CONSULTANT REPORT

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Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Strategic Energy Research

DEVELOPMENT OF A COMPOSITE REINFORCED ALUMINUM CONDUCTOR

Gray Davis, *Governor*

NOVEMBER 2000

CALIFORNIA ENERGY COMMISSION

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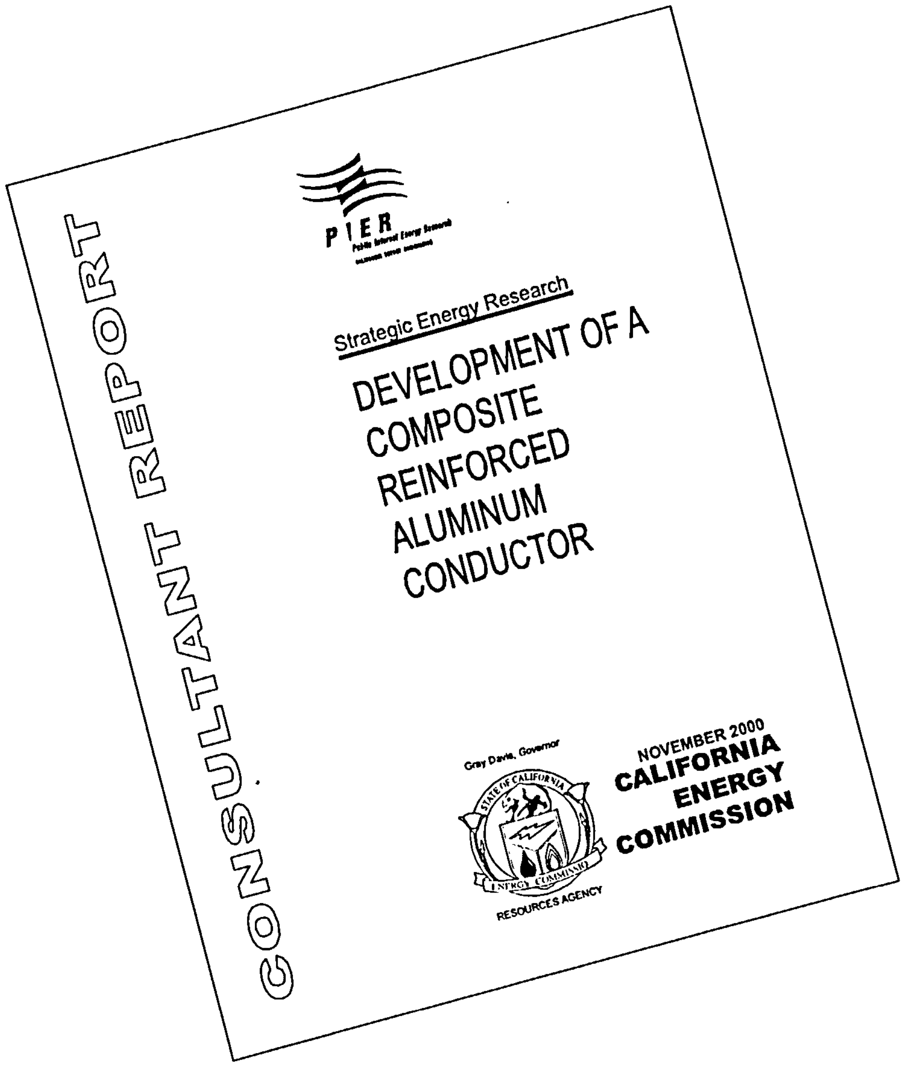

CALIFORNIA ENERGY COMMISSION

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the Development of a Composite Reinforced Aluminum Conductor, Contract Number 500-98-035, conducted by the W. Brandt Goldsworthy & Associates, Inc. The report is entitled Development of a Composite Reinforced Aluminum Conductor. This project contributes to the Strategic Energy Research program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Introduction

Many miles of California's overhead electricity transmission lines have reached the end of their service lives or are being stressed beyond their design limits due to load growth and heavy power transfers across long distances. The overall goal of this project was to improve the reliability and capability of California's transmission and distribution system by developing a stronger and lighter conductor to replace these aging and overloaded power lines. Specifically, this project planned to develop a Composite-Reinforced Aluminum Conductor (CRAC) to replace conventional Aluminum Conductor-Steel Reinforced (ACSR) conductors that are made from aluminum wires wrapped around a core of steel strands. One such conductor identified as DRAKE was used as a benchmark conductor throughout this project.

