SOUTHWIRE'S HIGH TEMPERATURE SUPERCONDUCTING (HTS) CABLE DEVELOPMENT

SUMMARY REPORT

Southwire DOE-SPI-1 Project Development
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Executive Summary:

Southwire started an HTS cable development program beginning early 1995 with a Co-operative Research and Development Agreement (CRADA) with Oak Ridge National Laboratory. The development task was to study the properties of HTS tapes, and construct hand wound 1-m cables to study the winding characteristics of the tapes. Within a short time several 1-m long cables were constructed and tested. A goal was established to construct a 30-m long, three single-phase cables suitable to carry 1250-A_{ac} at 12.4 kV and power Southwire's two main manufacturing plants, machinery division, and part of the corporate headquarters building.

Southwire chose to construct a cold dielectric (CD) design cable that has the advantage of shielding magnetic fields and suitable for carrying larger amounts of current for future applications. The CD design however, required a dielectric material that would be suitable at liquid nitrogen temperature. After considerable testing, a polymer based tape called "Cryoflex" was developed by Southwire for use as a cold dielectric.

Southwire developed a HTS cable making facility for the winding of HTS and dielectric tapes. At the same time Southwire and ORNL developed at Oak Ridge a dielectric testing laboratory and a 5-m cable test bed. The HTS cable requires special terminations that connect cables at 77 K and high pressures (design pressure of 150 psi) with outside power at ambient temperature and pressure. Two types of terminations called Vacuum (T-1) and Pressure termination (T-2) were developed. The vacuum termination needed very high vacuum (10^{-5} bar) and cold ceramic bushings that were expensive and unreliable. The modified pressure termination eliminated vacuum, utilize industrial bushings, reduced cost, and increased reliability.

Two 5-m cables were designed and constructed at Southwire with the same rating as needed for the 30-m cables. The 5-m cables were tested successfully at ORNL for the DC I_c, voltage withstand, ac loss, and other properties using both the Vacuum and Pressure Terminations.

The design concept was proven with the 5-m cables and the same design was used for the 30-m cables. Three 30-m cables were constructed during the first two quarters of 1999. The cables were made on flexible formers but they were introduced into three separate rigid vacuum jacketed pipes (VJP). The cables passed the DC I_c tests that were carried out at the manufacturing site. A site was developed at Southwire with a switch yard, liquid nitrogen tank, a cryogenic cooling and delivery system, and a control room with PLC control for the system. The HTS cables were installed by the third quarter of 1999.

The HTS cables were energized Jan. 6, 2000. The official opening was carried out on Feb. 18, 2000. As of April 30, 2005 the HTS site has been operating at 100% load for >29,000 hours. Since June 1, 2001 the system has logged over 21,000 hours at full load without an operator on duty at the site. The cryogenic system has been under operation for more than two years and has proven very reliable.

Southwire has developed World's First Industrial HTS cable and is continuing to prove its reliability.

This report contains several sections outlined below that are related to Southwire's HTS cable development

1. High Temperature Superconducting (HTS) Tapes
2. Hand Wound 1-m Cables
3. Development of Facilities for Construction and testing of HTS cables
4. 5-m HTS Cables
5. 30-m HTS Cables, Installation at Southwire
6. Continued Developments
7. Publications

Each of the above sections provide only a short report. The details are given in separate volumes (Vol. 1 to Vol. 7) with separate appendices for each section. These are available at the Cofer Center Technical Library.

Southwire's HTS Cable Development – Summary Report

Index	Page
1. Executive Summary	i
2. High Temperature Superconducting (HTS) Tapes.	1
3. Hand Wound 1-m Cables (Cable #1 to Cable #13).	8
4. Facilities Development for Construction and Testing of HTS Cables.	15
5. Development, Construction, and Testing of two Five (5) meter HTS Cables.	27
6. Construction, Installation, Testing and Operation of World's First 3-Single Phase, 30-m Industrial Cable.	39
7. Continued Development	49
8. Publications	52

High Temperature Superconducting (HTS) Tapes

Materials: There are several types of rare earth oxides that become superconducting when cooled to a very low temperature (90-125 K) called Critical Temperature. The superconductors are bound by three parameters: Critical Temperature, Critical Current Density, and Critical Magnetic Field. If any of these parameters are exceeded, the material loses its superconducting properties. The properties of superconductors are anisotropic and it will carry more current if their grains are textured or aligned in the a-b plane. This is the reason the superconductors are manufactured as thin tapes so that it can carry more current in the longitudinal direction.

1. Yttrium based oxides, generally called 123 material ($Y_1Ba_2Cu_3O_{8+x}$). The 123 material has a critical temperature of 92 K. It can carry larger current under applied magnetic field but at much lower temperature (~35-40K).

2. Bismuth based oxides:

(a) Bi 2212, $(Bi,Pb)_2Sr_2Ca_1Cu_2O_{8+x}$

(b) Bi 2223, $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+x}$, $T_c = 105-110$ K

Bi 2223 has an inherent tendency to texture during drawing and rolling operation. Due to this it has higher current density at 77 K. But on the application of magnetic field it loses current density faster than Y123. Since cables have only small self magnetic fields, Bi 2223 has become the choice material for cable manufacturers.

3. Thallium based oxides, $TlBa_2Ca_2Cu_3O_{9-y}$, (Tl-1223)

4. Mercury based oxides

The thallium and mercury based superconductors have not been fully developed because of their toxic behavior and environmental concerns. The National Renewable Energy lab in Golden, CO has been working on Tl based superconductors using an electro deposition process. Only very short length of tapes have been produced so far in the laboratory.

The use of HTS material became possible with the production of 100 + m lengths of HTS tapes during 1994/1995. These tapes were produced by a Powder in the Tube (PIT) process schematically shown in Fig. 1 of the HTS tape compendium. In this process a silver tube is filled up with superconducting powder. The ends are sealed and the tube is drawn into a wire form. The wire is then rolled to a flat tape. During the mechanical processing the HTS material loses some oxygen. It has to be annealed to oxidize the superconducting material to get its stoichiometric oxygen to make it superconducting. Most manufacturers produce multi filaments tape. The single filament wire produced after the drawing operation is cut into several pieces. It is then refilled into a larger silver tube and the process is repeated to produce tapes that contain multifilaments.

HTS Tape Producers:

1. Intermagnetics General (IGC), Latham, NY (37 filaments)
2. American Superconductors, Boston, NY
3. Nordic Superconductor Technologies (NST), Copenhagen, Denmark (19 filaments)
4. Sumitomo, Japan
5. Showa Electric Wire & Cable Co., Tokyo, Japan

Southwire Purchases 1000-m HTS Tape:

Southwire purchased from IGC 1000-m of Bi - 2223 silver clad tapes during early 1995. These tapes were delivered in nine (9) spools containing 86 to 194 m of tapes. The I_c of the tapes varied from 11.6-A to 19.6-A. This purchase of HTS tape was hailed as a first large purchase by an US Industry. It immediately brought SW into the limelight as one of the companies interested in cable development. Our goal was to test the HTS tapes for its physical and mechanical properties and amenability to winding and cable making. We wanted to construct one meter long, hand wind cables and test for ac current. During the later part of 1995, Southwire developed a Co-operative Research & Development agreement with Oak Ridge National Laboratory for their assistance with the testing of HTS tapes, design, construction, and testing of 1-m long cables.

DC I_c Measurements of IGC-HTS tapes (Appendix 1)

The DC I_c 's were extensively evaluated on IGC tape samples. A characterization of IGC tapes and summary of DC I_c measurements is given in a report by Uday Sinha (MP 95060 dated June 12, 1995)

DC I_c Test Results of ORNL (Appendix 2)

The DC I_c tests were carried out by Patrick Martin of ORNL. It shows the I_c of tapes under applied magnetic fields parallel to the tape, starting from zero to 0.5 Tesla (10^4 gauss = 1 Tesla). These tapes were used in Cable #1 layer 1 to 4. The histograms show the I_c of tapes under zero magnetic field followed by some representative graphs showing the full V-I curve. The measuring criteria for I_c is 1 μ v/cm. It should also be noted that the I_c degrades more when magnetic field is applied perpendicular to the tape. Two plots of results are included to show this effect. The test results show that the tapes do not have uniform I_c . It varies considerably and also decreases rapidly under applied magnetic fields as shown in Fig. 1. Note that the I_c of the tape is determined following the 1 μ v/cm criteria.

Fig. 1: DC I_c of an IGC straight tape

DC I_c of tapes wound on formers (Appendix 3)

The IGC HTS tapes are soft and break easily. Therefore it was a great concern that the I_c of the tapes may degrade on winding of the tapes on a former. I_c of the tapes were measured before and after winding on a 1" dia. mandrel at 15° lay angle measured from the longitudinal axis. The results are shown in the appendix. Another test was carried out after winding of tapes on a 1" dia mandrel at zero pitch (worst case) and parallel magnetic fields. The results show very large degradation in I_c of tapes with zero winding angle and even with small amount of magnetic fields. The tapes also exhibited bubbling during the I_c tests. The DC I_c of the same IGC tape shown in Fig. 1. was measured again after winding on a 1" dia. former at 30° angle for two pitch length. The result is shown in Fig. 2. The shift in the curves to the left indicates a drop in the I_c of the tape. For zero field the I_c decreased from 6.8-A to 4.4-A a drop of over 32%.

