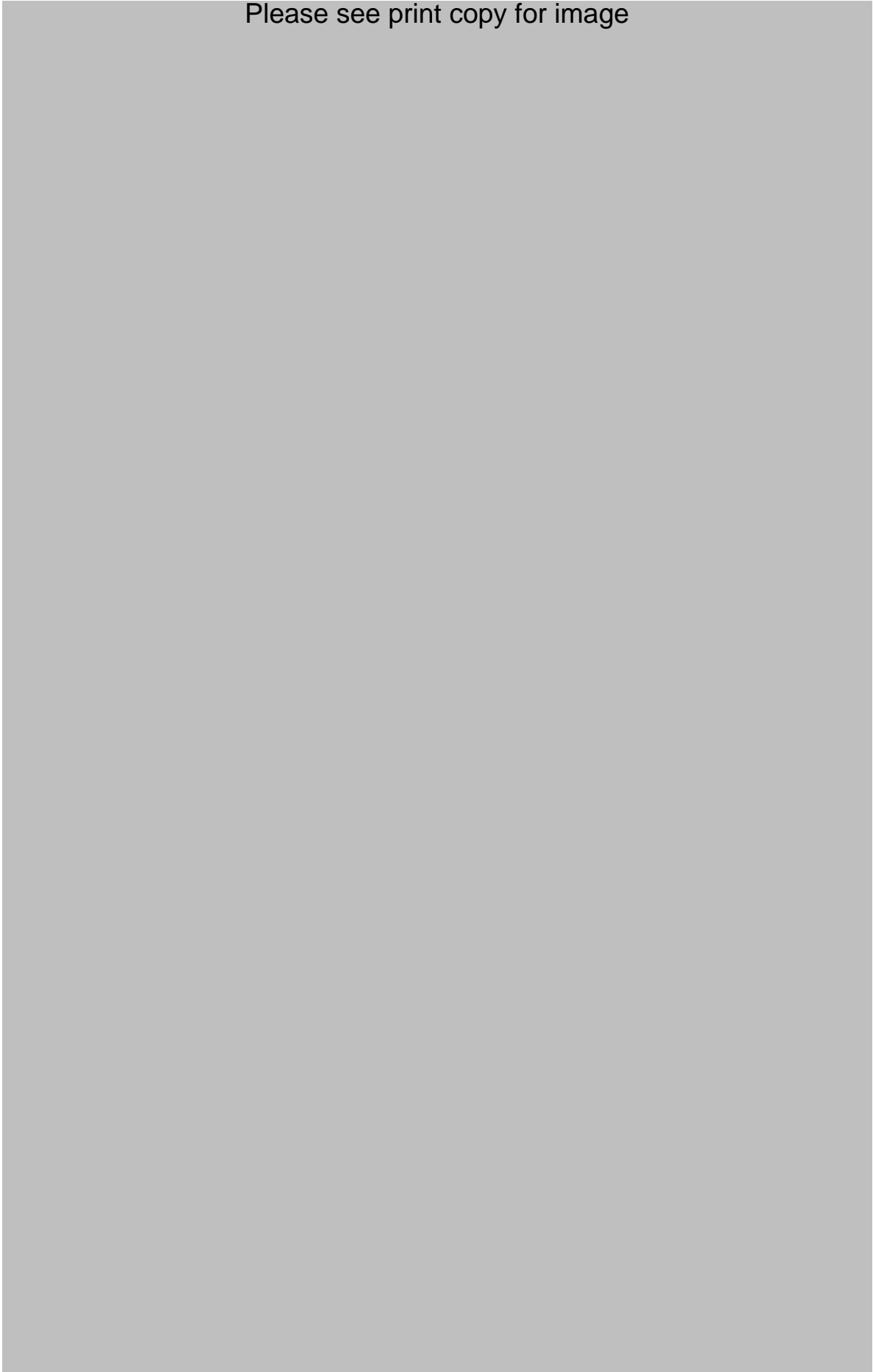
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**FIGURE No.1** TEMPERATURE Vs CREEP FACTOR for ACSR'S and ALL ALUMINIUM conductors.[77]

Data is from the following table.

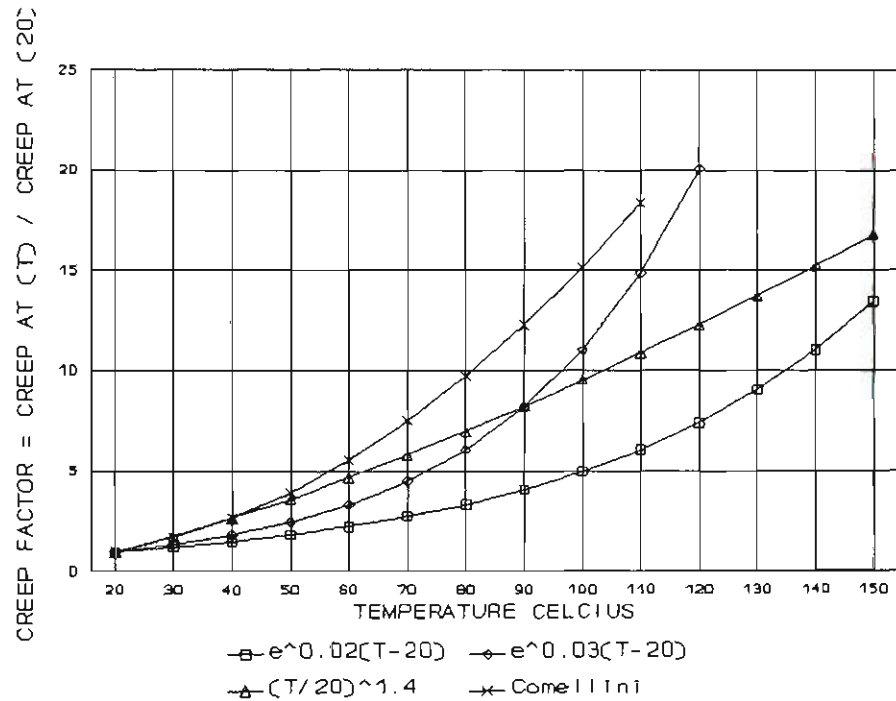
**TABLE I** Temperature Vs the Creep Factor for 30 year creep microstrain. [77]  
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In contrast references [12,20,26,54,55,56] detail the influence of Temperature on the creep rate as follows:-

$k = \lambda e^{\phi T}$  by Bradbury[12] where  $\phi$  is independent of load but  $\lambda$  is load dependent.  
 $e^{0.02(T-20)}$  from the work of Bradbury et al, Nicolini and Paoli, Electra 75 [20]  
 $(T/20)^{1.4}$  from the work of Harvey and Larson, Bradbury et al, Electra 75 [20]  
 $e^{0.03(T-20)}$  from the work of Electra 75 [20].

$k = h_1 T^2 - h_2 * T + h_3$  from the work of Comellini, [26] where for some undefined Italian conductors  $h_1 = 6.16 \times 10^{-9}$ ,  $h_2 = 54.6 \times 10^{-9}$ ,  $h_3 = 2892 \times 10^{-9}$  [26].



**FIGURE No.2** Comparison of alternative relationships proposed to explain the temperature dependence of 1350 aluminium.[20,54,55,56]

For single wire creep tests reference [57] the Swedish authorities use these relations with caution due to data scatter:

Nordisk Feral Al59  $e^{0.038 + 0.032 \text{Log}(R/R_m)(T-23)}$

AB Elektrokoppar Al59  $e^{0.018 + 0.018 \text{Log}(R/R_m)(T-23)}$

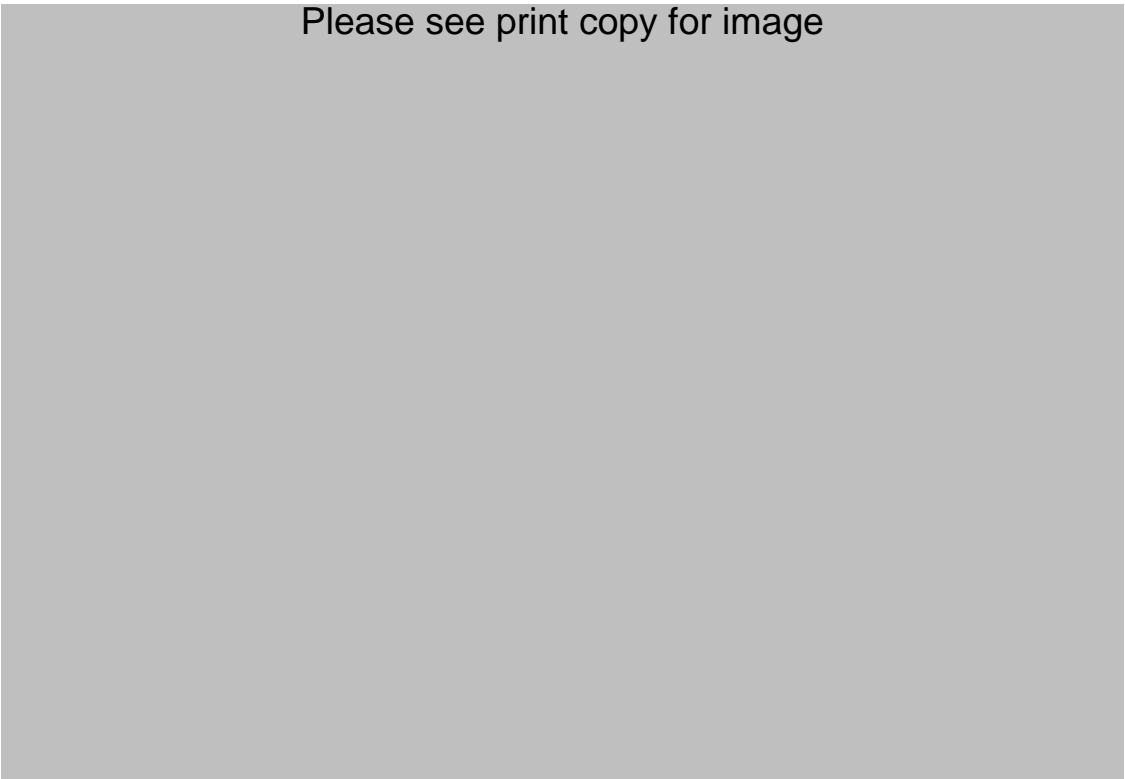
AB Elektrokoppar Al59  $e^{0.011 + 0.017 \text{Log}(R/R_m)(T-20)}$



#### 2.4.2 INFLUENCE OF THE PERCENTAGE OF STEEL vs ALUMINIUM IN AN ACSR UPON THE CREEP OF A CONDUCTOR.

CIGRE in ELECTRA 24 [77] on a limited number of creep tests predict that the influence of Weight Percent Steel on the creep after 30 years at 20% NBL could be described by:-

$$\text{ACSR Creep Factor} = 1.212 - 1.06 * (\text{Tension}/100)$$

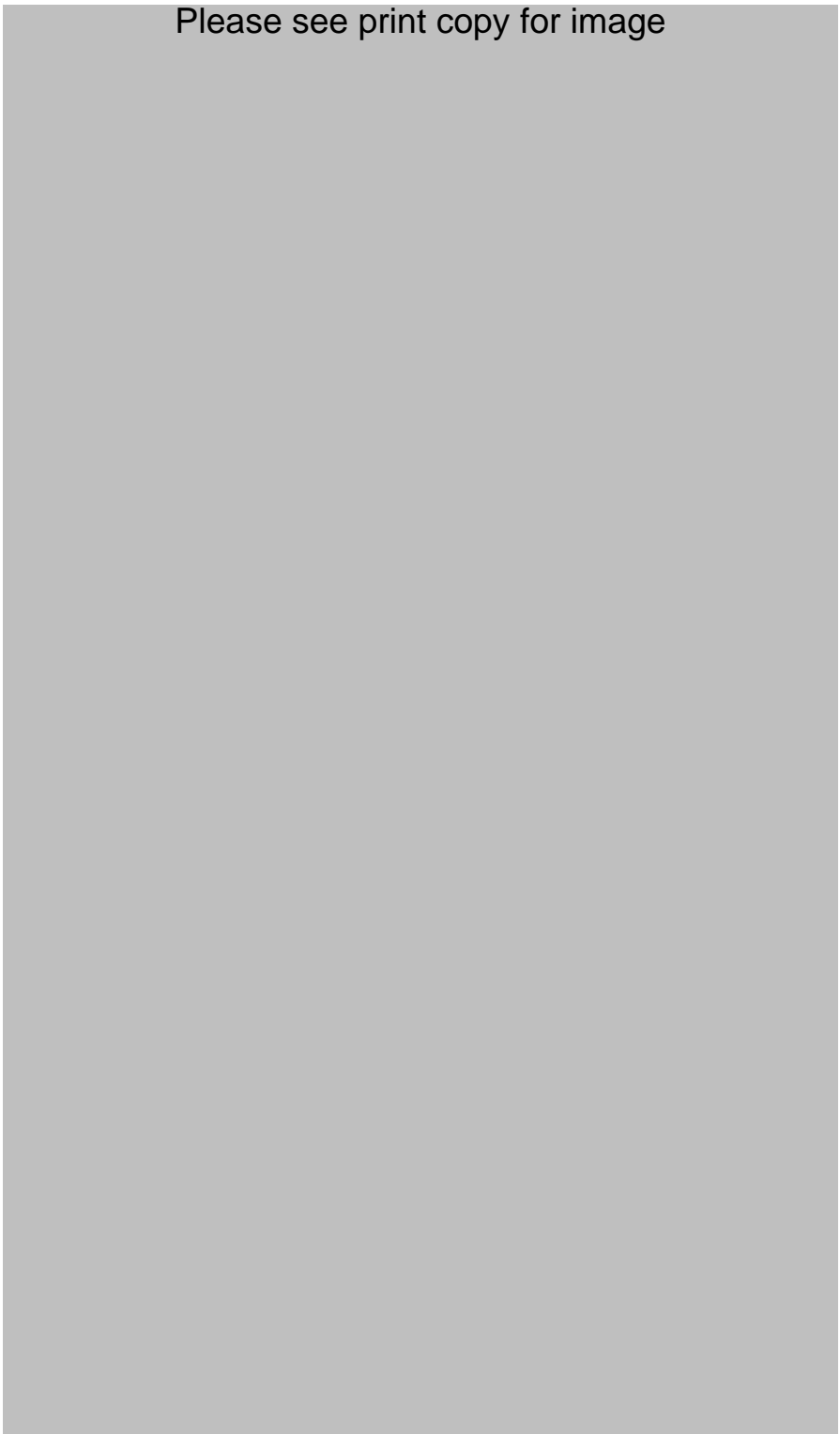


**FIGURE No.3** Percent Steel Vs Creep Factor. [77]

Data is from the following table.

**TABLE II** Percentage Steel Vs Creep Factor for 30 year creep microstrain. [77]

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### 2.4.3 TENSION

CIGRE in ELECTRA 24 [77] on a limited number of creep tests predict that the influence of Tension (% NBL) on the creep after 30 years at 20% NBL could be described by:-

$$\text{ACSR Creep Factor} = 0.05\text{Tension} + 13(\text{Tension}/100)^5$$

(Tested for 54/7 26.75% Steel)

$$\text{ACSR Approx Equation} = 0.0319 * \text{Tension}^{1.15}$$

$$\text{All Aluminium Creep Factor} = 0.05 + 10 * (\text{Tension}/100)^4$$

(19 Strand)

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**FIGURE No.4** TEMPERATURE Vs CREEP FACTOR for ACSR'S and ALL ALUMINIUM conductors.[77]

Data is from the following table.

**TABLE III** INFLUENCE OF TENSION Vs CREEP FACTOR. FOR 30 YEARS CREEP MICROSTRAIN.

% NBL	ACSR			ALUMINIUM	
	DATA	EQUATION	APPROX EQUATION	DATA	EQUATION
0		0	0		0
10	0.49	0.50013	0.450599	0.49	0.501
20	1	1.00416	0.999943	1	1.016
30	1.53	1.53159	1.59397	1.59	1.581
40	2.15	2.13312	2.219012	2.26	2.256
50		2.90625	2.868179		3.125
60	4	4.01088	3.537241	4.43	4.296
70		5.68491	4.223315		5.901
80		8.25984	4.924296		8.096
90		12.17637	5.638578		11.061
100		18	6.364887		15

For single wire creep tests reference [57] the Swedish authorities use these relations with caution due to data scatter:

Nordisk Feral Al59  $151.2(R/R_m)^{1.05}$

AB Elektrokoppar Al59  $587.4(R/R_m)^{2.24}$

AB Elektrokoppar Al59  $1078(R/R_m)^{2.42}$

Comellini, in discussing the load transfer behaviour of ACSR conductors, claims that at no point is a linear (log Time -Log Creep) secondary stage of creep achieved. Instead, the progressive transfer of load to the steel core could during "secondary stage creep" be approximated by two (2) straight lines. For varying percentages Figure 5 outlines the proposed theoretical relationships. Above 50% steel the values are constant with changing  $m$ .

Please see print copy for image



**FIGURE No.5** Theoretical values of  $k$  and  $n$  as a function of  $m$  at constant stress (20% NBL) with a constant temperature of 24°C.[26]

Bradbury [12] cites two effects of tension/stress upon the creep strain. These have been stated in EQUATIONS 5,6,7 above. Interpreting the relation in EQUATION 6 we find that the time power function "n" increases as the load/tension/stress on the conductor decreases. However,  $\gamma$  and  $\delta$  are conductor constants which must be determined.

Plotting Log k against Log tension produces a straight line relation of the form in EQUATION 7. Where  $\eta$  and  $\beta$  are conductor constants to be determined.

In reference [39] the influence of stress upon n in EQUATION 4 is to decrease the power as the stress increases which is the opposite of the effect noted in reference [70].

#### 2.4.4 INFLUENCE OF LAY LENGTH ON CREEP.

A survey of the available literature was unable to show any research looking at the influence of lay length on creep strain. However reference [39] looks at the effect on Modulus test behaviour of an ACSR conductor of long normal and short lay lengths. As would be intuitively expected the longer lay length sample had the highest initial modulus. A longer lay length requiring a higher loads to attain the same strain as its shorter lay length counterparts. If this can be followed through to creep, then longer lay lengths within the standard would result in lower creep rates.

## **CHAPTER 3            CREEP COMPENSATION METHODS**

### **3.1                    MARGIN ON SAG**

This method involves calculating how much a conductor will sag during its life time then provides for an additional allowance at the conductor attachment reduced level to compensate for the long term sag change resulting from inelastic stretch.

My experience has shown, that this method is closely linked to span lengths. Reference [14] does not recommend this method because, it is largely dependent upon span lengths.

### **3.2                    REDUCING THE LENGTH OF CONDUCTOR BETWEEN TOWERS.**

After calculating the inelastic elongation expected over the life time of the line, the Americans then subtract this length from the unstretched length prior to landing. Thus, at the end of the life time of the conductor it will be the design length. Has not gained popularity in Australia, its limitations are unknown since, little experience exists with this method.

### **3.3                    MECHANICAL ADJUSTORS.**

These are fitted to every cable at each dead end. Each set of adjustors has the ability to reduce the overall length of the line by 600 mm eg. each fitting allows up to 300 mm of take up in 6 mm increments reference [15].



### 3.4 OVER TENSIONING OR INITIAL STRINGING.

Over tensioning maybe defined as the erection and sagging of a conductor at a higher value of tension, ie above the design tension at which the conductor is finally sagged. Hence, creep can occur during the working life time of the conductor with the creep increasing the sag without dropping below the designed maximum allowable sag. After clamping in, axial tension on the conductor will initially decrease rapidly as the conductor lengthens resulting from the inelastic stretch of the conductor. Experience has shown that after 10 years the initially high creep rate has dropped to a level where further creep maybe ignored. If the conductor was correctly overtensioned, this final everyday conductor tension should be equal to the design tension. This method usually requires a knowledge of the creep behaviour of the conductor.

Fixed over tensioning is simply sagging the conductor at a tension which is a set percentage above the final design tension. This method has the advantage of great simplicity, but its disadvantages are significant especially when alternative construction conductors are considered.

In reference [14] compensation for creep by stringing at a fixed percentage above the design tension is not recommended as it is largely dependent upon span lengths, ie longer spans will produce larger tension reductions during any given time duration compared to smaller span lengths.

In reference [46] the author in quantifying the effect of a fixed over tension on the final conductor tension shows that for "short" spans the tension is lower than design, but "longer" spans are over tensioned and the degree of over tensioning is enhanced if the creep rate is "low" for the conductor. A higher every day tension has the draw back of enhancing the potential for vibration/fatigue damage. Only with a detailed knowledge of the creep characteristics for the conductor it is possible to individually tension each span to produce the desired design tension after 10 years. The level of over tensioning for any span will increase with increasing creep and vice versa. Over tensioning after a period in sheaves in which a significant level has occurred results in the conductor being over stressed to an even greater extent than if the conductor had been "virgin" at the time of over tensioning. Hence, the amount of over tensioning must be reduced with the magnitude of the reduction dependent upon the time at tension in the air.

In reference [13] it is stated that the effect of over tensioning on the final sag of a conductor due to conductor creep is of considerable importance in the design and installation of a line. In newly landed conductors strung during autumn, over tensioning can result in the conductor exceeding the maximum working tension, under the influence of ice and wind in winter (climatic overload).

In UK, over tensioning is usually in the order of 5-15% reference [15].

### 3.5 TEMPERATURE COMPENSATION

Creep can be built into the sag tension equation as follows:

$$\text{Final length} = \text{Initial length} + \text{change in length}$$

where:

$$\text{change in length} = \text{elastic strain} + \text{creep strain} + \text{temperature strain}$$

In its numerical form this equation is solved for the final tension from which the final sag is calculated. To allow for creep over x years, it is usual to tension the conductor to a slightly higher initial tension or lower sag so that in x years the conductor will have sagged no more than the maximum allowed.

To compensate for creep, it is necessary to calculate the temperature to be subtracted from the measured ambient temperature against the number of days that the conductor is "in the air" at a tension of say 20% of NBL. This is the standard method for allowing for permanent stretch which occurs over the life of the line.

Creep causes an increase in length with time, whilst an increase in conductor temperature also causes an increase in length. Thus, it is possible to equate creep strain with temperature rise for the conductor.

$$\epsilon = kt^n = \alpha \times \Delta T$$

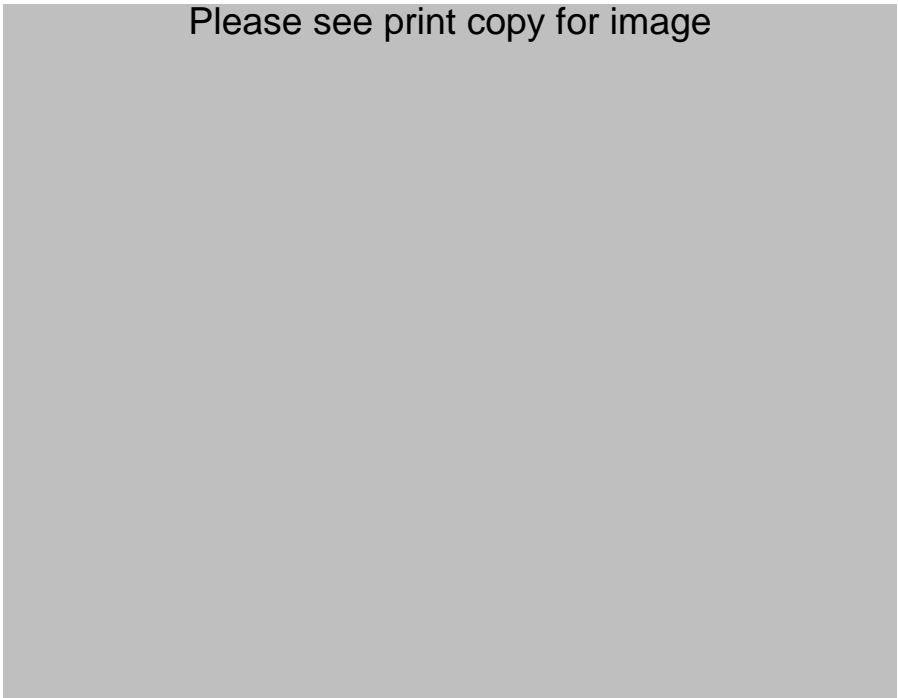
EQUATION No.(32) Equating creep at time  $t$  to an equivalent thermal expansion for a temperature increase of  $\Delta T$  [46].

where	$\epsilon$	= creep strain (mm/km)
	$k$	= regression constant (mm/km)
	$t$	= elapsed time in years
	$\alpha$	= co-efficient of thermal expansion
	$T$	= temperature ( $^{\circ}\text{C}$ )

Once this temperature is known, (usually 10 or 30 year creep) it can be added to the maximum operating temperature for that conductor. Hence, the sag calculated at this temperature will be equivalent to the sag due to the maximum temperature including the total expected creep extension. When this is done at the design stage no further allowance is required for creep.