Objectives

The objectives of this project were to:

- Develop one or more CRAC that, compared to DRAKE, would:
  - Achieve five percent more electrical conductivity
  - Achieve 40 percent more ampacity
  - Get 20 percent less mechanical elongation (line sag) at ambient operating temperatures
  - Achieve a 30 percent strength increase
  - Reduce weight by 66 percent
- Develop splicing techniques and tool(s) to enable the spliced CRAC to:
  - Achieve the same conductivity as unspliced CRAC
  - Conduct the same electrical loads as the parent cable

Outcomes

The project had the following outcomes:

- Two CRAC, CRAC-121 (one-to-one) and CRAC-Advanced, were developed during this project. Both achieved:
  - Five percent more electrical conductivity than DRAKE.
  - A minimum of 40 percent more ampacity than DRAKE.
  - Twenty percent less mechanical elongation at ambient operating temperatures.
  - A 30 percent strength increase compared to DRAKE.
  - Only a 25 percent weight reduction was achieved and the objective of a 66 percent reduction was not met. In retrospect, this turned out to be an ill-posed objective because the maximum possible weight reduction, achieved by taking all the steel out of the DRAKE conductor, is only 33 percent.
- Splicing techniques were developed and demonstrated for both CRAC.

- A splicing tool was developed to splice the composite strength member.
- There were two very positive unanticipated outcomes.
  - CRAC conductors were found to operate 9 (CRAC-121) to 25 percent (CRAC Advanced) cooler than ACSR conductors.
  - Both conductor designs can carry optical fibers in the hollow center. When optical fibers are added, these conductors are called CRAC-TelePower.

Conclusions

- We verified our hypothesis that it would be possible to replace a relatively heavy steel strength member with a much lighter weight composite. Making this replacement proved very beneficial to conductor performance.
- We found that utility personnel were much more comfortable with the CRAC-121 because it looks and splices like the DRAKE conductor they are used to. It is our belief that it will be easier to bring this conductor to market than the CRAC-Advanced.
- We also found out that the unanticipated outcome of being able to insert a fiber optic cable into the core of the CRAC was of at least as much interest to the utilities as the improvements in mechanical and electrical performance.
- As a general conclusion it can be stated that this project has pushed far beyond ACSR conductor technology, which essentially emerged in the late 1800's. The result is a modern twenty-first century CRAC-TelePower capable of transmitting electrical power as well as broadband data.

Benefits to California

This project contributed to the Public Interest Energy Research (PIER) program objective of improving the reliability of California's electrical system by developing a conductor better able to withstand adverse weather and high-load conditions, thereby avoiding power outages caused by line sagging and swinging.

When CRAC or CRAC-TelePower is commercialized, it will also contribute to the PIER program objective of improving the energy value of California's electricity by reducing the costs of re-conductoring (replacing inadequate transmission lines with new lines). Specifically, because new transmission lines made of CRAC can carry more electrical current than comparably sized ACSR conductors, support towers would not need rebuilding to accommodate heavier, equivalent-capacity conventional conductors.

In addition, the use of CRAC TelePower will increase the value and the use of the electric utility's right-of-way by providing new locations for high-speed, high-bandwidth data transmission. It might even lead to the creation of data transmission utilities.

Recommendations

We recommend that:

- Splicing techniques be developed and tested for use on the fiber optic cables.
- That tests be conducted as part of a Phase-II project to demonstrate that improvement as high as 200 percent more ampacity is attainable.
- Tests be performed on 150-foot lengths of conductor to verify sag and to demonstrate CRAC conductor's ability to transmit data in the optical fiber core, both to monitor the performance of the cable and to provide for the transmission of high-bandwidth data.
- Tests be performed on a 2000-foot span in a utility transmission system to demonstrate CRAC's performance in real world applications.
- The CRAC-TelePower 121 be pursued as the cornerstone of a Phase-II project.
- The original CRAC Team be strengthened with a member possessing expertise in digital data transfer using fiber optics technology.

Abstract

The purpose of this project was to develop a Composite Reinforced Aluminum Conductor (CRAC) for use in electricity transmission systems.

The objectives of this project were to develop one or more CRAC with greatly improved mechanical and electrical properties. Additionally the aim was to develop new splicing techniques for CRAC.

These objectives were met by the project, and in addition two unanticipated outcomes were obtained. First, CRAC was found to operate 9 (CRAC-121) to 25 percent (CRAC Advanced) cooler than ACSR conductors. Second CRAC designs can carry optical fibers in the hollow center. Due to this additional capability, these conductors have been called CRAC-TelePower.

The project's conclusions were that it is possible to replace a relatively heavy steel strength member with a much lighter weight thermoplastic composite material that proved very beneficial to the performance of the conductor.

The unanticipated outcome of being able to insert a fiber optic cable into the core of the CRAC conductor was of at least as much interest to the utilities as the improvements to the mechanical and the electrical performance.

This project contributed to the Public Interest Energy Research (PIER) program objective of improving the reliability of California's electrical system by developing a conductor better able to withstand adverse weather and high-load conditions, thereby avoiding power outages caused by line sagging and swinging.

