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ELEMENTS OF A SPECIFICATION FOR SUPERCONDUCTING CABLE AND WHY THEY ARE IMPORTANT FOR MAGNET CONSTRUCTION.

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ABSTRACT

The purpose of this paper is to point out several features of the specification for SSC superconducting cable[1] and its insulation[2] that are important for fabrication of dipole magnet coils. Among these are the dimensions of the cable and insulation and their relevance for obtaining coils with appropriate overall dimensions. Other important cable properties are related to the twist direction of wire used to fabricate it[3] and the opposite twist (or lay) direction of the cable. For some coils it is easier to work with cable of a particular lay direction. In conjunction with the ease of coil winding comes the requirement in the specification for superconducting cable which restricts the cable surface condition. The ease of winding coils is governed by the ability to bend and twist the cable at the coil ends without having wires come out of place, possibly later leading to insulation damage and a turn-to-turn short.

CABLE AND INSULATION DIMENSIONS

The dimensions of the cable and insulation and their fabrication tolerances are important elements for the construction of SSC dipole coils with satisfactory overall construction tolerances. The bare cable dimensions are described in Fig. 1 and the wrapped cable parameters are given in Fig. 2. The relevance of these dimensions and tolerances to the overall coil dimensions will be described below.

The variations of cable and insulation thickness are related to the variation of overall coil azimuthal size and are, therefore, among the most tightly controlled dimensions in the magnet. Azimuthal size is defined in Fig. 3. The azimuthal size is measured after the coils have been molded and the pre-preg fiberglass insulation has been cured. A special fixture and tooling are required to compare the coil size with a standard while applying 10.0 kpsi or 8.0 kpsi stress to the surface of the inner or outer coils respectively. These pressures are chosen because they are the nominal desired stress values for the coils when they are later collared

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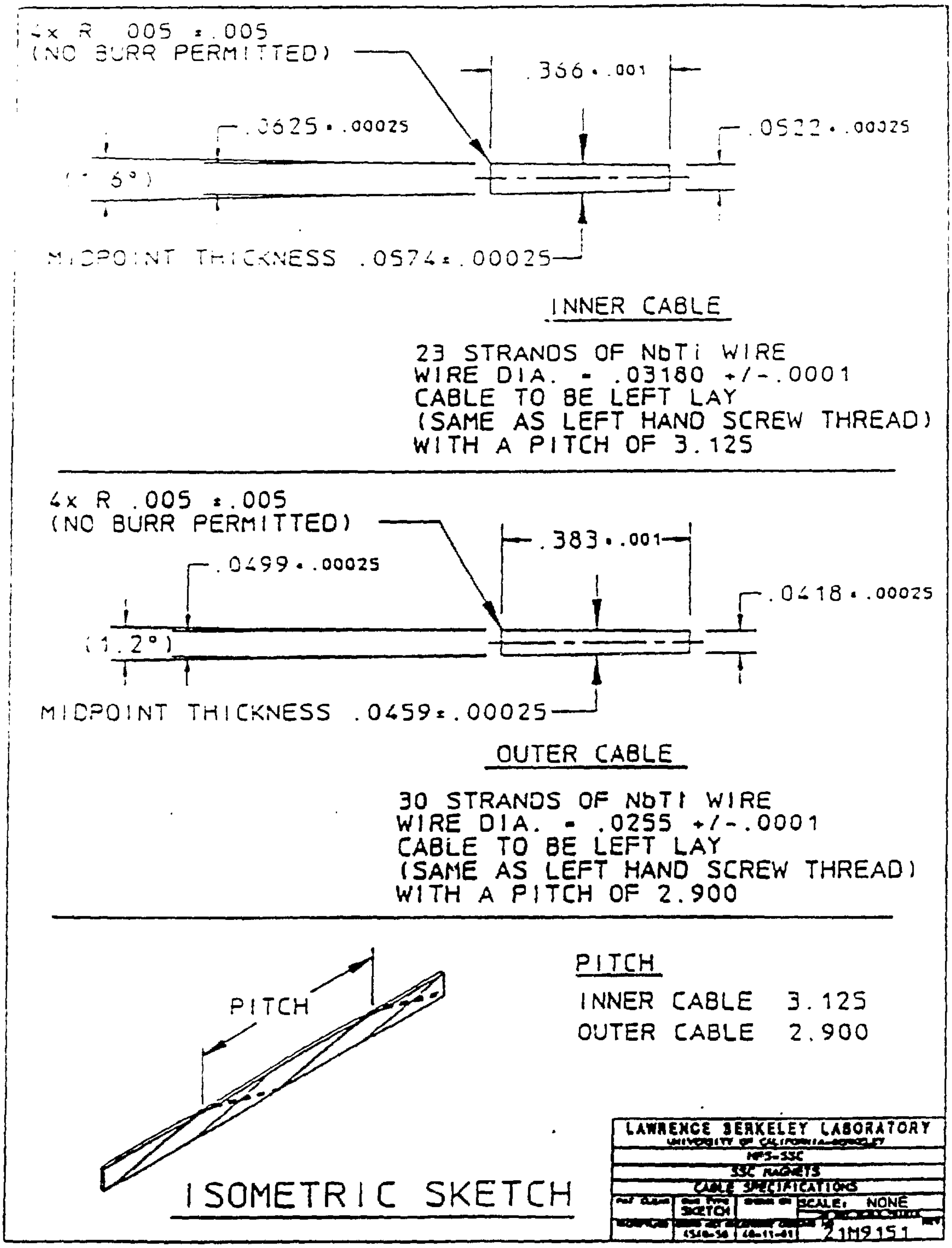

Fig. 1. Dimensional and Other Parameters of the SSC Inner and Outer Layer Superconductor Cable.

during magnet assembly. In order to meet the requirements of magnet field quality and to maintain an adequate assembly prestress window for the coils, the azimuthal sizes of all coils should be within ± 0.002 in.

