REVIEW OF TECHNOLOGICAL ADVANCES IN HIGH TEMPERATURE OVERHEAD LINE COMPOSITE CONDUCTORS

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Abstract

ACSR (Aluminium Conductor Steel Reinforced) conductors consisting of pure aluminum wires helically stranded around a core of high strength galvanized steel core wires are widely used in overhead transmission line applications. While the steel wires provides the required strength, the outer aluminium serves as electricity conducting member. The thermal rating or ampacity of conductors is the maximum current that a circuit can carry within the temperature limits as dictated by the allowable conductor sag or by the annealing onset temperature of the conductor, whichever is lower. On a continuous basis, ACSR may be operated at temperatures up to 100°C without any significant change in the conductor's physical properties. Above 100°C, aluminum wires loses tensile strength over time and becomes "fully annealed" giving rise to increased thermal expansion of the conductor; this causes excessive sagging reducing the clearance between the ground and the energized conductors.

While, the electric utilities are posed with increased challenges of production of additional capacities and building new transmission circuits to meet the ever growing demand and the high cost and environmental restrictions of constructing new lines, methods are being explored to increase their capacity with minimum changes in the existing towers. Replacement of the existing conductor with a advanced high temperature composite (HTC) conductors operating upto temperatures of 200°C with reduced sagging characteristics have been attempted and an increase in capacity of 30-80%, can be achieved through application of these composite conductors.

The advanced HTC conductors with varied combinations of core material and outer conducting wires are being tried so as to achieve wide ranging properties. In general, HTC conductors features the combinations of either soft aluminum wires with ultra high strength steel or temperature resistant aluminium with or fiber reinforced metal/polymer matrix composites as the core. Both the alumina fiber reinforced temperature resistant aluminium metal matrix composite and the carbon fiber reinforced high temperature polymer resin composite wires as the core material appears to have favorable applications. The comparative performance of the HTC depends on the degree to which both outer aluminum strand and reinforcing core's physical properties are stable at high temperature and on the elastic, plastic, and thermal elongation of the combined HTC.

The summary of various developments realized in the area of composite conductors and their relative merits and demerits have been discussed in detail.

Introduction

In the present day context, utilities are posed with increased challenges of additional capacities and building new transmission circuits to meet the ever growing demand. The transmission grid in the country is used up to its fullest capacity considering the safe operational conditions. Considerable research work in progress around the world to find innovative ways to increase the circuit capacities. ACSR (Aluminium Conductor Steel Reinforced) conductors are widely used in overhead transmission applications which consist of pure aluminum wires helically stranded around a core of high strength (HS) galvanized steel wires. While the steel wire provides the required strength, the outer aluminium serves as electricity conducting member. On a continuous basis, ACSR may be operated at temperatures up to 100°C without any significant change in the conductor's physical properties. Above 100°C, aluminum wire loses its tensile strength over time and becomes "fully annealed". The increased thermal expansion of the conductor causes power lines to sag reducing the clearance between the ground and the energized conductors.

In view of the stringent environmental restrictions and high cost involved in constructing new lines, methods are being explored to increase their capacity in the existing towers. These methods include

- Addition of second conductor of the same type and diameter in the existing line.
- Replacement of the existing conductor with a larger one of the same type
- Replacement of the existing conductor with a advanced HTCs of similar diameter capable of operating upto temperatures of 200°C

While methods first and second, result increase in capacity e capacity to the extent of 80-100%, it involves modifications of the existing towers. However, the application of HTC would result increased capacities upto 80% with lower sagging characteristics and can be achieved without tower modifications. Thus, the most effective way of uprating of an existing line is reconductoring with HTC with low sagging characteristics. While the application of HTC is increasingly employed in western countries, the technology is yet to be developed in the country. In general, HTC conductors feature either temperature resistant or soft aluminuim wires with high strength steel or fiber reinforced metal/polymer matrix composites as the core. The comparative performance of the HTC depends on the degree to which both outer aluminum strand and reinforcing core are stable at high temperature and on the elastic, plastic, and thermal elongation of the combined HTC. The choice of particular HTC has to be made taking into account of the constraints imposed by the existing structure as well as the economical aspects viz. cost-benefit ratio.

Thermal Rating of Transmission Line Conductors

The thermal rating or ampacity of conductors is the maximum current that a circuit can carry within the temperature limits as dictated by the allowable conductor sag or by the annealing onset temperature of the conductor whichever is lower. The maximum allowable conductor temperature is generally specified to limit the loss of strength to not more than 10% during their service life. The actual steady state operational temperature of the conductor depends on both load current and the weather conditions (intensity of solar radiation, wind velocity and ambient air temperature). Traditionally, the static line thermal rating is estimated based on steady state heat balance under severe weather conditions. Thus the actual temperature of the conductor during service is always lower than that of maximum allowable temperature.