Based on the success of the project the CRAC-Team recommends that the conductor design identified as CRAC-TelePower 121 be pursued as the cornerstone of a Phase-II testing and manufacturing demo-project.

Keywords: Composite, Thermoplastic, CRAC, TelePower, Fiber Optic Cable, Splicing, Reliability, Sag

1.0 Introduction

Many miles of California's overhead electricity transmission lines have reached the end of their service lives or are being stressed beyond their design limits due to load growth and heavy power transfers across long distances. The overall goal of this project was to improve the reliability and capability of California's transmission and distribution system by developing a stronger and lighter conductor to replace these aging and overloaded power lines. Specifically, this project planned to develop a Composite-Reinforced Aluminum Conductor (CRAC) to replace conventional Aluminum Conductor-Steel Reinforced (ACSR) conductors made from aluminum wires wrapped around a core of steel strands. One such conductor identified as DRAKE was used as a benchmark conductor throughout this project.

1.1. Objectives

The objectives of this project were to:

- Develop one or more CRAC conductors that, compared to DRAKE, would:
  - Achieve five percent more electrical conductivity
  - Achieve 40 percent more ampacity
  - Get 20 percent less mechanical elongation (line sag) at ambient operating temperatures
  - Achieve a 30 percent strength increase
  - Reduce the weight by 66 percent
- Develop splicing techniques and tool that enables the spliced CRAC to
  - Achieve the same conductivity as unspliced CRAC
  - Conduct the same electrical loads as the parent cable.

2.0 Discussion

2.1. Background on ACSR Conductors

This section provides a background on state of the art Aluminum Conductor Steel Reinforced (ACSR) conductors (Figure 1). These conductors were originally designed in the late 1800s with a steel strength member located in their center. The conductor shown in Figure 1 is identified throughout the industry as DRAKE. Because of its widespread use throughout the utility industry it was selected as a benchmark conductor for this research and development project.

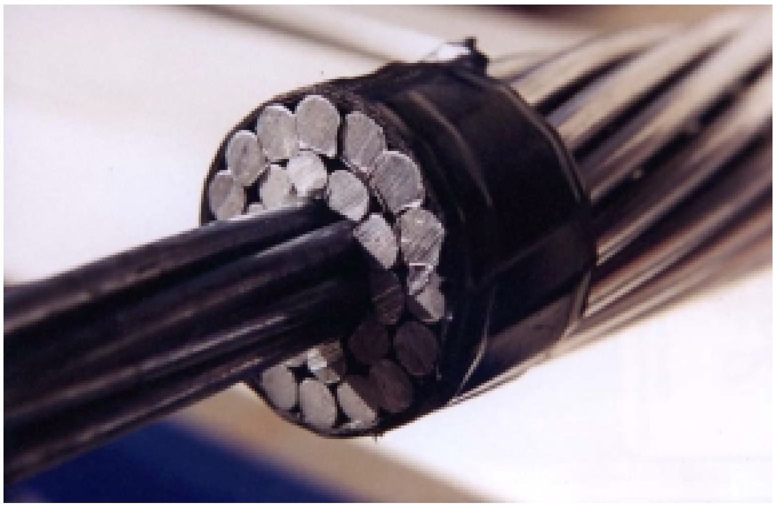

Figure 1. State of the Art ACSR Conductor

The outer two layers of DRAKE consist of a total of twenty-six individual wires of 1350-aluminum alloy. These are spirally wrapped around a core of seven individual steel wires. The arrows in Figure 1 pointing to the aluminum and to the steel strands indicate their weight per 1000 feet of conductor length. This report refers back to those numbers in the discussion on the performance objectives.

The wrapping of individual steel and aluminum strands was essentially inspired by the way ropes are made. This construction assured that the conductor is sufficiently flexible so that it could be stored and shipped on fairly small diameter drums.

The arrows also indicate the cross-sectional area occupied by aluminum and steel. This reveals that the steel, although it constitutes 31.5 percent of the conductor by weight, only occupies 14 percent of the cross-section and therefore of the volume.

The characteristics of ACSR-DRAKE are:

- The aluminum alloy is 1350 aluminum alloy with a minimum purity of 99.5 percent. The chemical composition is listed in American Society for Testing of Materials (ASTM) B-233
- The steel is a high carbon steel with a carbon content of 0.5-0.85 percent. The chemical composition is listed in ASTM B-498
- The outer diameter (OD) of the aluminum wires is 0.1749”

- The OD of the steel wires is 0.1360”
- The stranded core OD is 0.4080”
- Conductor OD is 1.108”
- The conductor weight is 1093.4 lbs / 1000 ft
- Aluminum wires have a minimum conductivity of 61 percent and a minimum average conductivity for all wires in the conductor of 61.2 percent
- Steel core conductivity is not defined but accepted to be eight to nine percent
- Conductor construction requirements are defined in ASTM B-232 for stranded conductor and ASTM B-498 for the steel core.