This coil size variation is difficult to achieve with thickness variations of the coil components. Therefore, a method has been developed to adjust the coil size to compensate for the variations of component dimensions by molding the pre-preg fiberglass tape to different thicknesses. The maximum adjustment required in the fiberglass tape is

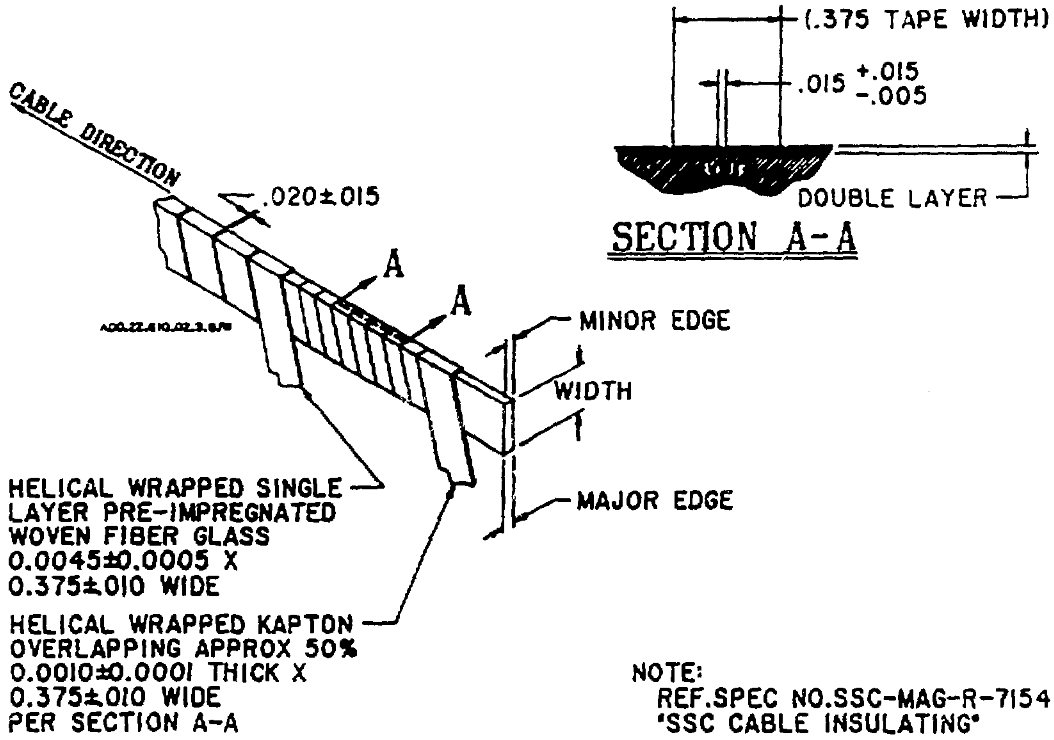

Fig. 2. Wrapped Cable Parameters for the SSC Superconductor Cable.

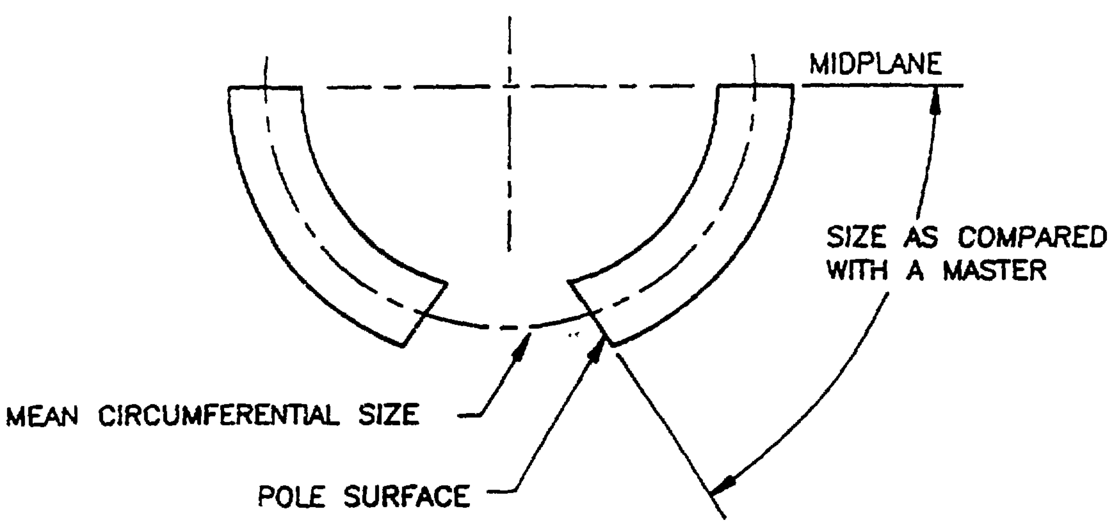

Fig. 3. SSC Dipole Cross Section Definition of Coil Azimuthal Size.

approximately 0.0003 in. per layer out of 0.0045 in. uncured thickness. In spite of this adjustment method, it is important to limit the variations of the component dimensions as shown in Table I. The copper wedges used in the coil fabrication are insulated in the same manner as the cable. The accepted specification tolerance for the Kapton insulation is ± 10% per layer. However, in practice the variation of Kapton thickness is ± 5% per layer. From Table I it is clear that the variation of bare cable thickness can contribute significantly to the variation of overall coil size and must be tightly controlled.