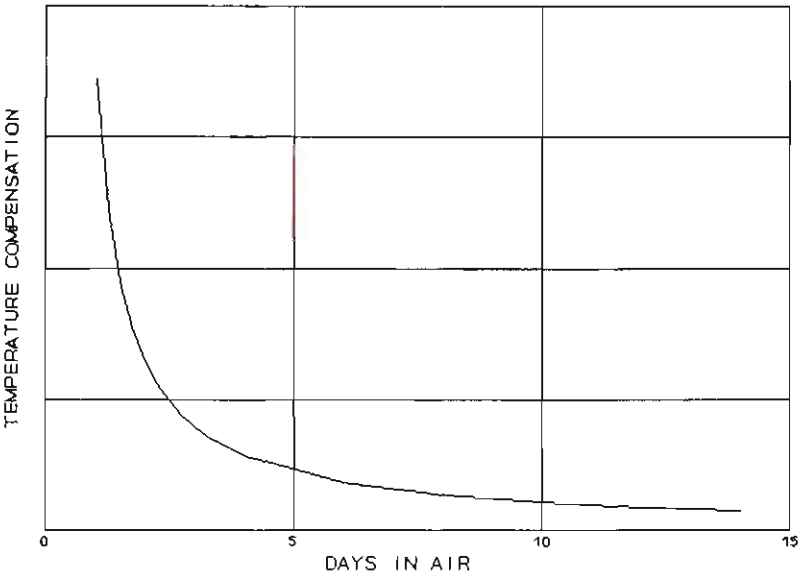
[46] Prefer this method over others and shows that the compensation temperature is independent of the span lengths. The following figure illustrates this behaviour.

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**Figure 6** Affect of span length up on the creep compensation temperature.  
[46]

The time a conductor is in the air prior to final sagging affects the amount of creep remaining and hence the amount of compensation required. Temperature compensation charts have the form below with temperature being read off after the days at tension have been determined.



**Figure 7** Affect on remaining creep in a conductor requiring compensation as a function of temperature after X days at tension.

The creep remaining in a conductor after X days in the air used to determine the temperatures on the Y axis in the above graph were calculated using the following equation.

$$\epsilon = k \left[ t_y^n - \left( \frac{t_d}{365} \right)^n \right]$$

EQUATION No.(33) Creep remaining after the first  $t_d$  days of creep have been removed [46].

where	$\epsilon$	= creep strain mm/km
	$k, n$	= regression constant mm/km
	$t_y$	= number of years creep requiring compensated.
	$t_d$	= days before final sagging.

Under normal operating conditions there is a two day delay in which the conductor is in the air but not clamped in at final sagging.

In reference [14], compensation of creep using an allowance based on a stringing temperature lower than the actual temperature, is said to be the preferred method.

CIGRE AP 22 SWG 501 stated that "The proposed method of allowance for inelastic stretch is by temperature compensation as this is the widely used and has been based on data compiled by SECV". No allowance for inelastic stretch during pull-out is made since it may result in reduced final clearance, particularly in line sections adjacent to the conductor drums/tensioner location.

### 3.6 CREEP RESISTANT ALLOYS/CONDUCTORS

In reference [11] the author describes two modified manufacturing methods devised to produce a conductor with superior creep resistance.

Method i/ involves reducing the bobbin tension during the stranding operation. How much of a reduction and what the variation must be per layer to achieve the designed behaviour of the aluminium only taking on load at final sag tension is not presented.

Method ii/ involves annealing the complete conductor after stranding (ACSR) (When the aluminium is fully annealed prior to stranding this type of conductor is known as a Steel Supported Aluminium Conductor in America). Both of these methods depend upon shifting the load bearing characteristics of the conductor.

In order for either to be successful they must transfer a significant proportion of the conductor load from the aluminium to the steel core.

Conductor containing Invar cores or wires have been proposed to reduce sagging at higher temperatures reference [41]. Mostly through the reduced co-efficient of thermal expansion but also from improved mechanical properties at high temperatures and high strength at "normal" operating temperatures.

In reference [15] straining steel wires at 400-500°C improved creep resistance and mechanical properties. The author decided to try the technique on aluminium alloys and found that straining aluminium wires to 1% plastic strain at 200°C reduced the creep rate by a factor of 2 in homogeneous conductors. ACSR's show this effect to a lesser degree. The author suggests that by heating ACSR conductors to say 200°C and producing a 1% strain the conductor will upon cooling exhibit enhanced mechanical properties including creep resistance.

No comparison between prestressed conductor to 1% strain and stabilised is given. However, 1% strain is well known as the point at which most conductors rupture. Therefore, great care is necessary prior to using this method.

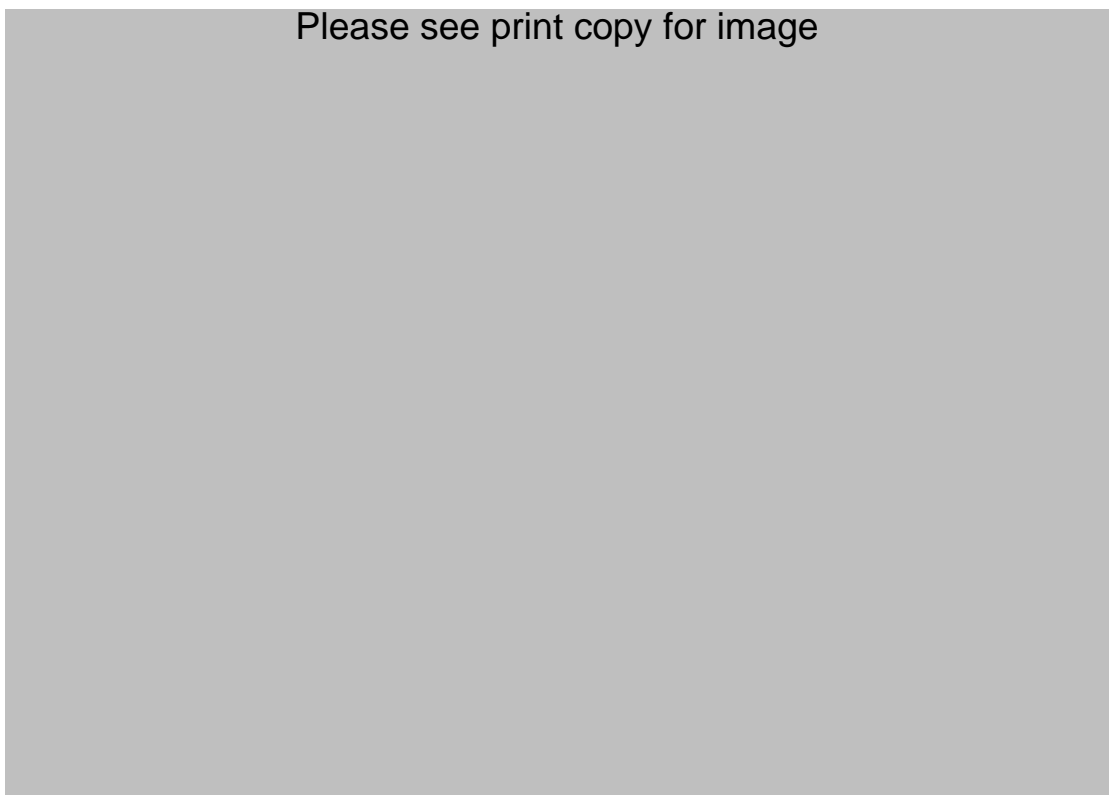


### 3.7 SECULAR CONDUCTORS

This method, like the previous section relies, upon changing the conductors to be used for a transmission lines. These are new conductors with limited history. These conductors vary from normal conductors in that the wires have been shaped to fit closer together and form a compact conductor. There are claims of improved creep behaviour, but little information is available.

### 3.8 RESAGGING AFTER A SET NUMBER OF HOURS.

Illustrated below is the affect on the total creep strain, of resagging a conductor which has been allowed to "age" whilst suspended on towers. Times chosen are only to typify the affect of resagging after a relatively short time, upon the total inelastic stretch. Reference [14] recommends this method of sag compensation for its simplicity.



**Figure 8** Schematic representation of how resagging after at set period at design tension can decrease the creep strain. [11]

This method delays final sagging whilst tying up equipment and man power.

### 3.9 PRESTRESSING OF THE CONDUCTOR.

Prestressing in broad terms means tensioning a conductor for a set period prior to final sagging. It has been known for many years that the creep rate drops off rapidly from the initial high rate to a constant level. The total amount of creep for say 30 years is independent of the order of changes in stress and/or temperature during the 30 years, instead, depending only on the amount of creep strain at that particular time. Thus, it is possible by applying a high tension during the initial days after landing but prior to final sagging to remove a significant portion of the total 30 year creep.

In reference [77] the authors have limited the use of prestressing to stabilising the conductor for 3 to 4 hours to facilitate accurate measurements during landing and final sagging.

In reference [14] when discussing the stringing of new conductor with aged, the authors are in favour of prestressing. They believe that it is almost certain that some form of prestressing must be used when stringing additional conductor into a bundle which has been in service for several years.

Reference [13] suggests that selecting the optimum prestressing tension and time on the final sag of a conductor are of considerable importance in the design and installation of power lines.

The author in reference [10] does not believe in prestressing based up on increased costs. It is difficult to find evidence to support this statement, especially to compare prestressed vs virgin conductors. In the discussion, Tubbs, states that prestressing has the added advantage of reducing the aluminium stress in ACSR conductors, ie controlling the distribution of stress. The bonus here is reduced vibration fatigue failures because of the lower stresses.

Reference [15] states that prestressing of conductors occurs at tensions up to 50 % NBL for periods of 0.5 to 24 hours. With the proviso that it may not be feasible with "light" towers.

The author in reference [1] discusses creep compensation of 76/0.1463 in<sup>2</sup> aluminium + 7/0.1138 in<sup>2</sup> steel conductor. He believes that with pretensioning, sag will more uniform between conductors and that the long term creep behaviour of all the conductors will be similar if erected during the stabilised period. A 4 hour stabilised period was required which could achieved by either a/ a 15 % overload for 6 hours or b/ a 25 % overload for 2.5 hours.

It was noted that the regression constant n increased after the stabilising periods in comparison to the "normal" creep exponent. However, by 100 hours the creep rates had again co-incided.

Recovery of some creep strain after the over load was removed was observed but not quantified. A time lag was associated with the recovery of about 15 minutes after load reduction. Interstrand friction was named as a probable partial cause of delayed recovery. Therefore, allow approximately 1 hour after the over load removal before measuring, marking, grounding, terminating, landing and final sagging. No significant difference was observed between conductor run out then held in sheaves for 24 hours, prior to over loading and conductor run out and immediate pre stressed. The author believes that prestressing dominates the other processes during installation.

In reference [14] the short term ( $> 1000$  hours) influence on creep of prestressing Zebra 0.4 in<sup>2</sup> ACSR conductor for combinations of 1, 3, or 6 hours at 10, 20 or 30 percent over normal stringing tensions, were tested. From the results it can be generalised that a/ as the prestressing time is increased for constant pre stressing tension the creep constant  $k$  increases whilst  $n$  decreases; b/ for any give time increasing the prestressing tension increases  $k$  whilst  $n$  decreases; c/ upon the removal of the prestressing tension, there is a period of time in which the strain (creep) shows little elongation or contraction. The authors propose that this effect is due to interstrand friction. There is some delayed elastic recovery which for a time, more or less, balances the continuing creep; and d/ prestressing affects the creep rate.

Increasing the severity of prestressing either the time or tension, reduces the total creep observed for the first 6 weeks after final sagging.

Decreasing the overload from 30-10% increases creep strain by 40 microstrain at 1000 hours. Increasing the over load time from 1 to 6 hours caused a decrease in creep strain by 80 microstrain. Variations in time at prestress loads are more likely to occur in the field and thus be the main source of problems. For Zebra, the following relations proved equivalent in creep at 1000 hours:

Overload	Overload Time	= Overload	Overload Time
30%	1 hour	10%	3 hours
30%	3 hours	10%	6 hours

Reference [11] states that pretensioning basically has two types a/ landing and holding at EDS for a number of hours before final sagging (see resagging in section 3.8) and b/ appreciably overloading the conductor for a number of hours prior to final sagging operations. The advantages of b) are shown in Figure 9 below, and can be compared to the figure in section 3.8 (see the addition creep saving by using this method).

The three practical methods of over tensioning conductors in the field include:- a/ the least effective, stringing a conductor at normal tension for a number of days, then retightening the conductor prior to final sagging;

b/ stringing the conductor, then using pull lifts to apply a slightly higher tension;

c/ fixing one end to an anchor tower and the other to a sprung device designed to allow length changes whilst maintaining constant (2%) tension.



**Figure 9** Affect of over tensioning on the creep strain of a conductor.[11]

Please see print copy for image



**Figure 10** Creep behaviour including recovery of a conductor after over load removal. [11]

### 3.9.1 CALCULATION OF TIME EQUIVALENCE.

For creep at constant temperature ( for simplicity ) but allowing varying stress levels assume the following relation ship accurately describes creep behaviour.

$$\text{Unit } \epsilon = K t^{\mu} \sigma^{\alpha}$$

EQUATION No.(34) Relationship between stress, time and creep strain.

If the conductor is subjected initially to a stress of  $\sigma_1$  for time  $t_1$ , followed by a stress increment to  $\sigma_2$  for time  $t_2$ ; it is necessary to calculate the equivalent age of the conductor at  $\sigma_2$  for the creep strain after time  $t_1$ . The figures following illustrate the stress-time relationships described here. The equations below describe the creep of the conductor after time  $t_1$  and time  $t_2$  respectively. The problem is to find  $t_{eq}$ .

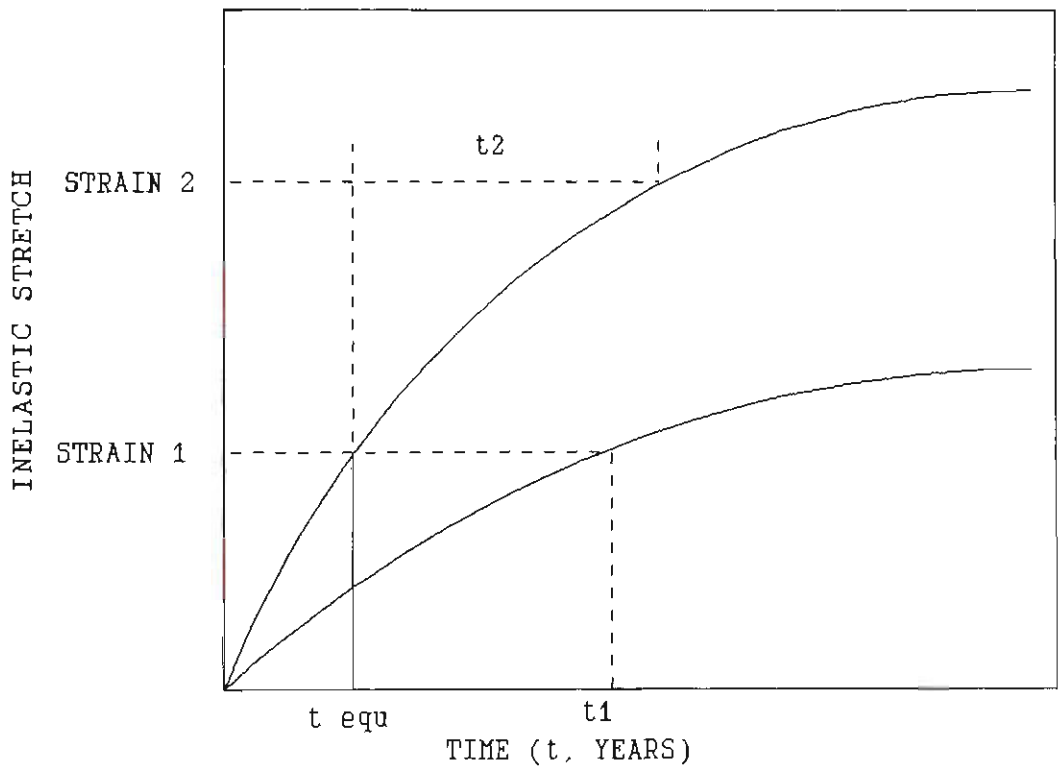


$$Unit \ \varepsilon_1 = K \ t_1^\mu \ \sigma_1^\alpha$$

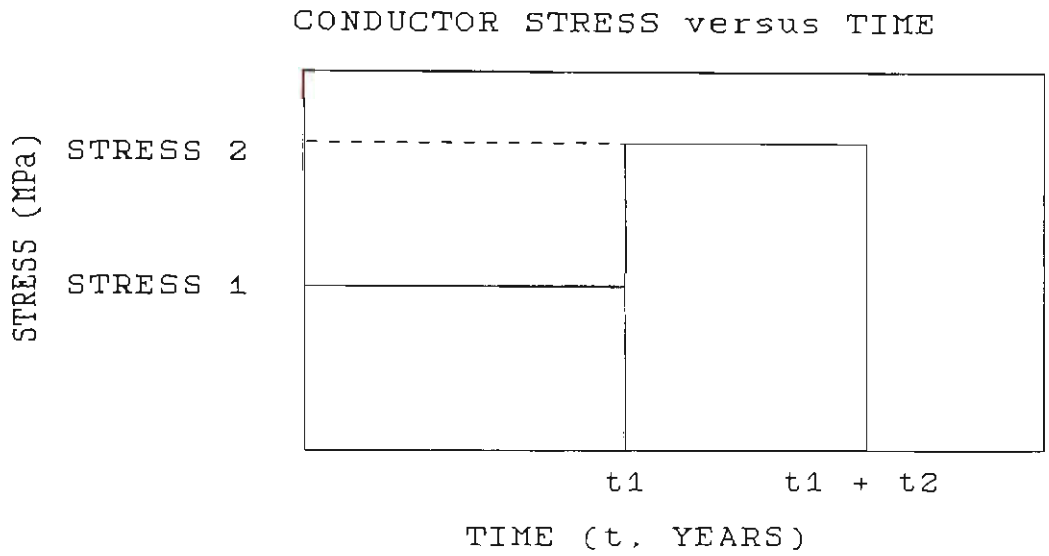
EQUATION No.(35) Relationship for interval 1 between stress , time and creep strain. Creep strain at the end of time 1.

$$Unit \ \varepsilon_1 = K \ (t_{eq} + t_2)^\mu \ \sigma_2^\alpha$$

EQUATION No.(36) General relationship between stress, time and creep strain, when there is a stress change.



**Figure 11** Creep curves for stress  $\sigma_1$  and  $\sigma_2$ .



**Figure 12** Relationship between time and stress.

At the time of the stress change it is necessary to equate the strain at the end of time  $t_1$  with the strain at the start of time  $t_2$ , as can be seen below.

$$\text{Unit } \epsilon_1 = K t_{eq}^\mu \sigma_2^\alpha = K t_1^\mu \sigma_1^\alpha$$

**EQUATION No.(37)** General relationship between stress, time and creep strain, when there is a stress change. The equivalent time must be calculated.

In words,  $t_{eq}$  in the above equation is the time required at stress  $\sigma_2$  for the creep strain the equal  $\epsilon_1$ .

Solving this equation for  $t_{eq}$  yields.

$$t_{eq} = \left( \frac{\sigma_1}{\sigma_2} \right)^{\frac{\alpha}{\mu}} t_1$$

EQUATION No.(38) Time equivalence for stress changes.

Thus, at the end of time  $t_2$  the total creep is described by:

$$\varepsilon_{tot} = K \sigma_2^{\frac{\alpha}{\mu}} (t_{eq} + t_2)^{\frac{\alpha}{\mu}} = K \left( \sigma_1^{\frac{\alpha}{\mu}} t_1 + \sigma_2^{\frac{\alpha}{\mu}} t_2 \right)^{\frac{\alpha}{\mu}}$$

EQUATION No.(39) Total creep equation after time 2.

Hence, to use this equation to calculate the creep strain after the life of the line,  $t_{life}$  must be divided into  $n$  intervals of equal stress.

$$\Delta t = \frac{t_{life}}{n}$$

EQUATION No.(40) Number of time intervals in the life of a line.

Thus, for constant temperature creep the total creep for the life of the line will be:

$$\varepsilon_{tot} = K \left( \sum_{i=1}^n \sigma_i^{\frac{\alpha}{\mu}} \Delta t_i \right)^{\frac{\alpha}{\mu}}$$

EQUATION No.(41) Summation of creep strain over the life of the line for  $n$  stress intervals.

Where  $n$  becomes large and tends to infinity the above equation becomes the integral:

$$\epsilon_{tot} = K \left( \int_0^{t_{life}} \sigma_i^{\frac{\alpha}{\mu}}(t) dt \right)^{\mu}$$

EQUATION No.(42) Integral of creep strain over the life of the line for  $n \rightarrow \infty$  stress intervals.

This relationship is independent of the order of the stress changes and thus, independent of time.

For conductors where both the stress and temperature are varying and can be described by the equation below, it is possible to extend the above equation to include temperature in a similar manner to the stress changes.

When this is done, the second relation becomes:

$$Unit \ \epsilon = K \ t^{\mu} \ \sigma^{\alpha} \ exp^{\phi T}$$

EQUATION No.(43) Relationship between stress, temperature exponential, time and creep strain.

$$\epsilon_{tot} = K \left( \int_0^{t_{life}} e^{\frac{\phi}{\mu} T(t)} \sigma_i^{\frac{\alpha}{\mu}}(t) dt \right)^{\mu}$$

EQUATION No.(44) Integral of creep strain over the life of the line for  $n \rightarrow \infty$  intervals in which stress and temperature are constant.

Or, where the temperature relationship is not exponential but a power it is described by:

$$Unit \ \varepsilon = K t^{\mu} \sigma^{\alpha} T^{\phi}$$

EQUATION No.(45) Relationship between stress, temperature power law, time and creep strain.

Then the integral is given as:

$$\varepsilon_{tot} = K \left( \int_0^{t_{life}} T^{\frac{\phi}{\mu}}(t) \sigma_i^{\frac{\alpha}{\mu}}(t) dt \right)^{\mu}$$

EQUATION No.(46) Integral of creep strain over the life of the line for  $n \rightarrow \infty$  intervals in which stress and temperature are constant.

The preceding discussion is applicable to EQUATIONS 21 & 22 for conductors and EQUATIONS 23 & 24 for wires. However, it cannot be applied to EQUATION 19. Strictly speaking the value of creep strain depends on the succession in time of the variations in stress and temperature. Errors though are in the order of  $< 1\%$  for normal operating conditions.

For maximum effect, pre-tensioning should be applied after initial bedding in and settling are complete. MMCables laboratory creep tests indicate that 3-4 hours are required for a linear relationship to be established, but 1 day would be safer since numerous experimentors have had difficulty establishing a relationship before 24 hours. If pre-tensioning is set to 40%NBL, there would need to be a method of maintaining this tension, especially if the temperature drops overnight, which would result in a much higher tension being applied, especially in short spans. Assuming that the pre-tension load cannot be controlled overnight a maximum pre stressing time of 6 hours is envisaged.

### 3.9.2           EXTRACTS FROM A SURVEY OF AUSTRALIAN ELECTRICAL AUTHORITY PRESENT PRACTICES.

Northern Queensland Electricity Board always pretension ACSR for 24 hours by temperature compensation of 11 °C.

Northern Rivers County Council sometimes pretension ACSR overnight at approximately 25 % of NBL.

State Electricity Commission of Victoria always pretension AAC.

State Energy Commission of Western Australia tension "by eye" with allowance for creep on spans up to 100 m.

Illawarra Electricity use a design life of 30 years. Compensation for the total inelastic stretch is achieved by employing a variety of methods. These are 20% by prestressing, 40% by clearance compensation and 40% by temperature compensation.

Conductors are usually pretensioned for up to 24 hours exemptions are:-

- a/ Queensland Electricity Commission which pretensions for 3 days,
- b/ State Electricity Commission of Victoria which pretensions for 7 days.

Tension used in pre tensioning is usually 16-25%NBL exemptions are:-

- a/ Sydney County Council, which uses the EDS plus 40-50 %.

Most authorities take steps to compensate for permanent conductor inelastic stretch (creep) after erection, prior to commissioning a line.

Three methods are commonly used.

a/ Overtension, the line during erection. The extent of over tension varies from 5-15%. Used by Queensland Electricity Commission and Hydro-Electric Commission of Tasmania (8%),

b/ Sagging at a lower temperature than actual ambient (temperature compensation). State Energy Commission of Western Australia, Electricity Trust of South Australia, South East Queensland Electricity Board, Papua New Guinea Electricity Commission, Electricity Division Ministry of Energy New Zealand, State Electricity Commission of Victoria, Shortland County Council, Capricornia Electricity Board, Northern Queensland Electricity Board, Prospect County Council, Ophir County Council, Northern Rivers County Council, Murrumbidgee County Council, South West Queensland Electricity Board, Wide Bay Burnett Electricity Board.

c/ Allowing extra clearance when profiling the line (eg 1 m). Used by Electricity Commission of New South Wales, Northern Rivers County Council, Ophir County Council, Sydney County Council, and Papua New Guinea Electricity Commission.



