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Author
Royet, J

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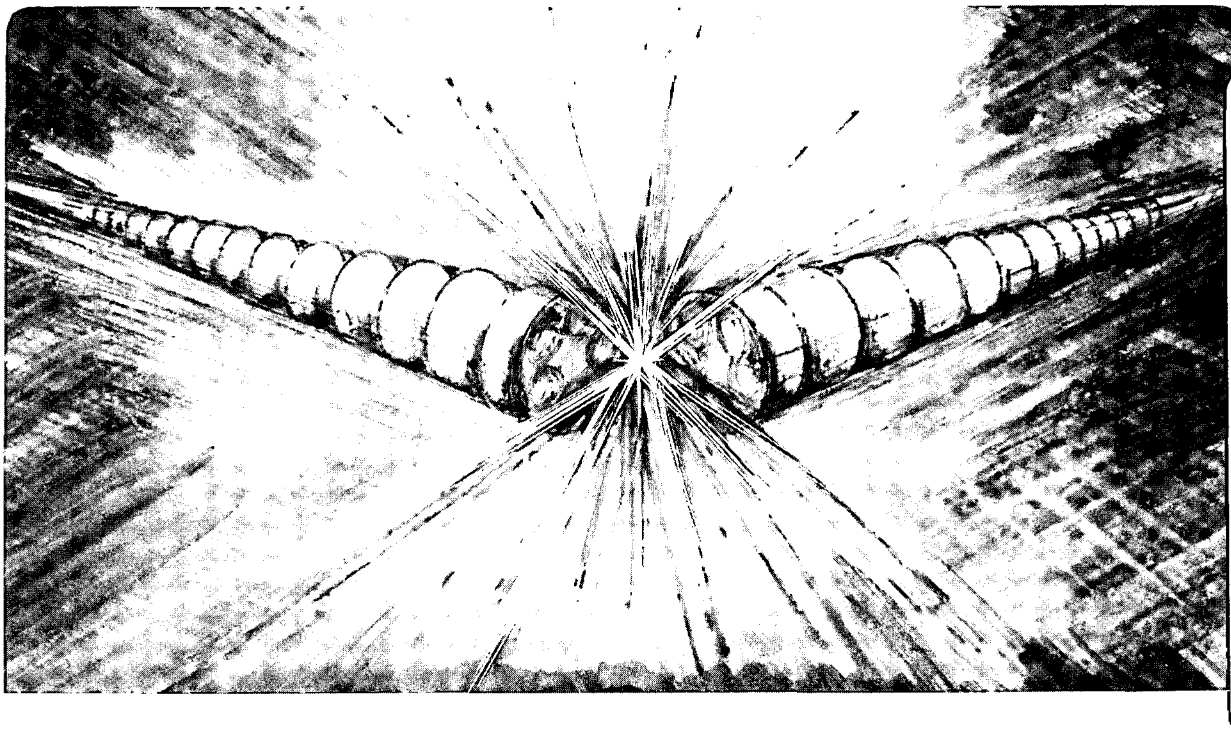
Accelerator & Fusion
Research Division

Magnet Cable Manufacturing

J. Royet

October 1990



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LBL-29345

Magnet Cable Manufacturing*

John Royet

Accelerator & Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

August 1990

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FOREWORD

The cable is the heart of a superconducting accelerator magnet. Since the initial development of the Rutherford Cable more than twenty years ago, many improvements in manufacturing techniques have increased the current carrying capacity. When the Tevatron cable was specified fifteen years ago the current carrying capacity was 1800 A/mm^2 at a field of 5.3T. During the intervening years it has been increased to 3000 A/mm^2. These improvements were due to refinements in the fabrication of the strands and the formation of the cable from the strands. The metallurgists were able to impart significant gains in performance by improving the homogeneity of the conductor. The engineers and technicians who designed and built the modern cabling machines made an enormous contribution by significantly reducing the degradation of wire performance that occurs when the wire was cabled. The fact that these gains were made while increasing the speed of cabling is one of the technological advances that made accelerators like the SSC possible. This article describes the cabling machines that were built to manufacture the cable for the full scale SSC prototype magnets and the low beta quadrupoles for the Fermilab Tevatron. This article also presents a compendium of the knowledge that was gained in the struggle to make high performance cable to exacting dimensional standards and at the throughput needed for the SSC. The material is an important part of the technology transfer from the Department of Energy Laboratories to Industry.

John Peoples

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Magnet Cable Manufacturing*

John Royet
Lawrence Berkeley Laboratory
1 Cyclotron Road, Bldg. 46-161
Berkeley, CA 94720 USA

1. Introduction and history

1.1 Background

The Superconducting Super Collider (SSC) project will need the largest amount of superconducting cable ever manufactured for one application in order to make the dipole and quadrupole magnets.

The conductor configuration used most often for high-current-density accelerator magnets is a compacted, high-aspect-ratio cable first made at Rutherford High Energy Physics Laboratory used in 1973. This Rutherford-type cable has since become widely used for particle accelerator magnets, for example at the Fermilab Tevatron in the US, HERA in the FRG and UNK in the USSR.

Compared with a monolithic conductor, the Rutherford-type cable is more flexible and easier to bend over a small radius, especially at the ends of small-aperture magnets. Until now, Rutherford-type cables have been made from 23 or 24 strands. The SSC project requires 36 strands in the external dipole layers. The 36-strand cable was made very successfully for the low-beta QUAD project at Fermilab.

1.2 Short History

Cables have been made for centuries. In the beginning they were used for mechanical applications such as ships, mines, elevators, etc. All of them were manufactured from strands using a one-to-one planetary twist ratio to obtain final product free of torque stress. First, the material used was natural fiber, then later metals.

Electrical cables were also needed for overhead power lines. In the beginning, they were made of copper, then aluminum or a combination of the two with a steel core for added tensile strength. The superconductor era was soon to follow.

The Rutherford-type cable originated in England after an evolution that culminated in the development of the "Flat 15" type cable, which was needed for the construction of pulsed superconducting dipole magnets. Several considerations determined the geometry of the assembly of strands into cable:

- Electromagnetic criteria. Operating current, magnetic field, magnetization losses, stability, and current sharing between the strands were challenging obstacles. The coupling criteria dictated the need for transposition of strands in the cable.

- Magnet construction criteria. Heat transfer, ease of winding, positional accuracy of the turns in the winding for magnetic field quality, and strength to support the Lorentz forces during operation were qualitites to achieve.

- Cable construction criteria. Low probability for strand breakage during cabling; high compaction of superconductor strand to increase magnetic field strength, good cooling from heat transfer between liquid helium and superconductor, positional stability and low degradation due to the strain developed during the cabling process were criteria needed for cable construction.

The considerations mentioned above were also important for the design and construction of the Tevatron dipoles for the Fermi National Laboratory.

The Tevatron program was the first large superconducting dipole enterprise. The cabling industry had the task to extrapolate the 15 strands of Rutherford cable to a 23-strand Tevatron cable. This was not easy and many bugs were a challenge to overcome. Among them, we have to mention that "cross over" defect which results in a local compaction increase of the strands with a degradation risk for the superconducting filaments.

Several years later, in 1983, the scientific community set its goals for a bigger project: the SSC. Very early, the superconducting cable was pointed out as one of the critical components, and the government laboratories started to work on the problem.

Lawrence Berkeley Laboratory took the lead, and in November 1984, a 36-strand Rutherford-type cable was made using an experimental cabler that had been assembled in-house. This milestone insured that a 30-strand cable could be incorporated into the early design of the SSC.

The following years were spent improving the cabling technology. This report summarizes the main steps.

Our recent efforts at LBL, in addition to the development of increasing the number of strands are focused on reducing critical degradation during cabling and improving the dimensional tolerances.

This work has resulted in a new concept for the tooling and the definition of specialized cabler characteristics.

2. Superconducting Strands

The wires used in this cable manufacturing task are made of superconducting filaments of niobium-titanium embedded in an OFHC copper matrix.