Fig. 2: DC Ic of tape wound over 1" diameter former

Soldering of Tapes and Heat Loss (Appendix 4)

There was a serious concern that the HTS tapes may break during winding on a stranding machine. This would require joining of tapes that will cause some resistive heating. A test was carried out at ORNL for joining of two tapes using a lap joint. Different types of solder were used for this test. It was found that solder using rosin flux produced best results. In fact, the joint showed lower resistance than the tape on either side. This was most likely because of double layer of tapes in the joint provided twice the current carrying cross-section. A report of John Demko of ORNL is shown in the appendix.

Mechanical Testing: Strain vs Ic (Appendix-5)

(a) Formulas

The strain due to bending of the tape during winding is given by the relation:

$$\varepsilon = (t / D) \sin^2 \varnothing, \text{ where,}$$

t = thickness of tape

D = diameter of mandrel or former

$\varnothing$ = angle of winding from the long axis

(b) Ic of IGC tapes as a function of winding angle and Former diameter

It is found that the degradation in Ic is reduced by using larger diameter formers and also by increasing the lay angle of tapes. A report is included.

(c) Comparison of IGC, Showa, and NKT tapes

We also obtained HTS tapes from Showa Electric and NKT. These tapes were tested at ORNL along with IGC tapes for comparison. The ORNL test results are attached. The NKT tapes had the smallest degradation in I_c compared to Showa and IGC tapes.

(d) Effect of Additional Processing of tapes

Patrick Martin of ORNL carried out some pressing and heat treatment of IGC, Showa, and NKT the DC I_c of tapes. The results show that there was considerable improvement in the I_c of IGC tapes after further oxy-heat treatment. NKT tapes had similar effect on the oxy-heat treatment of pressed samples. Showa Electric tapes showed only a marginal improvement in the I_c value.

(e) Strain vs I_c Tests done by National High Magnetism Field Lab., Tallahassee, FL

NHMFL carried out similar tests on IGC, Showa, and NKT tapes identified as A, B, and C tapes. A comparison of A, B, and C tapes and their test results are also attached. One can see that IGC tapes had the maximum and NST tapes the minimum degradation in I_c value on winding over 50 mm to 15 mm mandrel.

HTS Tape Modification by Plastronic Inc., Dayton, OH (Appendix 6)

Mike Tomsic of Plastronics carried out some further processing of IGC tapes by pressing and sintering. He found that the critical current of IGC tapes (I_c) increased on an average by about 20 to 30 %. Plastronics does not have a good controlled processing equipment and the edges of the processed tapes were not smooth. However, we got several meters of tape processed to improve the I_c of IGC tapes. Cable #5 was constructed using the re-processed tapes. The high cost of IGC tapes (\$60/m) and Plastronics cost of processing made it unrealistic for any further use. In the meantime, the quality of HTS tapes supplied by IGC and others improved to an extent that further processing was not desirable.

One of our great concerns was with respect to the softness of HTS tapes which had annealed silver on the outside. Several laminations test were performed to increase the I_c and the strength of the composite tapes. Some of the results of laminations tests carried out by Plastronics are given in the appendix. A report of Winston Lue is also attached.

Lamination's tests done by IGC (Appendix 7)

IGC did some development work for the lamination's of tapes with various combinations such as (1) one HTS with Cu backing (2) two HTS , and (3) two HTS with cu backing. There were always some degradations of I_c after the lamination.

Nordic Superconductor Technologies (NST) Tapes (Appendix 8)

NST produces HTS tapes using alloy silver. Due to this the tapes are stronger and have higher yield strength than pure silver. A tensile test result data is enclosed which shows acceptable UTS and breaking load for these tapes. The current density of NST tapes have been gradually increased to 40 – 45 Amps from about 20-25 A in 1998. NST uses a Zirconium oxide powder between layers of tapes in a spool. This helps keep the layers separated after the high temperature oxy-anneal of their tapes. But the surface oxides presents serious problem during the soldering of tapes. The tape surface has to be cleaned and a solder coat applied immediately to avoid re-

oxidation of the surface. A procedure for the surface cleaning of tapes as followed by NKT is enclosed.

NST Tapes Test Results of Argonne National Laboratory (Appendix 9)

ANL carried out testing of NST tapes. They reported that NST tapes can withstand 16 lbs tensile load without detrimental effects on I_c values. At 20 lbs load, the transport current is reduced from 37 A to 35 A in zero field. This is a very small degradation compared to the IGC tapes.

HTS Tape Specification (Appendix 10)

An HTS tape specification was developed in 1996 for the purchase of tapes for cable making. This specification is no longer valid since better tapes are manufactured today. A new specification should be written to include present day manufacturing capabilities.

	1996 Specification	Present Capabilities
DC I_c Tape (self field)	25-A minimum	45-50 A
Yield strength	40 MPa minimum	100 MPa minimum

I_c of the tape should be measured after winding the tape on a 1" diameter mandrel at 30 degree angle for two pitch length.

Coated Conductors- Second Generation HTS Tapes (Appendix 11)

The incentive for this development is to reduce the cost of tapes by eliminating silver and to increase the current under high magnetic field. Two processes RABiT's and IBAD have been developed for coated conductor tapes.

Rabit's (Rolling assisted biaxial texture substrate) process has been developed by ORNL. It involves a controlled repeated rolling of a nickel tape to produce biaxial texture. A buffer layer zirconium oxide followed by cerium oxide is deposited over the textured nickel surface. Yttrium 123 is deposited over the cerium oxide.

IBAD process has been developed by Los Alamos National Laboratory (LANL). It uses two ion beams in a vacuum chamber to produce a biaxially textured deposition of Zirconium oxide over a nickel tape. A buffer layer of cerium oxide followed by Y123 is deposited over the textured zirconium oxide surface. Both RABiT's and IBAD processes have been used to produce short HTS tapes that carry high current density. Short one cm wide and 1-m long LANL tapes have carried over 150-300 A. Both processes have several variables especially with regards to their architecture of buffer layers. It is expected that a usable length of coated conductor tapes may become available in 3 to 5 years time. The coated conductor tapes produced by the RABiT's or IBAD process has the potentials to increase the I_c to 150-300 A and reduce the overall cost of tapes to about \$10/kA-m.

The following companies are involved with the coated conductor tape development along with ORNL and LANL.

1. 3-M Company/Southwire

2. Intermagnetic General Company (IGC)
3. American Superconductor
4. Microcoating Technologies
5. Sumitomo and others in Japan.

Hand Wound 1-m Cables (Cable #1 to Cable #13)

Summary

Southwire Company initiated an R & D Project in 1995 to develop superconducting underground transmission cables using the newly developed high temperature superconducting materials. A goal was set to produce a 1-m long, 2000-A cable before the end of 1996. However, before making the 2000-A cable, it was considered prudent to make two 500-A cables first and test them for performance. During late 1995 a co-operative research & development agreement (CRADA) was made with Oak Ridge National Laboratory (ORNL). ORNL provided their technical expertise with the design and testing of the HTS cable. 1000-m of silver clad Bi-2223 tapes were purchased from IGC to test the tapes, develop winding parameters, and characterize the tapes for its physical and mechanical properties.

Cable #1: 1-m long, 500-A (Appendix 1)

A copper pipe (7/8" or 22 mm diameter) was used as a former over which four layers of HTS tapes were wound in alternate helix construction. The tapes were hand laid at 15° lay angle or 12" pitch length. The winding was carried out manually using one HTS tape at a time. The tapes were soldered at the ends using 44 Resin Core Kester Solder (Sn 62%, Pb 36%, Ag 2%). The four layers contained a total of 73 (17 + 18 + 18 + 20) tapes. IGC tapes averaged about 11.5 A for straight length tapes, thus allowing a maximum of 950-A without any tape degradation. The cable was tested for DC IC at IGC which reported 650-A for the cable. The cable was sent to ORNL for retesting using their vertical cryostat. ORNL reported getting over 900-A for the cable. The details of cable construction and testing are shown in Appendix 1.

Cable #2: 1-m long, 500-A (Appendix 2)

A 22 mm copper pipe was again used for the construction of Cable #2. The construction of this cable was slightly different than Cable #1 which was constructed with all four layers of tapes soldered together at the two ends. With this design, it was not easily possible to measure the critical currents of the four individual layers of tape and find out how the current distributes in the four layers. Cable #2 was constructed with the specific goal to understand the distribution of current in four layers of the tape. Kapton insulation tape was wrapped in between each layer to keep the layers electrically separated. The tapes in each layer were soldered together separately to allow measurements of I_c for the individual layers or for the full cable. The tapes in each layer were also separated from each other by means of knitting thread. Another goal was to study the difference in ac loss of this cable caused by the electrical separation of hts layers.