The maximum variation of the cable keystone angle is ±0.1 degree. It is necessary to control this dimension to maintain uniform coil prestress across the width of the cable when the magnet is collared. Non-uniform prestress may produce "creep" (or flow) of the Kapton insulation. This may eventually lead to an electrical short between adjacent turns if the "creep" is excessive.

It is also important to control the cable width within the specified tolerance of ±0.001 in. This dimension controls the coil radial thickness. Any variation beyond this tolerance may cause damage to the insulation during coil molding or may cause excess friction between the insulated cable and the molding fixture cavity during coil curing and sizing. Such friction may produce an uneven azimuthal distribution of cable turns in the coil and unacceptable variation of the magnetic field harmonics.

During manufacture of SSC cable it is normal practice to utilize a Cable Measuring Machine to monitor the variations in the bare cable dimensions. With a continuous measurement it is also possible to adjust, for example, the rolled cable thickness and to maintain the required tolerance. In

Table I. Estimated Variations of SSC Coil Component Thicknesses.

	Inner Coil (16 Turns, 3 Wedges) [Dimension-inches]	Outer Coil (20 Turns, 1 Wedge) [Dimension-inches]
Bare Cable (±0.00025 in./turn)	±0.004	±0.005
Wedges (±0.001 in./wedge)	±0.003	±0.001
Kapton (±0.0001 in. or 10% per layer specified/ ±0.0005 in. or 5% per layer actual)	±0.0076/±0.0038	±0.0084/±0.0042
Pre-Preg Fiberglass Tape (molded)	-	-
Totals:	±0.0146/0.0108	±0.0144/0.0102
Requirement:	±0.002	±0.002

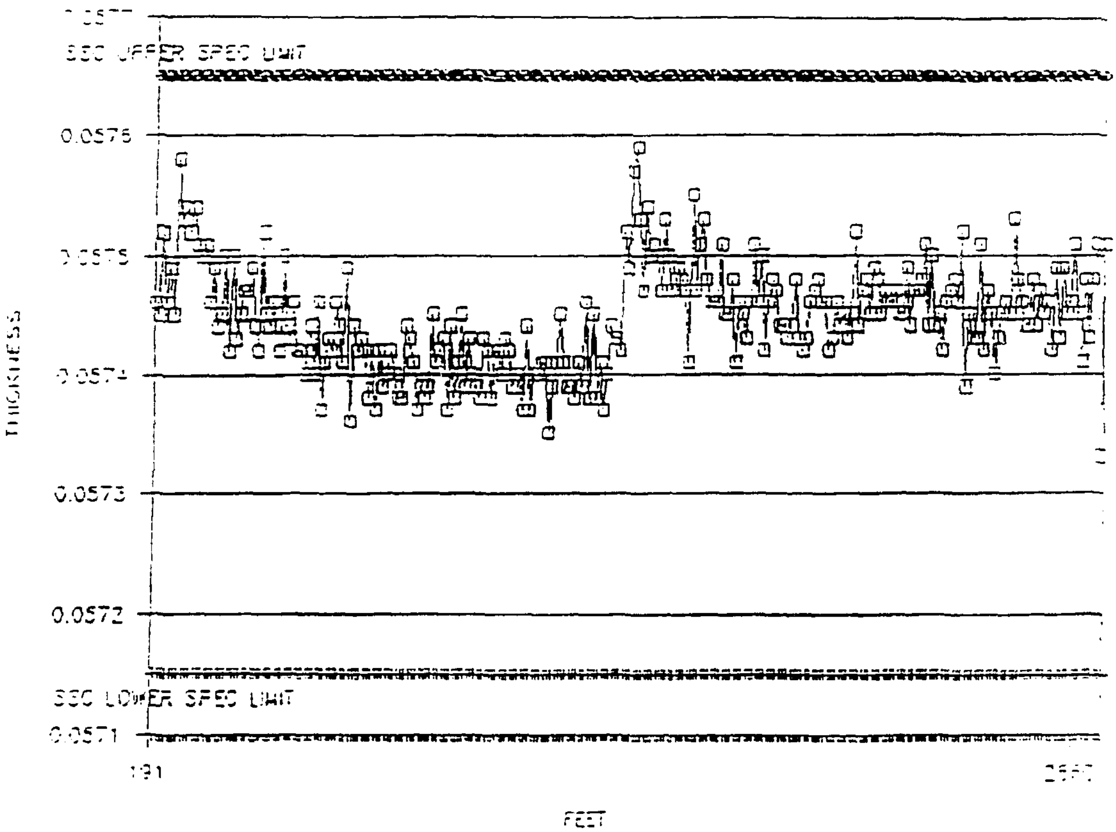

Fig. 4. Measurements of an SSC inner cable thickness using the *Cable Measuring Machine*. Mid-thickness measurements are made continuously along the fabricated cable length.

Figs. 4-6 are shown the cable thickness, keystone angle and width measured for a typical SSC cable using the Cable Measuring Machine; the estimated measuring accuracies are ±0.0001 in., ± 0.01 degree, and ± 0.0001 in., respectively for the three dimensions.[4]

Upon receipt of the cable for use in fabrication of coils it is normal practice to perform an incoming inspection of the cable dimensions.[5] These measurements are done using different equipment shown in Figs. 7-9. For these tests short sections of cable are cut from the end of each cable reel and are subjected to conditions similar to those in the continuous measurements by the Cable Measuring Machine. These measurements are simple to perform and are useful as an independent check of those taken during cable fabrication. Of course, since cable samples must be cut from the reel, checks can only be made at the end of a cable length.