2.1 Mechanical Characteristics

The superconducting material is a composite with highly anisotropic properties. The copper matrix is usually a 99.9% pure metal, which can be annealed to the softest grade and shows a high resistivity ratio between liquid helium and room temperatures. The cold working effect obtained by wire drawing deteriorates this resistivity ratio, requiring us to face the following alternatives:

- use the wire as drawn, accepting the reduced conductivity and the corresponding lower degree of cryogenic stability for the wire or:
- proceed with a final annealing. Heat treatment performed after wire drawing or cabling, can interfere with the ultimate cold working sequence. This is done to the material in order to produce high critical current at high field. In such case, the working parameters of the future magnet have to be considered.

We have to mention here that new developments in the flux pinning technique, through the use of an heavier niobium barrier around the filaments, could avoid the sequential heat treatment process.

2.2 Twist

The composite strands are twisted around their own axis during the manufacturing process, usually before the last sizing die. The purpose of this imperfect transposition is to improve the electrical behavior of the conductor when it is exposed to changing fields by reducing the magnetization effect. However, for the low pulse frequencies applied to accelerator magnets, the twist period is quite long (one to four twists per inch). Wire twist is also one of the parameters of the cable degradation and should be a matter of concern for both the wire and cable manufacturer. We will address this point later.

2.3 Mechanical Memory

The superconducting wire shows an important "memory effect". Any attempt to change the dimensions or the strand shape releases counter twist of varying amounts. Amazingly, a final wire anneal increases this memory effect because only the copper is affected by the annealing. Therefore, the superconducting filament bundles have more freedom to untwist or, if the wire ends are fixed, to generate a torque. This torque is one of the important parameters to understand in order to adjust the final residual twist of the cable.

2.4 Dimensions

Table I SSC Wire and Cable Parameters for the Initial Design

Parameter	Inner Layer	Outer Layer
Wire diameter	0.81 mm	0.65 mm
Copper to S.C. ratio	1.3	1.8
Cable mid thickness	1.458 mm	1.166 mm
Cable width	9.296 mm (23 str.)	9.728 mm (30 str.)
Keystone angle	1.6°	1.2°

Table II Dimensional Tolerances for Some Projects

	SSC	Tevatron	HERA
Wire diameter	±2.5 μm	±7.6 μm	±10 μm
Mid Thickness	±6.35 μm	±12.7 μm	±20 μm
Width	±36.5 μm	±25.4 μm	±30 μm
Keystone angle	±0.1°	±0.4°	±0.2°

Such dimensional tolerances look very tight, especially for the wire, which is the leading parameter, but the magnetic field configuration quality is based on this condition.

3. General Principles of Cabling

Making a cable is accomplished by organizing several strands (wires) compactly with an overall stable shape. This means that the product will return to its original shape after a mechanical attempt to disturb it. In order to achieve this condition, the gyration radius of each strand cross section must be minimum (minimal inertia). This is naturally obtained with "round" cables made of hexagonal array of strands around a central core. We assume the strand material shows elastic properties.

If the strands are parallel to the cable axis, we have a compact cable, but stability is obtained only in straight lengths and under tension. Stability could be also obtained by means of an external conduit or a tubular braid. This solution is common for fiber optic cables.

If the strands are cabled with fixed ends, which means that their ends are not free to rotate around their own axles ("solid cabler" configuration, Fig. 1A) the cable shows a residual torque. In other words, each strand reference-axis system rotates around the cable reference-axis system, which is fixed in space. If we try to remove one strand from such a cable, with the ends fixed in x,y position, we are obliged to twist the wire with respect to its own axis by an amount equal to one turn per lay pitch of the cable. This is the compulsory motion we have to perform in order to switch from one reference system to the other (strand to cable).

To obtain a stable cable without residual torque, the wires are cabled and twisted at the same time in the opposite direction with respect to the cable reference system at the ratio of one twist for one turn of the cabler's barrel. When we uncable any one of the strands, ends fixed as before, we do not observe any twist because the planetary motion has already changed the reference system (Fig. 1B).

This second process is currently applied in the cabling industry.

A third process was also proposed: the free planetary cabling: In this case, the spools on the cabler barrel are free to rotate, and the wire torque is absorbed through this free motion. However, since spool spinning friction is never the same for all the strands, this can result in cable irregularities.

Those general principles of cabling must be kept in mind since we will have to use them to understand the technique of cabling superconducting wires.

3.1 Basic Cabling Model

To start, we will imagine that we use an untwisted strand. A one-to-one (1:1) planetary ratio means that the fixed gear at the "sun" of the system (center of the barrel) has the same number of teeth as the gear attached to the spool. We will also assume that the mechanical connection between those two gears is not direct, having for example, a straight chain link or an intermediate gear of any size and resulting in a reverse rotation direction of one gear versus the other.

Figure 2A shows a CCW (counter clockwise) rotation of the barrel. We can observe that the spool rotates CW (clockwise) relative to the barrel.

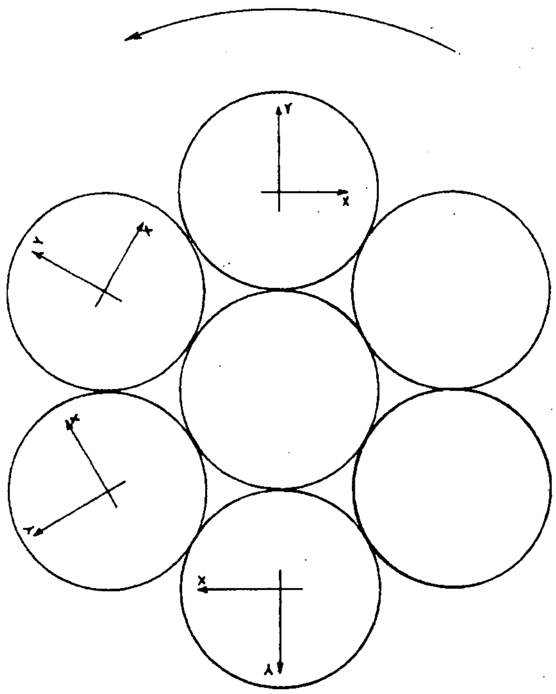

FIGURE 1A

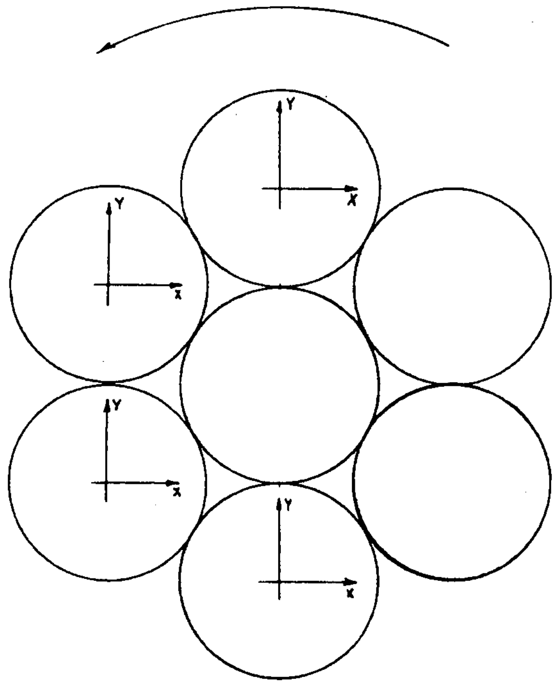

FIGURE 1B

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Figure 2B shows a CW rotation of the barrel. We can see that the spool is spinning CCW relative to the barrel.

In both cases the spool's relative motion about the barrel is one turn. However, for an observer facing the barrel and watching the spools, their orientation about a space reference appears stationary.

Now, we have to understand what happens with the same cabler, with the same 1:1 gear ratio but set in a reverse direction mode obtained with a crossed chain linkage or a direct gear contact. Figure 3A shows a CCW rotation of the barrel, and we see that the spools are spinning also CCW with a relative rotation around the barrel at the same rate and in the same direction. However, in relation to a space reference, the spools look to have accomplished two revolutions for each barrel turn. Figure 3B shows a C.W rotation of the barrel and the spools are spinning also C.W with one differential turn about the barrel's rotation.

Now we will look at a planetary cabling ratio different than one. In order to illustrate such condition, we have sketched a 2:1 planetary ratio, direct and reverse.

The Figure 4A shows a schematic cabler with a 2:1 gear ratio and a crossed linkage that generates the same spinning direction for spools and barrel. For an observer facing the barrel the spools have accomplished two revolutions about the barrel but three about a space reference.