Under these conditions, dynamic thermal uprating methods based on real time conductor temperature and sag tension are being attempted. Generation of reliable statistical data on local wind speed, variation in ambient temperature and real time monitoring of temperature and sag under different seasonal conditions are essential for arriving at the possible value of uprating. However, enhancement cannot be guaranteed at any specific time.

Requirements of Conductor Wire Properties

In order to achieve optimum performance of the overhead line conductor, specific properties viz. high conductivity, retention of strength at elevated temperature and increased strength to weight ratio are required. The advanced high temperature conductors with varied combinations of core material and outer conducting wires are being tried so as to achieve wide ranging properties.

The materials that are promising high temperature conductor applications are :

- TAL and ZTAL - Aluminum alloys that can be operated at temperatures up to 150°C and 210°C without loss of tensile strength respectively [1].

- Aweld - Alumoweld which is high strength (HS) steel wire with a thick cladding (10% of diameter) of aluminum that increases the wire conductivity and corrosion resistance in ACSR.
- Extra High Strength steel wires (EHS) - Typically supplied speciality "Galfan" galvanized coating for corrosion resistance upto 350°C [2].
- Invar steel alloy wires have reduced rate of thermal elongation and a slightly lower tensile strength than HS steel wires. At high temperature, the increase in sag of invar reinforced conductor is comparatively lower than that of ACSR [3].
- Alumina Composite wires made by 3M, USA provides the mechanical strength and low thermal elongation. This composite material has the highest conductivity and the lowest thermal elongation of the commercially available ones.
- Carbon and Glass fiber reinforced Polymer matrix composite wires are made by Composite Technology Corporation, USA. The single composite core wire offers extremely high strength properties with reduced weight of the conductors.

The properties of different materials used in conductors are given in Table-1.

Thermal Resistant Aluminium for Transmission Line Conductors

In pure aluminium, the conductivity reaches 64% IACS (International Annealed Copper Standard) and the electrical resistivity of aluminum increases with impurities. The variation of electrical conductivity with addition of different elements is shown in Fig.1. According to ASTM, the electrical grade (EC) aluminium should have a minimum of 99.45% Al content. Aluminum 1350 is a common EC grade, having 99.5% Al. The additions of elements viz. Ni, Zn, Fe, Ag, Cu, Mg, Zr, Sc etc. in small quantities helps in reducing the decline in electrical conductivity to a minimum. Of these elements, Fe which can form solid solution with aluminium provides maximum improvement in 0.2% proof stress to a value of 98 MPa per unit mass % added and aids in retaining the strength upto 200°C annealing temperatures. However, in AL-0.3Fe alloy, the electrical conductivity decreases by 1.5% IACS value at room temperature and at annealing temperatures above 250°C, the difference is less than 1% IACS. While the addition of 0.02-0.05% Zr or Sc to pure aluminium increases the thermal resistance of aluminium, decreases the electrical conductivity drastically. Thus judicious combination of Fe and Zr is required to be added to achieve optimum strength at elevated temperatures in combination with conductivity [5].

Table-1 : Physical and Mechanical Properties of Conductor Materials [4]

Wire Material	Max. Temp. (C)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Max. Elongation (%)	CTE (x 10^{-6}/C)	Conductivity (% IACS)
Conducting Wire Materials						
1350-H19 (Hard AL)	100	48.3	165	1	23	62
1350-H0 (Soft AL)	250	48.3	68.9	20	23	63
TAL	150	48.3	165	1	23	60
ZAL	210	48.3	165	1	23	60
Reinforcing Core Wire Materials						
A Weld	250	158	1310	3		20
HS Steel	200-350	193	1241	3	11.5	8
EHS Steel	-	193	1448	3	11.5	-
Invar	150	152	1104	3	6.6	15
AL-$A1_2O_3$ Fiber Composites	250	193	1379	0.7	6.3	30
Polymer-CF Composite	175	170	>1500	<1	1.5	-

The increased capacities which can be achieved through the application of thermal resistant aluminium (TAl) in place of pure 1350 grade is reported to be upto 45% for the same diameter. As seen from Fig.3, Al 1350 undergoes 2% reduction in tensile strength at 100°C where as for TAL, it occurs at 200°C, indicating lower annealing characteristics of TAL compared to pure AL1350 aluminium [6].

The improved creep resistance characteristics of TAl over AL 1350 at higher temperatures (Fig.4) indicates usefulness for elevated temperature applications.