The ten-stack fixture shown in Fig. 7 uses ten pieces of cable, each approximately 4 in. long and assembled into the fixture with alternating keystone direction. After calibrating the fixture with a standard block, 5 kpsi stress is applied to the coil stack. This stress is equivalent to that applied with the Cable Measuring Machine.

The cable keystone angle is measured using the device shown in Fig. 8. After calibration of the fixture with a standard, the cable is placed into a slot machined with appropriate dimensions. Tension of 40 lb. and stress of 2 kpsi are applied. The keystone angle is measured using sensors mounted to the fixture.

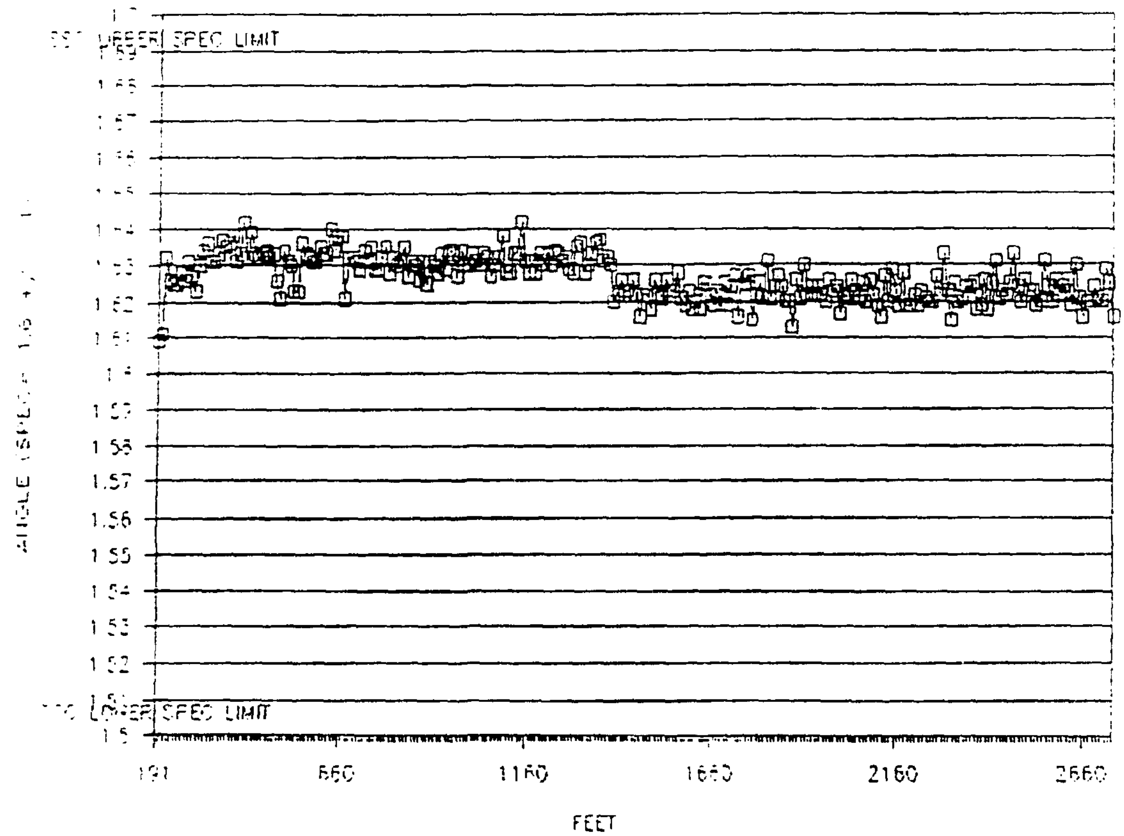

Fig. 5. Measurements of an SSC inner cable keystone angle using the Cable Measuring Machine.