The HTS tapes were again laid at 15° lay angle with alternate opposite helix pattern. The tapes in the first layer were soldered together to form a separate lead. Kapton tape was wound over the first layer before winding the second layer with opposite pitch. The tapes of second layer were soldered about 1" inside from the end of the first layer to form a separate lead. The next two layers were similarly constructed forming four separate leads for the four layers of tapes. ORNL tested the cable and reported the following results:

The cable carried over 550 A-dc. The four layers of tapes carried from outer to the innermost layers, 210, 93, 100, and 121 dc Amps respectively. As expected the outer layer carried the maximum amount of current. The HTS cable has a very broad transition as can be seen from the I-V curves. This allows the cable to be operated at a stable condition at more than 1 kA. However, there will be some resistive heating in the transition zone. Subcooling of LN to 69 K from 77 K can increase the cable I_c by over 25%. On the same tape of one layer, the I_c varied at different locations. This indicates non-uniform quality of HTS tapes. Thermal cycling of the cable caused degradation in I_c which leveled off after the 5th cycle. Overall I_c decreased from 670-A to 460-A after 10 thermal cycles, a 30% degradation. No appreciable AC loss was measured with ac currents up to about 300 A (rms). At 500 A the ac loss was estimated to be about 0.3 W/m for cable #2. Details of test results and reports are shown in Appendix 2.

Cable #3: 1-m long, 2000-A (Appendix 3)

HTS cable #3 was designed to carry 2000-A_{ac}. The construction of the cable was very similar to cable #1. Ten layers of HTS tapes were laid at 15° lay angle from the long axis, on a 1" dia. stainless steel former in alternate helix pattern. A total of 200 tapes were used for the ten layers of tapes. The former and the ten layers of tapes were electrically separated by means of Kapton tapes. However, the tapes were soldered together at the ends, tape to tape without insulation.

ORNL tested the cable and reported a critical current of 1630 A at the 1 μV/cm criteria. 2000 A_{ac} current was applied for 10 minutes. AC loss of the cable showed similar behavior as Cable #2. At 500 A the ac loss of cable #3 is about 1 w/m compared to 0.3 w/m for cable #2. At 1600 A (rms), the ac loss is about 8 W/m. The higher ac loss is perhaps due to unequal distribution of current in various layers. More current may be flowing in the outer layers. Details of test results and reports are shown in Appendix 3.

Cable #4: 1-m long, 1250-A (Appendix 4)

Cable #4 was constructed using a 1.5" diameter stainless steel pipe of 1-m length. Kapton tape was wound over the former and between each layers of tapes. The tapes were laid at 15° lay angle and the tapes were separated by means of knitting thread. ORNL tested this cable placed in a horizontal Styrofoam box. The V-I curves for different sections of tape indicated the tape was not uniform. The I_c of the cable was about 1000 A. There was no resolvable ac loss below 750 A (rms). Details of cable and test results are shown in Appendix 4. We did not get 1250-A in the cable with the present HTS tapes and four layers construction as described.

Phase-1: FY 1995/1996 Development

Cable #	# Tapes	Lay Angle and Dir.	Des. Ic	Nom. Ic (A)	Meas. Ic (A)	Ic, Tape (wound)	% Reten.
1	73	15 (+ - + -)	500	847	670	9.2	79.1
2	67	15 (+ - + -)	500	844	560	8.4	66.4
3	200	15 (+ - + -10)	2000	3400	1630	8.2	47.9
4	112	15 (+ - + -)	1250	2033	975	8.7	48

Nominal Ic is based upon the suppliers end to end Ic values. Cable #1 and #2 were wound on 7/8" diameter copper formers. Cable #3 & #4 were made on 1" and 1 1/4" dia. stainless steel formers.

Cable #5: 1-m long, 1250-A (Appendix 5)

This cable was made with IGC tapes after it had been reprocessed by Plastronics. The reprocessing consisted of pressing and sintering which improved the Ic of the tapes, but the edges of the tapes were not smooth and uniform. The cable was made with four alternate helix construction with tapes laid at 30° angle. Kapton tape was laid over the former and between layers #2, #3, and #4. We had two pairs of tapes layers #1 and #2 without insulation and layers #3 and #4 with insulation. An insert was specially designed to allow us to solder the two layers separately.

ORNL reported that the DC Ic of inner pair of layers measured 957 A while the outer pair measured 460-A. The tapes in the outer layers were slightly damaged while clamping and this caused the decrease in the Ic of outer layer. The details of construction and test results are shown in appendix 5.

Cable #6: 1-m long, NST (15-A) tapes, (Appendix 6)

A 1-m long two layer cable (with opposite helix) was constructed using NST tapes. We had planned to construct a four layer cable but soldering of the first two layers of tapes presented serious problem. The NST tapes have ZrO₂ on the surface which had to be removed before soldering. Scraping of the surface oxides after the two layers had been laid required bending of the ends of tapes. We were afraid of damage to the tapes and therefore it was decided to make this cable as a two layer cable. The average DC Ic of the cable was determined to be about 365 A

Cable #7: 1-m long, NST (15 and 20-A) tapes, (Appendix 7)

The cable was constructed using NST tapes in four alternate helix layers laid at 30^0 angle over 1.5" dia. stainless steel pipe. Kapton tape was laid over the former and on top of second layer. A total of 108 tapes were used with an expected maximum I_c of 1875-A using NST data for straight length tapes. ORNL measured an average cable I_c of 1520-A using 1 μ V/cm criteria.

ORNL also carried out a special test of measuring I_c after sequentially stripping off the outer layer to make it a 3 layer and a 2 layer cable. The results indicated that for minimum ac loss, the cable should have minimum number of layers (preferably 2) and it should be made with highest critical current HTS tapes available. The details of construction of cable and tests are shown in the appendix 7.

Cable #8: 1-m long, IGC new improved tapes, (Appendix 8)

This cable was made from a new batch of IGC tapes on a 1.5" diameter stainless steel pipe. The tapes were laid at 30^0 angle using a four layer alternating helix construction. Kapton tape was wrapped over the former pipe and between layers 2 and 3. However, all tapes of four layers were soldered together at the ends. A total of 104 tapes were used with 81 tapes @22 A ea. and 23 tapes @ 26 A ea. giving a nominal I_c of 2380 A. ORNL measured a DC I_c of about 1600-A for the cable resulting in about 15.4 A/tape in cable form. AC current of up to 1590 A (rms) was applied which gave a temperature rise of 0.24 K. The ac loss at the designed current of 1250 A rms was determined to be about 0.38 W/m. Full details of cable construction and testing is included in the appendix 8.

Cable #9: 1-m long, IGC (old) tapes, (Appendix 9)

The cable was made on a 1.5" former using the old IGC (14/14.5 A) tapes. In this cable the first two layers of tape were wound in one direction and the next two layers (layers #3 and #4) in the opposite direction. The cable simulated a two layer tape construction. Kapton tape was wrapped over the former pipe and between layers 2 and 3 and over the outer layer #4. A total of 100 tapes were used giving a nominal I_c of 1420-A. All tapes of 4 layers were terminated at the same location at the two ends. ORNL measured a DC I_c of about 1267-A which meant an average of about 13 A/tape in the cable form. It appears that a two layer cable retains more of the tape I_c than a four layer cable. Full details of cable construction and testing is included in the appendix 9.

Phase-1: FY 1997 Development

Cable #	# Tapes	Lay Angle and Dir.	Des. Ic	Nom. Ic (A)	Meas. Ic (A)	Ic, Tape (wound)	% Reten.
5	96	30 (+ - + -)	1250	2237	1100	11.5	49.2
6	51	30 (+ -)	500	765	311/ 514	6.1/ 10	47.7/ 67.2
7	108	30 (+ - + -)	1250	1875	1520	14	81.1
8	104	28 (+ - + -)	1250	2380	1605	15.4	67.4
9	100	28 (+ + - -)	1250	1420	1267	12.7	89.2

Referring to the above table, it should be noted that for cable #5, IGC tapes were reprocessed by Plastronics by pressing and sintering. The outer layers (#3 and #4) in the cable were slightly damaged due to twisting while attaching power cables for the test. The inner pair (layers #1 and #2) measured 957-A which is a retention in Ic of 85.6%. NST tapes were used for cables #6 and #7. The two layers of tape in Cable #6 were wound before cleaning of tapes for soldering. This caused some damage to tapes. The Ic of cable in the damaged area was 311 A where as it was 511 A in the undamaged area.

Note: By this time, we had determined that we could get over 1250-A with the IGC tapes following a four layers construction on a 1.5" diameter former. The preferred construction of four layers was to wind the first two layers (#1 and #2) in the same direction at the same angle, and the next two layers (#3 and #4) in the opposite direction at the same angle. We had chosen to construct a Cryogenics design cable. This design of cable required an outer layer of HTS tapes wound over the dielectrics tapes that are laid over the inner HTS tapes. We were concerned with the problems of soldering the outer layers of tapes over the dielectric materials. The heat generated during soldering of the tapes could damage the dielectric tapes. Therefore two more cables were made (#10 and #11) with different joints without any heating to check their performance.