The following relationships were taken from graphs in the referenced sources. Using the following equation.

$$t_{eq} = \left( \frac{\sigma_1}{\sigma_2} \right)^{\frac{\alpha}{\mu}} t_1$$

EQUATION No.(47) Time equivalence for stress changes.

TABLE IV Prestressing Creep Relations of Stranded Conductors

SOURCE	CONDUCTOR DETAILS	PRE STRESS TENSION %NBL	PRE STRESS TIME	REDUC ED STRESS	TIME TO EQUALI SE	$\alpha/\mu$
1	76/7 ACSR	27.5	2	22	6	4.3
1	76/7 ACSR	25	6	22	10	4.3
55	26/7 ACSR	30	1	20	12	6.1
55		30	1	20	80.2	10.8
38	ARBUTUS	20	500	40	1	8.97
38	26/7 ACSR	40	93	20	29700	8.3
39	24/7 ACSR	60	1	25	7000	10.1
39	26/7 ACSR	60	1	25	2850	9.1
77	PHEASANT 54/19 ACSR	25	1	20	10.6	10.6
77	PHEASANT 54/19 ACSR	30	1	20	40	9.1
77	PHEASANT 54/19 ACSR	25	16	20	600	16.2
66	84/19 ACSR	27.3	15	24.8	43	10.85
20		25	1	20	22	14.6
20		30	1	20	45	9.4
20		25	1	20	16	14.65

## CHAPTER 4 EXPERIMENTAL RESULTS

The aim and objectives of this project were to firstly to compile all available creep regressions and experimental results from around the world. Secondly evaluate the advisability of using overseas creep information for Australian made conductors, of similar construction. Thirdly assess what conductors must be tested to extend the available creep information for Australian made conductors. Fourthly to evaluate the ability to apply a CIGRE preferred prestressing relationship to Australian conductors, and lastly to prepare Guidelines for the Power Industry on the use of Conductor creep in Transmission Line Design.

Tables VII, VIII, IX and X summarise the creep constant information located during this investigation. Comparison between conductors of similar construction, made here and overseas, show significant differences in the predicted 10 year creep strain. Hence, it was shown that it is important to use actual test data and not use overseas creep information for Australian made conductors.

Having established from the literature survey the currently available creep data for Australian conductors, it was next necessary to evaluate which of the previously untested conductors could be included in the prestressing schedule. The experimental program followed during this project was as shown over:-

<u>STRAND</u>	<u>CONST- RUCTION</u>	<u>CODE</u>	<u>DURATION</u>	<u>PreStress Time/ %NBL</u>
19	AAAC/1120	NEON	2000	NIL
30/7	ACSR/GZ	LEMON	1000	NIL
54/7	ACSR/GZ	ORANGE	1000	NIL
30/7	ACSR/GZ	LEMON	1000/30%	7D/40%
30/7	ACSR/GZ	LEMON	1000/20%	7D/40%
54/7	ACSR/GZ	ORANGE	1000/30%	2D/40%
54/7	ACSR/GZ	ORANGE	1000/20%	2D/40%
30/7	ACSR/GZ	LEMON	1000/20%	2D/30%
30/7	ACSR/GZ	LEMON	1000/20%	1D/30%
19	AAC/1350	PLUTO	1000	NIL
37	AAC/1350	TRITON	1000	NIL
37	AAAC/1120	PHOSPHORUS	1000	NIL
61	AAAC/1120	SULFUR	1000	NIL
37	AAAC/1120	PHOSPHORUS	1000/20%	2D/30%
61	AAAC/1120	SULFUR	1000/20%	1D/30%

Whilst reviewing the historical results in the literature on creep tests it was found that in general only 2 readings are made after 1000 hours. These are at 1500 and 2000 hours. Since these readings did not significantly alter the creep predicted by the creep predictor equation it was decided to limit the creep tests to 1000 hours.

Results from tests, in numerous laboratories, in many countries, using alternative test methods are tabulated in the appendices. The method adopted for creep testing affects the test results. For this reason, during the project, the method adopted was the CIGRE preferred method for stranded conductors described in ELECTRA 75 [20]. Readers interested in the procedure are referred to ELECTRA 75 for details of the test method. Variations allowed within this test procedure, as used will now be outlined.

The author is currently working on an Australian Standard for Creep (Inelastic Stretch) testing of Conductors.

#### 4.1 TESTING AND ANALYSIS PROCEDURE

All samples were supplied on drums, in the as manufactured condition. Test pieces of approximately 14m length were prepared using epoxy resin terminations. Care was taken to ensure that the original positions of the stranded layers were retained.

Within a temperature controlled enclosure, a horizontal cable tensile test bench capable of handling 7 test pieces simultaneously was used for the ambient temperature tests in air. Digital thermocouples continually monitored the sample temperature.

Extension of the gauge length was measured by two precision dial gauges which were read to 0.002mm. For ambient temperature tests the extension measuring equipment was mounted on a reference bar of similar coefficient of linear thermal expansion and thermal mass to the conductor and rested on rollers which were adjacent to, but independent of, the test sample. The dial gauges measure the movement of gauge mark flags clamped lightly to the conductor with a constant clamping force.

The tensile load was measured by an elastic ring force gauge which was calibrated against the load cell of a Tensile Tester before and after every test. The load was raised to the nominated value smoothly by means of a hydraulic ram, and the initial gauge length was measured. The load was then held constant by a mechanical screw, for the duration of the test, and the extension of the gauge length was measured versus time.

The load and temperature were held constant for the period of the test, and measurements of extension taken at increasing intervals. Creep occurs most rapidly in the early stages of the test, and the initial extension readings were taken at thirty second intervals. It is recognised that the creep rate slows with time and hence, the frequency of readings were reduced, until after several weeks significant further creep was measurable only after some days. Tests were completed after 1000 hours.

## ANALYSIS

The CIGRE method assumes a logarithmic relationship between strain and time (based upon prior experimental results). Using log strain, log time data a least squares regression was fitted to a logarithmic equivalent of the following equation:

$$\text{Unit Strain} = k (\text{TIME, YEARS})^a$$

Data points taken in the early part of the test may not conform to this relationship because of factors such as settling in the conductor. For most tests the logarithmic law was established after three hours. Data points prior to the establishment of the logarithmic law are discarded from the regression. Because of limitations in the CIGRE regression model, no confidence limits are possible on the logarithmic data.

To include the influence of stress, three tests are normally performed, at loads of 20%, 30% and 40% of the calculated breaking load. The results of the three tests were then combined to give a composite equation including the effect of the stress:

$$\text{Unit Strain} = (\text{TIME, YEARS})^{C1} \times (\text{STRESS, MPa})^{C2}$$

This equation was determined by least squares multiple linear regression analysis.

When it was required to include the influence of temperature with stress on the regression model . The individual sample results were then combined to give a composite equation of the form:

$$\text{Unit Strain} = k (\text{Time, Years})^{C1} . (\text{Stress, MPa})^{C2} . \exp(C3 . (\text{Temp}^{\circ}\text{C} - 20))$$

Inherent limitations involved in taking the logarithm of the experimental data to linearise the data for analysis by a least squares linear regression model mean that it is not practice to produce confidence limits on the linearised data.

## 4.2 RESULTS

Graphs displaying the test data with regressions lines for 20% , 30% and 40% NBL are included in the following pages. For practical reasons tables containing the individual data points have been excluded. However tables of the single constant stress, temperature creep predictor equations and composite equations follow the graphs.

# CREEP OF 30/7/3.00 mm LEMON ACSR/GZ

20 DEG CELCIUS

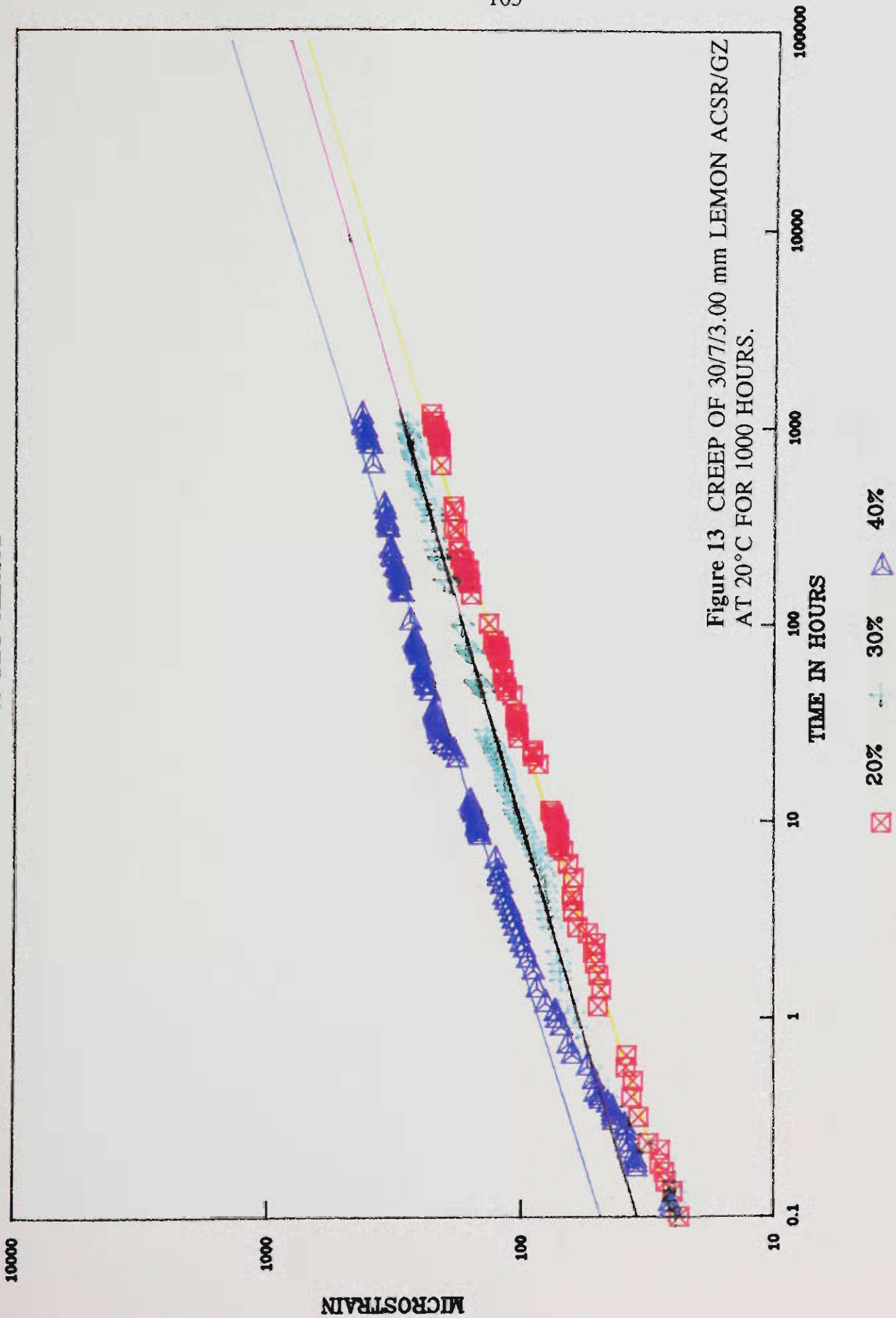
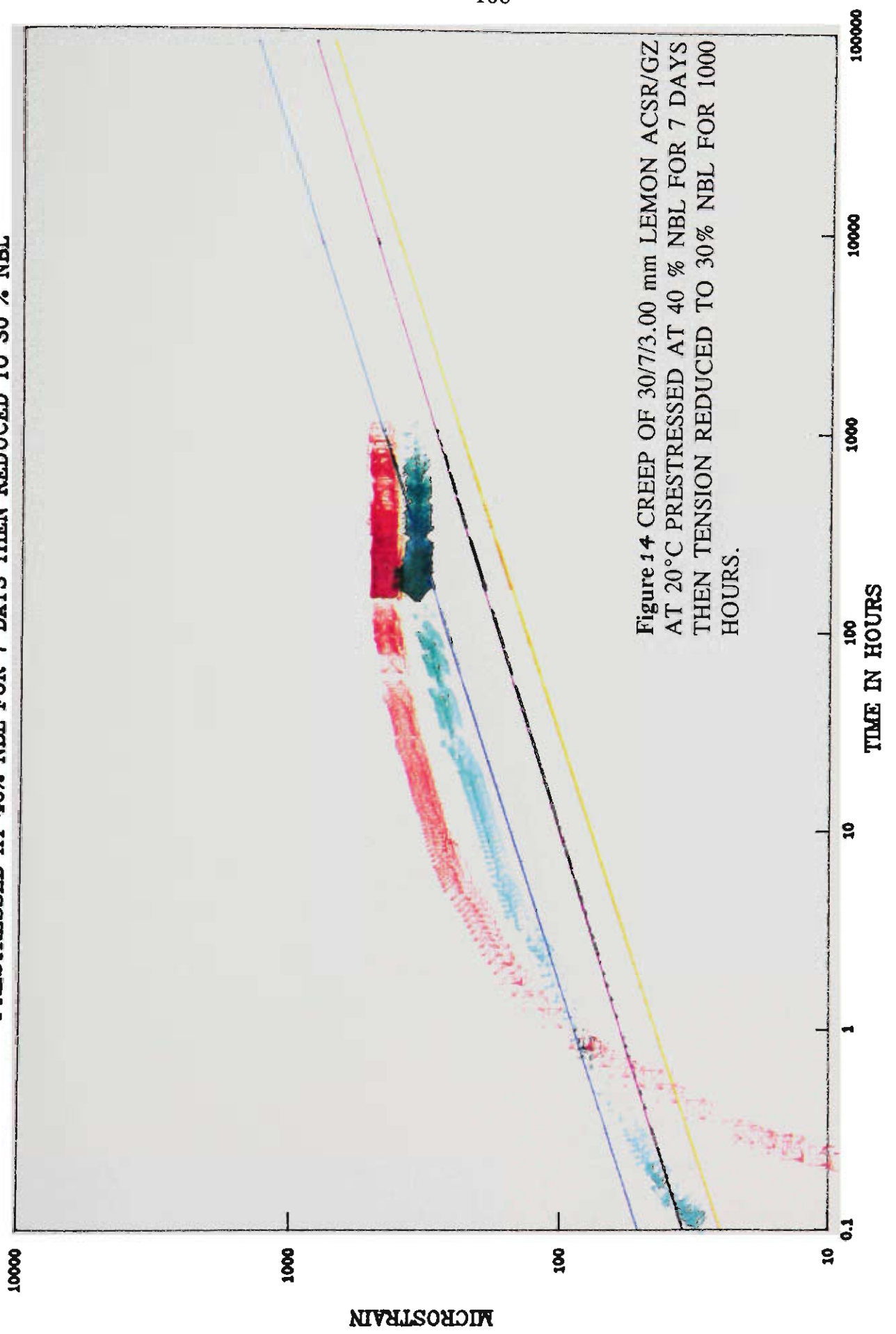


Figure 13 CREEP OF 30/7/3.00 mm LEMON ACSR/GZ AT 20°C FOR 1000 HOURS.