High Strength Aluminium Fiber Composites for Transmission Line Conductors

The aluminium composite wires as a core material in overhead line conductors have been attempted in many ways using the combination of carbon fiber, glass fibers and alumina fibers. The studies on long carbon fiber reinforced aluminium wires processed through pressurized infiltration technique revealed excellent conductivity and strength properties, indicating their suitability as a core material for HTC applications [7]. The studies also indicated that optimization of processing methodology for minimizing the interfacial reaction between the carbon fiber and aluminium which would result in new high temperature conductor (Fig.5).

In another development, alumina fiber reinforced aluminium composite wire has been successfully developed by 3M corporation [8]. The composite core wire has approx. 60% by volume of alumina fibers in pure aluminium matrix. The distribution of fibers in the aluminium matrix is shown in Fig.6. The benefits in terms of improved electrical conductivity and low thermal expansion over steel wire makes these composites most suitable for conductor applications. The advantages include lower thermal expansion, equivalent strength, durability, less weight, and consistent performance at high temperatures over long periods of time.

Both the composite core and the outer Al-Zr strands contribute to the overall conductor strength and conductivity.

Design Constraints on Reconductoring Existing Lines

While reconductoring of existing lines, trade-offs between conductor resistance, thermal elongation, mechanical strength, and high temperature stability of such properties need to be taken into account. The restrictions on reconductoring is also affected by the sag constraints as well as the transverse structure load and tension limits which are set for a specific tower design.

Sag Constraints : Traditionally, the original conductor is installed at the "Initial installed sag" using stringing charts. Over time, the initial unloaded sag increases to a final "everyday" sag condition due to occasional wind loading events and the normal creep elongation process of tensioned aluminum strands. Under final conditions, the sag further increases due to high electrical loads. For most transmission lines, the larger reversible increase in final sag occurs as a result of electrical rather than mechanical loads. The typical sag characteristics of Drake type ACSR conductor is also shown in Fig.7. When reconductoring, the final unloaded sag of the new conductor at the new maximum allowable conductor temperature shall not exceed the original conductor’s final sag at the original maximum temperature.

In general, increased thermal elongation rate of ACSR conductor above the knee-point temperature is mainly due to the relaxation of both compression effect and residual stress in the helically wound aluminium strands [9,10].

Tension Constraints : When reconductoring, the original load limits of the existing structures should not be exceeded. For tangent structures, the governing transverse loads are primarily a function of the conductor diameter and variation of 10% of the existing conductor is allowed without tower modifications. For angle and dead-end structures, the governing loads are primarily a function of the initial maximum conductor tension and hence maximum tension should not exceed the initial conductor tension.

Rated Strength of High Temperature Composite Conductors

The breaking strength of conductors get affected during service conditions viz. temperature induced softening, corrosion, or fatigue due to vibrations etc. In general, the conductor breaks at the minimum elongation applicable for core and outer strand component. In ACSR conductors, the pure aluminum strands break at an elongation of approximately 1% whereas the steel core breaks at an elongation of approximately 3%. The conductor’s breaking strength is therefore determined using the tensile strength of the aluminum strands and the tensile stress in steel with a 1% elongation. In contrast, HTC comprising annealed aluminum strands, the rated breaking strength is calculated using the tensile strength of the steel core and the stress of annealed aluminum strands at 3% elongation. When materials other than steel are used to reinforce aluminum conductors, the following points must be taken into account.

- The physical properties of the reinforcing materials must remain stable at high temperatures and reinforcing material must not react chemically with outer aluminium.
- Regardless of the reinforcing material chosen, if full hard 1350-H19 aluminum strands are used in the replacement conductor, the composite strength will decline at temperatures above 100°C.
- If high temperature alloys of aluminum are used, then the rated strength of the HTC conductor will be determined by the tensile strength of the stranded component with the smallest maximum elongation plus the stress of the other component at that elongation.

Sag Increase with Conductor Temperature

In order to maintain adequate clearance to ground and to other conductors, a maximum power flow on transmission lines (the thermal limit) is specified. In most cases, sag under wind loading is less than the sag that occurs for high currents. Low thermal elongation, initial sag and low plastic elongation properties are considered desirable. The variation of sag with conductor temperature for different conductors is shown in Fig.8. It may be noted that the transition to lower sag occurs in HTC s above 90°C to 100°C.

Status of Development on High Temperature Conductors

According to the type of core and outer stranding configurations, the various types of HT conductors are classified in the following category.