The Figure 4B shows the same cabler with a 2:1 gear ratio but with a straight chain linkage that generates a reverse planetary direction. For an observer facing the barrel the spools have accomplished two turns about the barrel in a reverse direction but only one turn about a space reference.

All these examples are given to avoid confusion regarding the wire twist in a cable.

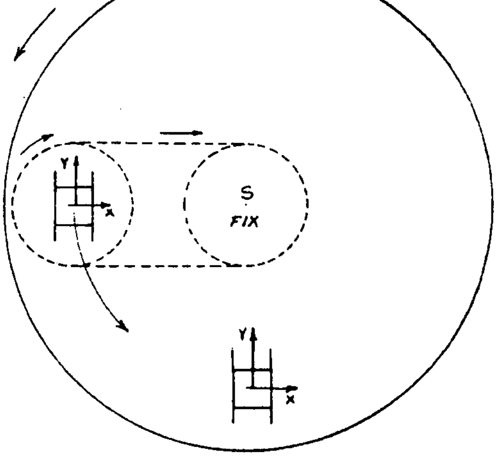


FIGURE 2A

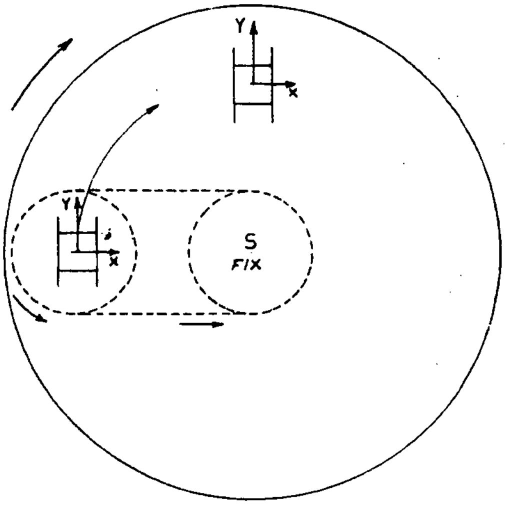


FIGURE 2B

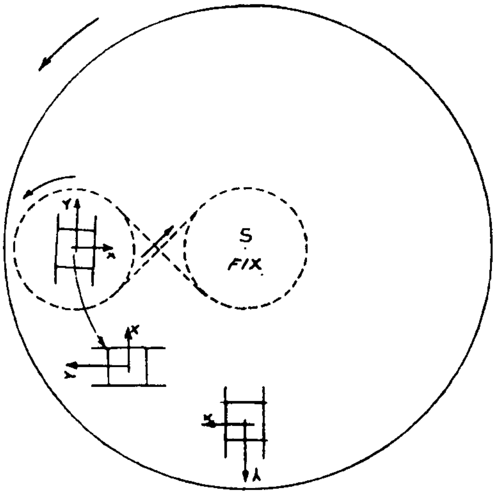
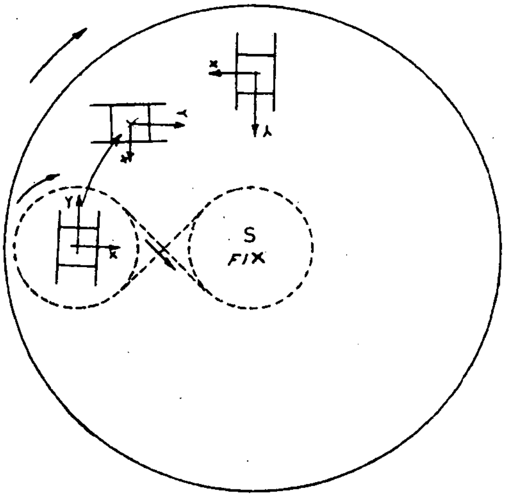

Y
X
S
FIX
X
Y
X
Y

FIGURE 3A


X
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Y
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Y
X
S
FIX

FIGURE 3B

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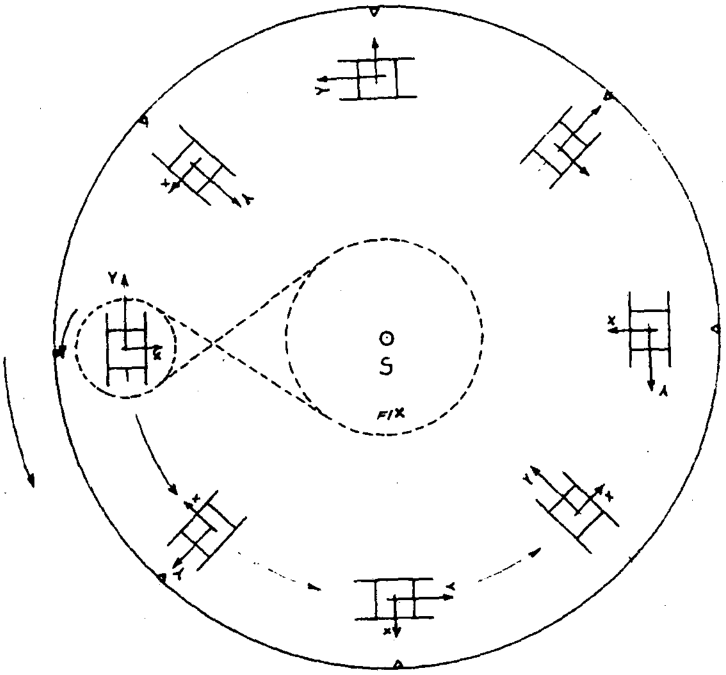

FIGURE 4A

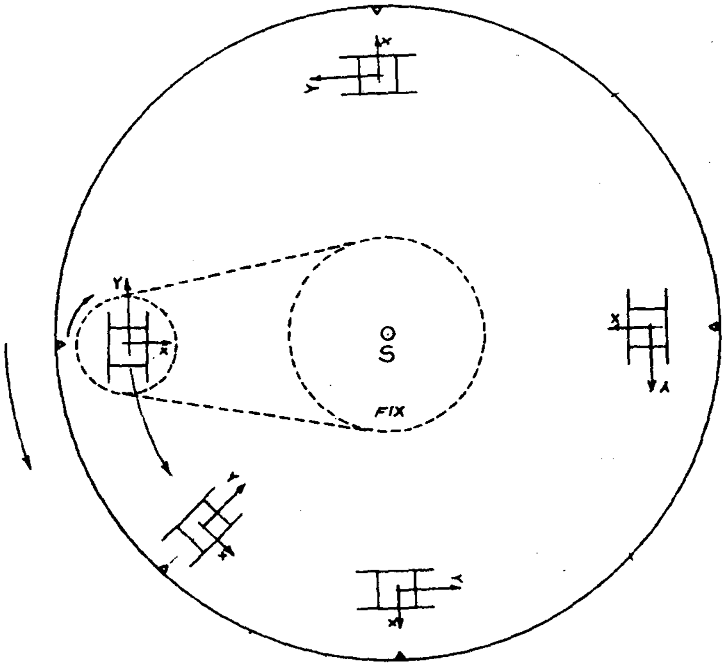

FIGURE 4B

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Several important terms are often defined and used erroneously and this is the main source of confusion. We recommend strongly use of the following definitions:

- Gear Ratio is the ratio of the number of teeth on the sun gear to the number of teeth on planetary gear to which the spool is attached, it is basic to the planetary motion. However, since the gears of a cabler are usually concealed in a box, other definitions are used:

- Differential turns, identical to the gear ratio, is the number of spool revolutions per barrel revolution.

- Space turns is the number of spool revolutions relative to a fixed point in space. This definition usually seems most natural to an observer, but, unfortunately, does not represent directly the value of the twist in the wire due to the cabling process.

It is essential to understand that the term "revolution" is meaningless without reference origin definition.

One turn of cabler's barrel produces one lay pitch length of cable.

In the following formulas, we will neglect the lay angle θ between the strands in the cable and the z axis of that cable, which results in a difference of 2 to 3% between the length of wire used and the length of cable produced. ($\theta \equiv 14°$) for SSC cable type, $\cos\theta = 0.97$ to 0.98 depending on 23 or 30 strands. We can use many other planetary ratios, integers, or fractionals. The results will be similar.