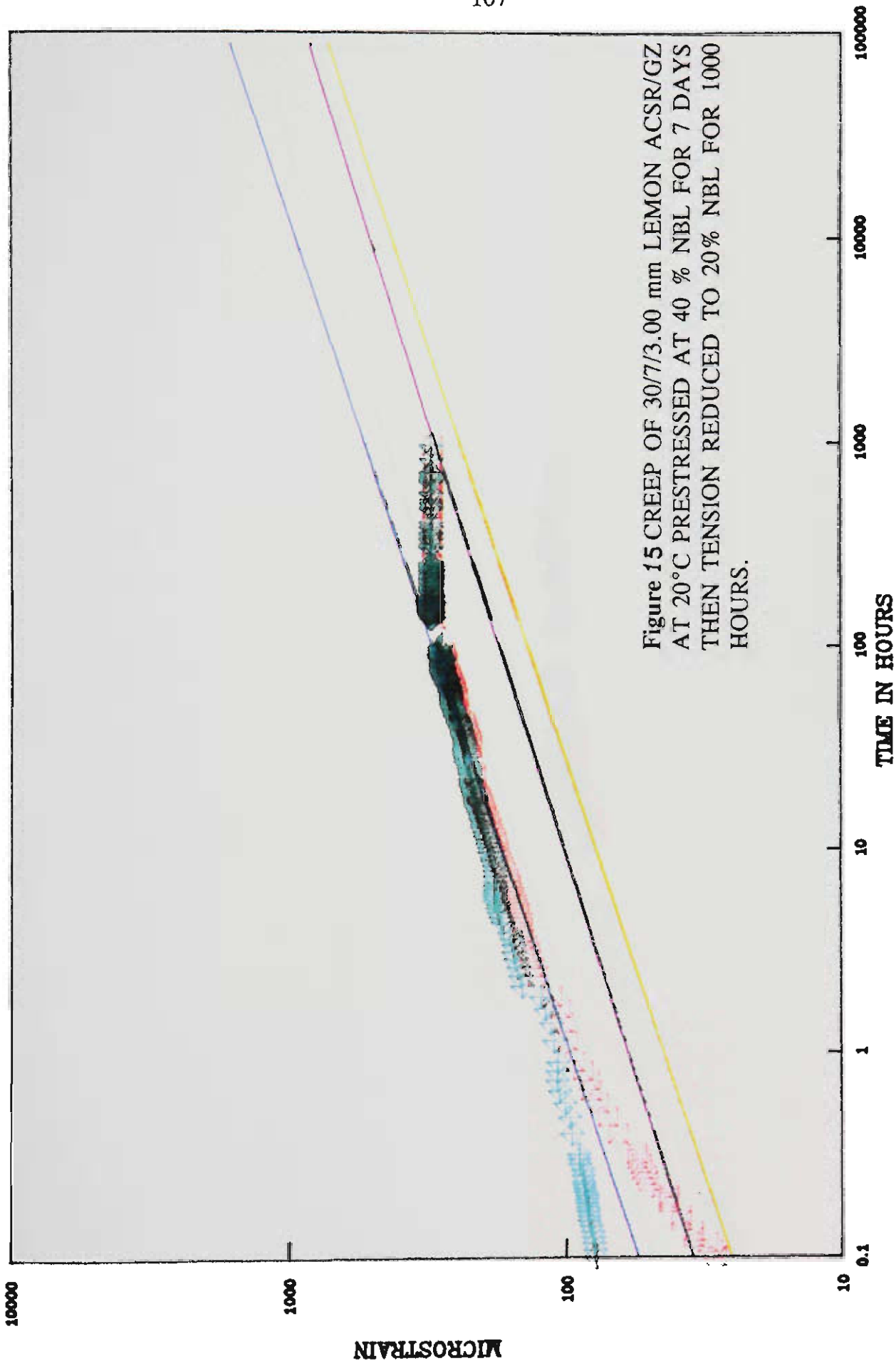


# LEMON 30/7/3.00 mm ACSR/GZ PRESTRESSED AT 40% NBL FOR 7 DAYS THEN REDUCED TO 30 % NBL



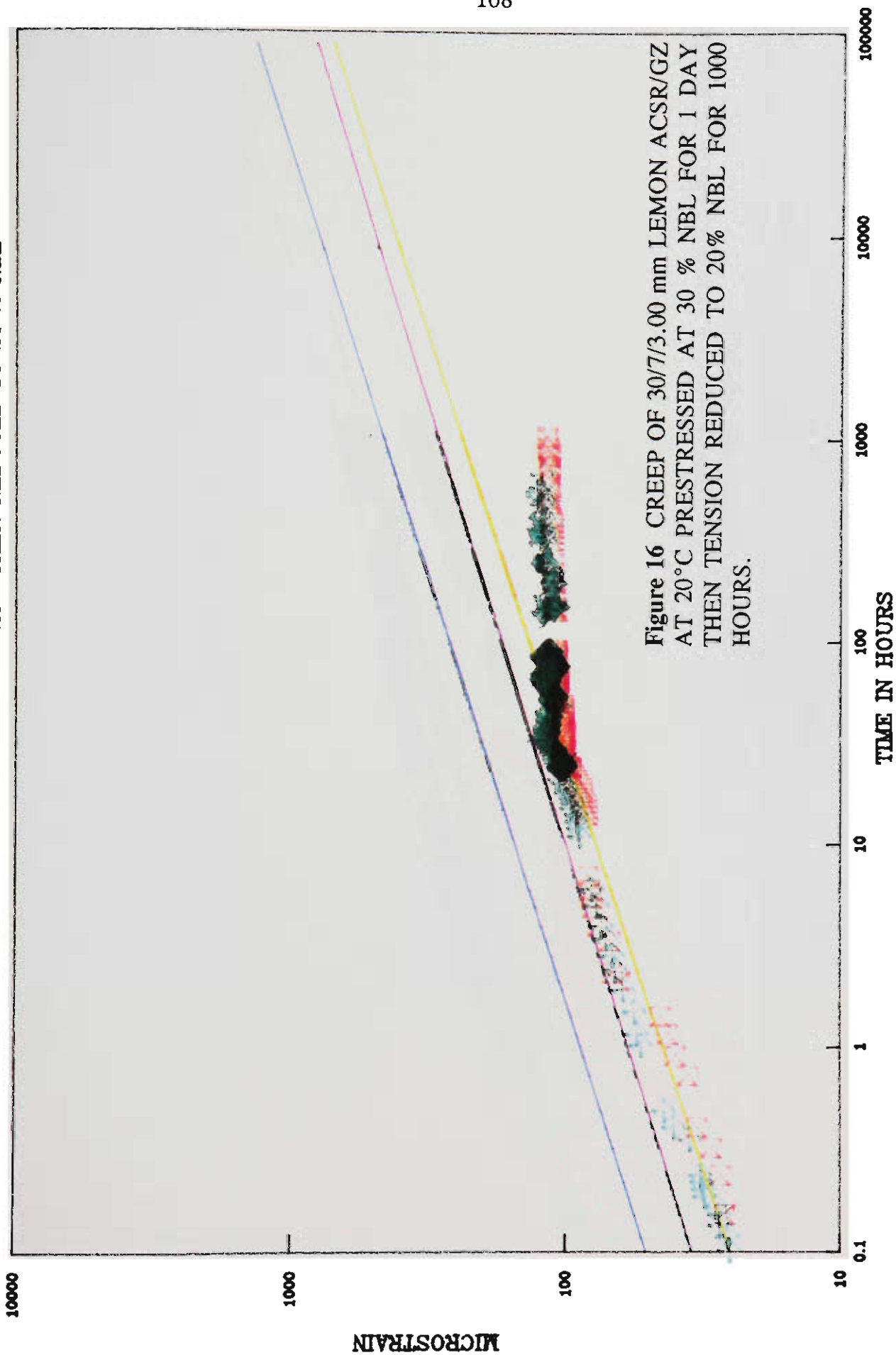
# LEMON 30/7/3.00 mm ACSR/GZ

PRESTRESSED AT 40% NBL FOR 7 DAYS THEN REDUCED TO 20 % NBL



# LEMON 30/7/3.00 mm ACSR/GZ

PRESTRESSED AT 30% NBL FOR 1 DAYS THEN REDUCED TO 20 % NBL



CREEP OF 54/7/3.25 mm ORANGE ACSR/GZ

20 DEG CELCIUS

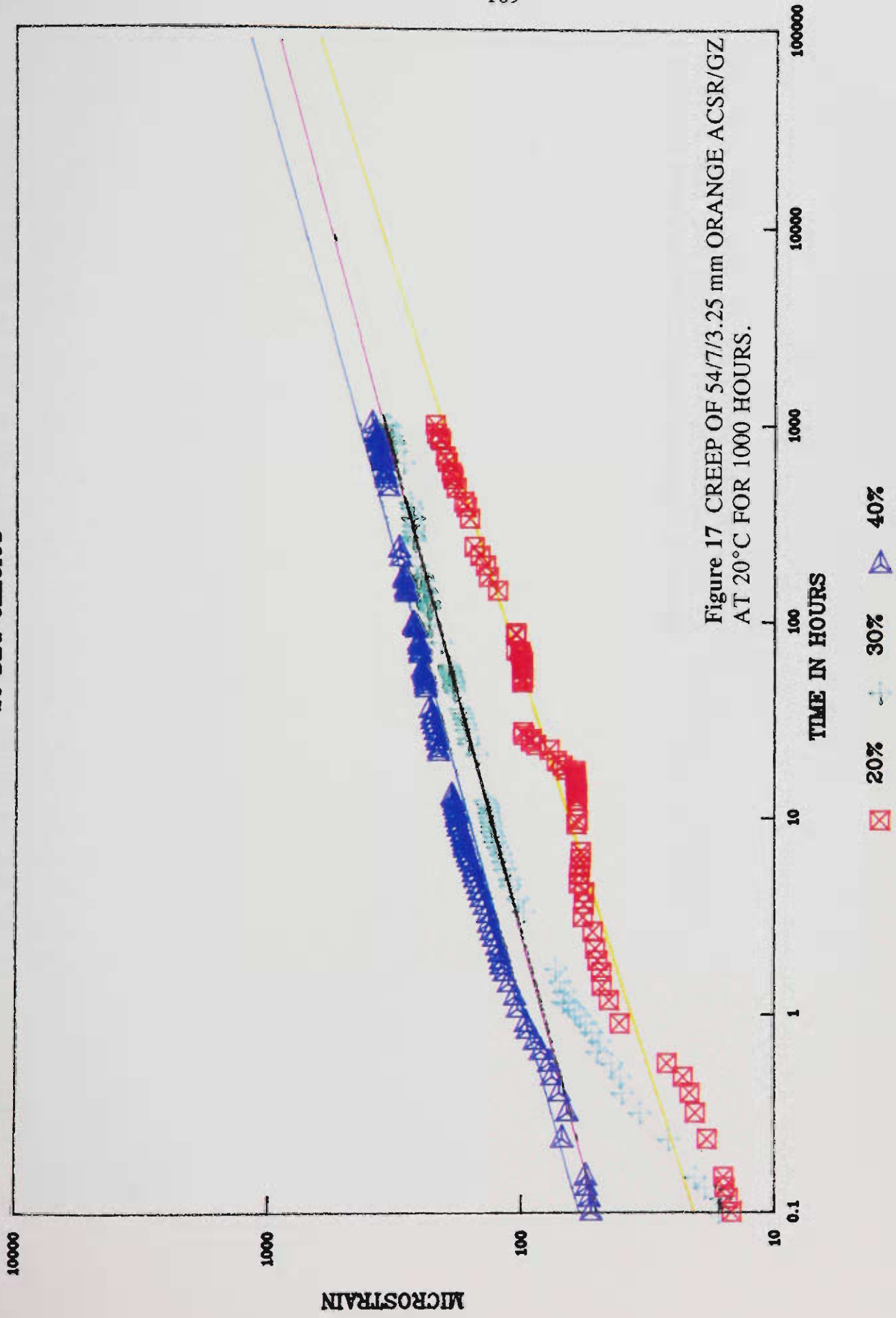
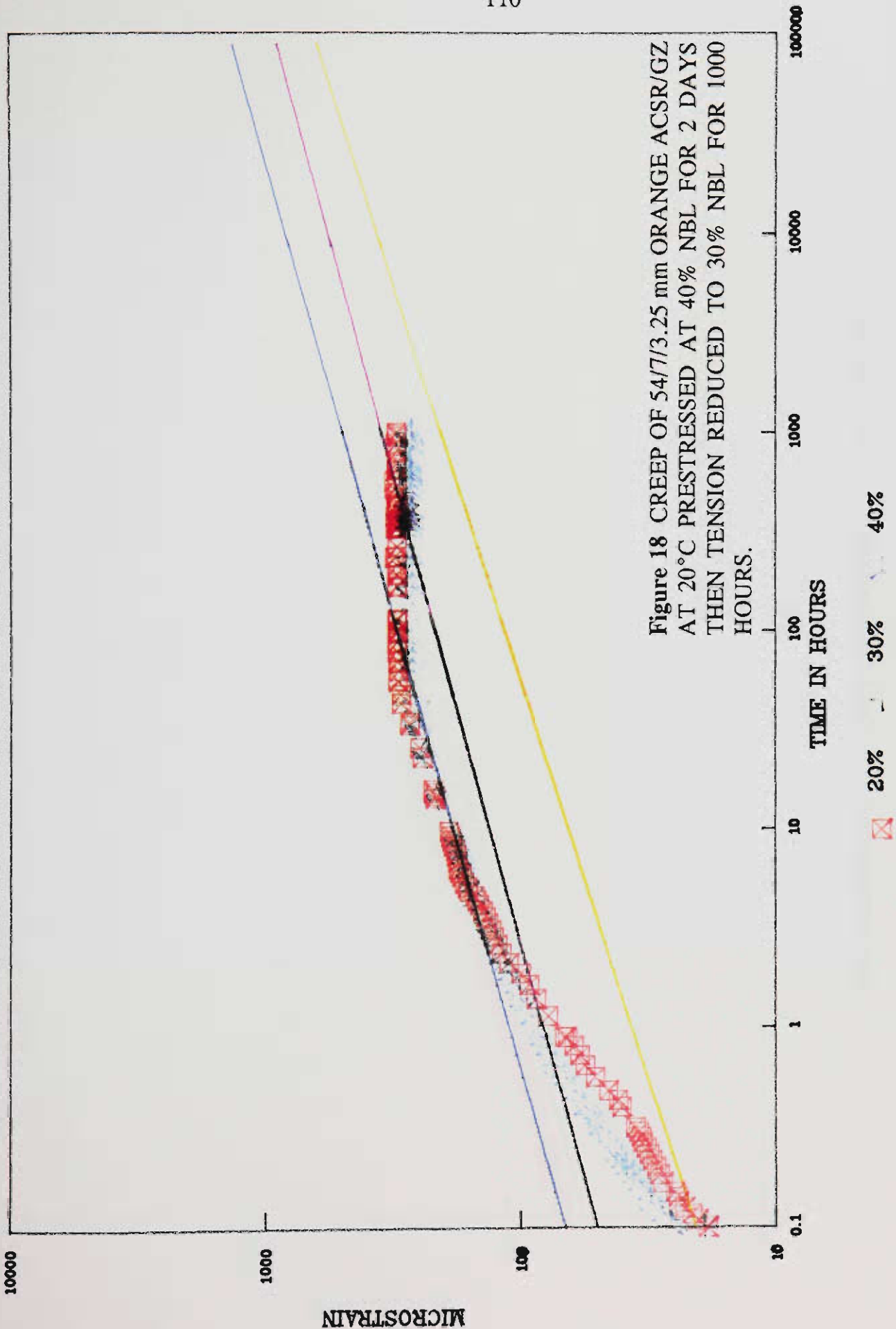


Figure 17 CREEP OF 54/7/3.25 mm ORANGE ACSR/GZ AT 20°C FOR 1000 HOURS.

# CREEP OF 54/7/3.25 mm ORANGE ACSR/GZ

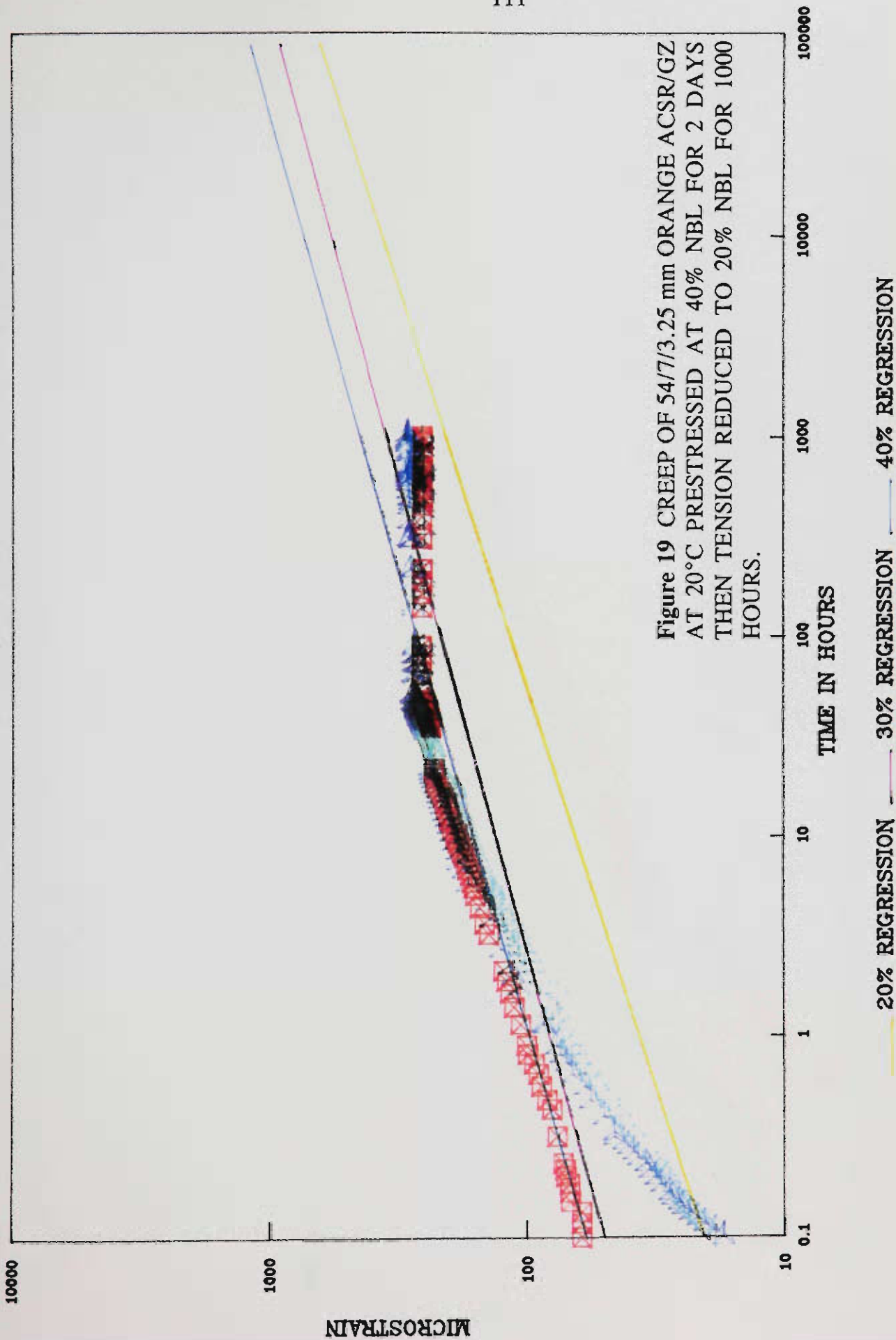
PRESTRESSED AT 40% NBL 48 HOURS THEN TENSION REDUCED TO 30% AT 20 DEG CELCIUS





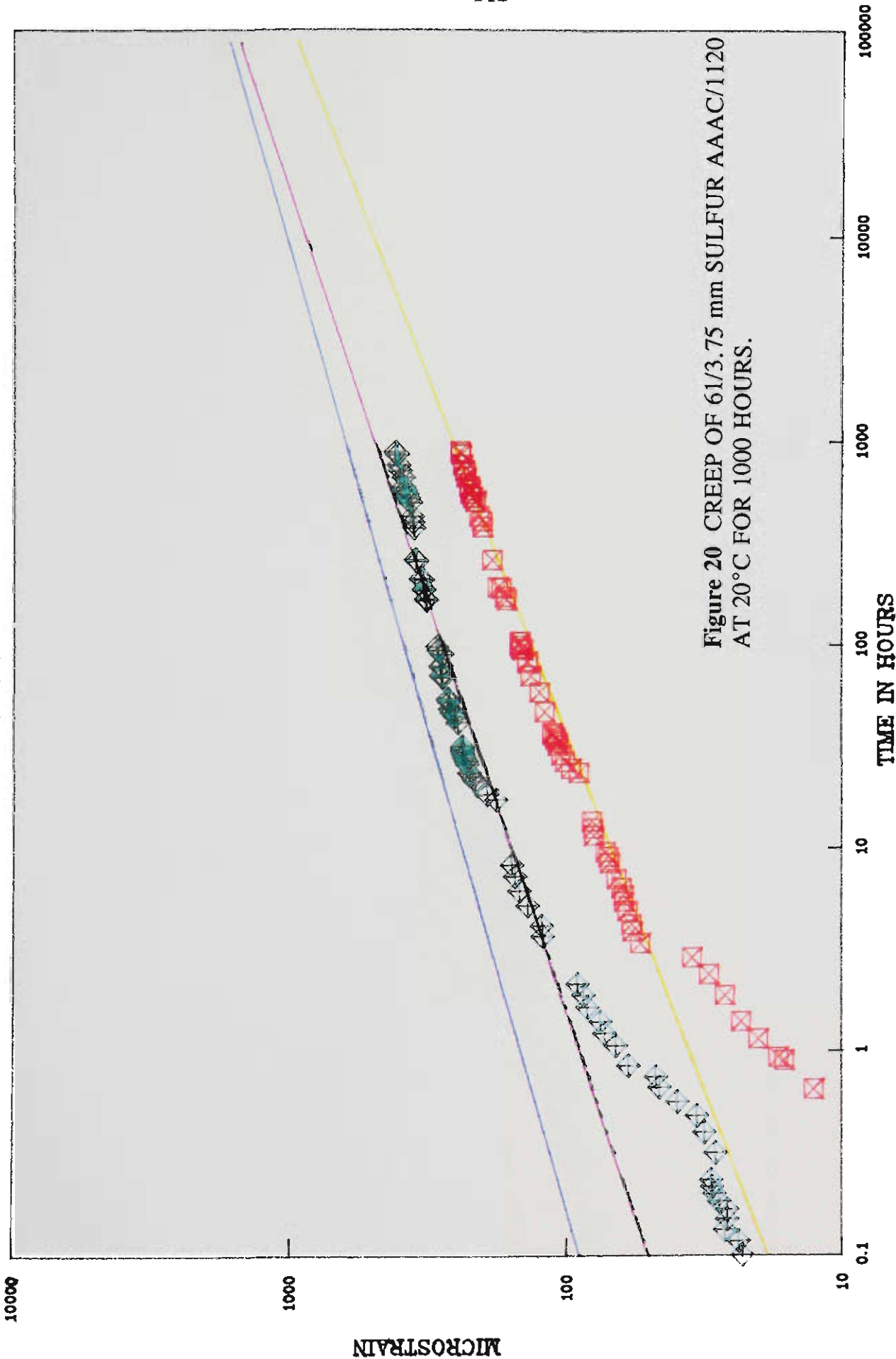
# CREEP OF 54/7/3.25 mm ORANGE ACSR/GZ

PRESTRESSED AT 40% NBL FOR 48 HOURS THEN TENSION REDUCED TO 20% AT 20 DEG CELCIUS



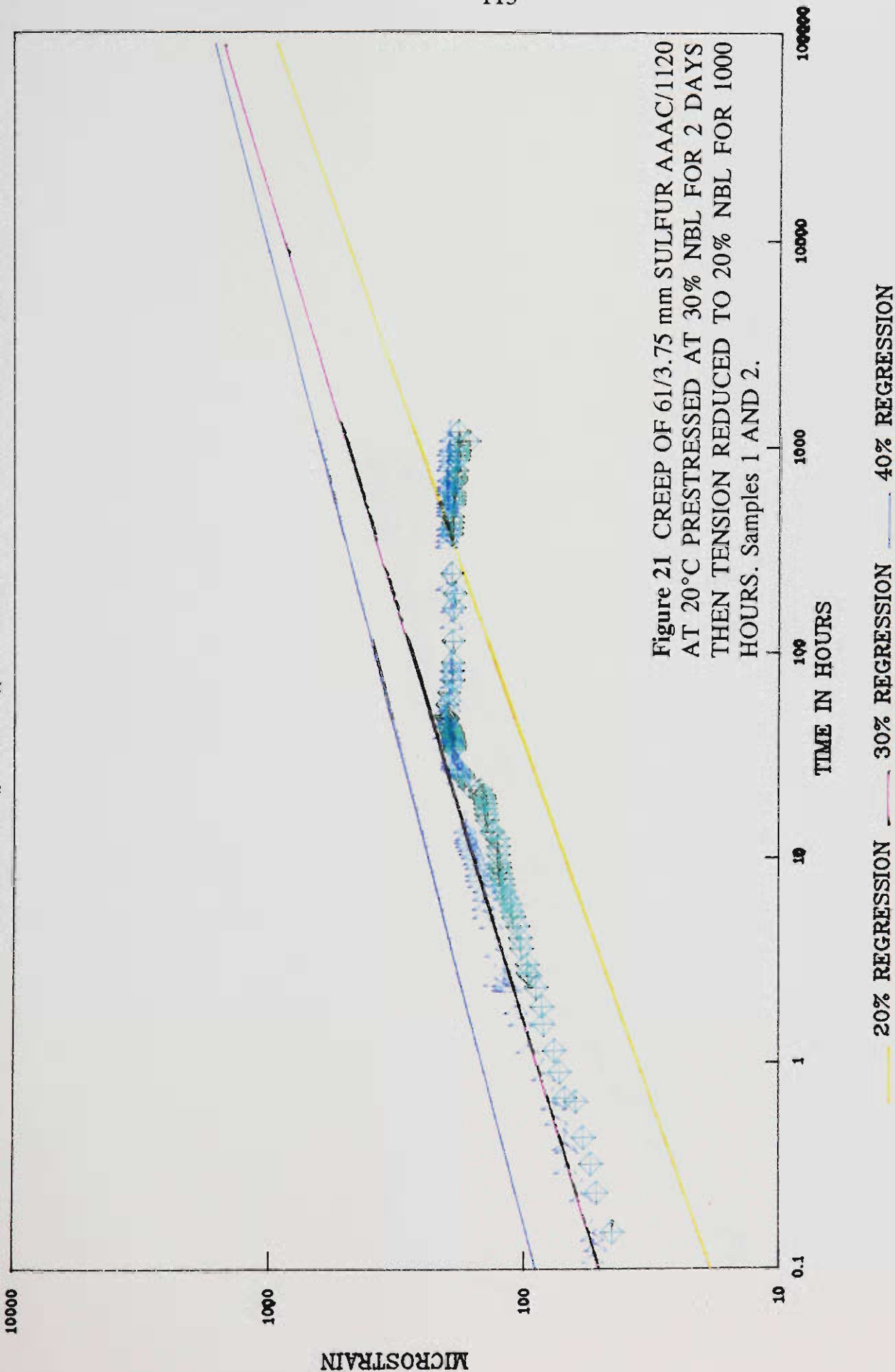
# SULFUR 61/3.75 mm AAAC/1120

20 DEG CELCIUS



# SULFUR 61/3.75 mm AAC/1120

PRESTRESSED AT 30% NBL FOR 48 HOURS THEN TENSION REDUCED TO 20% AT 20 DEG CELCIUS





PHOSPHORUS 37/3.75 mm AAAC/1120

20 DEG CELCIUS

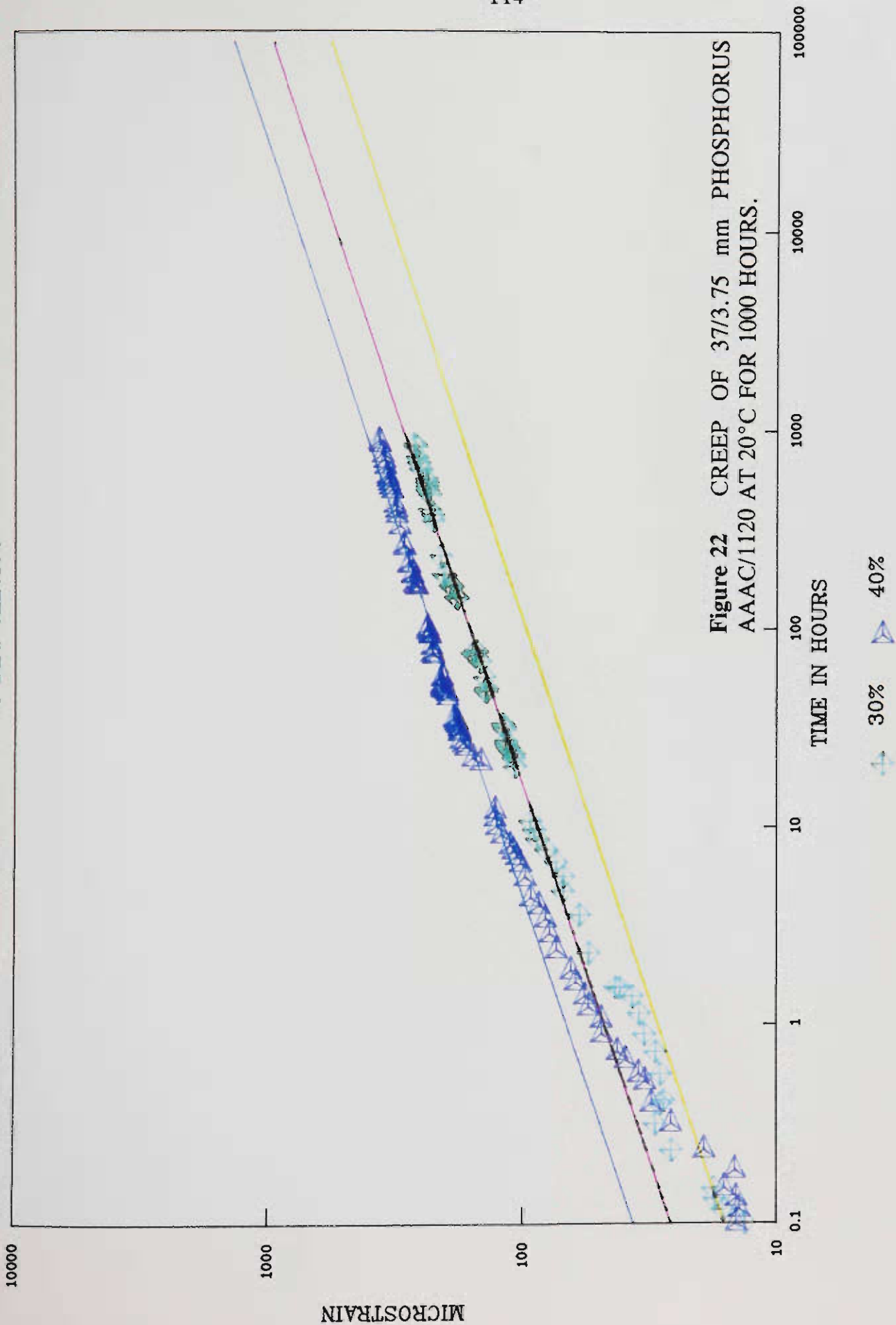
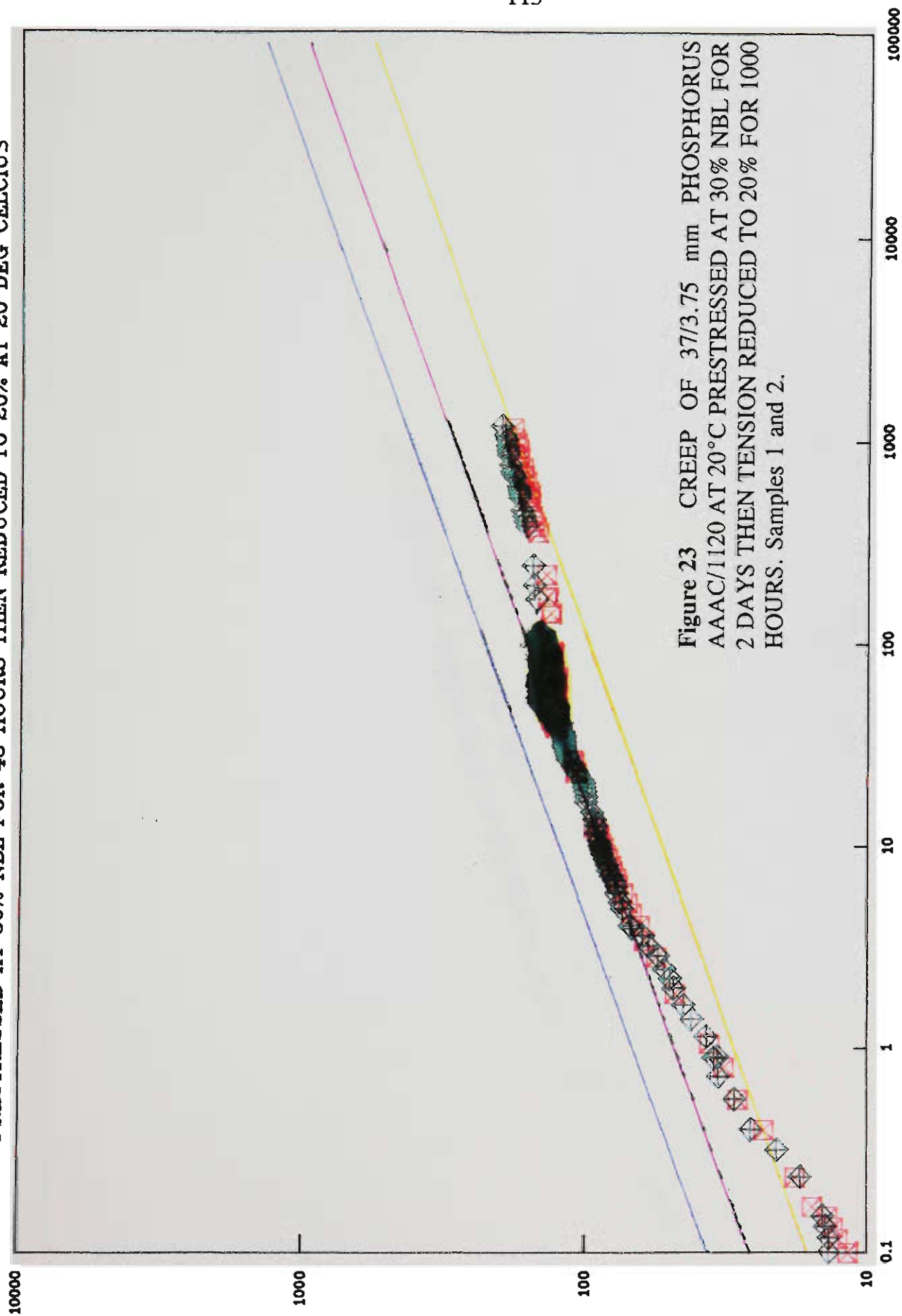


Figure 22 CREEP OF 37/3.75 mm PHOSPHORUS AAAC/1120 AT 20°C FOR 1000 HOURS.