ACSR/AW	ACSR, with Aluminium clad steel core
ACSR/TW	ACSR, with Trapezoidal aluminium strands
ACSS/TW	Aluminium Conductor Steel Supported, with trapezoidal shaped fully annealed soft aluminium
G (Z) TACSR	Gap-type Thermal resistance Aluminium Conductor Steel Reinforced
(Z) TACSR	Thermal resistant Aluminium Conductor Steel Reinforced
(Z) TACIR	Thermal resistant Aluminium Conductor Invar Reinforced
(T) ACFR	Thermal resistant Aluminium Conductor Fibre Reinforced
ACCR/TW	Aluminium Conductor Composite Reinforced/Trapezoidal wires
ACCC/TW	Aluminium Conductor Composite Core/Trapezoidal wires

The main characteristics of different configurations of primary HTCs are detailed below:

Modified ACSR Conductors

The ACSR conductor is considered not suitable for upgrading. While the modification in terms of aluminum clad steel core and trapezoidal shaped conducting wires of same diameter slightly brings down the electrical losses, the increase in ampacity achievable is very small. This invariably requires tower modifications.

ACSS Conductors

ACSS conductors are similar in design as ACSR but with higher strength steel alloy wires (EHS grade) having 20-30% elongation as its core [11]. ACSS conductors are designed to support 100% of the tensile load on the conductor core. The fully annealed strands of ACSS also provide a higher conductivity value and hence increased current can pass through a given conductor size at a given temperature. The performance of these conductors have been proven upto 250°C without the sag differential. Because of the low yield strength of annealed aluminium, inelastic elongation of the aluminum occurs quite rapidly when tension is applied to an ACSS conductor, thereby forcing most of the load on to the steel core. In ACSS, then, the steel is the least ductile material and it is not necessary to restrict its usable strength to one percent extension as it is in ACSR.

As the operating stresses in the aluminum wires of ACSS are much lower than in ACSR, there is less static-state frictional coupling between wires in successive layers. As a result, the aluminum wires in ACSS are much more free to move relative to the wires of other layers when the conductor is flexed, giving rise to improved self damping characteristics. The main limitation with ACSS is its relatively low strength and modulus and limits its use in regions experiencing high ice loads.

Gap Type Conductors

The gap-type conductor differs from the traditional conductor by its gap between the core and the outer thermal resistant aluminium alloy conductor strands. This gap is filled with thermal resistant grease allowing the core and the conducting strands to move independently from each other, without friction. The improved annealing resistance of conductor strands allows the conductor to operate at a higher temperature. Depending upon the outer conductor alloy type viz. TAL or ZAL, the Gap conductors are called as GTACSR or GZTACSR conductors. The typical Gap type conductor is shown in Fig.9.

Specific stringing procedures involving staged pulling and compression joint are required which in turn increases the installation time [12]. Since the TAL layers expand faster than the steel core, then the alloy carries no mechanical load and the conductor has a CTE equal to that of steel ($11.5x10^{-6}/^{0}C$). Conversely, at temperatures below the erection temperature, the TAL contracts faster than the steel core, resulting in the full conductor carrying mechanical load. The CTE under these conditions is similar to that of a standard ACSR (approximately 18 to $20x10^{-6}/^{0}C$). It may be noted that the knee-point temperature to lie on the stringing or tensioning temperature.

The advantages of the gap-type conductor includes higher operating temperature (150° to 180°C) and ampacity, lower sag, due to smaller elongation coefficient and higher elasticity modulus and high tensile strength.

Invar Cored HT Conductors (TACIR)

In this type of conductor, thermal resistant aluminium alloy conductor strands are reinforced by high nickel-iron alloy known as invar in a standard ACSR form and can therefore be installed using standard methods [3] (Fig.10). As invar has very low coefficient of thermal expansion (3 to $4x10^{-6}/^{0}C$) makes it suitable for higher temperature operations. However, the tensile strength of invar is lower than that of steel core wire used in ACSR conductors. The CTE of TACIR at ambient temperature is only 10 to 20% smaller than that of a standard ACSR but, as its temperature is increased, the core expands much more slowly than the TAl. At the 'transition' or 'critical' temperature, the TAl ceases to carry mechanical load and the CTE drops compared to that of invar. Thereafter, the increase of sag with temperature becomes very small. However, the value of the critical temperature is typically around 900°C. Since the NGC twin lines were originally designed for ACSR at 500°C, by the time a TACIR had reached its critical temperature, the available clearance would already have been infringed and no advantage could be taken of its low sag, 'supercritica'l performance. In contrast, the critical temperature for a GTACSR occurs at the erection temperature.

ACFR Conductors

The composite core wire technology is considered as one of the emerging conductor technologies for higher temperature applications. The development of fiberglass composite reinforced core is under progress and the effect of high temperature exposure is yet to be established. In view of low modulus of fiberglass, it appears that it is suitable for short span, low tension conditions [13]. This composite is capable of withstanding temperatures up to 150°C. The ACFR is about 30% lighter and it has an expansion coefficient (above the knee-point) of 8% than that of an ACSR of the same stranding, giving an increase in rating of around 50% without structural modifications [14].