Cable #10: 1-m long, IGC (old) tapes, (Appendix 10)

This cable was specially designed to study the use of Indium for solder at one end of the cable and thin copper strip for mechanical joint at the other end. The cable was made on a 1.5" stainless steel former. In order to provide a diameter large enough to allow use of the existing connector and to simulate the actual cable, the former was built up to a diameter of 1.935" using 12 layers of Bedding tape, 2 layers of aluminized shield, 16 layers of cryoflex dielectric, two layers of aluminized shield and 2 layers of bedding tape.

The four layers of HTS tapes were next wound on the former. The two inner layers were wound in one direction at 30° degree angle and the two outer layers in the opposite direction at the same lay angle. Thin copper strips were inserted between layers 1 & 2, 2 & 3, and 3 & 4, and on top of layer #4 at one end of joint. At the other end Indium foil was used between the layers and over layer #4 at the joint. Connection was made by clamping connector over area containing metallic strips and indium foil. The details are shown in Appendix 10.

Cable #11: 1-m long, IGC (old) tapes, (Appendix 11)

The construction of this cable was similar to cable #10. In cable #10 a copper termination block was tightened by means of screws to make good contact. In this cable however holes were provided to inject conductive epoxy to make tight joints. The two cables were tested at ORNL. The cable Ic was only about 600-dc A; only about 25% of nominal currents. The joint resistances with epoxy were very high and found unsuitable. The joint made with copper foil also had high resistance. The Indium foil had resistance approaching nano-Ohm range but still it was short of desired low resistance. It did not seem to conduct well at liquid nitrogen temperatures.

Cable #12 (for test at LANL) : 1-m long, NST tapes, (Appendix 12)

A 1-m long cable was specially made for testing at Los Alamos National Laboratory (LANL). LANL has a specially designed calorimetric equipment to measure the ac loss of a cable. The cable was made of proper length and end plugs to fit into LANL test equipment. The first two layers of tape were wound at 35° and 15° in the same direction. The next two layers of tape were laid at 15° and 40° in the opposite direction. These lay angles were chosen to provide equal distribution of current in the four conductor layers as theoretically calculated by our consultant Dr. Larry Dresner. A Rogowski coil (made at SW) was wrapped over each layer of tape at one end. Kapton tape was laid below and on top of each Rogowski coil. The Rogowski coil measures the magnetic field created by each layer and can indirectly indicate the current carried in that layer.

LANL measured about 3600 dc amps for the cable. The contact resistances of the two ends were measured to be 51 nOhms and 71 nOhms. The ac loss was about 0.3 W/m. The Rogowski coil data could not be interpreted properly and has not been reported. However, the performance of this cable was quite good with high dc Ic and low ac loss. After LANL completed their test, they sent the cable to ORNL where the cable was retested after thermal cycling for DC Ic and joint resistance. The cable Ic remained over 3000-A after five (5) thermal cycling. The joint resistance on end remained at 48 nOhms even after five thermal cycling. But the joint resistance on the other end increased from 130 to 280 nOhms. Details of construction and some of the test results are shown in the Appendix 12.

Cable #13: 1/2-m long, NST tapes, (Appendix 13)

The NST tapes have an oxide coating on the surface, which makes it very difficult to solder. To obtain a good electrical connection, the tape ends have to be properly scraped to remove the oxides before soldering. In fact, the cleaned surface has to be protected

immediately after cleaning with a coat of solder. Otherwise the surface may re-oxidize. By this time of the project, the first phase of our 30-m cable was already constructed using NST tapes as conductor. The solder joint of the cable was not as desired, since the tapes were not pre-cleaned before soldering. Joint at one end was made with cleaning on the outer surface of outer layer tapes only. At the other end, the tapes were scraped off to remove oxide at the inner and outer surface.

To check the resistance of the joints, a $\frac{1}{2}$ m long, 4 HTS layers cable was made. The cable was designed similar to the design of our 30-m cables with a worst and a best case joint. For the worst joint, the oxide layers were cleaned off only on the upper side of the tape. The other end simulating the best case joint included cleaning off of the oxide layer on both inner and the outer surfaces. ORNL tested the joint resistance of this cable after five thermal cycling. A thermal cycling consisted of cooling the cable in LN, taking it out of LN bath, wiping it dry, and cooling again. During the dc I_c test, ORNL could not go beyond 1500-A due to tripping problem experienced with their power supply. The voltage taps across the superconducting tapes showed no voltage. The cable remained superconducting with I_c well over 1500-A after all of the thermal and electrical cycling. The good joint measured a resistance of $0.05 \mu\Omega$ for all thermal cycles. The other joint resistance increased with increasing current and varied somewhat randomly between thermal cycles. The resistance averaged about $0.3 \mu\Omega$ at 1250 A which corresponds to 0.48 watts heat load. Thus even this poorer joint produced only a negligible amount of heat at the operating current of 1250-A. The ORNL report is shown in Appendix 13.

Facilities Development for Construction and Testing of HTS Cable

The goal of our project was to construct a cryogenics design, 3-single phase, 30 m cable and install it at Southwire. To meet these goals the following facilities had to be developed:

1. **Stranding Machine:** For the winding of HTS tape and dielectric tapes.
2. **Dielectric Test Equipment/Development**
3. **Termination**
4. **5-m Cable test facility**

We will describe below important features of the facilities. The details are given in Appendices.

1. Stranding Machine

A 1000 class clean room was installed within an existing building about 450 ft long. It should be noted that the cable was kept straight without bending it even though a flexible corrugated stainless steel former was used for the winding of tapes. There was no provision for pay off and take up equipment. A roller platform was used at both ends of the machine for laying the full length of cable. The cable was pulled forward and backward by means of steel ropes attached at both ends by means of pulley and drive arrangement. A photograph of the roller table is shown in Fig. 1.

Fig. 1: Roller support table at one end of the machine

Stranding Machine

Southwire purchased at an auction the Trafalgar Taping Machine that was used to make the low temperature superconducting cable of Brookhaven National Lab during 1972-1986. Two of the dielectric taping machines were used for the winding of dielectric tapes. Each machine has the capacity to wind up to 16 layers each at one time. SMD designed two separate heads, with 24 and 28 spools for the laying of HTS tapes. The head with 24 spools was used for the inner layers of HTS tapes and the head with 28 spools for the outer layers of HTS tapes. The stranding facility was specifically designed to construct 100 ft cables. About 100 ft of roller tables were provided at each end of the machine. A flexible former in straight length was guided into the machine for the winding of specific tapes and exited at the other end. The cable was pulled through the machine back and forth by means of a motor driven chain and pulley arrangement. A photograph of the stranding facility is shown in Fig. 2.

Fig. 2: shows a view of the installation of the facility from the HTS winding end

The photograph shows the HTS end of the stranding machine. It also shows two HTS stranding head, the roller table, and the clean room enclosures. Towards the other end are two drums of dielectric winding machines. The photograph also shows the chain attached to the cable for pulling the cable back and forth as needed.

A photograph showing the stranding of HTS tapes is shown below in Fig. 3.

Fig. 3: shows stranding of HTS tapes in progress

The stranding machine had originally two drives , one for the four drums (two HTS and two dielectric) and one for the pulling of former. The laying of the HTS tapes were carried out at a very low tension to avoid breaking of the HTS tape. Due to this the winding had some slack and it became pronounced with bird caging when an HTS tape layer was laid over the lower layer. The HTS tapes could be badly damaged by the bird caging. Two pairs of tape winders were installed; one before the outer drum and the other after the second HTS drum. The two winders allowed us to wind reject dielectric tapes over the HTS to move the slack on one end. The HTS tapes would be bound tight with Kapton tape and then the next layer of HTS will be laid.

Originally the stranding machine had only one motor and drive for the whole machine and one small motor at each end for pulling of the chain back and forth. This arrangement did not provide good control for the butt gaps on the dielectric and the HTS tapes. Therefore, individual motors and drives were installed for the separate units to give us a better control of speed. A PLC unit controlled the speeds of all motors and drives and the speed of cable winding.

2. Dielectric Taping Head

Two dielectric taping heads were installed to provide a capability to wind up to 32 tapes at a time. The dielectric tape winding of the stranding machine is shown in Fig. 4:

Fig. 4: shows one of the Dielectric Winding Machine

Dielectrics Development

Material:

To construct a cryogenics design cable, it was required to develop a dielectric material in tape form that will be suitable at LN temperature. A proprietary polymer based tape called “Cryoflex™” has been developed for use with our HTS cable. Several test equipment were needed to characterize the cryoflex tapes and find its suitability. It was also necessary to develop equipment for the cleaning of tapes and putting proper tension for winding.

ORNL developed a dielectric laboratory equipped with the following apparatus for the test of dielectric tapes.

#1: One atmosphere Liquid Nitrogen, Five Electrode Tape tester:

The equipment shown in Fig. 5 was designed and built by SMD and delivered to ORNL. This apparatus tests 1-in wide tapes in LN at 1-atm pressure for their breakdown strengths at ac and impulse voltage stresses.