2.2. Approach

To achieve the project’s objectives, we undertook three tasks:

- Design CRAC conductor configuration
- Develop CRAC splicing tool
- Develop CRAC fabrication tool
- Perform bench testing of CRAC.

The approach for each task is discussed below.

2.2.1. CRAC Configuration

This project demonstrated the feasibility of a new generation conductor (Figure 2). Because the steel was replaced with lightweight/high strength composite material we elected to name this conductor CRAC.

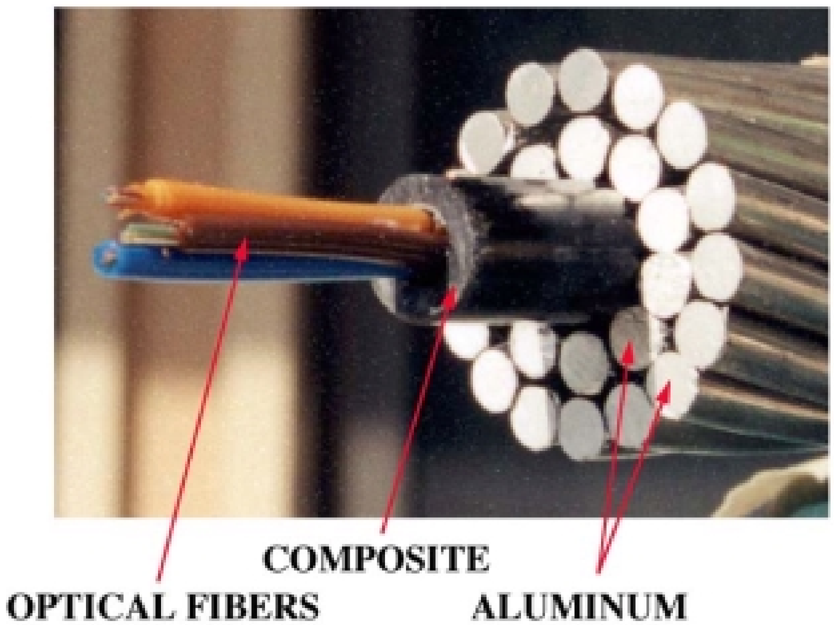

Figure 2. CRAC-121

The cornerstone of the approach lay in replacing the steel in the ACSR conductor with a lighter weight but stronger thermoplastic composite material. The specific composite material chosen for this project was commingled fibers consisting of E-glass and polypropylene. Several innovative CRAC configurations emerged as a result of this approach. This led to two proposed CRAC conductors that go even further beyond the current state of the art than we originally anticipated.

We identified the two conductor configuration designs as CRAC-121 and CRAC-Advanced. Both conductor designs can carry optical fibers in the hollow center. When optical fibers are added, these conductors are called CRAC-TelePower.

2.2.1.1. CRAC-121

The designation CRAC-121 is derived from the fact that this configuration replaces steel with composite in a one (1) to (2) one (1) fashion. Figure 3 shows the CRAC-121 that embodied our approach.

Figure 3. CRAC-121 Design Configuration

We assembled a prototype CRAC-121 conductor by placing six pie-shaped composite segments inside the DRAKE benchmark conductor.

This conductor has the exact same diameter of 1.08” as the benchmark DRAKE conductor. By respecting this diameter we ensure that there is no increase in the mechanical loads (wind, vibration, ice).

The use of trapezoidal aluminum wire in CRAC-TelePower instead of stranded aluminum wires provided a significantly better packing-density. DRAKE requires 0.6247 square inches of 1350 aluminum in its cross-section. This needed amount of aluminum is captured in the CRAC between the outside diameter of 1.08” and an inside diameter of 0.62”.

For the DRAKE conductor the needed amount of aluminum is captured between the 1.08” outside diameter and an inside diameter of 0.41”.

The density of composite material strength member is 1.4735 megagram (Mg) / m^3 as compared to the 7.8 mg / m^3 for high strength steel. This makes the CRAC-TelePower composite strength member lighter by a factor of 5.29 or 529 percent for a weight of 819 lbs / 1000 ft.

Also shown at the very center of CRAC-121 (Figure 2.) is a bundle of fiber optic cables used for the data transmission. By relying on the improved packing density of the aluminum only, the diameter in the center, which can be made available for fiber optics, is 0.23”. This provides a data transmission capacity far in excess of future needs. In addition this space is available in each of the three phases of the transmission line.

It is recommended that the CRAC-Team be strengthened with expertise in fiber optics to further capitalize on this advantage.