ACCR Conductors

3M, USA, has developed the Aluminum Conductor Composite Reinforced (ACCR). The core is an aluminum-matrix composite containing alumina fibers, with the outer layers made from a heat-resistant zirconium alloyed aluminum. As with the ACFR, the low-expansion coefficient of the core contributes to a fairly low knee-point, allowing the conductor to make full use of the heat resistant alloy within the existing sag constraints [15]. Depending on the application, increase in ratings between 50% to 200% are possible as the conductor can be rated up to 230°C.

In view of the increased aluminum for a given diameter of the conductor, increased current can be carried by these conductors. Also, as the use of steel is totally eliminated, the total weight of the conductor is reduced and intermetallic corrosion problems are eliminated. The stringing procedures typically followed for a ACSR with little modification can be easily followed (Fig.11).

ACCC Conductors

The ACCC conductors consist of fiber reinforced polymeric core surrounded by trapezoidal heat resistant aluminium wires. The reinforcement core is made up of both carbon fiber reinforcement with outer layer with glass fibers supported in a thermoplastic resin. In order to avoid the reaction between the carbon fibers and the aluminum metal, the core of thin shell of glass fiber reinforced composite layer surrounded by the carbon fiber reinforcement is made. The typical characteristics are

- 28% more aluminium - Greater capacity, lower losses
- 25% stronger and 60% lighter than traditional core - Lower structures
- Lower coeff. of thermal expansion - Less sag at elevated temperatures.
- Max. service temperature upto 175°C

The ACCC conductors, (Fig.12) exhibit both efficiency and increased current carrying capacity and resulting in corrosion free environmental conditions during service. At present, over 9,500 kilometers of ACCC conductor have been installed worldwide, which has definitely proven its effectiveness in transmission and distribution systems.

Comparisons of High Temperature Conductors

The choice of replacement conductor depends on parameters such as electrical losses (Resistance per unit length), Sag increase with temperature, modulus and rated strength.

Electrical losses over a given transmission path are a function of the conductor resistance, the length of the path, and time. The resistance of a stranded bare overhead conductor depends on the diameter, metal resistivity and ferromagnetic losses. The fiber reinforced polymeric core construction would result in lower losses compared to other metallic based core materials in view of the lower resistance compared to steel core. The conductivity of annealed aluminum is 1% more than that of hard aluminum. However, addition of alloying elements such as Zr decreases the conductivity marginally. Galvanized steel wires have a conductivity of 8% of IACS, Alumoweld wires of 20% IACS, and the 3M composite core wires of 30% IACS. The trapezoidal form of strands give rise to increased aluminium area and hence increase in ampacity is achievable.

Sag Increase with Temperature : The transmission lines are seldom run to temperatures in excess of 100°C. Only for the last couple of years the application of HT conductors capable of operation up to 200°C have been used. As such there is little field data to verify the calculated sag variation of HTC with temperatures above 75°C. In addition the accuracy of sag-tension calculations are affected by the uncertainties in respect of both "Knee point temperature" of ACSR and the conductor's radial temperature gradient. At the knee point temperature, the complete tension load is taken by the steel core. Above knee point, the thermal elongation characteristics are affected by the natural ability of helically wound aluminium strands to support limited compression as well as the residual stresses in the aluminum strands. The knee point temperature is typically a function of the steel content and increases as the % steel area decreases.

The applicability of these theories to HTC is uncertain but important from the view point of evaluation. In view of these uncertainties, collection and analysis of sag-temperature-tension field data for field installations with high current loading is required for evaluating HTCs.

Summary of Review

In the present day crisis, high temperature, low sag conductors appears possible solution to the capacity problems. The composite core conductors have the ability to increase the ampacity over 100% without tower modifications. The disadvantages of composite conductors are the increased electric losses associated with elevated temperature operation as well as higher investment costs. The other disadvantage is that their proven life time is yet to be fully established. Since these conductors are relatively new and have not yet been implemented on a large scale, there is a lack of experience concerning the ageing of the conductor.

The gap-type conductor and the ACSS conductor can increase the ampacity up to 65%, without tower modifications. Since these conductors are made of almost the same materials as that of the ACSR conductor, the lifetime can be expected to be comparable. The main limitation with ACSS is its relatively low strength and modulus that limits its use in regions experiencing high ice loads.

Invar steel is somewhat weaker than conventional steel core wire limiting its use in high ice load areas and compression effects in the aluminum strands may increase the thermal elongation.

When a higher ampacity over 65% is required, the ACCC and ACCR conductors can be used. ACCR conductor has an extremely low thermal elongation rate. The combination of alumina composite core wires and zirconium high temperature aluminum alloy yields higher rated strength and higher modulus in combination with low resistance. Largest increase in rating for the reconductoring applications are possible through ACCR conductors.