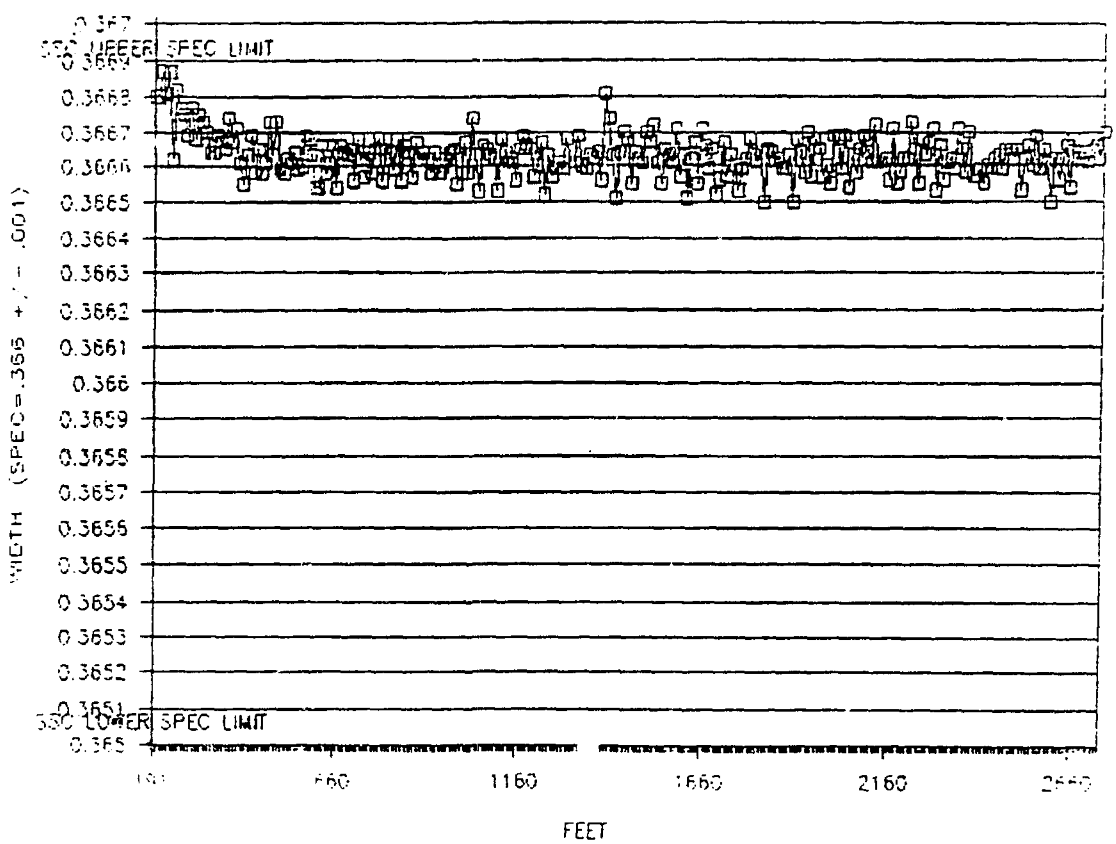

Fig. 6. Measurements of an SSC inner cable width using the Cable Measuring Machine.

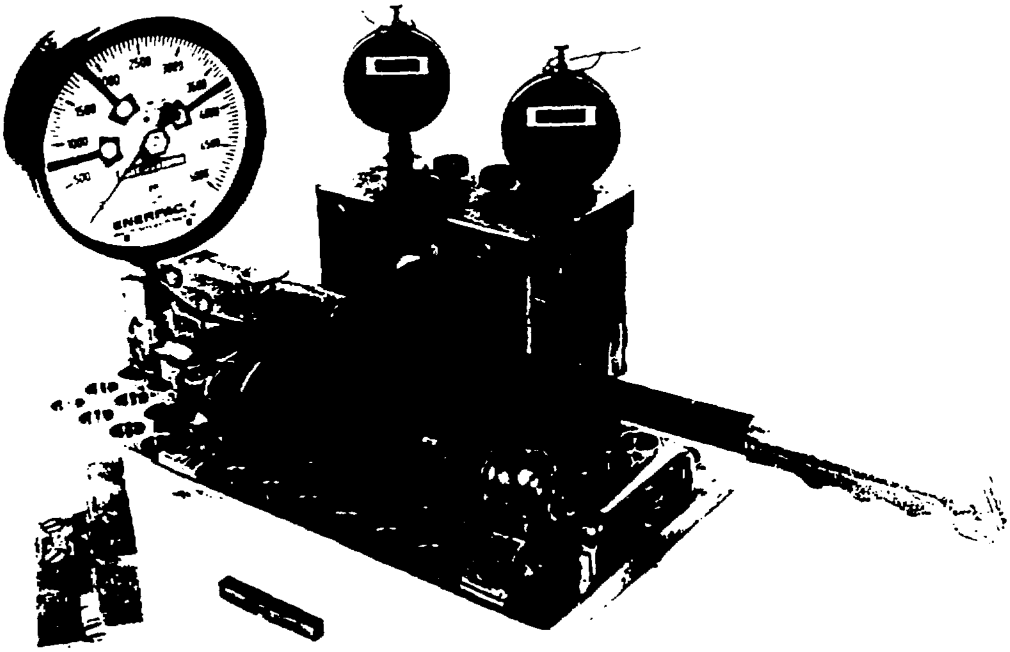

Fig. 7. Ten-stack measuring fixture for incoming inspection of SSC cable mid-thickness.

The cable width is checked using a device which allows a 3 ft. long piece of cable to hang while suspending a 40 lb. weight; this is shown in Fig. 9. The cable width is measured with a micrometer while it is under tension. At the same time the residual twist of the cable is measured, since the suspended 40 lb. weight is allowed to rotate. Measurement of an excessive residual twist angle may indicate a problem with the cable. This will be discussed further below.

CABLE MECHANICAL PROPERTIES

The direction of cable lay (or twist of the wires in the cable) is relevant to the ease of coil winding. All wire used to fabricate SSC cable has a "right twist", where the filaments in the twisted wire follow the same direction as a right-hand screw thread. The wire twist direction has been chosen to be the same for both SSC inner and outer wires to reduce the opportunity for twisting errors. All SSC cable has a "left lay", where the wires in the cable follow the same direction as a left-hand screw thread. In order to fabricate a cable with good mechanical characteristics, it is important to have the directions of wire twist and cable lay be opposite. Those desirable mechanical characteristics include producing a cable with minimal residual twist and having the surface of a cable be smooth with wires tightly registered adjacent to one another. Residual twist of cable will cause coils to be twisted, which is difficult to overcome during magnet assembly. As mentioned above, residual twist in a cable is checked during routine incoming inspection by suspending a 40 lb. weight from a 3 ft. length of cable. Experience has shown under these conditions that an acceptable cable will have a maximum twist of 90° in the direction of cable lay and 0° in the opposite direction.

There is a preferred direction for winding coils with a particular cable lay. SSC inner coils are wound in one direction and outer coils are wound opposite. This enables a simple splice between the inner and outer coils which is completed during coil assembly.