2.2.1.2. CRAC Advanced

We investigated an alternative design that reconfigured the conductor cross-section (Figure 4).

Figure 4. CRAC-TelePower-Advanced

The composite strength member was placed on the outside with the aluminum on the inside.

This conductor configuration was also taken into the prototype stage. Because of its different configuration, it is likely to be further away from market acceptance than the 121-conductor.

2.2.2. Techniques and Tool for Splicing

The CRAC designs include considerations for splicing, because without it the designs cannot be implemented by the utilities due to a lack of practicality. Figure 5 shows the splicing concept for CRAC-121.

Figure 5. Splicing of CRAC-121

By staggering the bond lines between segments in the lengthwise direction there is a gradual transfer of load. This type of joining is regarded in the aerospace industry as the strongest bonded connection that can possibly be made.

As a result of the ASTM mechanical testing, the failure occurred outside of the splices. This reveals that the spliced area is stronger than the parent material. This is a very significant result because it reveals that the splicing is both practical and feasible.

Figure 6. shows a schematic of the tool developed for splicing.

Figure 6. Tool for Conductor Splicing

As was discussed, this is needed to make the CRAC-TelePower conductor a viable and practical alternative for the utilities. The setup allows for the proper alignment of the strength member. The individual segments can be welded by simply heating them and simultaneously providing pressure to each bond line. This was accomplished with a heater / die assembly and splicing jig.

Figure 7 shows the splicing sequence for CRAC-121.

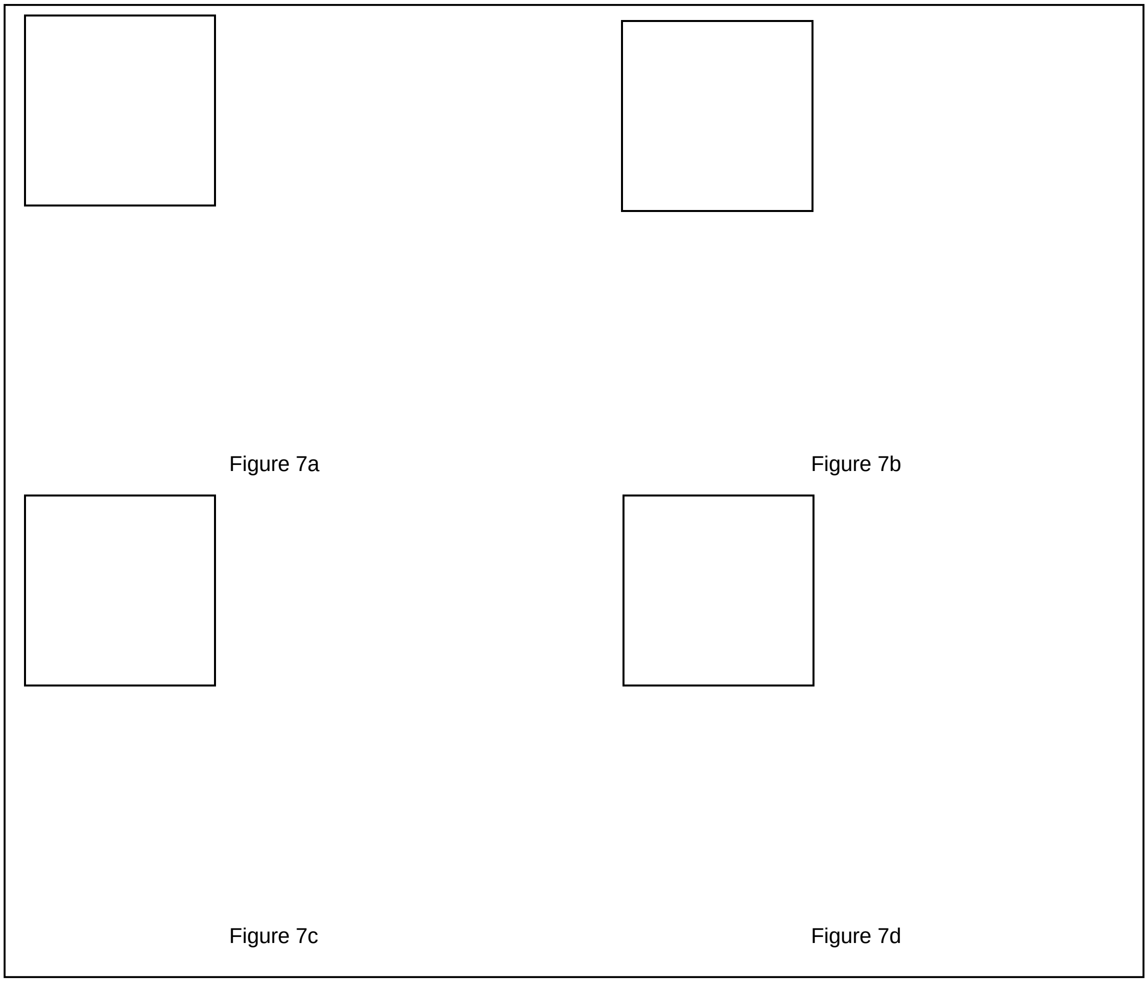

Figure 7. Splicing Sequence for CRAC-121

The installation of an aluminum sleeve on the outside follows standard practice for ACSR conductors. Because the electrical configuration has been well accepted and used in the field, we did not further scrutinize this configuration.