- When the gearing is set for a planetary direction reversed from the cabling direction, the strand twist generated is equal to

$$\frac{\text{Gears ratio}}{\text{Cable pitch}} \quad \text{or} \quad \frac{\text{Space turns} + 1}{\text{Cable pitch}} \quad .$$

- When the gearing is set for a planetary direction identical to the cabling direction the strand twist generated is equal to

$$\frac{\text{Gear ratio}}{\text{Cable pitch}} \quad \text{or} \quad \frac{\text{Space turns - 1}}{\text{Cable pitch}} \quad .$$

This explains the fact that on a cabling machine equipped with two rows of spools arranged back to back on a single barrel, the space turns of the spools in each row shows a difference of two rotations compared to the other row. Obviously, the filament twist in each strand issued from any side of the barrel is the same. This is a typical confusion case for an untrained observer.

3.2 Cabling a Pre-twisted Wire

Approximately 99% of Rutherford-type cable made to date has used pre-twisted wire.

In such occurrence, the resulting twist of the cable strands can be obtained using this formula:

$$\text{F.W.T.} = \text{W.P.T.} \pm \frac{\text{Gear ratio}}{\text{Cable pitch}}$$

F.W.T. = Final wire twist
W.P.T. = Wire pre-twist
(+) is used if the cabling direction is the same that the wire pre-twist
(—) is used if the cabling direction is reverse of the wire pre-twist

This formula can be used also to find the correct gear ratio to be installed on the cabler in order to obtain a desired wire twist after cabling a pre-twisted wire. This is quite important since the final specific wire twist per inch is obviously dependent on the lay pitch length of the final product. This fact is sometimes forgotten when an important change is required between two successive runs.

3.3 Cabling an Untwisted Wire - Twisting During Cabling

The first task is very common in the conventional cabling industry. This was the object in the introduction of Chapter 3. A planetary system with a gear ratio different from 1:1 allows a wire twist at the time of cabling. Such operations can save an important amount of time and money over the usual process, which consists of stopping the wire reduction drawing before the last die and transferring the spool on a twister that is followed by the sizing final die. This final die is needed to fix the twist in the wire. However, we have to point out that wire twisting is a risky mechanical treatment for the material and any weak point, inclusion, or defect in the stacking pattern is a potential rupture risk. This kind of destructive quality control on the material (of light consequence on a single strand) becomes a major accident if it occurrs during cabling.

Here we have to point out the difference between twist and torque:

- The twist is a stable geometrical organization of the filaments in the wire.
- The torque is a twisting force due to the unstable geometrical organization and the elastic behavior of those filaments.

Twisting a wire generates a stable state (which is a plastic deformation) and a residual elastic torque. The twister transforms most of this elastic torque in a plastic deformation with the help of the final sizing die. However, an additional plastic deformation can regenerate some of this torque. This happens, for example, under the turkshead roller's pressure. We call this phenomenon memory release.

To be successful, twisting during cabling operation must be performed in the reverse direction of the cable lay, or the result is a very loose cable or no cable at all. This risk increases with the width of the cable and its lay pitch.

In agreement with what was discussed at the beginning of this chapter, a reverse direction twist is increased by one turn for each barrel turn, the gear ratio is smaller, and so is the mechanical work of the planetary gearing. This is obviously not true if there is back spool row for which the ratio is larger.

Making a good compact Rutherford-type cable showing the correct amount of residual twist is a constant fight between various torques.

3.4 Correct Amount of Residual Twist

This is basically a small residual undertwist: 20 to 45° over a three-ft. long sample supporting a 30-lb tension. When a magnet is wound with such a cable, the straightening force to have a flat lay closes the thin gap between the strands. This is sometimes called locking the cable. Figure 5 shows an example of the various torques and twists.

According to this situation, it looks better to have a larger undertwist in order to have a tighter cable, less sensitive to eventual micro motions under Lorentz forces, which usually are claimed responsible for quenches and training. However, an excess of cable residual twist could be responsible for a coil twist, which will result in poor magnetic field quality and difficult magnet assembly. In the case of several layer magnets, an alternate winding direction between layers can reduce this resulting twisted behavior.

We have to mention that an interesting experiment was performed here a few years ago.

We made a cable with strands twisted during cabling, but in order to obtian less residual twist, each strand was twisted in the reverse direction.

The mechanical planetary gearing was quite sophisticated and a patent was granted for the device.

If we can get a more constant quality wire in long lengths to occur periodically, the process could be revisited.

The 30-lb tension under which the residual twist is measured is a convention that represents the average winding tension of the cable at the time of coil manufacturing. Without tension, a piece of cable could show some twist and inversely a piece of cable which looks flat can show a certain amount of twist under the 30 pound tension.

4. Manufacturing Rutherford-type Cable from Superconducting Strands

When flat or keystoned cable is made, we are obliged to somewhat disobey the general principles described in Chapter 3.

The rectangular cross section cable, made of two strand layers is far from the minimal inertia condition. Furthermore, there is no core to support the strand radial pressure. The prime tendency of such a cable is to collapse under the tension needed to form it.

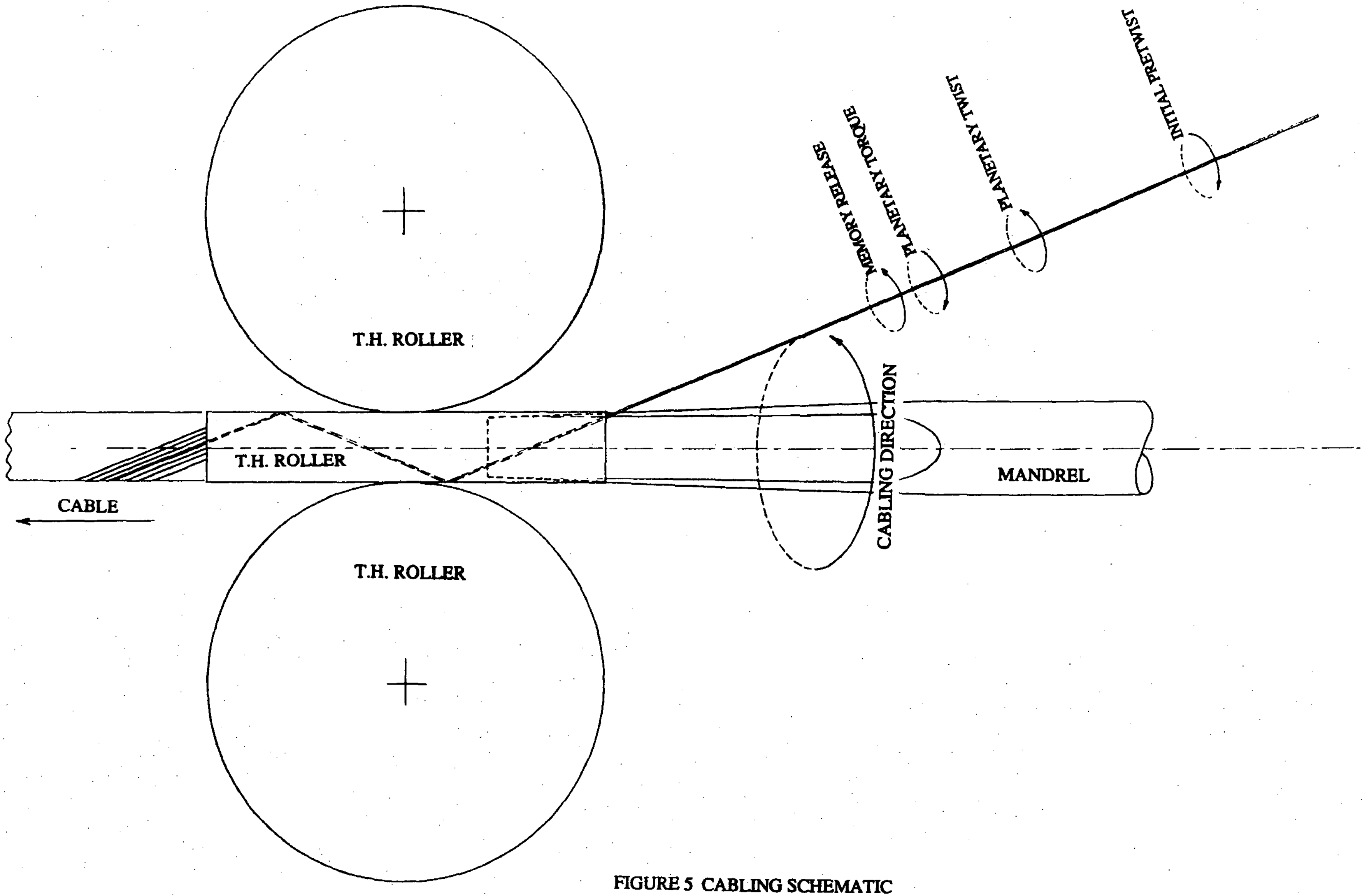

INITIAL PRETWIST
PLANETARY TWIST
PLANETARY TORQUE
MEMORY RELEASE
CABLING DIRECTION
MANDREL
T.H. ROLLER
T.H. ROLLER
T.H. ROLLER
CABLE

FIGURE 5 CABLING SCHEMATIC

XBL 903-940

4.1 Wire Tension Factors:

The tension is generated at several locations in the strand path:

- Brake on the wire spool to avoid free wheeling.
- Brake on the wire itself to provide a constant straight path up to the mandrel tip and maintain a uniform twist pattern, if any.
- Strand friction on the mandrel.
- Deformation between the turkshead rollers.