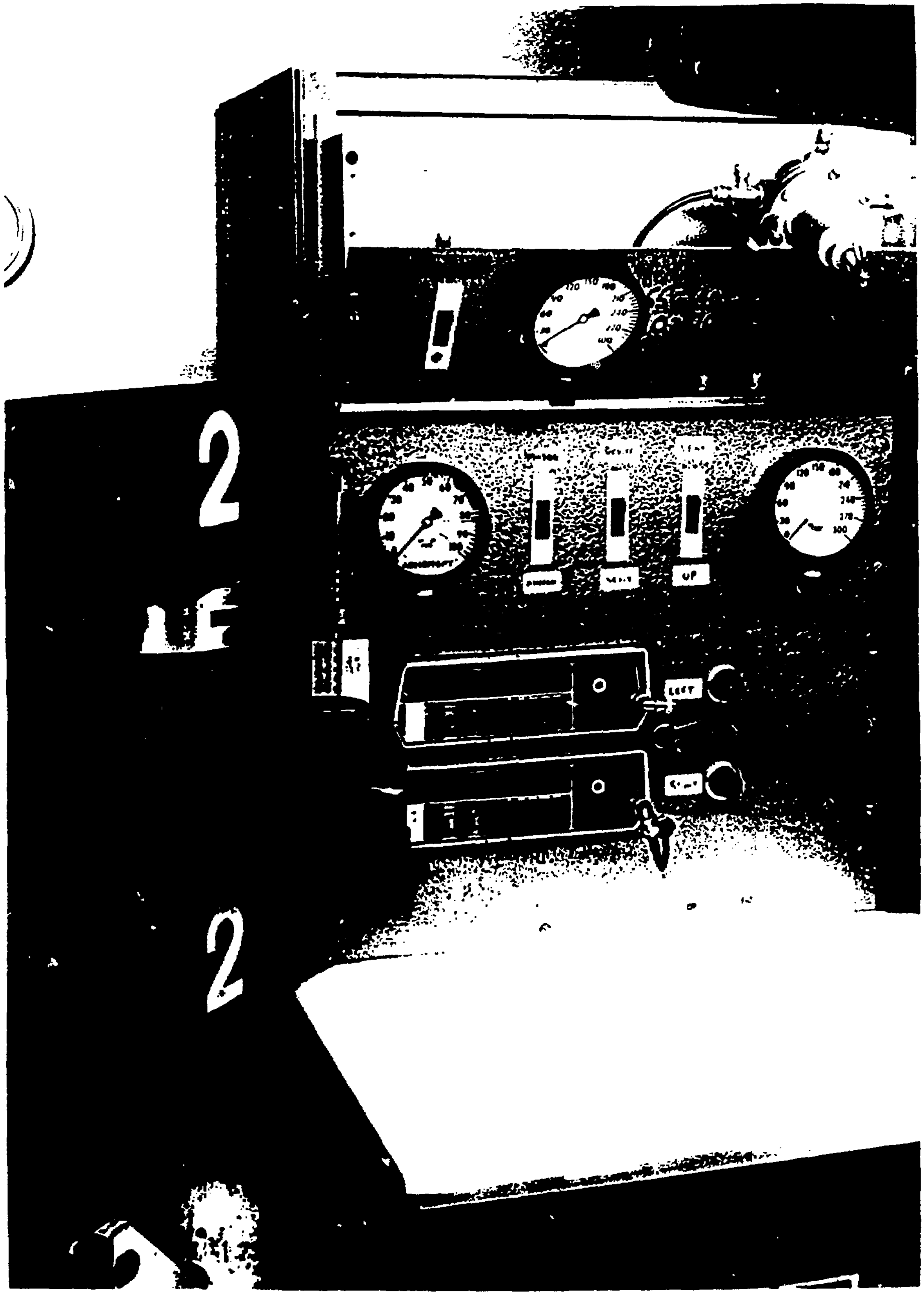

Fig. 8. Fixture for incoming inspection of SSC cable keystone angle.

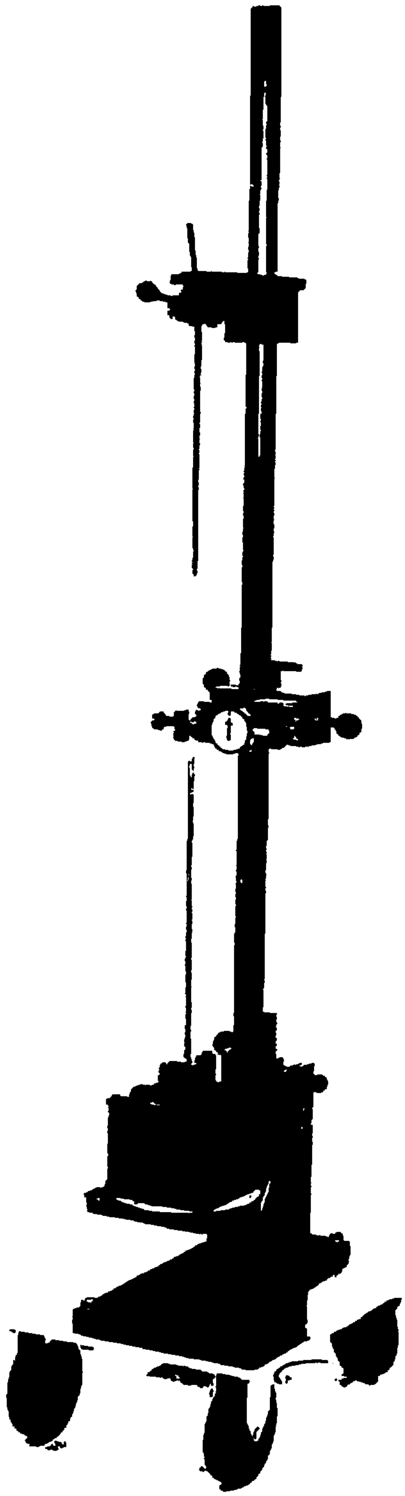

Fig. 9. Fixture for incoming inspection of SSC cable width and residual twist.