Figure 8 shows the splicing sequence for the case of the CRAC-Advanced conductor.

Figure 8. Splicing Sequence for CRAC-Advanced

We did not determine how to splice the fiber optic cable during this project. This will need to be done in the next phase, after the CRAC-Team has been strengthened with in digital fiber optics.

2.2.3. Development of Tool to Fabricate the CRAC Conductor

Figure 9 shows the lower part of the tool designed to fabricate CRAC-121. This tool enables fabrication of the pie-shaped composite material segments. Six of these pie-shaped segments form the composite strength member.

Figure 9. Tool for CRAC-121 Segments

Figure 10 shows the assembled tool in operation.

Figure 10. Tool in Operation

A segment is seen to exit the tool. The copper connections on the left and right of the tool allow for the flow of coolant that chills the tool and allows the unidirectional thermoplastic composite material to solidify.

Figure 11 shows a picture of the in-feed section of the tool as part of the overall manufacturing (pultrusion) setup for making the segments.

Figure 11. Setup for Fabrication of Pie-Shaped Segments

The commingled glass and thermoplastic fibers are pulled from the spools and fed into the entrance of the tool. A process of heating and chilling produces a continuous stream of solid pie-shaped segments.

2.2.4. Bench testing of CRAC Setup and Methods.

Two 4-foot long bench prototypes have been fabricated for each CRAC-TelePower conductor design. The fabrication made use of techniques and concepts, which can be scaled up, in later phases, to fabricate thousands of feet of the conductor.

The setup and methods for mechanical testing are discussed in ASTM D3039 [1]. This ASTM standard covers both the setup and the method. These tests were performed at University of Southern California (USC).

The setup and methods for electrical testing was established in cooperation with Southern California Edison (SCE). Figure 12 shows the electrical testing with a number of conductors in series. This includes two 4-foot prototype pieces of each CRAC and the Benchmark DRAKE conductor.

Figure 12. Electrical Test Setup at SCE

The conductivity (resistivity) of the conductor material was measured according to the test protocols of ASTM B193. We also conducted the bench tests using the standards, test setup, and tests methods provided in ASTM B193.

2.3. Results

The discussion below reviews the results in terms of the stated objectives.

<u>Both conductors achieved 5 percent more electrical conductivity than DRAKE.</u>

The three ways to increase electrical conductivity are:

- Take advantage of the higher electrical conductivity of higher purity aluminum
- Increase the amount of aluminum in the cross-sectional area
- Operate the conductor cooler

As was discussed in the introduction, the aluminum used in the DRAKE conductor is 99.5 percent pure (1350 Alloy) with a conductivity of 61.0 percent International Annealed Copper Standard (IACS) at 20C (68F). To get a five percent increase in conductivity we would need to substitute aluminum with a conductivity of 64.05 percent IACS.

Reference [2] reports a conductivity of 65 percent IACS for 99.996 percent pure aluminum (alectrolytically refined aluminum). The drawback is that this is not economically feasible because its cost is prohibitive ($1000 / lb).

Figure 13 illustrates the decrease in hardness, tensile strength, and yield strength as the aluminum purity evolves from 99 percent to 99.999 [3].

Figure 13. Dependence of Hardness, Tensile Strength and Yield Strength on Purity [4]

This graph explains the historical reason why the electrical conductor industry did not pursue technology for producing pure aluminum but instead went to alloying. Indeed the reduced mechanical properties make the material virtually useless.

When pursuing CRAC technology however, the use of pure (as smelted) aluminum becomes attractive because the lightweight composite material can compensate for the loss in mechanical strength.

The use of pure, as smelted, aluminum has been investigated with the help of Reynolds Aluminum Corporation. The electrical conductivity however is nearly identical to that of 1350 aluminum (61 percent IACS). Although this aluminum does not provide increased electrical conductivity, it is cheaper than its 1350 counterpart. It may therefore be considered in order to achieve the economic objective of the Phase-II project.

An alternative path that was pursued with the help of Reynolds was the use of an experimental aluminum P-404 (Reynolds designation). It concerns a laboratory breakthrough where the aluminum was doped with a rare earth metal. However initial conductivity measurements only showed marginal increase in conductivity.