**PHOSPHORUS 37/3.75 mm AAAC/1120**  
**PRESTRESSED AT 30% NBL FOR 48 HOURS THEN REDUCED TO 20% AT 20 DEG CELCIUS**



**Figure 23 CREEP OF 37/3.75 mm PHOSPHORUS  
AAAC/1120 AT 20°C PRESTRESSED AT 30% NBL FOR  
2 DAYS THEN TENSION REDUCED TO 20% FOR 1000  
HOURS. Samples 1 and 2.**

# TRITON 37/3.75 mm AAC 1350

20 DEG CELCIUS

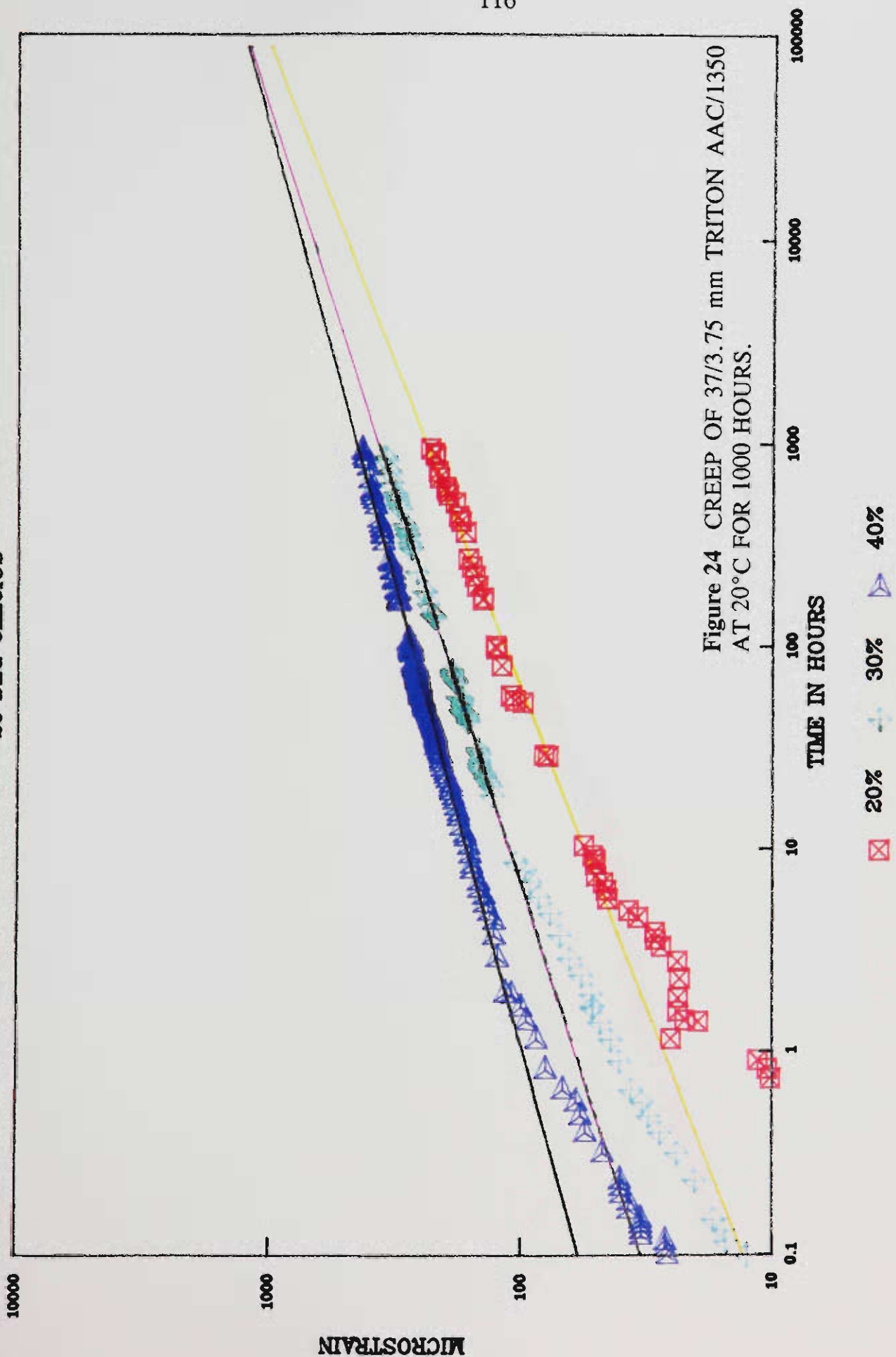


Figure 24 CREEP OF 37/3.75 mm TRITON AAC/1350 AT 20°C FOR 1000 HOURS.

# CREEP OF 19/3.75 mm PLUTO AAC 1350

20 DEG CELCIUS

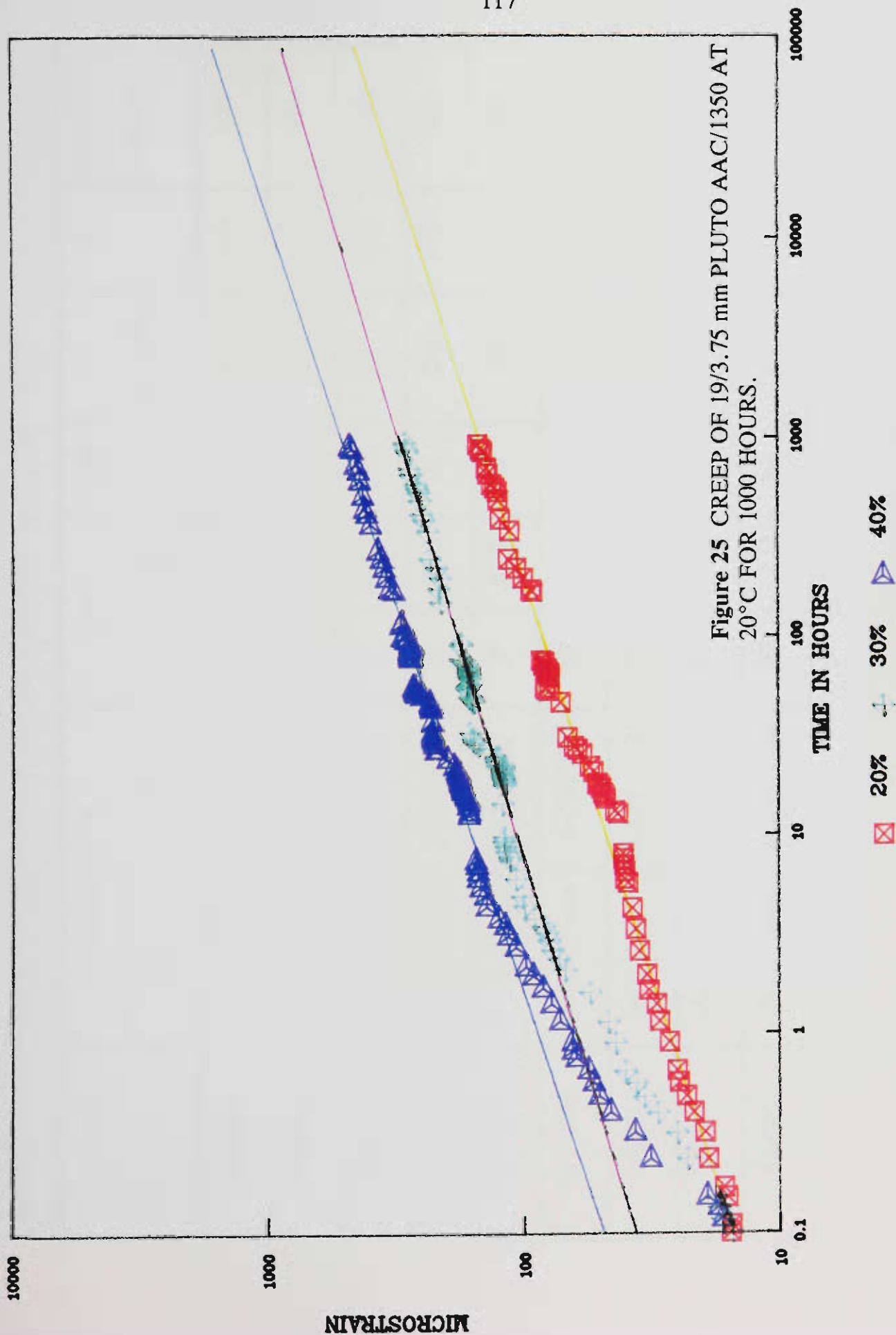


TABLE V Experimental Creep Relations of Stranded Conductors conforming to  $\mu\epsilon=kt^n$

CODE	CONDUCTOR		LOAD		TEMP °C	k μSTRAIN	n	Correlation Co-Ef.
	SIZE	TYPE	%NBL	kN				
LEMON	30/7/3.00 mm	ACSR/GZ	20	18.08	20	409	.245	.985
LEMON	30/7/3.00 mm	ACSR/GZ	30	27.12	20	490	.232	.991
LEMON	30/7/3.00 mm	ACSR/GZ	40	36.16	20	787	.240	.986
ORANGE	54/7/3.25 mm	ACSR/GZ	20	31.8	20	356	.250	.985
ORANGE	54/7/3.25 mm	ACSR/GZ	30	47.7	20	558	.212	.989
ORANGE	54/7/3.25 mm	ACSR/GZ	40	63.6	20	613	.219	.988
NEON	19/3.75 mm	AAAC/1120	20	9.56	20	234	.234	.998
NEON	19/3.75 mm	AAAC/1120	30	14.34	20	322	.186	.987
NEON	19/3.75 mm	AAAC/1120	40	19.12	20	453	.201	.991

CODE	CONDUCTOR		LOAD		TEMP °C	k μSTRAIN	n	Correlation Co-Ef.
	SIZE	TYPE	%NBL	kN				
PLUTO	19/3.75 mm	AAC/1350	20	6.44	20	270	.258	.994
PLUTO	19/3.75 mm	AAC/1350	30	9.66	20	509	.231	.989
PLUTO	19/3.75 mm	AAC/1350	40	12.88	20	897	.256	.992
TRITON	37/3.75 mm	AAC/1350	20	12.58	20	481	.317	.996
TRITON	37/3.75 mm	AAC/1350	30	18.87	20	656	.262	.989
TRITON	37/3.75 mm	AAC/1350	40	25.16	20	740	.222	.994
SULFUR	61/3.75 mm	AAAC/1120	20	29	20	487	.287	.989
SULFUR	61/3.75 mm	AAAC/1120	30	43.5	20	850	.248	.984
SULFUR	61/3.75 mm	AAAC/1120	40	58	20	1000	.212	.994

CODE	CONDUCTOR		LOAD		TEMP	k	n	Correlation
	SIZE	TYPE	%NBL	kN	°C	μSTRAIN		Co-Ef.
PHOSPHORUS	37/3.75 mm	AAAC/1120	20	18.62	20	314	.260	.995
PHOSPHORUS	37/3.75 mm	AAAC/1120	30	27.93	20	524	.263	.987
PHOSPHORUS	37/3.75 mm	AAAC/1120	40	37.24	20	743	.264	.996

**TABLE VI** Experimental Creep Relations of Stranded Conductors conforming to  $\epsilon = K\sigma^\alpha t^\mu$

CODE	CONSTRUCTION	K	$\alpha$	$\mu$	MCC
LEMON	30/7/3.00 mm ACSR/GZ	6.50 E-6	.964	.241	.973
ORANGE	54/7/3.25 mm ACSR/GZ	1.82 E-6	1.289	.219	.966
NEON	19/3.75 mm AAAC/1120	16.0 E-6	1.143	.203	.991
PLUTO	19/3.75 mm AAC/1350	.639 E-6	1.756	.245	.992
TRITON	37/3.75 mm AAC/1350	5.53 E-6	1.238	.259	.993
SULFUR	61/3.75 mm AAAC/1120	.654 E-6	1.655	.245	.987
PHOSPHORUS	37/3.75 mm AAAC/1220	3.22 E-6	1.206	.264	.992



## CHAPTER 5 DISCUSSION

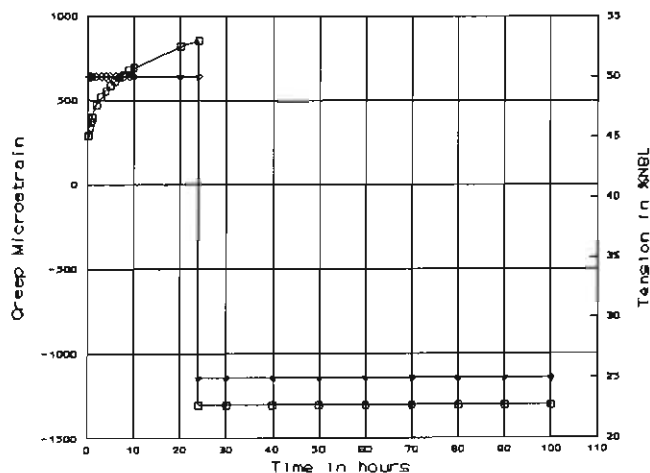
The investigation of conductor creep interests all users and designers of transmission lines. This work is aimed mainly at optimising all new transmission lines, and in part at the refurbishment of existing lines, in relation to creep and its resulting increase in sag. Australia has an ageing grid system, with a growing need to replace or assess the remanent life of the transmission lines. The significance of this work is based upon the idea that with accurate creep predictions, savings in the order of 1 or 2 transmission towers per 100 km of line can be achieved. Translated into dollars it means potential savings of \$80,000-\$160,000. Similar work overseas has been limited to one conductor construction. However, in this investigation the commonly used "heavier" constructions were tested.

Initial analysis of conductor prestressing tests show, a/ that prestressing will stabilise a conductor to eliminate creep strains for a period after load reduction, and b/ after prestressing, a conductor exhibits both elastic and inelastic contraction components.

From the graphs of the prestressing tests it can be seen that there is a high degree of repeatability between tests on any single conductor at a given stress. This is shown by the prestressing test data overlapping the original regression lines. Usually the test data fitted the regression line from the first 10 hours of the test.

All prestressed conductors exhibited an elastic contraction when the load was reduced to the final value. It was predicted that the final modulus of elasticity for the conductor could be used to predict the magnitude of the contraction. Measurements undertaken during these experiments confirmed that the final elastic modulus accurately described the behaviour of the conductor after a load reduction.

In all cases the magnitude of the elastic contraction resulted in negative creep after the load reduction. To overcome this anomaly, it is proposed that the method used by CIGRE [77], Bradbury [11] and Nigol & Barrett [54,55,56] be adopted, where the creep strain after the load reduction is set equal to the creep strain just prior to the load reduction. Thus, a smooth curve is produced with no step in the measured creep strain versus time function. Uncorrected stress-strain-time graphs have the form in the following figure.

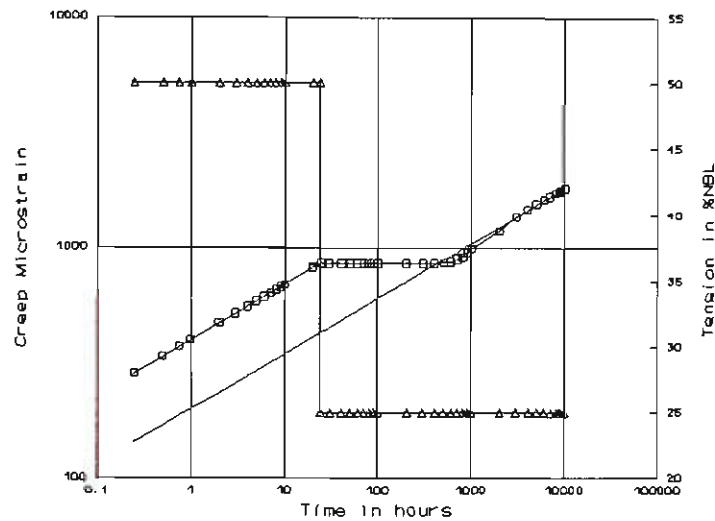


**Figure 26** Form of uncorrected stress-strain-time graph for a stress reduction from 50% NBL to 25% NBL.  $\square$  = Creep line,  $\diamond$  = Tension line.

The test rig used for these investigations maintains a constant length between two restraining points. After the load had been reduced to the final level and stabilised, it was noted that a time dependent elastic contraction was occurring which because of the fixed ends produced an increase in the measured load ( less than 1%). The time dependent contraction was usually observed after 10-15 minutes. Other researchers reference [33] [1] had noted a similar effect. In constant load tests where one end is free to contract, the full extent of the time dependent contraction would be measurable. However, with the current set up an artificial balance was established with the tension. How long the contraction lasts and its size are unknown. However, it has been noted reference [33] that from the time of load reduction, it is 1 hour after the conductor is stable in length. Hence, the conductor can be measured, terminated and sagged as usual.

On one Lemon test piece the load was reduced from 30% NBL to 10 % before raising the load to 20% NBL to gauge the effect upon the time dependent and independent strains. The results were that the final modulus still accurately predicted the strain reduction whilst the time dependent strain was missing.

To explain the time dependent contraction I propose that radial compressive stresses between the wires in each layer are contributing to the creep strain. When the load is reduced the majority of the strain is relaxed, however, friction at the strand cross over points between wires of different layers prevents the full release of pent up strains. With time, the friction is overcome and the conductor contracts back to its equilibrium strain for the applied load.



**Figure 27** Form of uncorrected stress-Log strain-Log time graph for a load reduction from 50% NBL to 25% NBL.  $\square$  = Creep,  $\Delta$  = Tension.

Other researchers reference [54,55,56] had noted that upon prestressing ACSR conductors the creep curve would not immediately follow the reduced stress regression line but would continue to creep at a lower rate until some time in the future when the two creep curves would co-incide. This type of behaviour is shown in the following figure. Unfortunately, none of the prestressed creep tests lasted long enough to confirm or dispute this behaviour. They claim that the normalisation of the two creep curves at the termination of the tests may have contributed to the phenomena but whether this is true or not cannot be confirmed here.

Using the following equation from Chapter 3 and the values below, the equivalent time for creep strain to occur at the final stress was calculated and is shown below:-

<u>Conductor</u>	<u><math>\alpha/\mu</math></u>	<u>PS Load %NBL/PS Time hours</u>	<u>Final Load</u> <u>%NBL/<math>t_{eq}</math> hours</u>
Lemon	4.0	40/168	30/530
		40/168	20/2688
		40/48	20/768
		40/24	20/384
Orange	5.88	40/48	30/261
		40/24	20/2826
Sulfur	5.02	30/48	20/367
Phosphorus	4.57	30/48	20/367

Comparison of the theoretical equivalent time to the graphs shows that:-

- a/ for Lemon prestressed at 40% NBL for 7 days then reduced to 30% NBL. There is a resumption of creep in the creep curve after the linear stabilised period beginning at approximately 580 hours.
- b/ for Lemon prestressed at 40% NBL for 7 days then reduced to 20% NBL, it is linear up to 1200 hours which is consistent with the prediction made by the equivalent time equation of 2688 hours to strain equivalence.
- c/ for Lemon prestressed at 40% NBL for 2 days then reduced to 20% NBL.

d/ for Lemon prestressed at 40% NBL for 1 or 2 days then reduced to 20% NBL. Both sets of tests disagree with the predictor equation which says that after 384 and 768 hours respectively the creep curve should show a resumption of extension. However both show a linear line to 1000 hours. This type of graph is consistent with a conductor in which the majority of the load is being sustained by the steel core. NOTE that no additional slackness was observed in the conductor either before or after testing thus, making this behaviour hard to explain. No wires were observed to have slipped in the terminations or upon destranding any localised necking.

e/ for Orange prestressed at 40% NBL for 2 days then reduced to 30% NBL. As predicted in reference [54,55,56] the conductor did not begin to creep at the 30% regression line but made a gradual increase in creep strain after passing the line but still at about 350-400 hours. This behaviour is consistent with the above researchers work.

f/ for Orange prestressed at 40% NBL for 2 days then reduced to 20% NBL. It was linear up to the test termination time of 1200. This is consistent with the 2626 hours predicted for the equivalent time.

g/ for Sulfur prestressed at 30% NBL for 2 days then reduced to 20% NBL. This conductor after a resumption in creep at about 380 hours entered into a second stabilised period lasting for the remainder of the test. This behaviour was not noted by other researchers and may be due to the initial loose stranding of the conductor sample when received for testing.

It may also account for the fact that the regression constants calculated for this conductor predicted almost twice the creep of previously tested sulfur samples from another plant. Using the same equipment and source of wire, however the equipment had been relocated.

h/ for Phosphorus prestressed at 30% NBL for 2 days then reduced to 20% NBL. This conductor after the stabilised period of about 300 hours began to creep again at approximately 380 hours which when compared to the predicted value of 367 is in good agreement with the theoretical value.

Based upon the limited range of test values it seems practical to believe that the use of the equivalent time expression developed for overseas conductors, to calculate prestressing times and tensions for the removal of creep is a valid method for Australian conductors. The consistency of the method to predict the equivalent time, not only to the correct power of 10 but to within 50 hours increases confidence in this method of creep compensation.

One of the original aims of this project was to establish the long term creep predictor equation after prestressing. However, creep tests of 5-6000 hours are required to achieve the stabilised regression line. This time frame is beyond the ability of the allotted time.

A major aim of this research project was to collate published creep regressions and their constants. This task was achieved, combining the results from the dozens of laboratories for the first time. Tables VII through XXII are the result of the extensive literature survey. Values in the tables have been transcribed from data in the literature. The accuracy of each number is that stated by the relevant author. However, a true reflection of reliability and precision of each entry is difficult since correlation co-efficients are missing from almost all published work. Where data was missing I have attempted to calculate the missing values and have included them in brackets in the tables.

After an initial search of the available literature and creep co-efficients it was proposed to extend the project to analyse the form of composite creep equations taking in to account stress/tension and temperature affects on  $k$  and  $\mu$ . Various alternative expressions for temperature and stress/tension were presented in Chapter 3. When all available creep information had been gathered it was attempted firstly to isolate any additional factors which could be included into a more generalised creep predictor expression.

From the standard  $\epsilon = kt^n$  type equation  $k$  and  $\mu$  were compared to conductor/test variables. These checks were made in three formats a/ linear where,  $k = f(\text{variable})$ ; b/ exponential where,  $k = \log f(\text{variable})$  and c/ power relationships  $\log k = \log f(\text{variable})$ .



The following variables were then tried in the above expressions, mean test temperature, % steel (by area and by weight) (homogeneous AAC conductors as a special case of ACSR with 0% steel), Wire Diameter (Steel and Aluminium), Lay Ratio, ACSR VERSUS 6201, 1120, 1350 for similar strandings, 6201,1120,1350 for different strandings (7,19,37,61).

Results from this part of the project were discouraging due to the wide spread of data from many sources. Correlation co-efficients above 0.6 were rare with the majority of the models tried, being from other authors work, yielding values of 0.4-0.5. Hence, the models can account for only 40-60% of the variation in the overall experimental results. I have therefor, omitted my analysis because of its limited usefulness. In addition there are many risks associated with the use of the above regression models by transmission line designers. Difficulty in establishing whether aluminium was processed by Properzi or hot rolled is of major concern, separating the two sources of aluminium processing has been shown by CIGRE to significantly increase the correlation co-efficient.

However, correlations restricted to information from each researcher, is high, in excess of 0.9. Within any single researchers set of test results, correlation coefficients for the influence of each variable is significantly increased.

Trends identified during the statistical analysis of the co-efficients are:- (i) at constant temperature,  $k$  decreased as the percentage steel (either weight % or area %) increased, however for a set percent steel increasing the test load reduced the rate of decrease in  $k$ , ie  $k$  increased at constant percent steel as the test load increased; (ii) alternatively increasing the present load increased  $k$ , however increasing the percent steel (either weight % or area %), lowered the magnitude of the increase in  $k$ ; (iii) an increase in percent steel (either weight % or area %) seems to reduce  $\mu$ , but there is a high level of scatter. At any percent steel (either weight % or area %), however an increase in the test load reduces the value of  $\mu$ ; (iv) alternatively increasing the test load appears to decrease  $n$ . For a constant test load increasing the percent steel (either weight % or area %), reduces  $n$  as would be expected as the steel creeps at a lower rate. Similar relationships between test load,  $k$  and  $\mu$  where found for homogeneous conductors. Thus, the trends appear to be independent of conductor and more dependent on conductor construction (components).