The SSC outer coils are wound in the direction favorable to the left lay of the cable. This choice was made at the beginning of the R&D program because of concern in having wires in the outer cable come out of place while winding coil ends. SSC outer cable is more delicate because it is fabricated from more wires of smaller diameter (outer cable: 30 wires with 0.0255 in. diameter vs. inner cable: 23 wires with 0.0318 in. diameter). Therefore, because the inner coils are wound in the unfavorable direction, it is necessary to check the coil ends closely for wires which may come out of registration in the cable particularly while winding the first few turns. If a wire comes out of registration it produces a high-spot in the coil which will puncture the insulation when it is subjected to high prestress during magnet assembly. Such damage to the coil insulation will always lead to an electrical turn-to-turn short in the coil.

In Fig. 10 is shown a diagram of the initial stages of winding an SSC inner coil and the region where a wire crossover is most likely to occur. An explanation will be given of the reasons for a favorable or unfavorable winding direction for cable having a particular lay direction. Because of the geometry of a $\cos\theta$-type coil end, the cable lay is always tightened on one side of a coil end and loosened on the opposite side. It is more likely to produce a wire crossover while loosening the cable and also twisting it to conform with the coil end. However, since a choice must be made, it is best to loosen the cable on the side while starting to wind the coil end. Then it is possible to rely on the cable winding tension of 35 lb. to help register the wires against the side of the center post. On the opposite side of the coil end, where winding tension is of no assistance, it is best to tighten the cable lay.

As shown in Fig. 10, the location in the coil end where the cable is loosened is where wire crossovers are most likely to occur. Care must be taken by the coil winding technicians in the fabrication of the inner coils in these regions so there is no excessive twisting of the cable. Computerized control of the cable carriage and coil winding mandrel rotation will greatly reduce the opportunities for errors.

To fabricators of superconductor cable there is a requirement on cable surface condition which is included in the cable specification. The requirement states that, "... the cable wide face shall be uniform to within 25% of a single wire diameter...". If this requirement is not met, there is a serious risk of wire crossovers in the cable, especially when winding the coil ends. Experience during SSC R&D has shown that a possible cause of this condition, normally referred to as "popped wires", is the use of wires in a cable which are not all from the same billet geometry or have not been processed using the same procedures. Other possible causes are incorrect wire tension during cabling, wire or cable dimensions outside the required tolerance limits, or incorrect wire twist direction. In order to check for this condition of "popped wires", use is made of lump detectors to detect high spots in the cable of greater than 0.005 in. These detectors are installed in the equipment used for cable insulating and on the coil winding machines. See Fig. 11. Because the popped wires may eventually be hidden by the cable insulation, it is important that the technicians involved in that operation be aware of this potential problem.

CONCLUSION

Superconducting cable fabrication and coil manufacturing for SSC follow routine procedures which have been developed during the R&D program. However, some lessons have been learned of methods to prepare the conductor and of associated quality control steps that should be followed to assure that the cable and coils will be satisfactory. Adherence to these steps should enable a successful outcome of the construction project.