A second way to increase electrical conductivity by five percent is to increase the amount of aluminum in the cross-sectional area by 5 percent. The drawback is that this would increase the weight of the conductor by 37.5 lbs. for every 1000 feet of conductor. Because of the reduction of weight by a factor of 5.29, as stated in the introduction, the 344 lbs. of steel strength member is replaced by 65 lbs. of composite material for every 1000 feet of conductor length. This weight savings of 279 lbs. is almost 7.5 times larger than the weight increase that needs to be accommodated for a 5 percent increase in conductivity.

The third way to increase conductivity comes from the absence of inductive effects between aluminum and steel. This, as is discussed below, is a very beneficial but unanticipated outcome of this project. Since the composite is not electrically conductive, nor magnetic, there are no inductive heating effects and therefore CRAC was shown to operate cooler.

We worked with the Edison Cable Testing Facility in Westminster, California to demonstrate the cooler operation of CRAC vs. ACSR conductor. This demonstration relied on the experimental data in Figure 14.

Figure 14. Test Results Comparing ACSR-DRAKE, CRAC-121, and CRAC-Advanced.

The significance of this data is that it not only demonstrates that the CRAC conductor technology is feasible but also that there are formidable advantages. The particular test was designed to track the heating rate and final operating temperature of the CRAC conductors and compare them to that of current technology (DRAKE standard conductor). This was accomplished by connecting the conventional conductor in series with each of the TelePower conductors shown earlier in Figure 12.

The obtained result shows a 9 to 28 percent cooler operating temperature. This more efficient power electrical transmission is a direct attribute of the use composite materials, which are electrically non-conductive, as opposed to the steel in conventional ACSR conductors. Therefore there are no inductive effects that allow cooler operation of CRAC conductors.

It was shown in [5] that the absence of the inductive heating effect reduces transmission loss by as much as six percent.

Both conductors are expected to achieve a minimum of 40 percent more ampacity than DRAKE.

The reliability is closely associated with the ampacity, defined as the amperage that can safely be transported over power lines. As the amperage increases, the conductor heats-up and sags due to thermal elongation. Safe operation is compromised if the conductor hits treetops or other objects that may result in a blackout.

The expectation for increased ampacity is based on the fact that the CRAC conductor would experience a 40 percent reduction in sag during periods of high demand. This is based on a comparison of the thermal expansion properties which are 6 10^-6/F for steel and 3 10^-6/F to 3.6 10^-6 for composite. Because ampacity involves multiple variables and their interactions, the actual increase needs to be determined and verified by sub-scale and full-scale tests.

An improvement as high as 200 percent may be demonstrated on the basis of tests, which are recommended in a Phase-II project.

Figure 15 illustrates the fact that CRAC allows for the transmission of more power without added weight. Therefore the towers do not need to be strengthened or replaced.

Figure 15. Schematic of Conductor and Tower System

The option to leave the existing towers in place makes CRAC a very attractive choice for conductor replacement and system expansion.

Both conductors achieved 20 percent less mechanical elongation at ambient operating temperatures.

The cooler operation (9 to 25 percent) combined with the 25 percent higher strength and the significantly decreased thermal elongation support the 20 percent reduction in elongation. The actual line sag is only verifiable in a sufficiently large-scale test setup (i.e. prototypes with a minimum length of 150 feet).

Both conductors achieved a 30 percent strength increase compared to DRAKE.

The strength tests, conducted by USC according to ASTM D3039, showed an average of 196 Ksi tensile strength for the pie-shaped composite segments that make up the strength member for CRAC. The full impact of this high strength needs to be seen in conjunction with the reduced weight of the conductor, which in turn means that CRAC is being subjected to lower loads, and therefore has considerably more strength reserve.

Figure 1 illustrated that the overall conductor weight is 68.5 percent aluminum and 31.5 percent steel.

A 25 percent weight reduction for CRAC would result in a weight of 819 lbs. per 1000 feet. Because a minimum of 749 lbs. of aluminum is needed on this conductor, the strength member can only weigh 70 lbs. Because of the reduction of weight by a factor of 5.29, as stated in the introduction, the 344 lbs. of steel strength member is replaced by 65 lbs. of composite material for every 1000 feet of conductor length.

Calculation done in the course of this project [6] showed a 25 percent load reduction as a result of the lower conductor weight. As a result, the load capacity will be 25 percent higher.

The CRAC-Team considers these estimates conservative because the ASTM D3039 test methodology does not uniformly tension all composite strands. It is therefore proposed that the actual numbers be verified on a sufficiently large-scale test setup (i.e. prototypes with a minimum length of 150 feet).