The negative thermal elongation behavior of carbon fibers combined with low density and "steel-like" tensile strength and modulus of ACCC seems to be potentially attractive but the low shear strength of carbon fibers, the problems of corrosion, and high fabrication and material cost appears possible drawbacks.

References

1. Kikuta Takatashi., "Low Sag Up-rating Conductor", IEEE Panel Session on Applications and Economics of New Conductor Types, Vancouver, BC, July, 2001.

2. Thrash, F. Ridley., "ACSS/TW - An Improved Conductor for Upgrading Existing Lines or New Construction", IEEE Paper 0-7803-5515, June, 1999.

3. Sato, K., Mori, N. et al., "Development of Extremely-Low-Sag Invar Reinforced ACSR (XTACIR)", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No.4, April, 1981.

4. "High Temperature Low Sag Conductors", EPRI, Final Report, June, 2002.

5. "Hitachhi Cable Review, Development of Alu-Minium Alloy Conductor with High Electrical Conductivity and Controlled Tensile Strength and Elongation", No.25, August, 2006.

6. Technical News Letter, Furukhava, No.3, 1999.

7. Pippel, E., Woltersdor, J. et.al., "Interlayer Structure of Carbon Fibre Reinforced Aluminium Wires", Jl. of Mat. Science, 35, p.2279, 2000.

8. Technical Data Sheet, 3M Aluminium Matrix Composites.

9. Barrett, J.S., Ralston, P. and Nigol, O., "Mechanical Behaviour of ACSR Conductors", CIGRE International Conference on Large High Voltage Electric Systems, September 1-9, 1982.

10. Rawlins Charles B., "Some Effects of Mill Practice on the Stress Strain Behavior of ACSR", Presented at IEEE Winter Meeting, Tampa, FL, February, 1998.

11. Thrash, F.R. Jr., "ACSS/TW - An Improved Conductor for Upgrading Existing Lines or New Construction", Transmission and Distribution Conference, IEEE, 1999.

12. Tunstall, M.J. et al., "Maximizing the Ratings of National Grid's Existing Transmission Lines Using High Temperature Low-sag Conductor", CIGRE Paper 22-202, Paris, France, August, 2000.

13. Hiel Clem., "Development of a Composite Reinforced Aluminum Conductor", California Energy Commission Report, November, 2000.

14. Smith Jack (Applied Thermal Sciences)., "Advanced cArbon Conductor Project Report".

15. Johnson Doug., "Composite Conductors - A New Overhead Conductor (ACCR)", IEEE Panel Session on Applications and Economics of New Conductor Types, Vancouver, BC, July, 2001.