Limited statements regarding the addition of an extra layer to a conductor upon  $k$  and  $\mu$  can be made. For 1120 and 1350 conductors of constant wire sizes, stranding from 19 to 37 to 61, at 3 test loads, in general,  $k$  increases and  $\mu$  decreases at any constant test load.

Regarding alloys 1350 creeps at a higher rate than 1120 whilst on limited data, there are some grounds to believe that 6201 will creep at a lower rate than 1120 conductor of similar construction. ACSR conductors appear to creep at high initial rates, where the steel core expands elastically, but could creep at a much lower rate after about 1000 hours when sufficient load has been transferred to the steel core and creep of the core becomes the rate controlling factor.

Lay lengths appear to affect the creep rate, but very little information about lay lengths is included in the literature. However, the longer the lay length the lower the creep rate, appears to be the trend. This seems consistent, since the conductor will behave more like a solid rod of similar cross sectional area to the equivalent area of the conductor.

Very few temperature variation tests were suitable for analysis to determine the form of a suitable expression for temperature affects. Therefor, no coefficients were found to be superior to any other.

The aims of this investigation have been achieved. Confirmation that the CIGRE proposed method of equivalent times for prestressing can be applied to Australian conductors, using Australian creep test data. Guidelines for the allowance for creep in transmission lines is drafted. Some conductor constructions still remain to be tested for a complete set of creep predictor coefficients to be available for the industry.

## CHAPTER 6

### 6.0 FUTURE RESEARCH

Research is required into how the creep rate constants vary with progressive annealing (Influence of time at temperature). Perhaps initially, a comparison of ACSR V's AASC. No creep data was found for AASC conductors, however it maybe available in the USA.

Also, how is the break point (unloading point) influenced as the strength of the aluminium wires change in ACSR's. eg annealed 1350, H19 1350, 1120, 6201. Will break point increase, decrease or remain a set percent of the applied load.

Creep undertakes a transition at approximately  $0.4T_m$  which is at about  $95^{\circ}\text{C}$  for 1350 and 1120 alloys whilst for 6201 the transition is at  $82^{\circ}\text{C}$ . If lines are uprated, as those in Canada have been, to operate at temperatures approaching  $100\text{-}150^{\circ}\text{C}$  high temperature creep information will become imperative.

Nigol and Barrett refer to an observation that there is a discontinuity in the creep curves for ACSR conductors at about 1000 hours, in creep tests lasting several years. If proven, then it will provide quantifiable information regarding the strain required to stabilise ACSR conductors.

Is it possible to simulate prestressing by using the modulus test to produce the required extension in a cable prior to creep testing. This method would greatly expedite the time for creep tests and allow more testing time for post stressing behaviour. Some modification of the test rig maybe required. However a single test can be performed now, on the external test rig at MM at room temperature using the elevated temperature test rig set up.

It is recommended that a new method of analysing the raw data be trialled using a non linear regression model however, using the same equations and variables. An advantage of this model will be the ability to produce confidence limits on creep redictions.

The experimental results gathered together in this thesis would form an excellent basis for a meta analysis of test results.

## 6.1 Conclusion

A comprehensive literature survey highlighted many alternative experimental models used to predict conductor creep behaviour. General application of the models beyond the experimenters data was possible. An attempt to create a general model explaining all behaviour for all conductors based upon the information in the tables was unsuccessful.

Prestressing removed a considerable portion of the total predicted creep of a conductor in a relatively short time. Analysis of the tests revealed that prestressing will stabilise creep strains for a period of time after load reduction. The stabilised period is adequately described by the CIGRE equivalent time relationship.

$$t_{eq} = \left( \frac{\sigma_1}{\sigma_2} \right)^{\frac{\alpha}{\mu}} t_1$$

Creep constants determined by this work and revealed by the literature survey for Australian conductors, were compared with those published for comparable conductors manufactured overseas. It was shown that there are significant differences between the creep constants of Australian and overseas conductors. Creep constants therefore, for overseas conductors, are not applicable to Australian conductors.

- |   |  |  |
|---|--|--|
| 1 | Aldrich, A.M.  | "New Zealand Benmore-Haywards<br>500kV Direct Current Line S.C.A.<br>Conductor - Laboratory and Field<br>time/extension studies at the<br>National Coal Board Establishment,<br>Bretby, and at Rye Hey, Prescott.<br>B.I.C.C. Report No OH/F/524, 2nd<br>August, 1962. |
| 2 | The Aluminium Association.<br>Technical Committee on<br>Electrical conductors. | Stress-Strain-Creep Curves for<br>Aluminium Electrical Conductors.<br>1969. The Aluminium Association.   |
| 3 | Barber, K.W. and Gallagher,<br>K.J.  | New Al Alloy Overhead Line<br>Conductors in Australia. 7 <sup>th</sup><br>Conference on Electric Power<br>Supply Industry (CEPSI). Brisbane<br>Australia. 15-22 October, 1988.<br>Transmission and Distribution<br>Systems and Equipment. Vol 3<br>Paper No 3-34.      |

- |   |  |   |
|---|--|---|
| 4 | Barrett, J.S.                            | High Temperature Operation of ACSR Conductors and Other Methods of Uprating Overhead Lines. 1986.   |
| 5 | Barrett, J.S., Dutta. S. and Nigol, O"   | A new Computer Model of ACSR Conductors.", IEEE Transactions on Power Apparatus and Systems, Vol. PAS 102, No. 3, March 1983, pp614-621.      |
| 6 | Barrett, J.S., Ralston, P. and Nigol. O. | 22-09 "Mechanical Behaviour of ACSR Conductors", International Conference on Large High Voltage Electric Systems, 1982 Session 1-9 September. |
| 7 | Barrien, J.                              | "Precise Sags and Tensions in Multiple Span Transmission Lines.", Elec. Eng. Trans. I.E. Aust, Vol EE II No. 1, 1975, pp 6-11.                |



- 8      Boal, G.R.      "Precise Sag-Tension Calculations of Overhead Conductors", Wire Journal August 1977, pp56-60.
  
- 9      Bogardus, K.O., Hunter, M.S., Holt, M. and Frank, G.R. Jr.      Paper 29 "Effects of Prior Creep on the Tensile Properties of Cold Worked Unalloyed Aluminium", pp1-17 to 1-29 1963.
  
- 10     Boyse, C.O. and Simpson, N.G.      "The Problem of Conductor Sagging on Overhead Transmission Lines", Journal of the Inst. of Elec. Eng. Vol 91, Pt II, Dec 1944, pp 219-231.
  
- 11     Bradbury, J.      "The Creep of Steel-Cored Aluminium Conductors.", Laboratory Report No. RD/L/R 1438 for Central Electricity Research Laboratories, 31 January, 1967.

- 12 Bradbury, J. "Creep of S.C.A. Conductors at Elevated temperatures.", Laboratory Report No. RD/L/N 134/69 for Central Electricity Research Laboratories, 05 March, 1970.
- 13 Bradbury, J., Dey, P., Orawski, G. and Pickup, K.H. "Long-Term-Creep Assessment for Overhead-line Conductors.", Proc. IEE. Vol. 122, No. 10, October 1975. pp 1146-1151.
- 14 Bradbury, J. and Vaughan, D.W. "Creep of Steel-Cored Aluminium Conductors", In "Progress in Overhead Lines and Cables for 220 kV and Above", 16-20<sup>th</sup> Sept, 1968 IEE Conference Publication No. 44, pp78-82.
- 15 Cahill, T. Development of a Low-Creep ACSR Conductor.", Wire Journal July 1973, pp66-73.

- 16 Chapman, W.G. "Tension Calculations for Overhead Conductors with the Elapsing of Time." 1983+
  
- 17 CIGRE SC 22, WG on Conductor Creep, Convenor Winkelman, P.F., Bonneville Power Administration, Portland, Oregon USA. "Conductor Creep and Transmission Line Construction.", Report No 22-70 (SC) 07, May 1970. 1<sup>st</sup> Draft for Electra 74.
  
- 18 CIGRE SC 22, WG on Conductor Creep, Convenor Winkelman, P.F., Bonneville Power Administration, Portland, Oregon USA. "Conductor Creep and Transmission Line Construction.", "Equating Basic Creep Factor Curves and Data Figures 5,6,7, Table II,(First Draft CSC 6-61-15.07 September 1961 Questionnaire) (Second Draft for Electra 74.) Report No 22-71 (WG 05) 04, April 1971.
  
- 19 CIGRE SC 22, WG on Conductor Creep, Chairman A. B. Wood. "A Practical Method of Conductor Creep Determination" CIGRE Electra No. 24 pp105-137. 1972.

- |    |   |   |
|----|---|---|
| 20 | CIGRE, Working Group<br>22.05 of Study Group 22,<br>Bourgsdorf, V.  | "Permanent Elongation of<br>Conductors. Predictor Equation and<br>Evaluation Methods", ( Draft SC 22-<br>78(WG 05)02) CIGRE Electra No.<br>75, pp63-98. March 1981. |
| 21 | CIGRE Australian Panel 22 -<br>Overhead Lines Overhead<br>Conductors for Transmission<br>Lines  | "Performance Tests on Complete<br>Conductors and Field Measurement<br>of Conductor Temperature.", Nov<br>1987.  |
| 22 | CIGRE, Working Group<br>22.05 of Study Group 22   | "Permanent Elongation of<br>Conductors", International<br>Conference on Large High Voltage<br>Electric Systems, 1983 Rio de<br>Janeiro, Paper 2.1.                  |
| 23 | CIGRE, Working Group<br>22.05 of Study Group 22,<br>Poffenberger, J.C., Bennett,<br>E., Howington. B.S.,<br>Ramon, G.J., Rawlins, C.B.,<br>Roche, J.B. and Ware. J.N. | "Overhead Conductors in the United<br>States", International Conference on<br>Large High Voltage Electric<br>Systems, 1983 Rio de Janeiro, Paper<br>2.3.            |

- 24 CIGRE, Working Group "Overhead Transmission Line  
22.05 of Study Group 22, Conductors used Recently in Canada  
Barrett, J.S. and McCulloch for High Temperature Operation",  
A.R. International Conference on Large  
High Voltage Electric Systems, 1983  
Rio de Janeiro, Paper 2.4.
- 25 CIGRE Australian Panel 22 Performance Tests on complete  
Overhead Lines. Conductors and Field Measurements  
of Conductor Temperature, 1987.
- 26 Comellini, E. "Some Comments about Creep  
Evaluations in Overhead Line  
Design.", CIGRE Study Committee  
No. 22 Working Group No. 05  
Report No. 22-72 (WG05) 03,  
Presented at Oslo, May 1971.
- 27 Dassatto, G. Schweiz Aluminium Rundsch. Vol  
16 No 3 1966, pp100-104.

- |    |  |   |
|----|--|---|
| 28 | Davies, G.   | "Aluminium Alloy (6201,6101A) Conductors" IEE Conference Publication No 297, Publ by IEE, London, Engl. pp93-98. 1988.                                    |
| 29 | Dey, P., Gaylard, B., Mott, C.W. and Nicholson, J.A. | "Influence of Conductor Design and Operating Temperature on the Economics of Overhead Lines. Proceeding IEE Paper 6413P, 29 <sup>th</sup> December, 1970. |
| 30 | Evans, R.W. and Wiltshire, B.                        | Creep of Metals and Alloys.   |
| 31 | Fritz, E.  | "The Effect of Tighter Conductor Tensions on Transmission Line Costs.", IEEE Trans Paper Vol PAS 79 1960, pp 513-527.                                     |
| 32 | Galand,J. and Nicoud, J.C.Moreau, M and Vieille, J.  | "All Aluminium Alloy Conductors (AAAC): Influence of Process on Service Behaviour", IEE Conference Publication No 273. Publ by IEE, London, Engl P71-75.  |

- 33     Gaylard, B. and Musgrave,     "The Effect of Prestressing on the  
K.C.     Short Term Creep Behaviour of  
Zebra 0.4 in<sup>2</sup> ACSR.", British  
Insulated Callender's Cables Limited  
(BICC) Report No. WM/F/561.  
1965.
- 34     Giblin, J.F.     "The Effect of the Upgrading of  
A.C.S.R. Overhead Line Conductor  
Temperatures Upon the Mechanical  
Properties of the Conductors- A  
Literature Survey.", B.I.C.C. Report  
No. CML/G/576. 17th August,  
1962.
- 35     Gouch, Dr A. and Saunders,     "Assessment of Remanent Service  
A.     Life of Stranded Conductors", Metal  
Manufacturers Metals Technical  
Department Report presented to the  
Illawarra Regional Conference of the  
Electrical Supply Engineers  
Association of NSW, 13-14 April  
1989.

- 36 Harvey, J.R. "Creep of Transmission Line Conductors", IEEE Trans on Power and Systems, Vol PAS-88 No. 4, April 1969, pp 281-286. (Paper No 68-TP-65-PWR 1968, pp1-7.)
- 37 Harvey, J.R. "Effect of Elevated Temperature Operation on the Strength of Aluminium Conductors", IEEE Trans on PAS Vol PAS-91 No. 5, Sept/Oct 1972, pp 1769-1772.
- 38 Harvey, J.R. and Larson, R.E. "Use of Elevated-Temperature Creep Data in Sag-Tension Calculations.", IEEE Trans on Power Apparatus and Systems, Vol. PAS-89, No. 3, March 1970. pp 380-386.
- 39 Helms, R. and Ziebs. J. CIGRE Study Committee 22 "Investigations on Aluminium Conductors Steel Reinforced (ACSR) under Tensile and Creep Load.", Report No 22-71 (WG05) 05, Oslo Meeting May 1971



- 40     Hughes, D.T.                    "The Metallurgical Significance of Changes in Production Practices for Overhead Line Conductor Materials", IEE Conference Publication NO 297,. Publ by IEE London , Engl, pp89-92, 1988.
- 41     Ishikawa, M. and Ito, H.        "Practical Application of an Extremely low-Sag Invar Reinforced Increased-Capacity Extra-Heat-Resistant Aluminum Alloy Conductor", Sumitomo Electric Technical Review, 1989, No 28, pp162-170.
- 42     Johnston, G.H.                    "Development of Aluminium Alloy Conductors", Metal Manufacturers Limited, Technical Service Department Port Kembla. 1984

- 43     Jordan, C.A.                                "A Simplified Sag-Tension Method  
for Steel Reinforced Aluminium  
Conductors.", AIEE Trans. Vol 71  
Pt III, Dec 1952, pp 1108-1117.  
(Alt AIEE Paper No. 52, 1952,  
p302)
  
- 44     Marin, J.                                        "Mechanics of Creep Structural  
Analysis.", Proc Am. Soc. Civil  
Eng. Vol 68 pp719-735. 1942
  
- 45     Mattock, A.F.L.                                "Tensile Creep Properties of  
Conductor Wire Materials- Fifth  
Interim Report", B.I.C.C. Report  
No. ME/T.521, 14 june, 1978.
  
- 46     Metal Manufacturers                                "Fixed Overtensioning as a Method  
Limited, Technical Service                                for Creep Compensation.",  
Department Port Kembla.                                Technical Note TS2.463 03  
February, 1987

- 47     Metal     Manufacturers     "Properties of Aluminium Alloy  
Limited, Technical Service     Conductors", 22 May, 1984.  
  
D e p a r t m e n t   P o r t  
  
Kembla.Johnston, G.H. and  
  
Stewart, W.H.
  
- 48     Metal     Manufacturers     "Overhead Conductors in Australia",  
Limited, Technical Service     13 October, 1986.  
  
Department Port Kembla.  
  
Reid, B.J. and Gouch, A.J.
  
- 49     Morgan, Vincent T.     "The Loss of Tensile Strength of  
  
Hard-Drawn Conductors by  
  
Annealing in Service", IEEE  
  
Transactions on Power Apparatus  
  
and Systems, Vol. PAS-98, No.3  
  
May/June 1979.
  
- 50     Musgrave, K.C. and Hewitt,     "Creep Measurements of 54/7/.125  
E.     ACSR, 61/.125 AAC, and on the  
  
Component Wires.", BICC Report  
  
No. WM/F/570. 1965.

- 51 Nakayama, Y. and Kojima, T., CIGRE Study Committee 22-70 (WG05) 02 "Field Measurement of the Creep of Overhead Line Conductor.", Report CSC 22-70 (WG05) 02, The Furukawa Electric Co. Ltd. Tokyo, Japan. May 1970.
- 52 Nakayama, Y. Yamagata, K. Tamura, Y. and Kojima, T., CIGRE Study Committee "Creep Characteristics of AAC and AAAC.", CSC-72 (WG05) 04.
- 53 Nigol, O and Barrett, J.S. "Characteristics of ACSR Conductors at High Temperatures and Stresses.", IEEE Transactions on Power Apparatus and Systems, Vol. PAS 100, No. 2, February 1981.
- 54 Nigol, O and Barrett, J.S. "Development of an Accurate Model of ACSR Conductors for Calculating Sags at High Temperatures -Part I: Sag-Tension Program - STESS." Report Prepared for the Canadian Electrical Association, Nov 1980.

- 55      Nigol, O and Barrett, J.S.      "Development of an Accurate Model of ACSR Conductors for Calculating Sags at High Temperatures -Part II: Sag-Tension Program - STESS." Report Prepared for the Canadian Electrical Association, Nov 1980.
- 56      Nigol, O and Barrett, J.S.      "Development of an Accurate Model of ACSR Conductors for Calculating Sags at High Temperatures -Part III" Report Prepared for the Canadian Electrical Association, March 1980.
- 57      Nord, E.      "Creep Tests on Aluminium Wires and Stranded Conductors for Overhead Lines - Survey of Results obtained in Sweden in the period from 1976-1985.", Laboratory Report No 25E.86 for Statens Vattenfallsverk - The Swedish State Power Board.

- 58 Northwood, D.O. and Smith, I.O. Shape of Transient Creep Curves following Stress Change During Steady State Creep.", Metal Science, Vol 18, Oct 1984, pp 485-490.
- 59 Palazuelos, E, Izquierdo, J and Fernandez, A. "Control of Conditions to Prevent Construction Problems.", IEE Conference Publication NO 297,. Publ by IEE London , Engl, pp84-88, 1988.
- 60 Pickens, B.M. "Sag-Tension Calculation Program for Digital Computer.", AIEE Trans on PAS Vol PAS 77 Pt III, Feb 1958, pp 1308-1315.
- 61 Popczyk, J., Zmuda, K., Malinowski. J. and Macekko. J.. "Evaluation of the Probabilistic Characteristics of Conductor SAC of an HV Overhead Line due to Service and Fault Current", CIGRE 1986 Session 27<sup>th</sup> August- 4<sup>th</sup> September. Paper 22-14, pp 1-6.

- 62     Price, W.P., Jackson, R.L.,     "An Overview of the Development  
Foster, D.I., Frew, N.J. and     and Performance of a Large  
Corderoy, B.     Transmission System", ELECTRA  
126, July 1989, pp 119-153.
- 63     Ramy, T.     "A Comparison of the Creep  
Characteristics of a Number of  
Commercially Available Aluminium  
Alloys", General Cable Research  
Laboratories Report No 33612. Feb.  
1, 1971.
- 64     Reedy, V.J.     Thesis titled "Inelastic Stretch  
Allowance in Transmission Line  
Conductors", The University of  
Technology, Sydney, School of  
Electrical Engineering Spring 1989.
- 65     Roest, C.A.     "Creep of Aluminium Conductor  
Alloy" IEEE Trans PAS, Vol PAS-  
88, No 11, Nov 1969, pp1690-1695.  
(Paper 69 TP 21-PWR)

- 66 Roche. J.B. and Dziedzic, E. "Some Factors Affecting Creep and Sag in EHV Transmission Lines.", Report to Pacific Coast Electrical Association 28 March, 1968, from Kaiser Aluminum and Chemical Sales, Inc, Electrical Products Division.
- 67 Schlosser, S., Snowman, A. and Ramy, T. "Creep Behaviour of Aluminium Wire Affects Performance of ACSR Cable.", Wire Journal December, 1971, pp48-52.
- 68 Stickley. G.W. "Stress-Strain Studies of Transmission Line Conductors", Paper presented at Summer Convention of AIEE Cleveland Ohio, 20-24 June, 1932.
- 69 Stubbs, E.L. and Harrington, B.J. "Evolution of Transmission line Design and Development in Australia" ELECTRA 124, May 1989 pp112-127.



- 70     Sturm, R.G., Dumont, C.     "A Method of Analysing Creep  
and Howell, F.M.     Data", J Appl Mech, 1936 pp A62-  
A66.
- 71     Swedish Standard     Svensk Standard SS 11 23 18 1987.  
Aluminium and Steel - Stranded  
conductors for Overhead lines -  
Non-interrupted creep testing
- 72     Tilbury, C.O. and Bradbury,     "A Computer Program for Long  
J.     Term Creep Assessment", B.I.C.C.  
Report No. MA/T.217, 9th NOV,  
1973.
- 73     Tilbury, C.O. and Bradbury,     "A Computer Program for Long  
J.     Term Creep Assessment",  
(REVISED EDITION) B.I.C.C.  
Report No. MA/T.237, 9th NOV,  
1973.

- 74 Toth. T Creep Testing of Aluminium Alloy and Steel-Reinforced Aluminium Conductors of High-voltage Power Transmission Lines", *Magy. Alum* 1982, Vol.19 No 2-4, pp 102-113.
- 75 Turner, T. and Wendel, K. "The Influence of Stress on Aluminium Conductor Life.", 23rd Annual Proceedings Reliability Physics 1985. 26-28 March 1985, Orlando, USA, pp142-7.
- 76 Winkelman, P.F. "Sag-Tension Computations and Field Measurements of Bonneville Power Administration", *AIEE Trans. Pt III*, Feb 1960, pp 1532-1548.
- 77 Wood, A.B. "A Practical Method of Conductor Creep Determination", *ELECTRA* No 24, 1972, pp105-137, WG05 SC22.

- 78 Kiebling, F. Sperl, H. and Mocks, L. "Planning and Design of the New 380 kV River Elbe Crossing of the Nordwestdeutsche Kraftwerke AG" FBE MITTEILUNGEN c/o ALM Division, Electrical Equipment Ltd. 1978.
- 79 Kremer D. "Measuring of permanent elongation of conductors and shield wires.", Transmission Lines Open Conference, Part V. Theoretical and Experimental Research, Paper 22.14, Yugoslav National Committee-CIGRE Group 22 Overhead Lines, Sarajevo, October 11, 1989.
- 80 Metal Manufacturers Collection of early creep test experimental worksheets, 1970-1980.
- 81 22-76(WG 05)03 "Progress Report of Working Group 05 "Conductor Creep" for CIGRE Study Committee No. 22 Meeting in Paris, on August 1976.