<u>Only a 25 percent weight reduction was achieved and thus the objective of a 66 percent reduction was not met.</u>

In retrospect, the 66 percent turned out to be an ill-posed objective because the maximum possible weight reduction, which would be achieved by taking all the steel out of the DRAKE conductor, is only 33 percent. The achievement of a 25 percent weight reduction was achieved by comparing the weight of prototype CRAC conductors with the weight of the DRAKE benchmark.

3.0 Outcomes

The merits of the CRAC conductor have been verified against the ACSR benchmark conductor identified as DRAKE. This specific conductor was chosen because of its widespread use for worldwide power transmission. Additionally DRAKE is also used for power distribution lines. This sets the stage for introducing the CRAC alternative into the distribution market at a later date.

The conductor design work resulted in two novel configurations identified as CRAC-121 and CRAC-Advanced. Both of these designs have a lightweight composite strength member, which replaces the steel that is traditionally used in ACSR.

Specific project outcomes were:

- Improved performance was demonstrated by meeting stated objectives:
  - CRAC-TelePower achieved a five percent increase in conductivity. Additionally, laboratory testing at SCE's conductor test facility revealed a 9 to 25 percent cooler operation of the CRAC-TelePower designs. This is ascribed to the absence of inductive heating effects.
  - Additional increase in reliability resulted from an estimated increase in ampacity of at least 40 percent and possibly as much as 200 percent. Because ampacity involves multiple variables and their interactions, the actual increase needs to be determined and verified by sub-scale and full-scale tests.
  - Twenty percent less mechanical elongation (line sag) at ambient operating temperatures.
  - A 30 percent strength increase compared to DRAKE.
  - Only a 25 percent weight reduction was achieved and thus the objective of a 66 percent reduction was not met. In retrospect, this turned out to be an ill-posed objective because the maximum possible weight reduction, which would be achieved by taking all the steel out of the DRAKE conductor, is only 33 percent.
  - Increased reliability has also been met. The CRAC-TelePower is 25 percent lighter than ACSR-DRAKE. This results in a 25 percent higher load capacity, which makes the conductor more reliable.
- Splicing techniques were developed and demonstrated for both CRAC Conductors. This technology was proven to be both successful and practical for utility implementation.
- There were two very positive unanticipated outcomes.
  - CRAC was found to operate 9 (CRAC-121) to 25 percent (CRAC Advanced) cooler than ACSR conductors.
  - Both conductor designs can carry optical fibers in the hollow center. When optical fibers are added, these conductors are called CRAC-TelePower.

4.0 Conclusions and Recommendations

4.1. Conclusions

We verified our hypothesis that it would be possible to replace a relatively heavy steel strength member with a much lighter weight composite. Making this replacement proved very beneficial to conductor performance.

We found that utility personnel were much more comfortable with the CRAC-121 because it looks and splices like the DRAKE conductor they are used to. It is our belief that it will be easier to bring this conductor to market than the CRAC-Advanced.

We also found that the unanticipated outcome of being able to insert a fiber optic cable into the core of the CRAC conductor was of at least as much interest to the utilities as the improvements in mechanical and electrical performance.

As a general conclusion it can be stated that this project has pushed far beyond ACSR conductor technology, which had essentially emerged in the late 1800's. The result is a modern twenty-first century CRAC-TelePower conductor, capable of transmitting electrical power as well as broadband data.

4.2. Benefits to California

This project contributed to the PIER program objective of improving the reliability of California's electrical system by developing a conductor which is better able to withstand adverse weather and high-load conditions, thereby avoiding power outages caused by line sagging and swinging.

When CRAC or CRAC-TelePower is commercialized, it will also contribute to the PIER program objective of improving energy value of California's electricity, by reducing the costs of re-conductoring (replacing inadequate transmission lines with new lines). Specifically, because new transmission lines made of the CRAC conductor can carry more electrical current than comparably sized ACSR conductors, support towers would not need rebuilding to accommodate heavier, equivalent-capacity conventional conductors.

In addition, the use of CRAC TelePower will increase the value and the use of the electric utility's right-of-way by providing new locations for high-speed, high-bandwidth data transmission. It might even lead to the creation of data transmission utilities.

4.3. Recommendations

We recommend that:

- Splicing techniques be developed and tested for use on the fiber optic cables.
- That tests be conducted as part of a Phase-II project to demonstrate that improvement as high as 200 percent more ampacity is attainable.
- Tests be performed on 150-foot lengths of conductor to verify sag and to demonstrate the ability to transmit data in the optical fiber core, both to monitor

the performance of the cable and to provide for the transmission of high-bandwidth data.

- Tests be performed on a 2000 foot span in a utility transmission system to demonstrate CRAC's performance in real world applications.
- The CRAC-TelePower 121 conductor be pursued as the cornerstone of a Phase-II project.
- The original CRAC team be strengthened with a member possessing expertise in digital data transfer using fiber optics technology.

5.0 References

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