Fig. 5: Tape testing apparatus

#2: Liquid Nitrogen Sheet Breakdown tester (15 atm)

The sheet testing apparatus shown in Fig. 6 utilizes a stainless steel chamber that can be pressurized to 15 atmosphere. A dewar was designed and built by ORNL, allowing HV breakdown experiments in LN at high pressure.

Fig 6: Sheet testing apparatus

Impulse tests at one and five atmospheres were performed on five (5) layer sheets of Cryoflex. $\frac{1}{4}$ " diameter holes were punched in layers #2 and #4 and holes were superimposed on another for the test to simulate butt gaps. The mean breakthrough strength was approximately 160 kV/mm at 1 atm and 260 kV/mm at 5 atm.

#3: Model Dielectric Cable Tester

A model dielectric testing laboratory was assembled in a high bay at ORNL. The facilities includes a high pressure dewar, high impulse voltage power supply, and control equipment. It also has equipment to wind a four (4) feet long dielectric cable. The dewar can be pressurized to 15 atm and incorporates instruments for the monitoring of liquid nitrogen level and temperature. A model cable is 1-m in length and simulates the construction of the entire electrical insulation for the 30-m cable. Fig. 7 shows the model dielectric cable test apparatus.

Fig. 7: Model Dielectric Cable Test Apparatus

#4: Tape Radial Press, Cleaner, and Tensioner

SMD designed a dual use machine that can determine the required radial pressure on the tapes and to remove the dust particles during respooling of the tapes. Filler gauges were used to determine the radial pressures in different layers of the tapes. It was determined by test that a 2.5 lbs tension

did not cause increase in radial pressure. All dielectric tapes were wound on spools using a tension of 2 to 2.5 lbs.

Dielectric Test Results:

The impulse breakdown of Cryoflex insulated model cables as a function of LN pressure remained at about 160 kV over the LN pressure range of 5 to 15 atmospheres. A test data is shown in Fig.8.

Fig. 8: Test data of model dielectric cable test

Dielectric Aging Tests:

Aging tests are required to determine the life of dielectric over a long period of time.

The life expectancy vs stress is given as: $tE^n = \text{constant}$, where t is the time to failure, E is the Electrical stress, and n is a function of both the type of insulation and LN pressure. A very large value of n (~ 100) represents a material for which a small increase in stress will cause a dramatic decrease in lifetime. On the other hand, dielectric materials having a very low n (~ 10) will show good resistance to overvoltage but extrapolation to 30 years life time may yield an unacceptably low working stress.

The tests were designed to be carried out on model dielectric cables. The voltage will be rapidly “ramped up” until breakdown occurs. Each subsequent test will be run at a voltage setting that is 5% lower than the previous value. Run times will be in minutes, hours, and days. Slopes of time-to-failure vs ac stress will be determined from the accumulated data which will indicate the life of the cable over a long time.

A preliminary determination of “ n ” for Cryoflex, deduced from the first ten cable models tested at ORNL yielded a value approximately 26.2. An automatic LN fill equipment has been added which allows the test to be continued for much longer duration. The data (red data points) as shown in the graph of Fig. 9 for large model cable (1-m length) were all taken from life times of only several hours duration only because of limitation of LN supply. The green and blue data points,

taken with the model cable aging dewar (equipped with automatic LN fill system), are also shown in Fig. 9, where one of tests (blue data points) was run for several days.

Fig. 9: Aging data of some model dielectric cables

Continuing Dielectric Tests:

ORNL is continuing to test properties of different dielectric materials. Aging tests on model dielectric cables are continued to develop information on long time life for the dielectric. Model dielectric tests are also continued to study variations in dielectric construction of the cable.

3. Termination's

The cable termination is the interface from the superconductor operating in a pressurized liquid environment to copper operating at room temperature and atmospheric pressure. The termination has to be designed to allow smooth transition of temperature.

Originally a **vacuum termination** was designed which uses the vacuum for both electrical and thermal insulation. Each vacuum termination had two sets of feed through bushing; one set for the HTS phase conductor and the other set for the HTS neutral conductor. Each set had a warm ceramic bushing making the transition from ambient (295 K, 1 atm) to vacuum (295 K) and the second ceramic bushing making the transition from vacuum to liquid nitrogen (at $\sim 72\text{-}81\text{ K}$) at 3-7 bars. These bushings were rated for full cable current and voltage. The two terminations are pumped through a common 6-in vacuum header by a mechanical / turbomolecular vacuum pumps. Typical vacuum is in the range of 10^{-5} to 10^{-4} torr range, which provides sufficient thermal insulation when combined with multiple layers of superinsulation. Fig. 10 shows the Vacuum (T-1) termination installed with 5-m cable at ORNL.

Fig. 10: Vacuum Termination (T-1) installed with 5-m cable

Pressure Termination (T-2):

The vacuum termination required very high vacuum (10^{-5} torr) with LN on the cable end under very high pressure (designed 150 psi). They were separated by feed through bushings which caused minute cracks due to the very high thermo-mechanical stresses. The T-1 termination worked for major part of tests for 5-m cable, but it was not reliable for a long term operation. A pressure termination was developed which allowed some LN to go into the termination chamber, vaporize, and cause same gaseous pressure. Due to this design the cryogenic bushings and high vacuum were not required. Commercially available bushings were adequate. The T-2 termination became cheaper and simpler. The vacuum termination was replaced by the T-1 termination for 5-m cable and used also for the 30-m cable installation. A photograph of Pressure termination is shown in Fig. 11.

Fig. 11: Modified T-2 Termination at ORNL 5-m cable test bed

The pressure termination is very simple in construction and does not require the large diameter pipe (22") as needed for T-1 termination. A sketch showing the size comparison of T-1 and T-2 terminations is shown in Fig. 12.

Fig. 12: Size comparison of T-1 and T-2 terminations

A block diagram of Pressure Termination installation with a 5-m cable is shown in Fig. 13.

Fig. 13: Shows a block diagram of T2 termination with a 5-m cable

1. 5-m Cable Test facility

ORNL has designed and installed a versatile HTS cable test facility in their Fusion Research Laboratory. The facility is located in Room 298 (formerly the high power test facility), an enclosed room in the high bay area on the second floor of Building 9201-2, of ORNL Y-12 plant. Power supplies are available for steady-state currents of 3000 A (dc). This has been upgraded to provide currents up to 25,000 A (dc) for pulsed loading at low voltage. A high voltage power

supply is available (rated at 100 mA at 100 kV) to test the cable at the peak voltage levels of 2.5 times the operating voltage. Electrical and cryogenic data are taken by dedicated sensors scanned by three 10-channel multimeters connected via cable (for low voltage signals) and fibre optic (for signals with potential to be at high voltage) to a PC-based, data acquisition system using the LabView program. These diagnostics allow measurement of the dc V-I characteristics and the ac losses of the cable, dielectric integrity via a partial discharge measurement, and cryogenic performance at rated voltage (7.2 kV ac rms) and current (1250-A).

Cryogenic cooling is provided by an Air Products liquid nitrogen supply system with the capability of providing about one (1) kilowatt of cooling at nitrogen pressures up to 10 bar over a temperature range of 67-77 K. There is an 11,000 gallons liquid nitrogen tank outside the building maintained at about 4-5 bar to supply LN for the initial fill of the pressure and auxiliary dewars and to replenish LN to the subcooler for the gaseous nitrogen lost in the subcooler bath by the skid vacuum pump.

Development, Construction, and Testing of two Five (5) meter HTS Cables:

Two 5-m cables were constructed to test the design of 30-m cables to be installed at Southwire. The cable was constructed using the stranding machine for HTS and dielectric tapes described in the previous section. The finished cable was transported to ORNL for testing. The cables were installed with the termination at the cable test facility as described in the previous section. In this section we will only discuss the design, construction and testing of two 5-m cables. Both cables were made using IGC tapes.

Design of Cable:

The cable was designed to carry 1250 Amps at 12.5 kV similar to the power ratings of overhead cable at Southwire. Two types of design of HTS cable have been reported in the literature ; Room Temperature dielectric (RTD) design and Cryogenics design (CD) of cable. Both designs use a hollow former which is wrapped with HTS tape conductor. In the RTD, a thermally insulated double wall cryostat covers the former wrapped with HTS tape. Liquid Nitrogen flows inside the hollow former and exits at the other end. The outside of cryostat remains at the room temperature. Therefore, in this design conventional dielectric can be extruded over the cryostat. In the cryogenics design cable however, the HTS tape is covered with dielectric tapes followed by an equal number of HTS tapes over the dielectric. The whole cable is then covered by a thermally insulated double wall cryostat. The liquid nitrogen goes through the hollow former and return at the other end in the space between the outer layers of HTS tapes and below the cryostat. The CD design of cable requires a tape dielectric which is suitable at liquid nitrogen temperatures. The outer layers of HTS tapes act as shielding layer of cable and it keeps the magnetic flux between the inner and outer layers of HTS tapes. Therefore there is no magnetic fields or eddy current outside the cable. This cable can carry larger amounts of current than the RTD cable which is limited by the eddy current heating of any metallic enclosures outside the cable.