The superconducting wire tension on the cabling machine was one of our first concern. This tension was suspected to be one of the factor of degradation of the superconducting filaments at the time of cabling. A statistic study suggested that the degradation was tied to the wire diameter: larger the diameter, smaller the degradation.

In fact, the specific wire tension of the wire including the copper to superconductor ratio was the leading factor:

If ρ is the cu/sc ratio,
$\Delta$the wire cross section surface area
τ the s.c. yield at 1% strain
μ the cu yield at 2% strain
T the recommended total tension on the wire

$$T = \frac{\Delta}{1+\rho} x\, \tau + \frac{\Delta x \rho}{1+\rho} x\, \mu \; (1)$$

The 1% strain for the s.c. looks quite conservative but we have to remember that the filaments have also to sustain the twist stress without degradation; the application of the formula (1) was used for several months on various cables manufacturing campaign, resulting in a much lower and uniform degradation coefficients. The actual yield strength used for the wire components are:

copper:	38 - 40 MPa
NbTi:	107-110 MPa

In English System Units we find:: Total tension: 7.5 to 8 pounds for the 0.8 mm or 0.0318" 1.3/1 wire and 3 to 3.2 pounds for the 0.53 mm or 0.0208" 1.8/1 wire. We obtain degradation factors of 1% to 3%.

Any cabler operator has a natural tendency to increase the wire tension to correct a non-uniform wire pattern on the cable. I think that it is more important to have an equal tension for all the wires, if all the wires have similar mechanical characteristics.

Blending wires in a cable in order to get a better average electrical properties could result in a less uniform cable surface.

4.2 Cable Tension

The cable tension is the sum of the individual strand tension multiplied by the number of strands plus the force needed to compact the cable cross section to the required shape between the turkshead rollers. There is also some friction between the turkshead rollers themselves since they need to be tightly pressed against each other to avoid copper flashing at the edges of the cable. This is such a composite tension that could trigger a cable collapse between the turkshead exit and the capstan device.

Cable collapse can be avoided up to a certain tension value if the flattening in the turkshead is large enough to reshape the round strands into a polygonal cross section, which increases the wire-to-wire friction and generates a locking effect between the strands at the cable's edges. This restrain's the strand's radial motion toward the cable axis. However, such compaction has to be monitored accurately when keystoned cables are manufactured. The main limit of compaction is a possible superconducting filaments breakage, which will degrade the electrical properties of the cable.

There are very few things that can be done to reduce the cable tension:

- A well made mandrel with carefully blended and polished surfaces where the strand's spirals are preformed is necessary.
- A large turkshead rollers diameter does not generate a lower drag but does produce a smoother deformation due to the shallower angle between the forming surfaces.
- We have to mention also that in some cases when the cable is made of dirty wire; oxidized surface or annealing residues, those impurities are partially loosened in the turkshead and transferred on the rollers' working surfaces. Such accumulation could

result in a loss of cable dimension accuracy or worse: increase the drag and cable tension between turkshead and caterpillar, sometimes up to the collapsing accident.

- Adequate lubrication is essential.

4.3 Lubrication

Lubrication is a very important parameter. The only point to be lubricated is the tip of the mandrel where all the wires take shape as a cable. The wire friction on the mandrel generates heat and can also result in a copper smear on the tip of the mandrel.

The wire thermal conduction is responsible for the heat transfer to the turkshead rollers. After a few hundred feet of cable (depending of the speed), the rollers expand before the turkshead frame, and then the cable compaction increases and the mean thickness decreases. Several types of lubrication were proposed and tested:

- Regular automotive oil drip. This gives good lubrication but the cable carries this oil onto the caterpillar belts or drums, and could jeopardize the traction. A possible remedy is the installation of a degreasing device between turkshead and capstan. An "AIR WIPE" good gives results when using light oil.

- Diluted oil. A 98% oil dilution in freon or trichlorethane was used successfully. The diluent evaporation helps to remove some of the friction heat, but the 2% oil remaining has to be removed from the cable before insulation. The solvent vapors are also environmentally a burden and should be eliminated. The operator safety is also a concern and even a Chivas Regal is not permitted.

c. Vanishing oil. The use of vanishing oil with 0% residue is an interesting solution. The very low viscosity of the product allows the use of laboratory metering pumps, which can be adjusted to a very low flow rate.

In summary, we need lubrication. However, at the time of its choice, we should remember that sooner or later we will have to remove it before supplying insulation. The progressive elimination of freons due to the environmental concern does not simplify the problem. Much-more-sophisticated in-line degreasing machinery must be designed and built.

4.4 Turkshead

The turkshead is the cable shaping device. Most of the forming in the wire and cable industry results in a rectangular-cross-section product. The standard setting of the machine gives an infinity of dimensions from zero to almost the width of the rollers. This flexibility is the main reason to use such a device.

For the keystoned cables, we need at least one roller ground to the keystone angle. However, such setting results in the two linear contact tracks, which can generate rapid wear and chipping problems. Two rollers ground to the half keystone angle are more symmetrical but have the same wear problem. Four ground rollers are more wear resistant but difficult to adjust, especially if the device shows excessive play.

Another way to work with the turkshead is to grind two opposite rollers at the cable width and at half the keystone angle. The other two rollers are kept flat and apply a symmetrical pressure on the sides of the keystoned rollers. This setting gives a far more constant dimension of the cable cross section, but we need a set of two rollers for each cable dimension and shape. The only flexiblity is the cable's mean thickness, which is not a problem for mass production. Those various possibilities are illustrated in Figure 6.