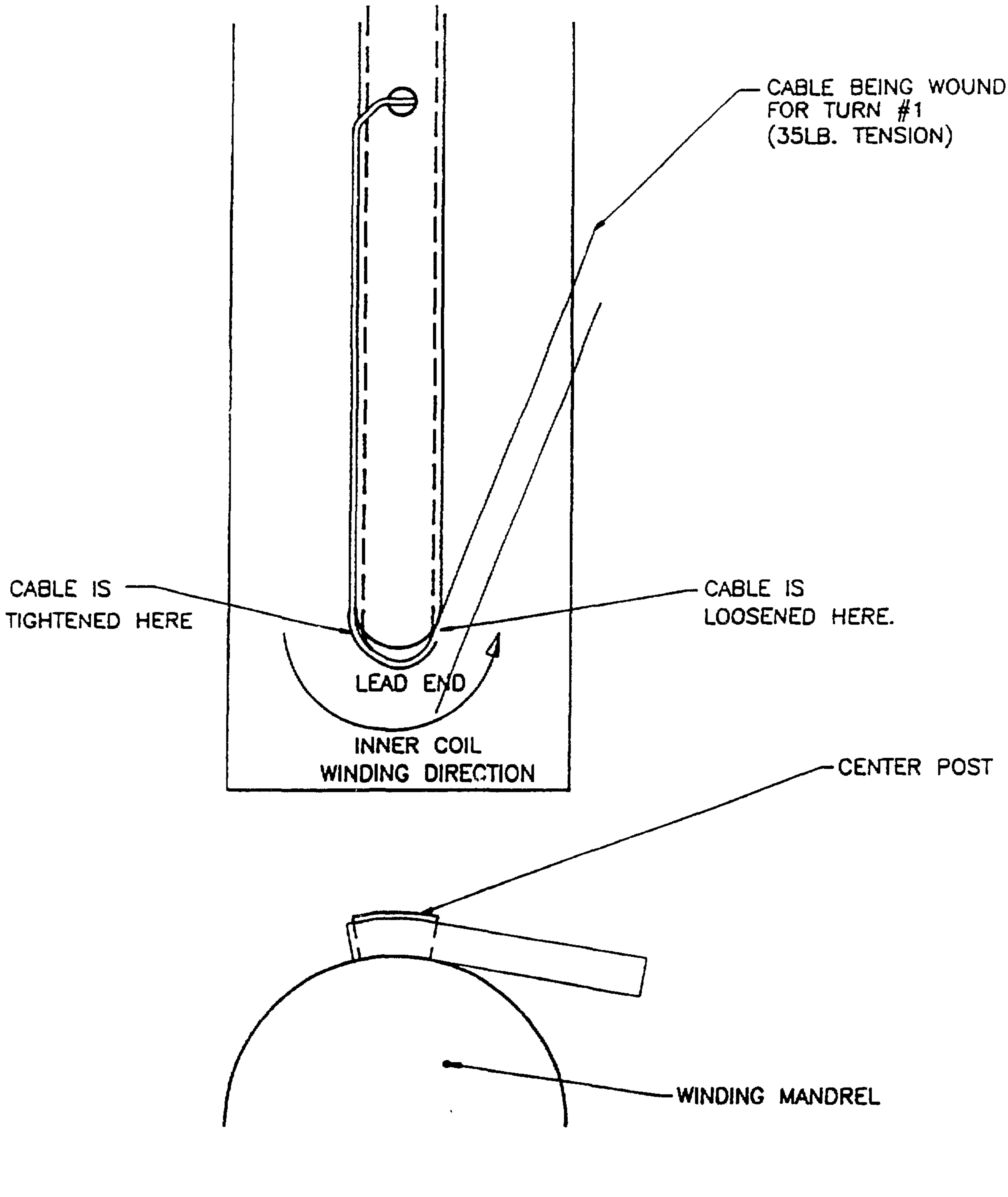

Fig. 10. Cable characteristics while winding SSC inner coils.

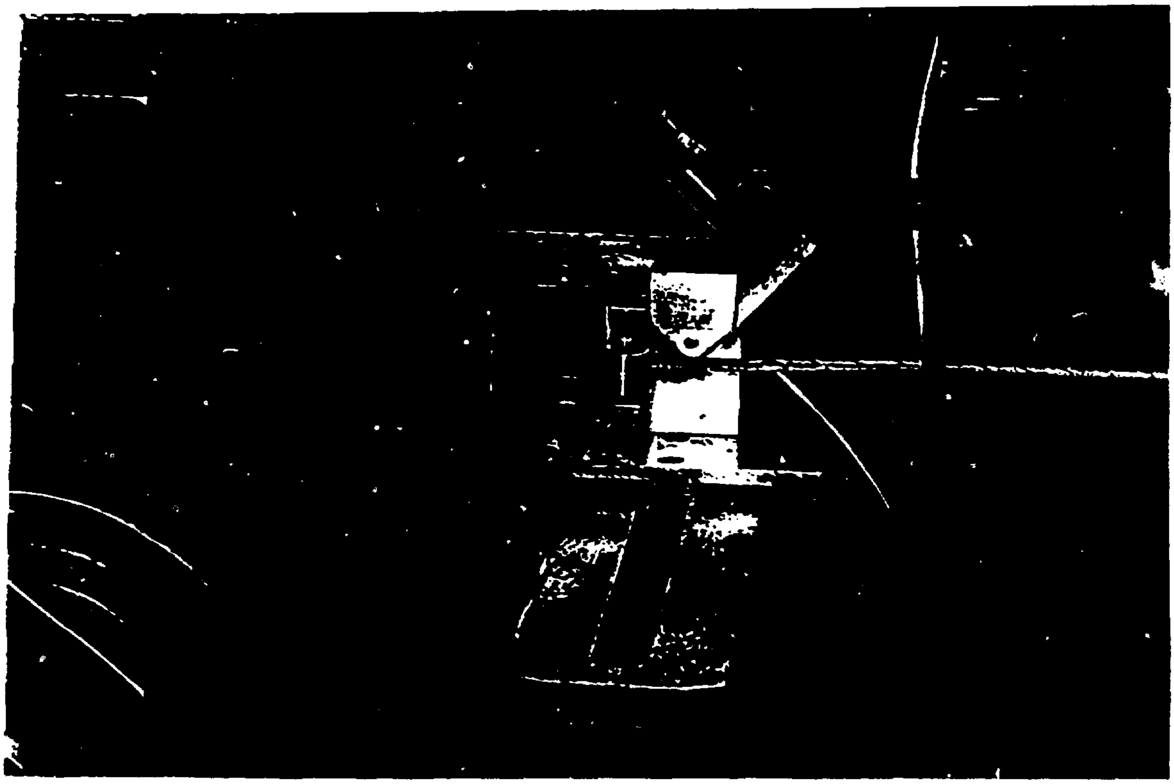

Fig. 11. Lump detector used in the insulating process and during coil winding to look for irregularities in the surface of SSC cable.

REFERENCES

[1] SSC Specification SSC-MAG-M-4142, NbTi Superconductor Cable for SSC Dipole Magnets.

[2] SSC Specification SSC-MAG-R-7154, SSC Dipole Cable Insulating.

[3] SSC Specification SSC-MAG-M-4141, NbTi Superconductor Wire for SSC Dipole Magnets.

[4] J.A. Carson, et.al., "A Device for Precision Dimensional Measurement of Superconducting Cable", Proceedings of the ICFA Workshop on Superconducting Magnets and Cryogenics, Brookhaven National Laboratory, May 12-16, 1986, 162-65 (1986), P.F. Dahl, Editor, BNL 52006.

[5] SSC Specification SSC-MAG-R-7142, SSC Dipole Cable Test Methods.