Southwire chose to construct Cryogenics Design Cable with four layers of HTS tapes over the former and four layers of HTS tapes over the dielectric tapes. IGC tapes carrying approximately 20 to 30 amps were used to construct the cable. The first two layers (#1 and #2) were laid at 30 degree angle followed by the next two (#3 and #4) laid in the opposite direction at the same angle. A schematic view of a Cryogenics Design cable is given in Fig. 1:

Fig. 1: Cryogenic Dielectric Design of HTS cable

The cable was installed at ORNL HTS cable test bed. It was connected to two Vacuum Terminations (T-1) at the ends. Liquid Nitrogen was supplied by an Air Products system. The LN cooling system has the capacity to provide about 1 kW of cooling at nitrogen pressures up to 10 bar over a temperature range of 67-77 K. Power supplies are available for steady state currents of 3000 A (dc) and 2000 A (ac). A 25,000 A (dc) has now (YR 2000) been made available for pulsed current tests. A high voltage power supply rated at (100 mA at 100 kV) is also available to test the cable at peak voltage levels of 2.5 times the operating voltage.

ORNL HTS Cable Test Facility

A schematic layout of the Cable Test facility at ORNL is shown in Fig. 2.

Fig. 2: Schematic installation of 5-m HTS cable test bed at ORNL

Initially vacuum termination's were used with the first 5-m cable. A view of the vacuum termination with the LN cooling system, and vacuum pumps is shown in Fig. 3.

Fig. 3: shows vacuum termination's installed with 5-m cable.

The photograph shows HTS cable test facility at ORNL. The 5-m HTS cable is installed between the two vacuum termination at the ends. The Air Products LN cooling system is on the right side. The photograph also shows the LN circulating and the vacuum pumps.

Cable 5m #1 Test Results (Cable was constructed in Feb/Mar 1998)

Installed at ORNL on March 20, 1998 and removed on 2/1/99

The cable was cooled down to 90 K range temperature. ORNL had a problem cooling the cable to 77 K or lower temperatures. One of the main reasons was a very long run (~300 ft) for LN from the LN tank to the testing site. The Air Products sub-cooling and delivery system also did not perform as desired. Some sections of pipes bringing LN from the outside tank was changed to double wall thermally insulated pipe and the leaks in the delivery pipes were fixed. The changes made it possible to get the LN to the AP cooling system.

The cable was tested on May 22, 1998 for dc I_c at a LN temperature range of about 90 K. The testing was done with DC currents up to 1400-A. The I_c was determined to be 980-A using a $1 \mu\text{V}/\text{cm}$ criteria as shown in Fig. 4. The cable was held at 1000 A for 30 minutes. The outer shield layer had an I_c of 600-A.

Fig. 4: V-I curve of #1 5-m cable

The #1 5-m cable was also tested for the dc I_c at LN temperatures varying from about 76 K to 84 K. It was found that the I_c of the cable increases with the lower cooling temperatures as shown in Fig. 5.

Fig. 5: Variation of DC Ic with LN temperatures

The cable was also tested for PD. At voltages up to 3 kV there was very low PD. However, it increased at 4 kV causing voltage trip of the system at 6 kV. The PD and arcing in the cable was resulting from the voltage test leads. These were disconnected and Cable 5m #1 Test Results (Cable was constructed in Feb/Mar 1998) properly sheathed to make no contact. The high voltage tests were repeated with voltage ramped to 7.2, 12.4, and then to 18 kV. The cable was retested for low voltage and high ac current to 1300-1400 A rms. Next the cable was ramped to 7.5 kV and tested at 1400 A rms. The 5-m cable #1 has been successfully tested and run at the rated current and voltage.

Cable 5m # 2: (Cable was constructed in Nov/Dec 1998)

Installed at ORNL Feb. 1-4, 1999

Cable 5 m #2 was constructed similar to the 5m cable #1 and all initial tests were carried out with the vacuum termination's. ORNL measured a dc Ic of 900 A to 1130 A at LN temperatures of 80.5 K to 75.0 K. The critical currents of outer neutral layers of tapes (IGC) were determined to be 940 A to 1090 A at LN temperatures of 79.75 K to 75.0 K. The cable was tested at the rated current and voltage.

Problems with Vacuum Termination (T-1)

A major problems encountered with the Vacuum Termination was the performance of the cryogenic ceramic bushing. This bushing separates the cable from the termination housing. On the cable end, there are two cryogenics bushings. One connected to the main conductor HTS and the other connected to the HTS neutral conductors. This side of the bushing is at the liquid nitrogen temperature (~ 77 K) and pressure (5 to 10 bars), while the bushing towards the termination side is at lower temperature but under a high vacuum (10^{-4} - 10^{-5} mm). The thermal contraction of the bushing at 77K caused minute cracks, which immediately sucked nitrogen due to high vacuum in the termination. As soon as the vacuum in the termination was lost or reduced the voltage will trip. With the vacuum termination and primarily due the problems with the cryogenics bushing, the cable could be tested only for short durations.

Development of Pressure Termination (T2)

The pressure termination does not require cryogenic bushings as in the T-1 termination. The termination consists of a splice between the HTS power (inner) and neutral (outer) conductors and concentric copper pipes which are the conductors in the termination and connect to the outside power source. At the warm end of the termination, the copper pipes are connected via copper braided straps to the conventional warm bushings. The termination allows for a natural transition in temperature in the copper pipe conductors inside the termination which enables a controlled flashing of pressurized LN to the gaseous state. Thus the entire termination is near the coolant supply pressure and the high voltage and shield cryogenics bushings, a highly stressed ceramic component are eliminated. Proper seals, static vacuum in the outer termination pipe, and multi-layer of superinsulation minimize radial heat leaks. The Pressure Termination resulted in the following advantages:

- It eliminated the need for cold inner and shield bushings. It needs just two warm bushings per termination.
- There is no need for dynamic vacuum.
- It has a simplified flange and bus arrangement.
- The entire termination is at the cryogenics system pressure and there is a natural thermal transition from liquid to gaseous nitrogen in the termination along copper conductor pipes.
- It considerably reduced cost by eliminating the need for a turbomolecular vacuum pumping system and leak detectors and the cold bushings.

A photograph of 5-m cable installed with the T-2 termination is shown in Fig.6.

Fig. 6: Shows Pressure termination's installed with 5-m cable #2.

Tests carried out on T-2 termination with 5-m cable #2

1. 24 hour test with AC current (1250 - A) but with very low voltage:
6/9 -10/1999: 1250 - A ac for 22 hours
1400 - A ac for 2 hours
2. 6/11/99: DC current scan to 1500 - A on center conductor
AC withstand test: 18 kV at 0-A for 30 mins.
3. 72 hour test of T-2 with rated voltage and current
6/14- 17/99 : 7.5 kV and 1250-A ----- 65.5 hrs
10.0 kV and 1250 - A ----- 7.5 hrs

Besides the above tests, the cable has also been tested for DC I_c and ac loss. The two termination's and cable have been through 5 cool down cycles. The cool down can be accomplished in 1-2 hours with no component being stressed by the rate of cool down.

It was considered necessary to test the 5-m cable for BIL test, which is 15 times the rated voltage. For our cable the BIL limit will be about 110 kV. Since the impulse voltage is directly related to the quality of insulation, a model dielectric cable was made with similar construction as 5-m cable.

The model dielectric cable simulated the HTS/cryoflex to Cu/G-10 splice as well as the termination at the warm end of T-2. The model cable was tested by Alvin Ellis and Isidor of ORNL at the X-10 plant.

- no PD up to 12.5 kV ac
- 3-5 pC at 18 kV
- AC voltage was held at 18 kV for 30 mins (12 mA leakage current) and then held briefly to 40 kV with increased PD.
- Impulse tested. It withstood 123 kV and had a breakdown at 137 kV. It withstood 123 kV again after this breakdown and had a second breakdown at 137 kV.

BIL Test for 5m Cable #2 (7/9/1999)

The cable and the termination's were tested up to an impulse voltage of 90 kV which was the upper limit of the test equipment. There was no evidence of breakdown.

Over current Test: The cable was also tested for over current test up to 12.8 kA for a 2-s pulse length. This is about ten times the design current and simulates a short circuit on the load side.

Bend Test for 5m Cable #2:

The cable was reverse bent four (4) times around a 96" diameter mandrel as shown below in Fig. 7:

Fig. 7: shows the bending of 5-m cable #2 for further tests

The cable was reinstalled and tested for DC I_c . The I_c (dc) showed a very slight degradation (~15 %). The cable was also tested at 15 kA for 0.5 s and 6.8 kA for 5 s. There was no ill effects on cable voltage, joint resistance, coolant temperature or pressure. The cable was again impulse tested at 90-95 kV.

A summary of tests carried out on 5 m cables (#1 and #2) and the two termination's (T1 and T2) is shown in Table #1.