## APPENDIX 1

TABLE VII Creep of Homogeneous Stranded Conductors conforming to  $\mu\epsilon = kt^n$ 

SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k $\mu$ STRAIN	n	10 YR CREEP $\mu$ STRAIN
		SIZE	TYPE	%NBL	kN					
MM	FLUORINE	7/3.00 mm	AAAC/1120					205	.1895	317
46	IODINE	7/4.75 mm	AAAC/1120	23	6.23	(50.3)	20	50	.9731	470
MM	KRYPTON	19/3.25 mm	AAAC/1120	20	7.48	47.46	19	139	.2344	238
MM	KRYPTON	19/3.25 mm	AAAC/1120	30	11.22	71.18	19	237	.1819	360
MM	KRYPTON	19/3.25 mm	AAAC/1120	40	14.96	94.91	19	328	.1673	482
MM	KRYPTON	19/3.75 mm	AAAC/1120	20	7.48	47.46	80	222	0.238	384
MM	NEON	19/3.75 mm	AAAC/1120	20	9.56	45.57	20	235	.2344	403
MM	NEON	19/3.75 mm	AAAC/1120	30	14.34	68.35	20	343	.1855	495
MM	NEON	19/3.75 mm	AAAC/1120	40	19.12	91.13	20	453	.2008	719
MM	NEON	19/3.75 mm	AAAC/1120	20	9.56	45.57	50	410	.3006	819
MM	OXYGEN	19/4.75 mm	AAAC/1120	21	15.46	45.92	21	212	.1827	323
MM	OXYGEN	19/4.75 mm	AAAC/1120	21	15.46	45.92	21	205	.1899	318
MM	OXYGEN	19/4.75 mm	AAAC/1120	30	22.08	65.58	19	278	.2129	454
MM	OXYGEN	19/4.75 mm	AAAC/1120	40	29.44	87.44	19	397	.177	597
MM	OXYGEN	19/4.75 mm	AAAC/1120	20	14.62	43.32	79	551.4	.23143	940
MM	NITROGEN	37/3.00 mm	AAAC/1120	30	18.66	71.36	20	109	.28884	211
MM	SULPHUR SET 1	61/3.75 mm	AAAC/1120	20	29.00	42.98	20	221	.24351	387
MM	SULPHUR SET 1	61/3.75 mm	AAAC/1120	30	43.50	64.48	20	300	.23872	519
MM	SULPHUR SET 1	61/3.75 mm	AAAC/1120	40	58.00	85.97	20	509	.18649	782
MM	SULPHUR SET 1	61/3.75 mm	AAAC/1120	21.4	31.00	45.99	80	604.1	.27714	1144
MM	SULPHUR SET 2	61/3.75 mm	AAAC/1120	20	29.00	43.05	20	238.7	.32788	508
MM	SULPHUR SET 2	61/3.75 mm	AAAC/1120	30	43.50	64.57	20	325.2	.21696	536
MM	SULPHUR SET 2	61/3.75 mm	AAAC/1120	40	58.00	86.09	20	483.3	.1812	733
MM	SPINEL	61/3.25 mm	AAAC/6201	20	27.00	53.36	20	98.4	.22067	164
MM	SPINEL	61/3.25 mm	AAAC/6201	30	40.50	80.04	20	269.4	.21942	447
MM	SPINEL	61/3.25 mm	AAAC/6201	40	54.00	106.72	20	357.2	.14401	498
46	MOON	7/4.75 mm	AAC					40	1.4393	1100
MM	MOON	7/4.75 mm	AAC	20	3.76	30.32	RT	139	0.2437	243

SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k μSTRAIN	n	10 YR CREEP μSTRAIN
		SIZE	TYPE	%NBL	kN					
MM	MOON	7/4.75 mm	AAC	30	5.64	45.48	RT	240	0.2298	408
MM	MOON	7/4.75 mm	AAC	40	7.52	60.65	RT	347	0.1691	512
MM ?	NEPTUNE	19/3.25 mm	AAC	20		43.42	80	9	0.2380	15
50		61/0.125 in	AAAC/6XXX	20			RT	355	0.28	676
50		61/0.125 in	AAAC/6XXX	30			RT	502	0.30	1002
50		61/0.125 in	AAAC/6XXX	40			RT	638	0.27	1188
50		61/0.125 in	AAAC/6XXX	50			RT	731	0.26	1330
34	ARBUTUS	37/0.147	AAAC/6201	20			RT	486	0.2189	804
39		19/2.80mm	AAC	15		2.45 (kp/mm <sup>2</sup> )	20	529	0.320	1105
39		19/2.80mm	AAC	25		3.99 (kp/mm <sup>2</sup> )	20	733	0.240	1273
39		19/2.80mm	AAC	40		6.53 (kp/mm <sup>2</sup> )	20	-1413	0.240	2455
77	NARCISSUS	61/3.67 mm	EC A1	20			24	384	0.285	739
77	ARBUTUS	37/3.72 mm	AAC	15			26	463	0.212	754
77	ARBUTUS	37/3.72 mm	AAC	15			26	343	0.212	559
77	ARBUTUS	37/3.72 mm	AAC	15			50	740	0.245	1300
77	ARBUTUS	37/3.72 mm	AAC	15			75	1257	0.245	2209
77	ARBUTUS	37/3.72 mm	AAC	15			100	1849	0.245	3250
77	ARBUTUS	37/3.72 mm	AAC	15			125	2774	0.275	4876
77		19/2.58 mm		20			RT	587	0.195	920
77		19/2.58 mm		20			93	3215	0.205	5154
74		19/2.87 mm		50	15.7		100	734	0.3022	1472
74		19/2.87 mm		50	15.7		80	441	0.2193	729
57		61/	AlMgSi TYPE B	30.3	91		20	619	0.213	1010
57		61/	AlMgSi TYPE B	32.3	91		20	484	0.175	724
57		61/	Al59	37	83.6		20	685	0.257	1237
57		61/	Al59	37.8	83.6		20	603	0.260	1097
57		61/	Al59	37.8	83.6		23	510	0.245	897

SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k μSTRAIN	n	10 YR CREEP μSTRAIN
		SIZE	TYPE	%NBL	kN					
57		19/	Al59	40.5%	14.8		20	595	0.248	1053
57		61/	Al59	36.5%	81.9		20	434	0.164	633
57		61/	Al59	36.5%	81.9		20	552	0.214	903
57		61/	Al59	38.3	83.6		23	512	0.187	787
16	SATURN	37/3.00 mm	AAC 1350	20			20	585	0.2109	951
3	(RUBY)	37/3.00 mm	AAAC 6201	40	29.4	112	120	949	0.7397	5211
3			BBE	40			120	253	0.37	593
3		37/3.00 mm	EC AL AAC 1350	40			120	98	0.29	191
3		37/3.00 mm	DUCTALEX AAAC 1120	40			120	43	0.2431	75
3	OXYGEN	19/4.75 mm	AAAC/1120	20	14.7	(43.7)	20	223	0.172	331
3	OXYGEN	19/4.75 mm	AAAC/1120	20	14.7	(43.7)	50	264	0.218	601
3	SULFUR	61/3.75 mm	AAAC/1120	20	29	(43)	20	271	0.205	343

## APPENDIX 2

TABLE VIII Creep of Composite Stranded Conductors conforming to  $\mu\epsilon = kt^n$ 

SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k $\mu$ STRAIN	n	10 YR CREEP
		SIZE	TYPE	%NBL	kN					$\mu$ STRAIN
MM	OLIVE	54/6/0.139 + 1/0.145 in	ACSR/GZ	14			120	480	.2355	826
MM	OLIVE	54/6/0.139 + 1/0.145 in	ACSR/GZ	14			120	358	.1885	553
MM	OLIVE	54/6/0.139 + 1/0.145 in	ACSR/GZ	14			120	328	.1898	508
MM	OLIVE	54/6/0.139 + 1/0.145 in	ACSR/GZ	22			21	223	.2100	362
MM	OLIVE	54/6/0.139 + 1/0.145 in	ACSR/GZ	22			21	198	.2469	350
MM	OLIVE	54/6/0.139 + 1/0.145 in	ACSR/GZ	22			21	106	.1964	167
MM	APPLE	6/1/3.00 mm	ACSR/GZ					220	0.182	334
MM	OLIVE	54/6/3.53 + 1/3.75 mm	ACSR/GZ	14	22.248		120	56.5	.23578 0	827
MM	OLIVE	54/6/3.53 + 1/3.75 mm	ACSR/GZ	14	22.248		120	64	.18829 7	546
MM	BANANA	6/1/3.75 mm	ACSR/GZ	19	6.3	56.03	RT	276	0.3044	556
MM	BANANA	6/1/3.75 mm	ACSR/GZ	30	10	88.47	RT	260	0.1720	387
MM	BANANA	6/1/3.75 mm	ACSR/GZ	38	12.6	112.07	RT	407	0.1481	573
MM	GRAPE	30/7/2.50 mm	ACSR/GZ	20	12.74	70.15	20	284	.16854 2	418
MM	GRAPE	30/7/2.50 mm	ACSR/GZ	30	19.11	105.21	20	435	.16806 3	637
MM	GRAPE	30/7/2.50 mm	ACSR/GZ	40	25.98	140.29	20	519	.16979 3	767
MM ?	GRAPE	30/7/2.50 mm	ACSR/GZ	46.7	30.3	163.8	RT	334	0.1508	473
MM	GRAPE	30/7/2.50 mm	ACSR/GZ	20	12.74	70.15	20	244	.15705 9	350
MM	LIME	30/7/3.50 mm	ACSR/GZ	30	36.3	101.97	20	211.7	.20810 2	342
MM	PAWPAW	54/3.75 + 19/2.25 mm	ACSR/GZ	20	35.8	52.9	20	221	.1821	336
MM	PAWPAW	54/3.75 + 19/2.25 mm	ACSR/GZ	30	53.7	79.4	20	349	.1852	534
MM	PAWPAW	54/3.75 + 19/2.25 mm	ACSR/GZ	40	71.61	105.9	20	542	.1805	821
46	CARROT	6/4.75 + 7/1.60 mm	ACSR					50	1.0792	600

SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k μSTRAIN	n	10 YR CREEP
		SIZE	TYPE	%NBL	kN					μSTRAIN
50	ZEBRA	54/7/0.125 in	ACSR	20				481	0.34	1052
50	ZEBRA	54/7/0.125 in	ACSR	30				681	0.29	1327
50	ZEBRA	54/7/0.125 in	ACSR	40				918	0.29	1790
50	ZEBRA	54/7/0.125 in	ACSR	50				974	0.27	1813
34	DRAKE	26/0.175 + 7/0.136 in	ACSR	20			RT	196	0.1549	280
34	CONDOR	54/7/0.121 in	ACSR	20			RT	467	0.2041 2	747
34	COOT	36/1/0.148	ACSR	20			RT	890	0.2477 9	1575
76		54/7	ACSR	30			RT	656	0.18	993
76		54/7	ACSR	10			RT	174	0.18	263
39		7/3.22 + 12/3.20 mm	ACSR/GZ	15		7.96 (kp/mm <sup>2</sup> )	20	324	0.208	523
39		7/3.22 + 12/3.20 mm	ACSR/GZ	25		12.94 (kp/mm <sup>2</sup> )	20	401	0.179	605
39		7/3.22 + 12/3.20 mm	ACSR/GZ	41		21.20 (kp/mm <sup>2</sup> )	20	634	0.145	885
39		7/2.30 + 24/3.49 mm	ACSR/GZ	15		4.22 (kp/mm <sup>2</sup> )	20	347	0.207	560
39		7/2.30 + 24/3.49 mm	ACSR/GZ	25		7.04 (kp/mm <sup>2</sup> )	20	544	0.190	843
39		7/2.30 + 24/3.49 mm	ACSR/GZ	40		11.25 (kp/mm <sup>2</sup> )	20	977	0.171	1448
39		7/2.30 + 24/3.49 mm	ACSR/GZ	50		14.06 (kp/mm <sup>2</sup> )	20	1393	0.171	2065
39		7/2.30 + 24/3.49 mm	ACSR/GZ	60		16.86 (kp/mm <sup>2</sup> )	20	2257	0.171	3346
39		7/2.68 + 10/3.45 + 16/3.44 mm	ACSR/GZ	15		5.40 (kp/mm <sup>2</sup> )	20	390	0.220	647
39		7/2.68 + 10/3.45 + 16/3.44 mm	ACSR/GZ	25		7.71 (kp/mm <sup>2</sup> )	20	548	0.172	814
39		7/2.68 + 10/3.45 + 16/3.44 mm	ACSR/GZ	40		12.34 (kp/mm <sup>2</sup> )	20	991	0.172	1472
39		1/2.33 + 6/2.31 + 48/2.99 mm	ACSR/GZ	15		3.77 (kp/mm <sup>2</sup> )	20	554	0.216	911
39		1/2.33 + 6/2.31 + 48/2.99 mm	ACSR/GZ	25		6.28 (kp/mm <sup>2</sup> )	20	579	0.198	913
39		1/2.33 + 6/2.31 + 48/2.99 mm	ACSR/GZ	40		10.03 (kp/mm <sup>2</sup> )	20	1066	0.186	1636



SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k μSTRAIN	n	10 YR CREEP μSTRAIN
		SIZE	TYPE	%NBL	kN					
39		1/2.33 + 6/2.31 + 48/2.99 mm	ACSR	60		15.06 (kp/mm <sup>2</sup> )	20	1548	0.153	2202
39		1/3.04 + 6/3.01 + 54/3.00 mm	ACSR	15		4.30 (kp/mm <sup>2</sup> )	20	479	0.220	795
39		1/3.04 + 6/3.01 + 54/3.00 mm	ACSR	25		7.16 (kp/mm <sup>2</sup> )	20	715	0.220	1187
39		1/3.04 + 6/3.01 + 54/3.00 mm	ACSR	40		11.45 (kp/mm <sup>2</sup> )	20	1066	0.186	1636
39		1/3.04 + 6/3.01 + 54/3.00 mm	ACSR	48		13.60 (kp/mm <sup>2</sup> )	20	1372	0.135	1872
29		54/7/0.125 in <sup>2</sup>	ACSR				20	459	0.240	798
77		24/4.0 + 7/3.1 mm	ACSR	20			20	397	0.182	604
77		24/4.0 + 7/3.1 mm	ACSR	20			60	553	0.182	841
77		24/4.0 + 7/3.1 mm	ACSR	20			90	835	0.182	1270
77		24/4.0 + 7/3.1 mm	ACSR	20			120	898	0.182	1365
77	DRAKE	26/0.175 + 7/0.136 in	ACSR	20			26	424	0.240	737
77	DRAKE	26/0.175 + 7/0.136 in	ACSR	20			50	499	0.195	782
77	DRAKE	26/0.175 + 7/0.136 in	ACSR	20			75	617	0.190	956
77	DRAKE	26/0.175 + 7/0.136 in	ACSR	20			125	863	0.130	1164
77	3 TEAS	26/4.0 + 7/3.1 mm	ACSR	13.7			150	334	0.110	430
77	3 TEAS	26/4.0 + 7/3.1 mm	ACSR	11			200	369	0.100	465
77		26/4.0 + 7/3.1 mm	ACSR				20	307	0.140	424
77		26/4.0 + 7/3.1 mm	ACSR				120	506	0.140	698
77		54/7/3.80 mm	ACSR				20	378	0.140	522
77		54/7/3.80 mm	ACSR				120	723	0.140	998
77		54/7/3.80 mm	ACSR				20	185	0.140	255
77		54/7/3.80 mm	ACSR				180	372	0.080	447
77	ZEBRA	54/7/3.18 mm	ACSR				RT	459	0.240	797
77		54/3.85 + 19/2.30 mm	ACSR				15	381	0.200	604

SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k μSTRAIN	n	10 YR CREEP μSTRAIN
		SIZE	TYPE	%NBL	kN					
77		54/3.85 + 19/2.30 mm	ACSR				15	799	0.200	1266
77	HAWK	26/3.44 + 7/2.68 mm	ACSR				15	134	0.120	177
77	CONDOR	54/7/3.08 mm	ACSR				15	245	0.200	388
77	CONDOR	54/7/3.08 mm	ACSR				21	427	0.210	693
77	PHEASANT	54/3.90 + 19/2.34 mm	ACSR				24	392	0.263	674
77	PHEASANT	54/3.90 + 19/2.34 mm	ACSR				24	303	0.230	515
77	CHUKAR	84/3.70 + 19/2.22 mm	ACSR				24	406	0.197	639
77	CHUKAR	84/3.70 + 19/2.22 mm	ACSR				24	342	0.267	632
77	CHUKAR	84/3.70 + 19/2.22 mm	ACSR				24	321	0.263	588
77	KIWI	73/4.41 + 7/2.94 mm	ACSR				26.7	423	0.1173	554
77	COYOTE	26/.100 + 7/0.075 in	ACSR	20			26.7	364	0.200	578
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		51.93	(107.2)	21.1	621	0.233	1062
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		53.69	(110.8)	35.3	789	0.275	1486
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		53.06	(110.6)	51.0	1007	0.245	1770
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		53.7	(110.8)	65.6	1077	0.208	1739
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		35.45	(73.2)	13.6	381	0.263	698
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		34.29	(70.8)	34.4	495	0.242	864
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		34.93	(72.1)	51.5	693	0.259	1258
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		34.44	(71.1)	66.1	886	0.272	1657
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		35.32	(72.9)	80.7	1134	0.259	2059
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		34.12	(70.4)	84.1	1236	0.285	2388
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		22.60	(46.6)	16.8	215	0.256	388
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		22.16	(45.7)	34.4	442	0.308	898

SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k μSTRAIN	n	10 YR CREEP μSTRAIN
		SIZE	TYPE	%NBL	kN					
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		22.18	(45.8)	71.4	527	0.243	922
12	ZEBRA TYPE 2	54/7/0.125 in	ACSR/GZ		14.86	(30.7)	24.6	177	0.328	377
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		91.07	(188)	14.7	4674	0.187	7189
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		53.38	(110)	18.1	1480	0.207	2384
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		44.48	(91.8)	17.6	1080	0.211	1756
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		35.58	(73.4)	19.2	886	0.224	1484
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		35.58	(73.4)	15.6	809	0.204	1294
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		34.11	(70.4)	34.5	977	0.214	1599
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		34.11	(70.4)	61.7	762	0.125	1016
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		26.69	(55)	17.7	604	0.262	1104
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		22.00	(45)	81.9	703	0.149	991
12	ZEBRA TYPE 1	54/7/0.125 in	ACSR/GZ		15.87	(34.8)	14.1	256	0.213	418
74		26/2.35 +7/1.9 mm	ACSR	40	15.7		100	271	0.227	458
74		26/2.35 + 7/1.9 mm	ACSR	40	15.7		80	194	0.201	311
57		54/7	ACSR	17.1%	33.2		23	320	0.239	555
57		54/	ACSR	34.3%	66.4		23	685	0.167	1006
57		54/19	ACSR	38.6%	100.8		23	1064	0.178	1603
15	LYNX	30/7/0.110 in	ACSR	40			20	704	0.225	1182
15	LYNX STABILISED	30/7/0.110 in	ACSR	40			20	260	0.225	436
15	ZEBRA	54/7/0.125 in	ACSR	40			20	732	0.185	1121
15	ZEBRA STABILISED	54/7/0.125 in	ACSR	40			20	302	0.146	423
29	ZEBRA	54/7/0.125 in	ACSR					459	0.240	798
3	GRAPE	30/7/2.50 mm	ACSR	23	15	(104)	20	205	0.171	304

APPENDIX 3  
TABLE IX Creep of Composite Alloy Stranded Conductors conforming to  $\mu\epsilon=kt^n$

SOURCE	CODE	CONDUCTOR		LOAD		STRESS MPa	TEMP °C	k $\mu$ STRA IN	n	10 YR CREEP $\mu$ STRAIN
		SIZE	TYPE	%NBL	kN					
MM	RIVER CROSSING	42/19/2.75 mm	AACSR/AC/ 1120	20	37.8	104.42	20	317	.2098	514
MM	RIVER CROSSING	42/19/2.75 mm	AACSR/AC/ 1120	30	56.7	156.63	20	513	.1626	745
MM	RIVER CROSSING	42/19/2.75 mm	AACSR/AC/ 1120	40	75.6	208.84	20	732	.1174	959
MM	DIVING	30/6/3.50 + 1/3.65 mm	AACSR/AC/ 1120	20	29.2	81.73	20	233	.2308	396
MM	DIVING	30/6/3.50 + 1/3.65 mm	AACSR/AC/ 1120	30	43.8	122.93	20	357	.2222	595
MM	DIVING	30/6/3.50 + 1/3.65 mm	AACSR/AC/ 1120	52	75.92	211.6	20	834	.1494	1176
MM	PHASE	30/7/3.50 mm	AACSR/AC/ 1120	20	29.2	81.73	20	230.8	.2261	392
MM	PHASE	30/7/3.50 mm	AACSR/AC/ 1120	30	43.8	122.59	20	354	.2186	591
MM	PHASE	30/7/3.50 mm	AACSR/AC/ 1120	52	75.92	211.6	20	826	.1489	1175
MM	GRAPE /1120	30/7/2.50 mm	AACSR/AC/ 1120	20	29.2	81.93	20	176	.1768	265
MM	GRAPE /1120	30/7/2.50 mm	AACSR/AC/ 1120	30	43.8	122.91	20	283	.195	444
MM	GRAPE /1120	30/7/2.50 mm	AACSR/AC/ 1120	40	58.4	163.86	20	417	.1339	560
MM	GRAPE /1120	30/7/2.50 mm	AACSR/AC/ 1120	20	29.2	81.93	20	167	.1863 5	257
MM	GRAPE /1120	30/7/2.50 mm	AACSR/AC/ 1120	30	43.8	122.91	20	257	.1157 6	336
MM	GRAPE /1120	30/7/2.50 mm	AACSR/AC/ 1120	40	58.4	163.86	20	402	.1367	551
MM	FINCH /6201	54/3.65 + 19/2.19 mm	AACSR/GZ/ 6201	17.8	45.4	69	RT	375	0.259 9	675
3	GRAPE /1120	30/7/2.50 mm	AACSR/GZ/ 1120	20	15	104.17	20	149	0.232	254

## APPENDIX 4

TABLE X Creep of Stranded Conductor conforming to the Composite Equation  $\epsilon = k\sigma^{c1}t^{c2}$ 

Source	Conductor	Test Temp °C	Test Loads NBL %	k $\mu\epsilon/\text{yr}$	c1	c2	Creep $\mu\epsilon$ 22%NBL	
							1 yr	10 yr
MM	54/7/3.50 mm ACSR/GZ ORANGE	20		350		.2189		458
MM	7/4.75 mm AAC MOON	20	20,30, 40	$3.0504 \times 10^{-1}$	0.222	1.757	145	241
MM	19/3.25 mm AAAC/1120 KRYPTON	20	20,30, 40	$2.6368 \times 10^{-1}$	0.181	1.586	137	207
MM	19/3.75 mm AAAC/1120 NEON	20	20,30, 40	10.05	0.203	1.143		
MM	19/4.75 mm AAAC/1120 OXYGEN	20	21,21, 30,40	$4.319 \times 10^{-1}$	0.190	1.008	213	329
MM	61/3.75 mm AAAC/1120 SULPHUR	20	20,30, 40	$6.5745 \times 10^{-1}$	0.212	1.493	208	340
MM	61/3.75 mm AAAC/1120 SULPHUR	20	20,30, 40	$2.1929 \times 10^{-1}$	0.243	1.776	207	362
MM	61/3.25 mm AAAC/6201 SPINEL	20	20,30, 40	$7.429 \times 10^{-3}$	0.191	2.375	109	170
MM	30/7/2.50 mm ACSR/GZ GRAPE	20	20,30, 40	6.9813	0.170	0.877	316	467
MM	30/7/2.50 mm ACSR/GZ GRAPE	20	20,20, 30,40	4.4783	0.164	0.963	295	430

Source	Conductor	Test Temp °C	Test Loads NBL %	k $\mu\epsilon/\text{yr}$	c1	c2	Creep $\mu\epsilon$ 22%NBL	
							1 yr	10 yr
MM	54/3.75 + 19/2.25 mm ACSR/GZ PAWPAW	20	20,30, 40	1.3434	0.185	1.282	246	377
MM	30/7/2.50 mm AACSR/GZ/1120 GRAPE/1120 SET 1	20	20,30, 40	2.4201 $\times 10^{-1}$	0.147	1.472	183	256
MM	30/7/2.50 mm AACSR/GZ/1120 GRAPE/1120 SET 2	20	20,30, 40	1.2971 $\times 10^{-1}$	0.159	1.622	171	246
MM	30/7/3.50 mm AACSR/AC/1120 PHASE/1120	20	20,30, 52	1.2427 $\times 10^{-1}$	0.203	1.670	227	361
MM	42/19/2.75 mm AACSR/AC/1120 RIVER CROSSING	20	20,30, 40	1.1340 $\times 10^{-1}$	0.163	1.672	316	459
MM	42/19/2.75 mm AACSR/AC/1120 RIVER CROSSING	20	20,30, 40,	1.5442	0.158	1.892	279	401
26	ALL ALUMINIUM CONDUCTORS ( ITALIAN )	24		5.13	0.2	1.75		
26	ALL ALUMINIUM CONDUCTORS ( GERMAN )	20		16.5	0.25	1.15		

APPENDIX 5  
TABLE XI Creep of Individual Wires conforming to  $\mu\epsilon = kt^n$

SOURCE	Wire Details	Test Temp °C	Test Stress/ Load	k $\mu\epsilon/\text{yr}$	n	10 yr
70	0.188 in dia ELECT GRADE A1	RT	42% NBL	2109	0.25	3750
70	0.188 in dia ELECT GRADE A1	RT	62% NBL	773	0.25	1374
70	0.149 in dia HARD DRAWN ELECT GRADE A1	RT	86% NBL		0.26	
70	0.0525 IN GALVANISED EXTRA HIGH-STRENGTH STEEL WIRE	RT	98% NBL		0.11	
70	7AS-O 99.95 Al ANNEALED 7AS-O 99.95 Al 80% COLD REDUCED (SHEET)	RT			0.20 0.26	
70	2S-O 99.95 Al ANNEALED 2S-O 99.95 Al 80% COLD REDUCED (SHEET)	RT			0.20 0.30	
50	0.125 in DIA ALUMINIUM BEFORE STRANDING	RT	20% NBL	603	0.26	1097
50	0.125 in DIA ALUMINIUM BEFORE STRANDING	RT	30% NBL	1065	0.23	1808
50	0.125 in DIA ALUMINIUM BEFORE STRANDING	RT	40% NBL	1313	0.19	2034
50	0.125 in DIA ALUMINIUM BEFORE STRANDING	RT	50% NBL	1992	0.21	3230
50	0.125 in DIA HEAT TREATABLE ALUMINIUM ALLOY ALDREY 6XXX BEFORE STRANDING	RT	20% NBL	442	0.24	768
50	0.125 in DIA HEAT TREATABLE ALUMINIUM ALLOY ALDREY 6XXX BEFORE STRANDING	RT	30% NBL	584	0.18	884
50	0.125 in DIA HEAT TREATABLE ALUMINIUM ALLOY ALDREY 6XXX BEFORE STRANDING	RT	40% NBL	1465	0.18	2217
50	0.125 in DIA HEAT TREATABLE ALUMINIUM ALLOY ALDREY 6XXX BEFORE STRANDING	RT	50% NBL	1506	0.17	2227
50	0.125 in DIA ALUMINIUM AFTER STRANDING	RT	20% NBL	262	0.21	425
50	0.125 in DIA HEAT TREATABLE ALUMINIUM ALLOY ALDREY 6XXX AFTER STRANDING	RT	20% NBL	254	0.26	462
39	Aluminium Wire Destranded	20	2.45 (kp/mm <sup>2</sup> )	328	0.260	597
39	Aluminium Wire Destranded	20	3.97 (kp/mm <sup>2</sup> )	477	0.260	868
39	Aluminium Wire Destranded	20	6.63 (kp/mm <sup>2</sup> )	847	0.260	1541
39	Aluminium Wire Destranded	20	6.51 (kp/mm <sup>2</sup> )	1080	0.260	1965
39	Aluminium Wire Destranded	20	9.54 (kp/mm <sup>2</sup> )	2754	0.260	5011
39	Steel Wire Destranded	20	14.30 (kp/mm <sup>2</sup> )	325	0.190	503