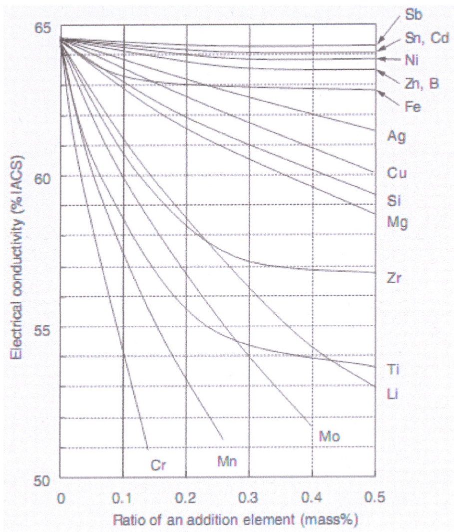

Fig.1 Influence of the Addition Element on Electrical Conductivity of Aluminium

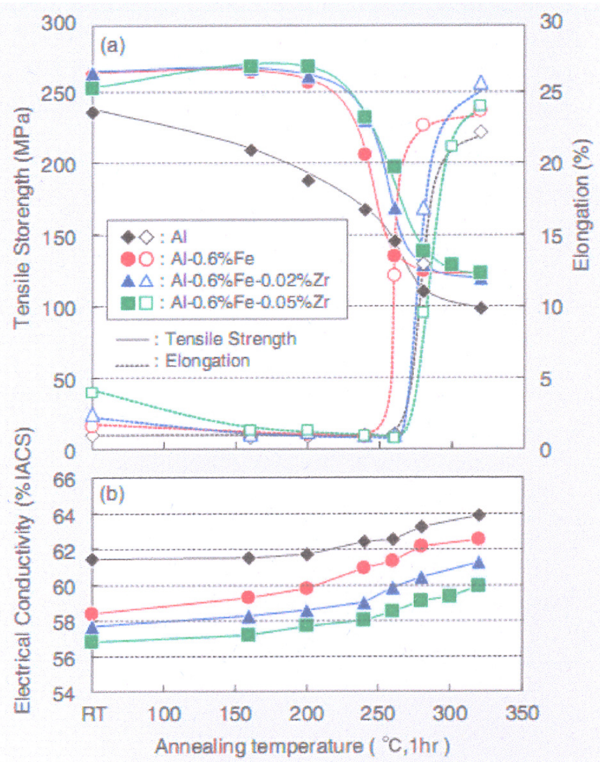

Fig.2 Effect of Heat Treatment on Strength and Conductivity of A1-Fe-Zr Alloy

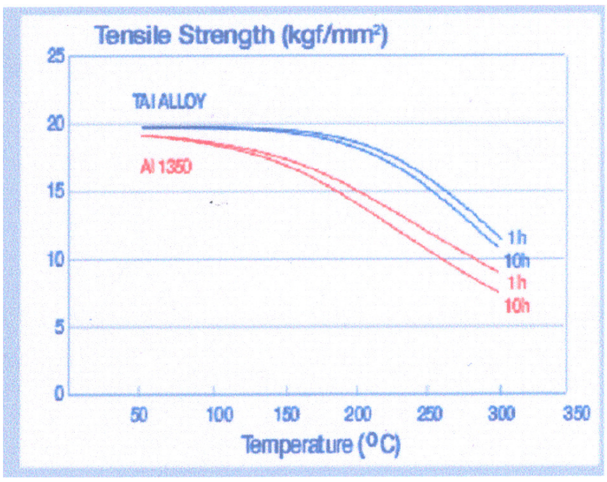

Fig.3 Annealing Characteristics of TAL

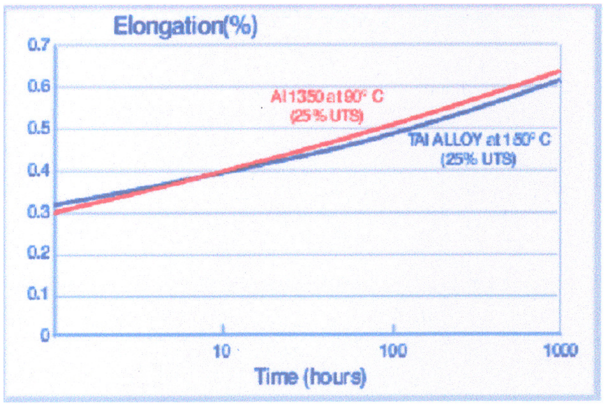

Fig.4 Comparison of Creep Characteristics of TAL and AL1350 Grade

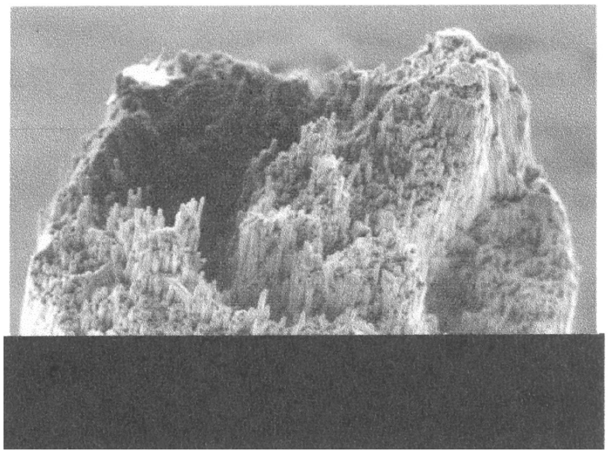

Fig.5 Fracture Surface of Tensile Test Specimen of Aluminium-Carbon Fiber Composite Wire