Table 1: shows status of 5-m Cable Tests

Test	5-m cable 1	5-m cable 2	T1(vacuum)	T2 (pressure)
DC V-I curve to ~ 1500 A	Complete	complete	N/A	N/A
AC losses up to ~1400 A rms	Complete	complete	N/A	N/A
AC withstand to 18 kV for 30 minutes	Passed	passed	passed	passed
Partial Discharge	not tested	Less than 5 pc up to 10 kV	not tested	Less than 5 pc up to 10 kV
Long term operation at rated voltage (7.2 kV) and 1250 A	26 hours	72 hours	72 hours	72 hours
Overcurrent test	not tested	12.8 kA for 2 s 15.3 kA for 0.5 s	not tested	12.8 kA for 2 s 15.3 kA for 0.5 s
Impulse test	not tested	Pass up to ~80-85 kV	not tested	Pass up to ~80-85 kV
Bend test	not tested	Bent on Feb. 24	N/A	N/A

Bend Test of Cable installed in a Flexible Cryostat

The bend tests described above were carried out on cable after bending and reinstalling it in the straight VJP. There was a question if the cable will carry the same current if it was tested in bent condition. Therefore a plan was developed to test the cable in bent condition at 0° , 30° , 60° , and 90° bent conditions. The 5-m #2 cable was reinstalled in a flexible VJP as shown in Fig. 8. The cable has been tested for DC I_c in the straight and 30-, 60-, 90- degree bent conditions. The bending radii were 3.68, 1.84, and 1.23 meters corresponding to 30-, 60-, and 90- degree bent conditions. The DC I_c of the cable was determined respectively to be 875, 865, 835, and 855 A as shown in Fig. 9. There was only a 2.3% variation in the DC I_c values from 0-degree to 90-degree bend angles.. The cable was also tested for BIL voltage and it passed the 110 kV impulse test.

Fig. 8: shows 5-m cable #2 in a bent condition in a flexible VJP

Fig. 9: DC I_c of 5-m cable #2 for the 0 and 30 degrees bent conditions

Splice Development:

For any long length cable it is necessary to be able to join two cables. Also it is required that a cable can be fixed by splicing if there is a break in the cable due to any reasons. To develop the splice and a method to join two cables, we made two 2.5-m cables which were then spliced together. For the convenience of manufacturing, the two pieces of formers were connected together and then the winding of HTS tapes and dielectrics were carried out using our stranding machine. During manufacturing of the cables, the HTS tapes were soldered for the conductor and the neutrals at their proper places. The cable was made using the architecture similar to 30-m cables Phases 1 and 2.

After the cable was made, the two 2.5 –m cables were separated. A splice was made to connect the two cables. The former of the cables are joined by means of a copper plug of right diameter. The gap between the inner conductors on the two cables are filled up by wrapping silicon tapes. The HTS tapes could be joined tape by tape, but it will take long time for the repair in the field. Therefore a technique was developed to use a split copper tube method to make the connections. The dielectric Cryoflex™ tapes are then wound over the HTS tapes making proper joints with the tapes at each end. The joining of the tapes is done using a splice made with Kapton tape. The outer layers of shield HTS tapes are then connected using the same method as used for the inner conductor.

Test Results of Splice:

The 5-m cable with a splice was installed in the cable testing lab at ORNL. The cable was tested for the DC I_c of cable and variation of DC I_c with LN temperature. A preliminary test shows I_c of the cable to be about 2650-A for phase conductor at 77 K, and 1900-A for the shield conductor at 80 K. The two 2.5 m cables were made with four layers of IGC old tapes. The shield however was made only with two layers of new NST tapes. The results are shown below in Figs. 10 and 11.

Fig. 10: DC I_c of cable with splice

Fig. 11: Variation of DC I_c of cable with LN temperature

The construction and test results of splice are very encouraging. It appears splice in the field can be easily made following the above techniques. The splice was tested at 7.4 kV operating voltage. It passed 30 min. 2.5 X ac withstand at 18 kV. The pressurized termination (T-2) and the spliced cable were tested for BIL voltage. The cable withstood 111 kV with positive polarity and 117 kV with negative polarity without any failure. It passed the 110 kV BIL requirements.

Construction, Installation, Testing, and Operation of World's First 3-single Phase, 30-M Industrial Cables

Summary:

A 30-m, cable was installed at Southwire by September 1999. It consists of 3 single phase HTS cables, LN tank, cryogenic cooling system, switch yard, and control room. The cables were constructed with a cryogenic dielectric design, similar to the 5-m cables, suitable to carry 1250 A at 12.4 kV. The cables were tested at site for the DC I_c , high current endurance, and voltage tests. It was energized in January 2000 and inaugurated on Feb. 18, 2000. The cable and the cryogenic system have proved to be very reliable and have provided 100% load for over 12,000 hours without any failure.

Conceptual Installation Design:

A conceptual installation design shown in Fig. 1 was developed during the early stage of development. It shows three single phase HTS cables installed between two overhead poles along with the switch yard. Power comes to Southwire from Georgia Power Substation at 12.4 kV and carries 1250-A. The power goes to Southwire's two main manufacturing plants (building wire and utility plants), Southwire Machinery Division, and part of the main administrative building.

Fig. 1: Conceptual Installation Design

Construction of Cables:

A cold dielectric (CD) design for the 30-m cables was used similar to the two 5-m cables. The design of cable was proven with the successful testing of 5-m cables. The cables were constructed on a 1.5" diameter flexible corrugated stainless steel former. The build up of cable was similar to that shown for 5-m cables. Cable #1 and #2 had 16 layers of Cryoflex as dielectric between the conductor and shield HTS layers. For Cable #3, 24 layers of Cryoflex were used in stead of 16 layers as in Cables #1 and #2.

The current carrying inner conductors were wound with IGC supplied NST tapes where as the outer shield layers were wound with IGC tapes. Four layers of HTS tapes were used for both conductor and shield layers. NST tapes has a zirconium oxide coating on

the surface which makes it very hard to solder the tapes. The inner and outer surfaces of NST tapes were cleaned using Dremmel tool before soldering. The IGC tapes did not require any special preparation for soldering. Soldering was carried out using 2% silver, lead tin solder. After the cables were constructed, they were pulled into a vacuum insulated double wall pipe (VJP) as shown below in Fig. 2:

Fig. 2: 30-m, Phase 2 cable ready to be pulled into the VJP on the right.

The DC I_c of cables Phase 1 and 2 were tested at the manufacturing site using 77 K bottled liquid nitrogen. The test results are shown in Fig. 3.

Fig. 3: DC I_c of 30-m Phase 1 cable tested at the manufacturing site

Installation of 3-30 M HTS Cables

The SW HTS cable phases are made on flexible corrugated stainless steel formers. However, the cable phases were pulled separately inside three solid 100 ft long 5 ½" od and 3 ½" id vacuum jacketed pipes (VJP). The cables were carried to the HTS site and installed on stands as shown below in Fig. 4 and 5..

Fig. 3: Photograph shows Phase #3 being installed at the HTS site

Fig. 4: Shows 3 –30m HTS phases installed on stands and the control room building.

A photograph of completed HTS site with cables, switch yard, control room building, LN tank and LN cryogenic cooling system is shown below in Fig. 5.

Fig. 5: HTS Cable Site at Southwire Company

The HTS cable is cooled by circulating liquid nitrogen through the three cable phases. Based upon the 5-m cable testing program, the requirements for the 30-m cryogenic system was determined to be about 3 kW heat load, 70-80 K operating temperature and approximately 21 gpm flow rate. We have selected open loop system as cryogenic refrigeration system to reduce the capital expenditure needed for closed loop system. The cryogenic system supplied by PHPK, Inc. consists of three main components; a liquid nitrogen storage tank, a cryogenic skid, and vacuum jacketed piping. /the cryogenic skid contains a cold box which houses a sub-cooler, a phase separator, and two buffer volumes, under a common insulating vacuum. The cryogenic skid also contains three vacuum pumps used to lower the pressure on the subcooler bath and lower the operating temperature. A photograph of PHPK cryogenic system along with the liquid nitrogen tank (on left) is shown in Fig. 6.

**Fig. 6: shows LN tank on left and PHPK cryogenic system on the right.
The picture also shows the cable termination on the delivery end.**

The flow of LN follows a path through the system from the circulating pump, through the subcooler, through the supply line to the cable, and returns via the return line to the phase separator at the inlet of the pump. The phase separator is used during system start up to prevent vapor from reaching the circulating pump. The subcooler is filled from the bulk LN storage tank. The subcooler boil off is vented to the atmosphere through the vacuum pumps, when operating below 80 K. The buffer tanks alternate in use, one providing system pressurization while the other is filled up and waiting.

A test protocol shown below was developed for the prior testing of HTS cables and the cryogenic system before applying the actual load on cable.

Test Protocol for 30-m HTS Cable:

1. Pressure Test Cables and Terminations - 10/25-26, Using a N₂ bottle pressure test the cables and termination to 100 to 110 psi. Each phase will be pressure tested separately.
2. Program Skid Controls - 10/22-25, Complete programming of control logic for automatic control of cryogenic system.
3. PHPK Modifications - 10/26-29, Modify thermocouples, valve seal, and pressure relief from 175 psi to 125 psi.