SOURCE	Wire Details	Test Temp °C	Test Stress/ Load	k $\mu\epsilon/\gamma$	n	10 yr
39	Steel Wire Destranded	20	31.70 (kp/mm <sup>2</sup> )	1003	0.065	1165
39	Steel Wire Destranded	20	50.80 (kp/mm <sup>2</sup> )	1371	0.065	1592
39	Steel Wire Destranded	20	76.20 (kp/mm <sup>2</sup> )	2129	0.065	2473
63	IMPEC ALUMINIUM ALLOY	21	50 lbs	1849	0.206	2971
63	CK 76 ALUMINIUM ALLOY	21	50 lbs	1298	0.242	2266
63	BEE ALUMINIUM ALLOY	21	50 lbs	867	0.153	1233
63	EC GRADE ALUMINIUM	21	50 lbs	745	0.171	1104
63	CM 71 ALUMINIUM ALLOY	21	50 lbs	364	0.142	505
77	EC GRADE ALUMINIUM 4.0 mm diameter	20	20% NBL	347	0.225	583
77	EC GRADE ALUMINIUM 4.0 mm diameter	60	20% NBL	1182	0.252	2112
77	EC GRADE ALUMINIUM 4.0 mm diameter	90	20% NBL	2597	0.268	4813
77	EC GRADE ALUMINIUM 4.0 mm diameter	120	20% NBL	6940	0.320	14500
57	Al WIRE	23	40%NBL	428	0.208	691
57	Al WIRE	23	40%NBL	428	0.199	677
57	AlMgSi WIRE TYPE B	20	35%NBL	473	0.191	734
57	AlMgSi WIRE TYPE B	40	35%NBL	577	0.165	844
57	AlMgSi WIRE TYPE B	60	35%NBL	966	0.159	1393
57	AlMgSi WIRE TYPE B	20	52%NBL	1101	0.171	1632
57	AlMgSi WIRE TYPE B	40	52%NBL	1421	0.162	2063
57	AlMgSi WIRE TYPE SUPER B	23	36%NBL	303	0.173	451
57	AlMgSi WIRE TYPE SUPER B	23	36%NBL	315	0.220	523
57	Al59 2.99 mm rolled	23	24.4%	188	0.216	309
57	Al59 2.99 mm rolled	23	32.6%	239	0.201	380
57	Al59 3.52 mm rolled	23	37.1%	366	0.191	568
57	Al59 3.52 mm rolled	23	55.6%	845	0.222	1409
57	Al59 4.36 mm rolled	23	39.7%	338	0.244	566
57	Al59 4.36 mm rolled	20	39.1%	404	0.221	672
57	Al59 4.36 mm rolled	23	39.1%	346	0.224	579
57	Al59 4.36 mm rolled	23	39.1%	331	0.212	539
57	Al59 4.36 mm rolled	40	39.1%	487	0.201	773
57	Al59 4.36 mm rolled	40	39.1%	566	0.191	878
57	Al59 4.36 mm rolled	60	39.1%	654	0.132	886
57	Al59 4.36 mm rolled	20	58.7%	747	0.189	1154
57	Al59 4.36 mm rolled	23	58.7%	679	0.208	1096



SOURCE	Wire Details	Test Temp °C	Test Stress/ Load	k $\mu\epsilon/\text{yr}$	n	10 yr
57	A159 4.36 mm rolled	23	58.7%	717	0.224	1200
57	A159 4.36 mm rolled	40	58.7%	1510	0.195	2366
57	A159 4.36 mm rolled	23	36.5%	315	0.214	516
57	A159 4.36 mm rolled	20	36.1%	378	0.221	629
57	A159 4.36 mm rolled	23	36.1%	273	0.216	449
57	A159 4.36 mm rolled	23	36.1%	316	0.211	514
57	A159 4.36 mm rolled	40	36.1%	596	0.152	846
57	A159 4.36 mm rolled	60	36.1%	1004	0.197	1580
57	A159 4.36 mm rolled	20	54.1%	693	0.175	1037
57	A159 4.36 mm rolled	23	54.1%	606	0.211	985
57	A159 4.36 mm rolled	23	54.1%	661	0.212	1077
57	A159 4.36 mm rolled	40	54.1%	1162	0.178	1751
57	A159 4.36 mm rolled	23	32.9%	278	0.208	449
57	A159 4.36 mm rolled	23	16.4%	144	0.151	204
57	A159 4.36 mm rolled	23	24.6%	208	0.175	311
57	A159 4.36 mm rolled	23	32.7%	280	0.179	423
57	A159 4.36 mm rolled	23	40.9%	401	0.203	640
57	A159 4.36 mm rolled	20	38.5%	348	0.207	560
57	A159 4.36 mm rolled	23	38.5%	350	0.177	526
57	A159 4.36 mm rolled	23	38.5%	360	0.179	543
57	A159 4.36 mm rolled	40	38.5%	490	0.184	748
57	A159 4.36 mm rolled	40	38.5%	575	0.165	841
57	A159 4.36 mm rolled	60	38.5%	966	0.159	1393
57	A159 4.36 mm rolled	20	57.7%	777	0.136	1062
57	A159 4.36 mm rolled	23	57.7%	796	0.146	1114
57	A159 4.36 mm rolled	23	57.7%	754	0.175	1128
57	A159 4.36 mm rolled	40	57.7%	1315	0.129	1769
57	A159 4.36 mm rolled	20	36.9%	340	0.244	596
57	A159 4.36 mm rolled	23	36.9%	314	0.155	449
57	A159 4.36 mm rolled	23	36.9%	271	0.186	416
57	A159 4.36 mm rolled	40	36.9%	489	0.164	713
57	A159 4.36 mm rolled	60	36.9%	800	0.128	1074
57	A159 4.36 mm rolled	20	55.4%	868	0.160	1254
57	A159 4.36 mm rolled	23	55.4%	588	0.156	842
57	A159 4.36 mm rolled	23	55.4%	637	0.158	917

SOURCE	Wire Details	Test Temp °C	Test Stress/ Load	k $\mu\text{E}/\text{yr}$	n	10 yr
57	A159 4.36 mm rolled	40	55.4%	1344	0.131	1817

APPENDIX 6  
TABLE XII Creep of Stranded Conductors conforming to  $\mu\epsilon=kt^n$  including prestressing.

SOURCE	CODE	CONDUCTOR		PRESTRESS LOAD/TIME (HRS)		LOAD %NBL	NO PRESTRESS		AFTER PRESTRESS	
		SIZE	TYPE	%NBL/HRS	kN/L BS		k $\mu$ STRAIN	n	k $\mu$ STRAIN	n
33	ZEBRA	54/7/0.125 in	ACSR/GZ	0/0	0/0	7000 LBS	460	0.24		
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/1	/7700	7000 LBS			584	0.31
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/3	/7700	7000 LBS			464	0.27
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/6	/7700	7000 LBS			435	0.25
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/1	/8400	7000 LBS			735	0.36
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/3	/8400	7000 LBS			464	0.25
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/6	/8400	7000 LBS			406	0.20
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/1	/9100	7000 LBS			477	0.24
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/3	/9100	7000 LBS			464	0.21
33	ZEBRA	54/7/0.125 in	ACSR/GZ	/6	/9100	7000 LBS			379	0.18

**APPENDIX 7****TABLE XIII** Co-efficients for CERL equation (14) for ACSR conductors having 54/7 stranding [73].

	CONDUCTOR CONSTANTS				
Type of Al rod	k mm/km $10^{-6}$	$\beta$	$\phi$	$\gamma$	$\delta$
Extruded	238	1.42	0.0174	10.6	0.455
Hot Rolled	6.09	1.98	0.0238	2.95	0.313

**TABLE XIV** Co-efficients for creep of ACSR/GZ 54/7/0.125 in Zebra from [14]

	CONDUCTOR CONSTANTS			
Type of Conductor	k min/km $10^{-12}$	$\beta$	$\gamma$	$\delta$
1	0.0784	2.339	1.893	0.2375
2	0.1749	2.177	20.54	0.5081
3	1.183	2.061	101.6	0.7279

Type 1 Electrolytically galvanised, Type 2&3 hot dipped galvanised.

**TABLE XV** Co-efficients for creep of ACSR/GZ 54/7/0.125 in Zebra from [12]

		CONDUCTOR CONSTANTS				
Type of Conductor	Units of Tension (T)	k mm/km $10^{-6}$	$\beta$	$\phi$	$\gamma$	$\delta$
2	kN	0.169	1.42	0.0174	1.29	0.455
	lb	$77.9 \times 10^{-6}$	1.42	0.0174	15.1	0.454
1 Above Upper Transition	kN	0.0578	1.98	0.0238	0.694	0.313
	lb	$1.28 \times 10^{-6}$	1.98	0.0238	3.78	0.311
1 Below Upper Transition	kN	0.868	1.44	0.0165	1.29	0.659
	lb	$259 \times 10^{-6}$	1.43	0.0163	38.4	0.639

Type 1 Electrolytically galvanised, Type 2&3 hot dipped galvanised.

Transition load is the load at which a layer of strands take load. Upper transition is 2 to 3 layers of aluminium taking load.



**TABLE XVII** Co-efficients for equation below for aluminium wires alloy unknown, produced by Properzi method.[81]

$$\varepsilon = He^{\phi\tau}\sigma^{\alpha}t^{\mu}$$

Diameter (mm)	H	$\phi$	$\alpha$	$\mu$
3.5	$0.235 \times 10^{-5}$	0.02	2.276	0.174
3.85	$0.425 \times 10^{-6}$	0.02	3.06	0.170

**TABLE XVIII** ACSR conductors co-efficients for EQUATION 22. [20,73]

INDUSTRIAL PROCESSING OF ALUMINIUM ROD	VALUES OF CO-EFFICIENTS							
	K		$\phi$		$\alpha$ OR $\beta$		$\gamma$ OR $\mu$	
	m $\leq$	m $>$	m $\leq$	m $>$	m $\leq$	m $>$	m $\leq$	m $>$
	13	13	13	13	13	13	13	13
HOT ROLLED	2.4	0.24	0	1	1.3	1	0.16	0.16
EXTRUDED OR PROPERZI	1.4	0.24	0	1	1.3	1	0.16	0.16

**TABLE XIX** Co-efficients for EQUATION 19 (all aluminium, all aluminium alloy, ACSR, etc). [20,73]

STRANDING		AL AREA	INDUSTRIAL PROCESS OF ROD	VALUE OF CO-EFFICIENTS				
No OF AL WIRES	No OF ST WIRES	STEEL AREA		K	$\phi$	$\beta$ OR $\alpha$	$\gamma$ OR $\mu$	$\delta$
54	7	7.71	HOT ROLLED	1.1	0.018	2.16	0.34	0.21
			EXTRUDED OR PROPERZI	1.6	0.017	1.42	0.38	0.19
48	7	11.37	HOT ROLLED	3.0	0.010	1.89	0.17	0.11
			EXTRUDED OR PROPERZI					
30	7	4.28	HOT ROLLED					
			EXTRUDED OR PROPERZI	2.2	0.011	1.38	0.18	0.037
26	7	6.16	HOT ROLLED	1.9	0.024	1.83	0.23	0.080
			EXTRUDED OR PROPERZI					
24	7	7.74	HOT ROLLED	1.6	0.024	1.88	0.19	0.0077
			EXTRUDED OR PROPERZI					
18	1	18	HOT ROLLED					
			EXTRUDED OR PROPERZI	1.2	0.023	1.50	0.33	0.13
12	7	1.71	HOT ROLLED	0.66	0.012	1.88	0.27	0.16
			EXTRUDED OR PROPERZI					

**TABLE XX** AAC and AAAC conductor co-efficients for EQUATION 21. [20,73]

INDUSTRIAL PROCESSING OF ALUMINIUM ROD	VALUE OF CO-EFFICIENTS			
	K	$\phi$	$\alpha$ OR $\beta$	$\gamma$ OR $\mu$
HOT ROLLED	0.15	1.4	1.3	0.16
EXTRUDED OR PROPERZI				

**TABLE XXI** All Aluminium conductor co-efficients for EQUATION 21. reference [20,73]

INDUSTRIAL PROCESSING OF ALUMINIUM ROD	VALUE OF CO-EFFICIENTS						
	K				$\phi$	$\alpha$ OR $\beta$	$\gamma$ OR $\delta$
	No. OF WIRES IN CONDUCTOR						
	7	19	37	61			
HOT ROLLED	0.27	0.28	0.26	0.25	1.4	1.3	0.16
EXTRUDED OR PROPERZI	0.18	0.18	0.16	0.15	1.4	1.3	0.16

**TABLE XXII** ACSR conductor co-efficients for EQUATION 21. Reference [20,73]

INDUSTRIAL PROCESSING OF ALUMINIUM ROD	VALUE OF CO-EFFICIENTS			
	K	$\phi$	$\alpha$ OR $\beta$	$\gamma$ OR $\mu$
HOT ROLLED				
EXTRUDED OR PROPERZI	$0.04 + 0.24$ $m/(m+1)$	1.4	1.3	0.16

$m = \frac{\text{aluminium area}}{\text{al alloy area}}$



There is NO Appendix 8

## APPENDIX 9 TEST PROCEDURES

ROOM TEMPERATURE CREEP CONDUCTOR SAMPLE PREPARATION  
PROCEDURE1.0 PURPOSE AND SCOPE

This procedure details the steps used to make creep conductor test pieces of bare overhead conductors. This task takes two men 1 day to complete.

2.0 INSTRUCTION2.1 PRELIMINARIES

2.1.1 Order two terminations per test piece.

2.1.2 Calculate, using the enclosed procedure, the number and size of spring washers needed for each test piece. Necessary to reduce shock loading during startup.

2.2 IDENTIFICATION

When a drum of conductor is delivered for testing it should be accompanied by production details of Customer, Batch No Conductor Code name, Size and Stranding **and previous stranded drum number**. All samples supplied for testing must be representative of the general material and be free from all obvious defects.

## 2.3 MEASURE AND CUT CONDUCTOR

2.3.1 Select the required wall mounted clamping brackets for the conductor to be tested, each bracket is set up for a range of conductor sizes.

2.3.2 Measurements are to be made on the test rig from "Face Plate to Face Plate" (usually 14.150 metres) then add the length of the three "steel sleeve ends" (usually 30 mm) plus an allowance for "C" spring washers (varies with setup) & support plates(5mm), plus the length of the two terminations (600 mm for homogeneous or 900 mm for composite conductors). ( In general the test length for Creep tests is about 14.5 m between terminations.

## 2.4 At free end of conductor.

NOTE TO MINIMISE MANUAL HANDLING PROBLEMS THIS STAGE REQUIRES A MINIMUM OF THREE (3) PEOPLE.

2.4.1 Using the retaining clamp block unwind the outer wraps from drum onto rack. Leave approx 3.5 m from the clamping position to the end. Conductor is to be supported along it's length by brackets fixed to support boards.

2.4.2 Mark conductor 800 mm from clamp point on free side of clamp. Protective tape must be wrapped around conductor where conductor comes in contact with timber brackets (to avoid damage).

2.4.3 At free end tape either side of cut for about 200 mm to prevent strand movement. On the drum side of the free end timber clamp, tape up conductor for 1 m to prevent wire movement.

2.5 At the drum end of the conductor test piece.

2.5.1 Re-measure conductor length before actually cutting the conductor from the drum (Golden Rule). From the mark on the free end, measure conductor length for test. Mark conductor 800 mm from clamp point on drum side of clamp. Protective tape must be wrapped around conductor where conductor comes in contact with timber brackets (to avoid damage).

2.5.2 Before cutting conductor from drum, tape conductor a minimum of 1 m on free end side of the clamping position.

2.5.3 Next tape approximately 200 mm of conductor on either side of proposed cut position. On drum side of cut position, tape up conductor approximately 800 from the end for approx 1 m. (To secure stranding during cleaning operation).

**NOTE** This taping procedure is especially important for AACSR and ACSR conductors as the steel core has a tendency to spring when cut.

2.5.4 Cut test piece from drum.

2.5.6 Run out next test piece and repeat steps 2.4.1-2.5.4 above.

2.5.7 When all test pieces have been cut to rough length, slide spring washers along cable.

2.5.8 Place identity tags on each test piece to avoid sample mix ups.  
Tag shall contain i) stranding details, ii) alloy type, iii) Code name, iv) Customer, v) Drum No.

## 2.6 Terminations

Terminate the cables using a method suitable to the test machines gripping mechanism.

Calculation of Spring Washer Requirements.

- 1 Spring washers must be used on creep test pieces to eliminate shock loading of the conductor during initial loading.
- 2 Confirm the identity of the conductor to be tested:- Code Name and Stranding.
- 3 In the relevant Australian Standard note the Nominal Breaking Load for the conductor.
- 4 Calculate 20, 30 and 40% of the Nominal Breaking Load.
- 5 Identify the Number of each size of spring washers available for use.
- 6 Washers should be selected so that the load on the cable will be between 0.75-1 times the load to compress the selected number of washers. Use the attached table (extracted from the Schnorr book of Spring Washers) to identify both the number and size of spring washer(s) which are suitable to be used. Note Inside Diameter of washer must be greater than outside diameter of cable!

- 7 The number of washers selected above constitute 1 stack, of a group of 4 stacks of washers to be used per cable. The total number of washers used per cable will thus be 4 times that calculated in (5) above.

No more than 40 washers should ever be used!! When a large number are required use a larger washer size to carry the load.

- 8 When the washers are put onto the cable, adjacent groups (of the number determined in 6) must face opposite directions.

## CONDUCTOR ROOM TEMPERATURE CREEP TEST PROCEDURE

### 1.0 PURPOSE AND SCOPE

This procedure details the steps i) to prepare the bench and ii) those used for Creep Testing of bare overhead conductors.

### 2.0 INSTRUCTION

#### 2.1 BENCH PREPARATION

2.1.1 Lay conductor on the bench rollers, starting from the North or Dead end of the bench and work along the bench to the Southern end. Take special care not to allow the cable to twist on the bench or during transport to the bench.

**NOTE IT WILL REQUIRE 4 PEOPLE TO LAY THE CABLES ON THE TEST BENCH.**

2.1.2 Close and lock double doors into creep enclosure.

2.1.3 Remove all Herbie Clips, Hose Clamps, Silastic and tapes from test pieces, without cutting or damaging wires.

2.1.4 Set up Dead end of bench. Extra spacers maybe used as required.



### 2.1.6 At Loading end

2.1.6.1 Place support bracket/bar from end of rollers to end of bench.

2.1.6.2 Select proof ring and fittings for cable. Attach to end of bench and lay onto support bar.

2.1.6.3 Lay termination holder on support bar and attach to other end of proof ring.

2.1.6.4 Place termination in holder.

2.1.6.5 Adjust nuts to ensure cross head is square (even loading of cable). Use a rule to check alignment.

2.1.6.6 Attach crosshead bar and nuts to threaded rods for loading system.

2.1.7 Lay reference bar on rollers, ensuring that the reference bar is on the outside of the cable on the bench.

2.1.8 Attach Dial gauges to reference bars. Ensure that they are axial over the centre of the cable.

- 2.1.9 Attach the correct sized flag holder to the conductor. Then attach a glass flag to the face of the flag holder. The glass flag should always face the centre of the cable.

## 2.2 TESTING

- 2.2.1 For the cable look up the Nominal Breaking Load as stated in the relevant standard, next calculate a/ the required load as a percentage of the NBL to be used, then b/ the deflection on the dial of the proof ring for the required load.
- 2.2.2 Fill in the blanks on the header page of the creep report.
- 2.2.3 Start creep tests. Aim to balance loads on the test bench.
- 2.2.4 Begin loading cables. With the cable straightened make any final adjustments to the axial position of the flag. So that dial gauges will not run out of travel during test. Flag should be perpendicular to dial gauge. Ensure that Dial gauges are both parallel to the long axis of the cable and positioned over the centre of the cable.
- 2.2.5 Increase the load on the cable smoothly up to the set point. At the load set point, start clock counting up and start readings (North and South dial gauges against elapsed time). **DO NOT** overshoot the set point.

2.2.6 Maintain the load at the set point.

2.2.7 At each dial gauge reading times ensure that the load is correct and record both the temperature (when time permits) and the strain on the dial gauges.

2.2.8 Record time temperature and strain throughout test.

2.2.9 Data is now ready for numerical analysis.

## CREEP AT ROOM TEMPERATURE- ANALYSIS OF DATA

### 1. SCOPE

When analysing data from a creep test this procedure lists the requirements and restrictions to be placed upon the raw data.

### 2. CONDITIONS

#### A/ Correction of Strain

If a temperature change occurs during the test from the initial temperature of the reference bar or conductor and the temperature existing when a reading of strain is taken, the resulting strain measurement shall be corrected for the change in temperature by assuming the theoretical values of the co-efficient of thermal expansion.

#### B/ Fast loading tests

The results of strain against time shall be plotted on linear scales for the first 10 minutes of the test and the best curve drawn through the results. The strain which occurs during the first 6 minutes shall be estimated from the curve and the strain thus found shall be subtracted from the strain readings. This procedure is adopted to make the results from the fast and slow loading periods compatible.

### C/ Initial Analysis

A graph of strain against time shall be plotted on logarithmic (log-log) scales for all readings and the best straight line drawn through the points. From this graph the time ( $t_s$ ) from the start of the test until the straight line is established will be determined. All points in which the strain varies by more than 2% from the value predicted by the straight line, or a strain greater than 20 mm/km shall be discarded in the final analysis.

### D/ Final Analysis of strain

A linear regression law will be fitted to all points in which the time exceeds  $t_s$  and disregarding any point mentioned in section 3/ whose accuracy is doubtful.

### E/ Temperature

The test temperature shall be assumed to be the average of the temperature readings.

## F/ CURVE FITTING

The data are fitted by regression methods to an equation:-

$$\text{Unit strain} = k. (\text{time, years})^n$$

Data points taken before this relationship is established are not considered. For most tests the logarithmic law is established after three hours.

Three tests are normally performed, at 20%, 30 and 40% of the CBL. The results of the three tests are then combined to give a composite equation including the effects of stress:-

$$\text{Unit strain} = K . (\text{time, years})^{c1} . (\text{stress, MPa})^{c2}$$

This equation is determined by multiple regression analysis.

Tests are completed after 2000 hrs. However interim results after much shorter times give results which experience has shown to be accurate to approximately 50 microstrain (microstrain=strain $\times 10^{-6}$ ) after 100 hrs. The stability of the prediction as a function of time is reported.

Creep results can be presented as direct output from the computer used to evaluate the results. For each of the three individual tests of 20%, 30% and 40% of the CBL of the stranded conductor an equation is derived by regression:-

$$\text{Unit strain} = k. (\text{time, years})^n$$

This maybe reported as :-

$$\text{Log (Unit strain)} = K + (n. \text{Log}(\text{Time,years}))$$

The correlation co-efficient is then given. There follows a table of values predicted from the equation, where 8760 and 87600 hours correspond to 1 and 10 years respectively. Two 95% confidence limits shall then be given. The narrow limit is for the mean of the distribution, and the wider limit, which is usually used, includes the error in both the co-efficient and constant in the equation.

A further table of results shall show the development of the creep prediction over time. The measured values for a series of increasing time periods are fitted to the simple logarithmic creep equation given above. The table of results gives the parameters of the equation and the regression. This analysis provides information about the reliability of prediction of the final result of a creep test in its early stages.

The results of tests at three levels of load are then merged to give a composite equation including the effect of stress:-

$$\text{Unit strain} = K \cdot (\text{time,years})^{e1} \cdot (\text{stress,MPa})^{e2}$$

The co-efficients are determined by regression, and one and ten year creep predictions made for loads of 20%, 22%, 30% and 40% of the nominal breaking load.

Finally all results shall be presented for comparison on a single data sheet.

### REJECTION OF A TEST

A test shall be determined to be void if:

- the time before the straight line law is established is greater than 10% of the duration of the test.
- if the points rejected under section 3 exceed 10% of the points taken after the straight line law is established.
- if the temperature is more than 2.5°C different from the mean temperature for more than 2% of the temperature readings.