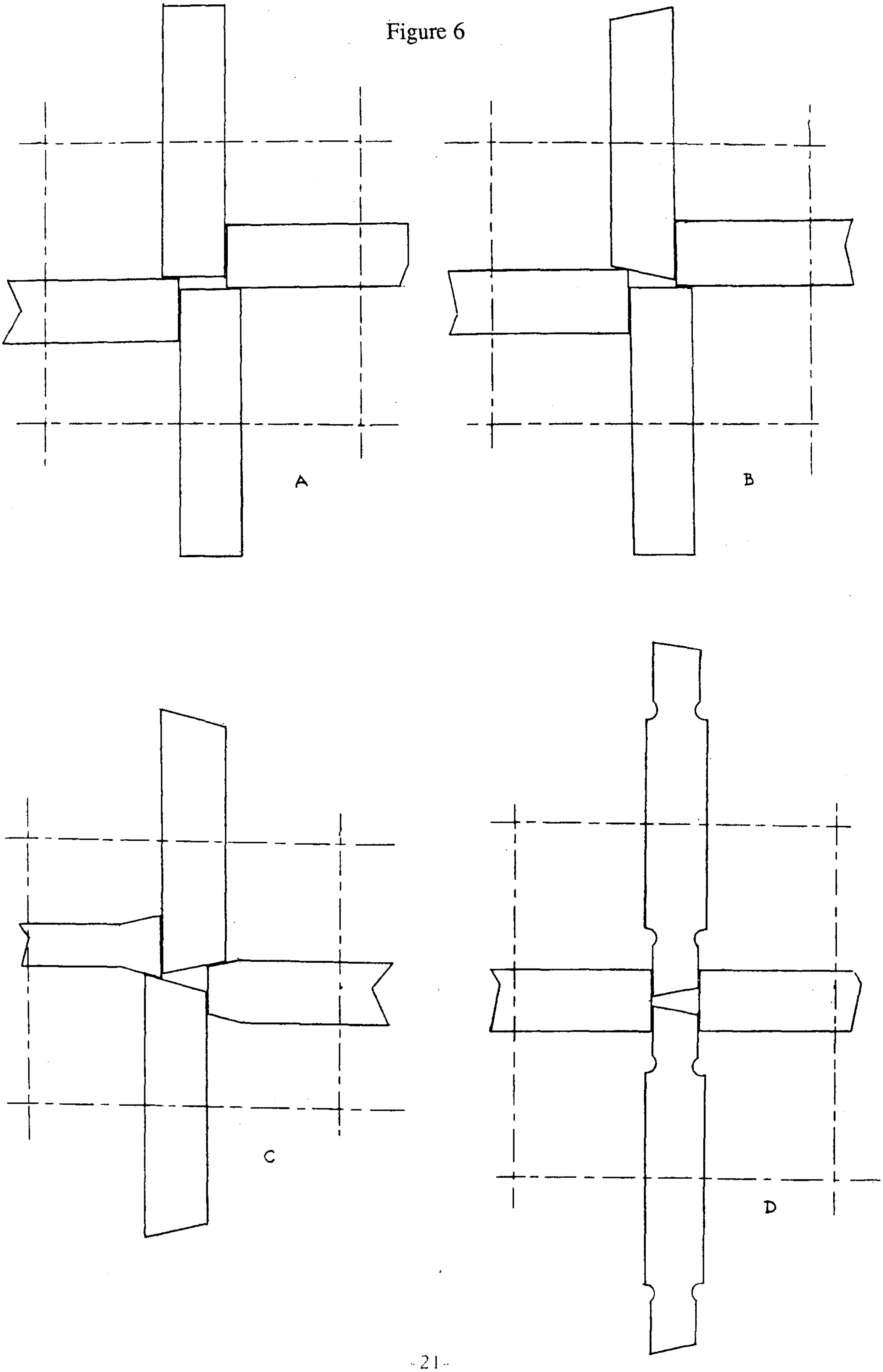
4.5 Turkshead Setting and Compaction

Another point should be noted, mostly for the novice. Even if there is a good relationship between the reading on the dial around the screw moving the rollers and the roller's position when there is no wire in the turkshead aperture, this will no longer be exact as soon as the compaction process begins, due to the elastic behavior of all the parts mainly the turkshead frame. The same mean thickness reduction needs more degrees of screw rotation at high compaction than at the beginning.

A consequence of this elastic behavior are the oscillations of the mean thickness measures, even when all the other parameters are constant: temperature, wire dimensions, speed, etc.

The mean thickness tolerance specified for the SSC cables ± 0.0002 in., reflects this limited accuracy.

Figure 6



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4.5.1 Keystone Fine Tuning

The compaction of a keystoned cable in a turkshead leads to a difference in pressure between the major and minor edge of the cable. The mechanical assembly of a turkshead, even for a new one, must have a minimum of play and tolerances. This results in a slight tilt of the forming rollers about their axles, and the resulting keystone of the cable is not exactly equal to the ground angle. The result is always a shallower angle.

This fact has to be considered when designing the forming rollers surface: A few minutes of angle should be added so that the resulting cable meets the specifications.

Another way to adjust the resulting keystone angle consists of changing the pressure applied against the flat rollers. This can compensate for the wear of the machine. It is not recommended however, due to the possible deterioration of contact surfaces between rollers, but it can help in some cases.

4.6 Powered Turkshead

This question is the object of a special section due to the specific and sometimes controversial conditions of use. Such powered turksheads are widely used in the metal forming industry, mostly for rod shaping. It is basically a small rolling mill device, sometimes associated with a downstream pulling device. Such system is often used to make solid rods of a specific cross section with soft materials such as copper, aluminum, or tin alloys or large rectangular copper and aluminum flat cable. The reason is that the total tension seen by the material is divided between the power turkshead and the puller, which is frequently a linear belt capstan or caterpillar. Therefore, this tension can be locally half the total needed to perform the forming operation.

For the last twenty years, this technique was also used in large flat electrical cable manufacturing. So far this process is not required for the Rutherford-type, narrow cables. To date, the largest superconducting cable production was made for the "Tevatron" in Fermilab. This 23-strand cable was manufactured on a cabling line with one to one planetary ratio, a normal turkshead, and a drum capstan downstream before the take-up device. More recently, some Rutherford cable needed for DESY was made on a large existing machine equipped with a power turkshead. It is important to mention here that experimental wide Rutherford cable (40 strands) was produced the same way for CERN.

At LBL, the superconducting R&D program was performed on a specially designed cabling line, where a conventional (not powered) FENN 4U high-speed turkshead was incorporated. The experimental superconducting cable assembled on this line range from 8 to 36 strands. Pictures 1 and 2.

The specifications for the first industrial cabler devoted to the SSC project included a variable-power turkshead. This was more due to exploratory concern than to a strongly motivated decision.

The successful bid was by Dour Metal in Belgium. After one year of operation with various superconducting wires, 23- and 30-strand keystoned cables were produced. We can draw some preliminary conclusions:

- The very accurate tension measurement device installed on the caterpillar allowed us to make cables in a wide range of tensions.
- The cables made without power to the turkshead look slightly more uniform than those where the power was on, the mean thickness of the cables made this way is 0.0002 - 0.0003 in. lower than with power. This result is not surprising due to the aforementioned fact: without power help, the strands have to sustain the total tension of the cabling as described in Chapter 4.2 and they have a better reason to keep a straight path when they are in progressive compaction between the turkshead roller.
- When a keystoned cable is manufactgured, there is a dissymmetry of the compacting stresses between the cable edges. Without any traction device, the cable will exit the turkhead curved and twisted. When tension is applied on such cable a partial straightening can occur, but the strands will keep some of the scars of such treatment: non uniform compaction and popping strands.
- A last point and may be the most important is that in a normal powered turkshead the forming rollers are geared together and any difference in their diameter or in the keystone angle generates a shearing stress between the two cable sides which result in a non uniform cable surface. A separate magnetic coupling for each roller or an individual torque control should be considered. The Rutherford cable is a product much more sensitive to those shearing stress than any solid metal rod usually processed through such machine in the industry.

4.7 Stress Configuration

When manufacturing a keystoned cable, the torque stress configuration of any origin, pre-twist or planetary, is periodic along the wire because on one side of the cable the cold work is maximum at the minor edge and the corresponding torque from memory release is pushed along each strand toward the major edge where the cold work is minimum and the amount of torque memory release pushed along the strand is lower.

The upstream twist torque is partially kept through the turkshead and is the origin of the twist pattern we can observe on each strand when a pre-twisted wire is cabled with a "solid" cabler configuration.

The motion of the twist pattern along each strand is responsible for a slight rotation of the strand about its own axis. This explains why the imprint pattern is smooth and shiny and not a pure cylindrical notch as if two crossed wires were pressed against each other. In some instances, when the cable is loose, we can see a part of this dotted shiny pattern between the strands.

The stress and strain configuration in the wire is very complex, mainly for the keystoned cables. We found experimentally that a 2% strain was a safe limit.

4.8 Optimal Over- or Undertwist

There are many factors involved in the determination of an optimal mechanical twist:

- Number and size of the superconducting filaments
- Value of the Cu/superconductor ratio
- Level of annealing of the copper matrix
- Amount of compaction wanted
- Value of magnetic coupling tolerated.

All those factors mean that trial and error ar the fastest process for cabling an unknown material. The final criteria being the cable residual twist and the dimensional control.

5. Mandrel or Pin Core

The mandrel is the most critical forming tool for cabling any Rutherford-type cable. The two strand layers are contained externally by the turkshead rollers aperture and internally by the mandrel. Then the mandrel is a transitional wire positioning tool between the conoidal surface made by the wire array issuing from the guide plate and the rectangular or keystoned cross section of the cable.

The mandrel position accuracy and stability are very critical parameters in the cabling process. It should be an rigid guide for the strands without any floating freedom. The result is that at the mandrel tip, the strands have never enough space to cross over each other.