4. Test Cryogenic System - 10/27-29, Test cryogenic system operation in automatic control mode. Previous test used manual control.
5. Cable Drying - 10/21-31, Dry cables by purging with dry, warm nitrogen gas. Nitrogen gas will flow through cables and terminations and pressure should not exceed 60 psi.

Drying with ambient nitrogen - 10/21-22
Drying with warm nitrogen using heating strips - 10/22-24
Drying with warm nitrogen using heating strips - 10/27-31
6. Cool Down Cables - 11/1-4, Slow cooling over many hours using colder and colder nitrogen gas. Anticipate a cool down to four temperature stages - 250K, 200K, 150K, 100K - until system stabilizes at each temperature stage. Pressure will probably not exceed 60 psi.
7. Run Cryogenic System with Cable and Termination - 11/5-9, Check heat loads, temperature, pressure drops as function of LN flow rates. Test steady operation. Use low pressures (60 psi max) for all tests.
8. Setup Voltage Supply - 11/8-9, Move voltage power supply from Cofer Center to site. Provide weather proof housing for supply. Temporarily install 208 V service for voltage supply.
9. Voltage Withstand for 3 Phases at 18 kV - 11/10-12, No current. Operating conditions are 72 K and pressure up to 100 psi.
10. Voltage Withstand and Partial Discharge - 11/15-16 (Detlev Gross), Energize each phase separately and measure partial discharge using the recently ordered pd detector. This would have to be done after or as part of the installation and checkout of the pd equipment. A variable voltage power supply to cable site. The variable voltage supply would need to supply 18kV (2.5 times rated) and approximately 400 milliampere. (During the pd test of the 5-m cable on 9/25/99, at 6 kV, 22 ma; at 12 kV 44 ma; at 16 kV, 58 ma. For a 30-m cable the current would be about 6 times larger based on the increased length
11. Move Current Supply to SW - 11/11-12, ORNL will transport 3000 amp dc power supply to HTS site in Carrollton. Also data acquisition system to measure I_C .
12. Setup Current Supply and Voltage Taps - 11/15-16, Need weather proof housing and temporary 480 V, 60 A, three phase service for power supply. Install 12 voltage taps (main and shield). Need current leads for power supply and jumper between two phases. Need to connect leads to bus to test main conductor. Need to connect leads to neutral bushings to test shield conductor.
13. Measure Dc IC of the 3 Cables - 11/17-24, At low pressure (60 psi max), inner and shield conductors, temperature expected to be 72 K, LN pressure min at low pressure (60 psi). Measure the critical current on all three inner conductors and all three shield conductors. For the inner conductors, a 3000 amp dc power supply would be needed. For the shield conductors, 1400 to 1600 amps should be sufficient to reach critical current. Voltage taps would need to be temporarily installed on all 12 bushings (6 main bushings and 6 shield or neutral bushings). The testing configuration -will test two conductors at a time using a short jumper lead. The current would pass down on phase A then be jumpered to phase B and then return on the second phase. Repeat test with phase B and phase C. The inner conductors need to be tested separately from

the shield conductors as the critical currents are different by a factor of 2 (i.e. can't jumper inner to shield) [four tests].

14. DC Endurance Test (run 3-phases at one time) - 11/17-24, Operating conditions are 72 K and pressure of 60 psi. Current levels at 800 A, 1000 A, and 1250 A for 24 hours each. DC Endurance test on inner conductors
15. Outage - 11/25, A 4 to 12 hour planned outage on 11/25 starting at 7:00 a.m. The cryogenic system will be configured for this outage. This will demonstrate the ability of an HTS cable to idle through a planned outage.
16. Restart Cryogenic System - 11/25, After the outage, return to normal operation of cryogenic system.
17. Rated Voltage Endurance Test - 11/29-12/3, Operating conditions are 72 K and up to 100 psi cable pressure. Energize all three phases at one end and open circuit at the other end. Measure PD for changes in dielectric system.
18. Energize UG Cu Cables - 11/29-12/3, All three underground conventional copper cables will be placed in service and will operate in parallel with the overhead line.
19. Energized the three single phase cables on 1/6/2000, the same day several hours apart.

The test protocol were followed as per our schedule. The DC I_c of cables remained similar to the ones measured at the site. A representative DC I_c of installed cable is shown below in Fig. 7. The curve also shows the DC I_c of our first 5-m cable. It should be noted that by the time the cables were constructed, the quality of HTS tapes had greatly increased. It resulted in the DC I_c of 30-m cable being close to 3000-A against the designed current of 1250-A ac needed for the cable.

Fig. 7: DC I_c of 30-m Phase 1 cable at site.
The dc I_c of the first 5-m cable is also shown for comparison

Inauguration of HTS Cable:

An official inauguration of HTS cables were carried out on Feb. 18, 2000 by the Energy Secretary Mr. Bill Richardson and Georgia Governor Roy Barnes, A photograph showing the switching of power is shown in Fig. 8.

Dedication of cable 2/18/2000

GA Gov. Roy Barnes and Energy Sect. Bill Richardson

Fig. 8: Inauguration of cable on Feb. 18, 2000.

Operating Experience:

In the beginning of operation, we had 24 hours operators watching the system but later on the system has been operated without any operator at the site. The cable has run for over 21,000 hours @ 100% loading without any operator. Representative photographs of variations of Phase 1 current and liquid nitrogen exit temperature during one month operation is shown in Fig. 9.

Fig. 9: HTS Phase-1 current (1 hour sampling)

The return liquid nitrogen temperature remains within a very close limit (<1.5 K) as shown in Fig. 10.

Fig. 10: Variations of return liquid nitrogen temperature for phase 1

Another graph in Fig. 11 shows the variation of current and voltage for the month of Nov. 2000.

Southwire HTS Cable System

Phase 1: November 2000

Fig. 11: Variations of current and voltage for Phase 1

Present Status of HTS cable operation

The HTS cable has been in operation for over 29,000 hrs at full load supplying power to Southwire's utility and building plants, machinery division, and a part of the main administrative building. The liquid nitrogen system has been in operation for over five (5) years. During this time, the HTS cable system has never dropped the load off-line due to a failure in the system.

CONTINUED DEVELOPMENT

The HTS cable system requires minimization of cable and termination cost, and improved dielectric material for high voltage applications. With this in mind the SW-ORNL team has been working on the following new developments:

1. Triaxial Cable
2. Termination for Triaxial Cable
3. Super CryoflexTM dielectric with much improved properties

1. Triaxial Cable:

A triaxial cable is made with the three HTS phases wrapped concentrically over the same former. The three phases are separated layers of dielectric tapes. No shielding layer is required in such triaxial configuration. It would be more compact and require only about one-half of the HTS tapes as that of three separately shielded phases. With this design only one VJP is required compared to three VJP of the present system. The overall cryogenic heat load will be greatly reduced. A comparison of a Triaxial and 3-single phase of the present cable is shown in Fig. 1. The liquid nitrogen flow cross-sectional areas are about the same but the dielectric thickness is somewhat thicker for the triaxial cable due to the higher phase-to-phase voltage between the HTS conductors relative to the phase-to-ground voltage in a coaxial single phase cable.

Fig. 1: Shows 3-single phase vs. one Triaxial Cable

A 1.5-m- long Triaxial HTS cable prototype was constructed on a stainless steel former. Two layers of BSCCO-2223 tapes were used for each phase. The cable was designed to carry $1250\text{-}A_{\text{rms}}$ per phase, the same as the 30-m demonstration cable. A cross-section view of the cable is shown in Fig. 2.

Fig. 2: 1.5 Triaxial Cable hand made at Southwire. ORNL added the G-10 tube filled with wax for testing purposes.

The V-I curves for each of the three phases was tested at ORNL and the test results are shown in Fig. 3. At the $1\text{-}\mu\text{V}/\text{cm}$ criteria, the critical current was determined to be 3.6 kA, 3.1 kA, and 2.8 kA for phases 1 to 3 respectively. The currents in each phase are comparable to the 30-m cable installed at Southwire even though the Triaxial cable was constructed with only two layers of HTS tapes per phase. During the tests the lead connections for Phase 2 and 1 were possibly slightly damaged which resulted in lower phase currents. The current of Phase-3 however, remained the same throughout the test period.

Fig. 3: V-I curves of each of the three phases

AC losses were measured both electrically and calorimetrically. The three phase calorimetric data are close to the sum of three individual phases. There was no measurable excess ac loss due to the presence of other concentric phases. At the design current of 1250-A, the total measured ac loss for the prototype triaxial cable was only 1 W/m.

The encouraging test results of 1.8 m triaxial cable has led to a development program to construct a 5-m cable and test it at the ORNL test bed. The cable was designed to carry 2500-A at 15 kV.

2. Termination for 5-m Triaxial Cable

Design and development work has continued for a new termination suitable for the triaxial cable. This termination will have reduced heat load compared to earlier terminations. Several changes are being considered to make this termination suitable for higher voltages.

3. Dielectric Development

SW-ORNL are investigating dielectric performance of several materials similar to Cryoflex used on our 30-m cable. Model cable tests are continued for ageing study to determine the expected life of the cable. Model cable tests for BIL voltage are also being carried out to study the different design concepts for construction of the cable.

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