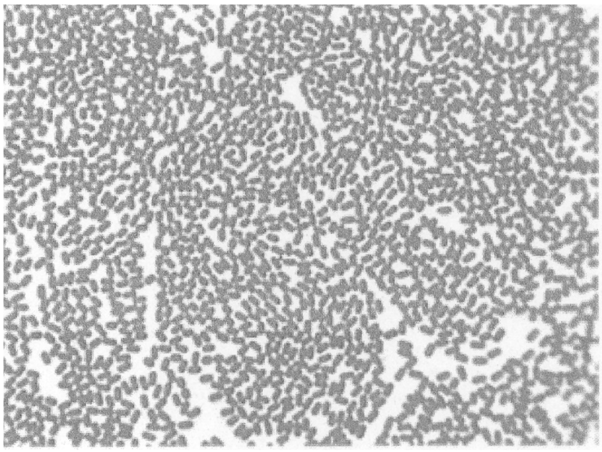

Fig.6 Conductor Wire with Sub Micron $A1_2O_3$ Fibers in Aluminium Matrix

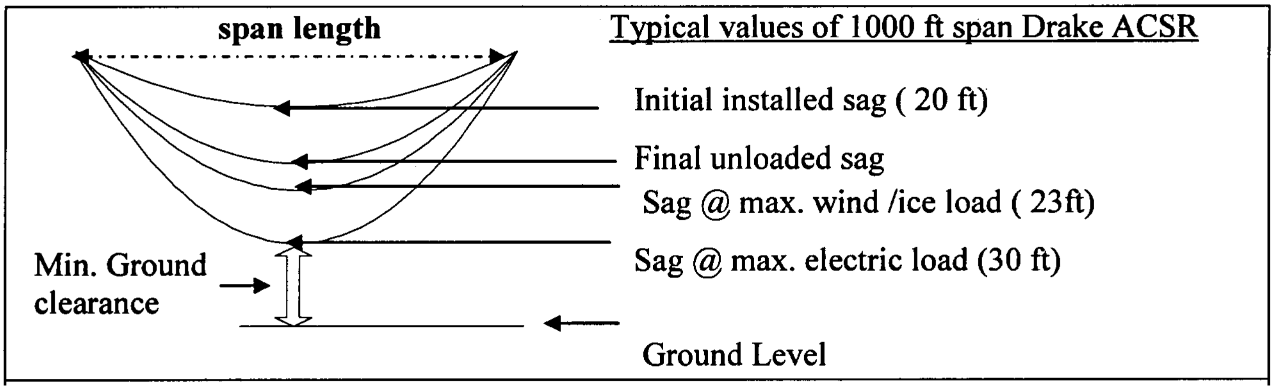

Fig.7 Typical Sagging Characteristics of Line Conductor

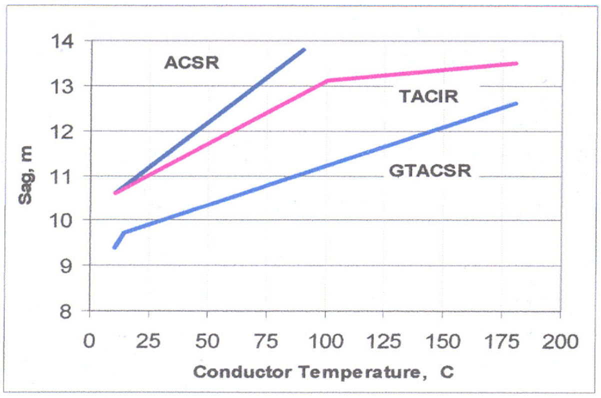

Fig.8 Sagging Characteristics of ACSR and HTCs

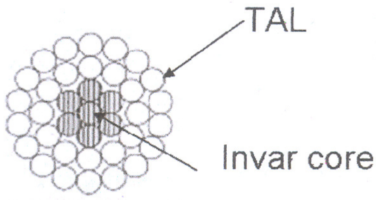

Fig.10

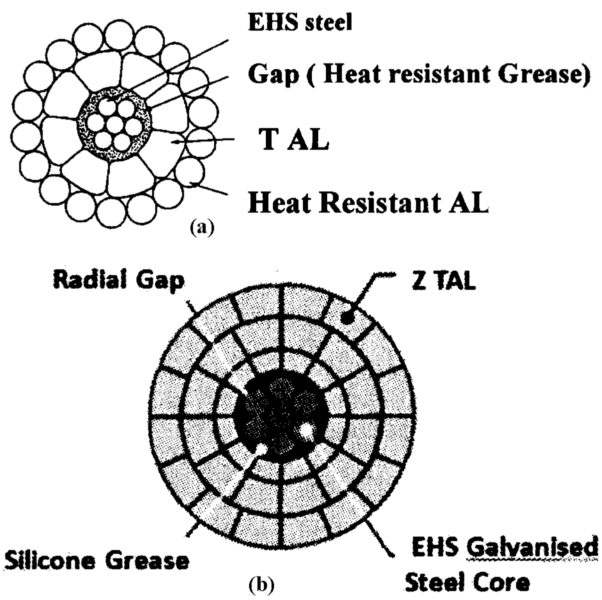

Fig.9 Different Configurations of Gap Type Conductors (a) GTACSR (b) Z Type GTACSR

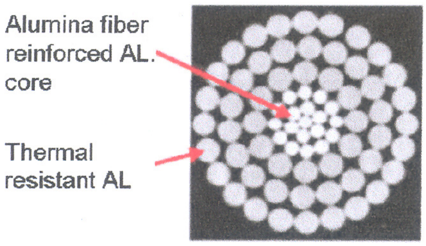

Fig.11

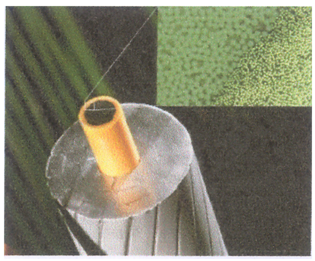

Fig.12