5.1 Mandrel Design

The mathematical definition of the wire array is an hyperbolic conoid, the wires being one of the generative family.

In order to minimize the caterpillar tension on the cable due to friction between strands and mandrel, this one should be:

- made of a rod larger in diameter than the width of the cable.
- made of heat treatable steel: 60 R_C, but not higher to avoid brittleness.
- shaped as close as possible to an internal tangential surface to the wires generative system, especially in the last inch from the tip.
- carefully blended and polished surfaces.

Consequently, a mandrel looks like a conical blade, the edges of which are converging to the width of the turkshead aperture and the faces converging to the center plane of the cable. The end of the mandrels, over about one inch, is the last tangential contact with the strands. Due to the capstan effect, this contact over 1/3 of the cable lay pitch length is the maximum we can tolerate without amplifying dangerously the cable tension. We have to mention here that a loss of synchronization between the barrel and capstan motion could be due, for example, to an excess of lubricant on the cable. This is one of the main reasons for an increased length of contact or "mandrel wrapping" which leads quickly to a cable collapsing between turkshead and capstan, under excess of tension.

A cable-tension measuring device is very useful and strongly recommended at this point. This accessory should be connected to an emergency stop switch to avoid the loss of the cable.

5.1.1 Strands Pattern

The conoidal strands pattern, which takes place between the guide plate and the mandrel section where the wires first contact the mandrel surface, shows an included angle A of some 35° to 40°. The value of this angle depends upon the length of mandrel out of the guide plate, upon the carbide guide's row diameter on the guide plate, and upon the lay pitch of the cable. This angle is also self adjusting; the variable parameter is the length of mandrel tip wrapped with wire.

As mentioned earlier, the friction between strands and mandrel is a decisive parameter. The mandrel wrapping, however, is essential due to the wire spiral forming at this very place.

If there were no wrap, a permanent crossover defect will appear on the cable major edge because, in such cases, the strands will enter the roller aperture without preforming.

Note also that for a given mandrel length and a given guide-row diameter, we can change the wrap length by changing the cable pitch: the shorter the pitch, the higher the wire twist for a given planetary ratio. All those factors have to be adjusted in order to produce a quality cable.

5.1.2 Tip Dimensions

The width and thickness of the mandrel tip are the most critical dimensions for cabling:

Roughly, the width should be

$$W = \frac{N - 1}{2} \times D$$

W = width

N = number of strands

D = strand diameter

tolerances: W should be + 0 — 0.005 in.

The tip thickness should be

$$\tau = \frac{3D}{4} \pm \frac{D}{20}$$

τ = tip thickness

5.1.3 Wedged Tip

A supreme refinement consists of grinding the mandrel end into a wedge shape for a constant strand support in large keystoned cables and large rollers diameter. See 5.3 for calculations.

5.2 Other Design

The constant-perimeter design was proposed several years ago. In such a design, the perimeter of the mandrel is constant and calculated to be equal to the internal perimeter of the strands tube in contact. The weak points of such a mandrel are

- Increased friction due to the longer length of contact with the wires.
- The shape transition enlarges the tip, which also increases the drag.
- The core of the mandrel is obviously $1/\pi$ times the cable width; this results in an unwelcome flexibility of the tool.
- The small bending radius of the wires around the mandrel core leads to a permanent deformation of some sections of the strands, which results in defect of the cable aspect (popping strands).

5.3 Mandrel Positioning

The theoretical positions of the mechanical parts involved in the turksheading operation are given in Figure 7.

H - Minimum distance between mandrel tip and turkshead rollers center axle. In this position, the mandrel tip is at the "pinch point."
R - Turkshead roller radius.
C - 1/2 cord at H distance from center.
S - 1/2 cable mean thickness.
T - 1/2 mandrel tip thickness + 1 wire o.d.

The geometrical relationships between those parameters are very simple:

$$H = \sqrt{R^2 - C^2}$$
$$C = R+S-T$$
$$H = \sqrt{R^2 - (R+S-T)^2}$$

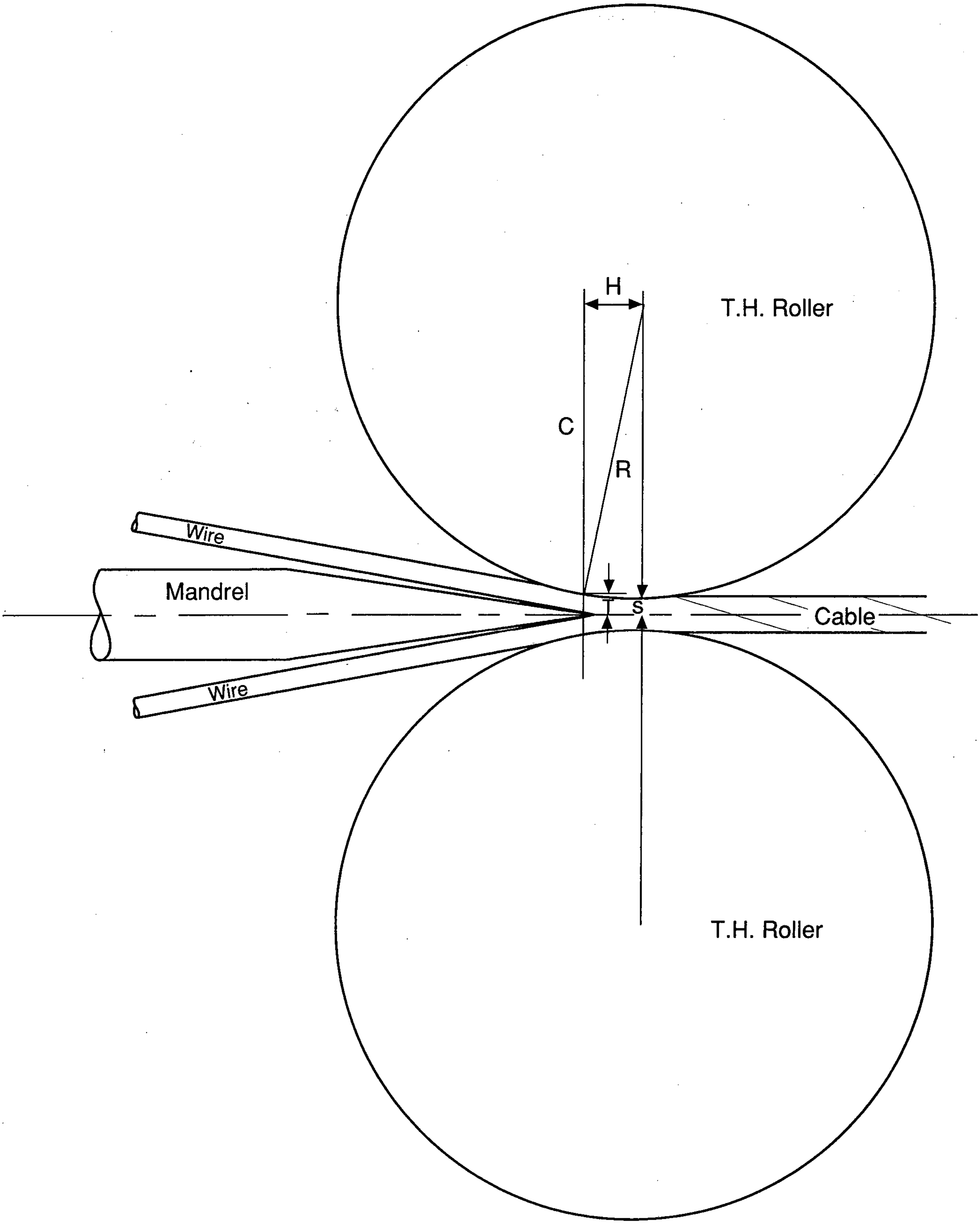
A numerical example will illustrate how to use those formulas:

Assuming that the rollers are 5 in. in diameter
the mandrel tip is 0.020 in. thick.
the cable 1/2 mean thickness: 0.023 in.
the wire o.d. is 0.0255 in.

$C = R+S-T= 2.5 + 0.023 - (0.010 + 0.0255)$ in.
$C = 2.4875$ in.
$C^2 = 6.187$ $R^2 = 6.25$
$H = \sqrt{6.25 - 6.1877}$ $= 0.2497$ — 0.250 in.

At the "pinch point" position the mandrel tip will be at 0.25 in. of the center. Now, what could be the maximum for H? A dangerous position will be observed when there is enough space at the mandrel tip to allow another wire to enter between the rollers and generate a "cross over."

Figure 7


H
T.H. Roller
C
R
Wire
Mandrel
T
s
Cable
Wire
T.H. Roller

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Using the same symbols than before we will have

T = 1/2 tip mandrel thickness + 2 wires o.d.:
$C = R+S-T = 2.5 + 0.023 - (0.010 + 0.051)$ in.
$C = 2.462 \qquad C2 = 6.061$
$H = \sqrt{6.25 - 6.061} = \sqrt{0.1886}$
$H = 0.434$

This value is 0.184 in. longer than the value calculated for "pinch point" position.

We will, practically, never, use such tolerances. Because of mandrel flexibility and wire o.d. tolerances, "crossover" could occur much before observing this gap. For the wires actually specified for the SSC cable, 0.030 in. from the "pinch point" position is a reasonable value. In our example figured for a 30-strand 0.0255 in. o.d. cable, at the level of the median cable's width we have

$$H_f = 0.250 + 0.030 = 0.280 \text{ in.}$$

The same formula and calculation can be used in a fine tuning operation/

When making a keystoned cable, we have two cable thicknesses: one for the major edge and one for the minor one. Introducing those two values in the formula applied in the former example we find

S major = 0.025 in.
S minor = 0.021 in.
H major = 0.2289 in.
H minor = 0.2689 in.
DH = 0.040 in.

The width of the mandrel tip is 0.359 in. To obtain an homogeneous support of the wires, we have to wedge the mandrel tip by θ degrees. So that

$$\mathrm{tg}\theta = \frac{0.040}{0.383} = 0.1044$$

$$\theta = 5.96^\circ$$

Obviously, we could alternatively have the mandrel tip keystoned at the same value as that of the cable, but such machining is much more difficult than wedging.

5.4 Mandrel Position and Cable Thickness Adjustment

Considering the mathematical relationship previously mentioned in Chapter 6.3, we can evaluate the effect of a change in the parameter S = 1/2 cable thickness. If S changes by 0.001 in., or the cable mean thickness by 0.002 in. the value of H is changed by 0.010 in.

This means that when starting a cable run, if the mean thickness has to be adjusted after an initial cable thickness measurement, the mandrel position must be adjusted accordingly. In this example, if you compact the cable by 0.002 in. more, you must move the turkshead downstream by 0.010 in., to keep the initial safety margin with respect to the pinch point position. See Figure 8.

6. Pulling Device

The pulling devices are mainly designed from two concepts: the drum capstan and the linear capstan, more commonly called a "caterpillar."

6.1 Drum Capstan

The drum capstan type is made of two narrow drums usually installed in a vertical position and with a few inches gap between them with several grooves with flat bottoms machined at the periphery. One drum is mechanically connected to the same power unit as the cabler, and the cable is wound several times around this drums assembly with straight segments at the top and bottom. The cable end is attached to the cable spool on the take-up system.

The total tension needed to form the cable in the turkshead is gradually reduced at each turn around the drums assembly to the value fixed at the take-up system by torque control or dancer counter weight.

6.2 Linear Capstan or Caterpillar

The caterpillar is basically a system of two belts between which the cable is pressed and pulled by the counter rotating motion of the pulleys mechanically connected to the main cabler power unit. Only the downstream pulleys are driven then the cable tension is smoothly reduced from the front end to the back.

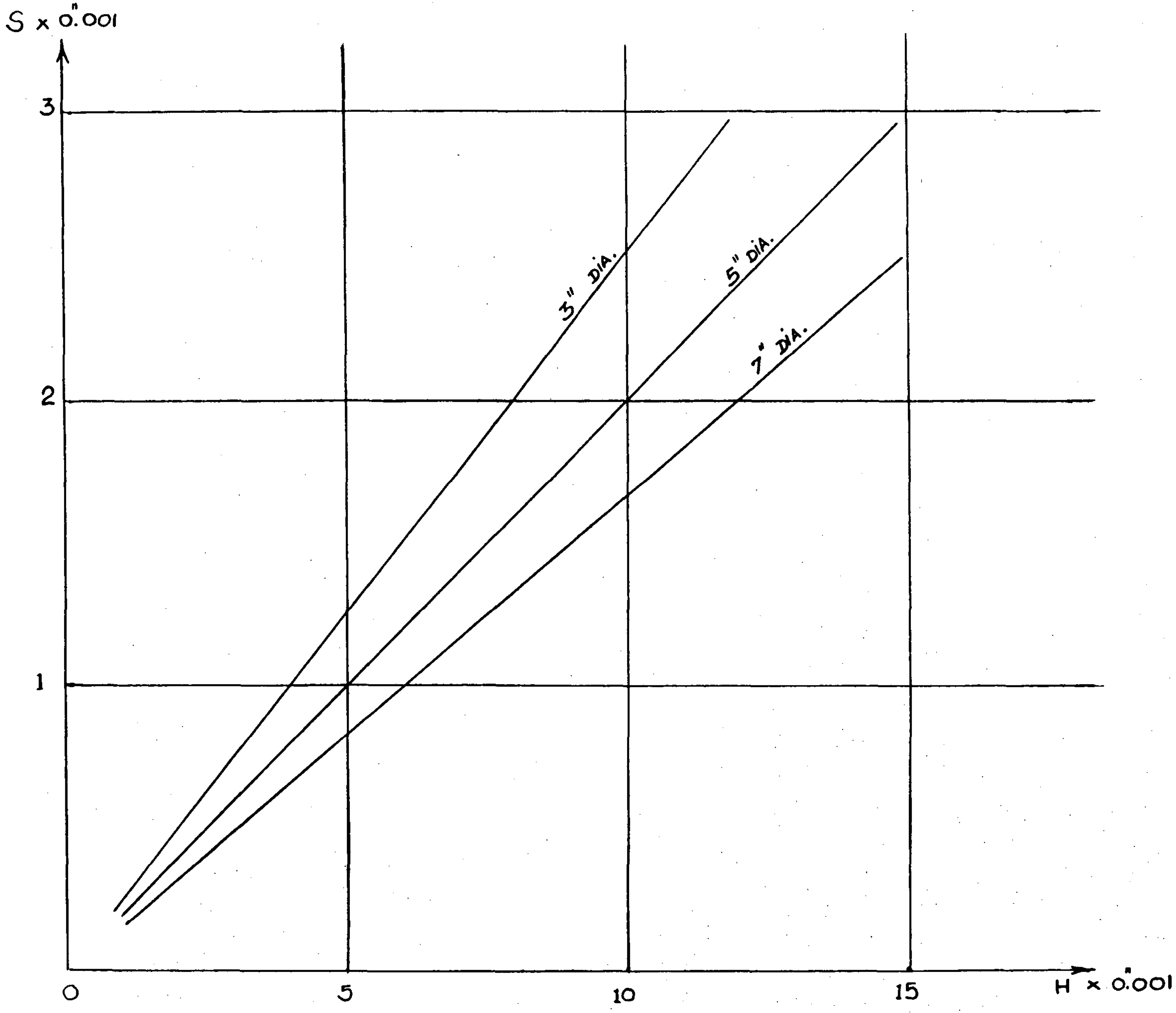

Figure 8

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Such a system works as a self-tailing capstan, which means that there is no need of back tension during operation. This is one of the main differences with the drum type. Another advantage of the caterpillar is the small amount of cable needed to have the system running: only a few feet before a cable sample is available for measurements and test. For a drum capstan, we need several tens of feet and a clamping device to hold the tension.

We have to mention three potential problems connected with the caterpillar use.

- The rubber belt traction is more sensitive to an excess of lubrication.
- The tension of each belt should be carefully adjusted to be almost identical. If not, we can observe a sheering effect between the two sides of the cable and a faster wear. The length of the belts has no effect in an eventual sheering stress.
- After a long use for the same cross section cable the belt surface could be deformed so that the contact pressure on the cable is reduced due to the possible contact of the two belts outside the cable cross section.

In order to avoid these 3 problems, we have designed a special cross section for the belts. It is a T-shaped belt with a narrow center track slightly larger than the cable to be pulled. This applies the full pressure of the machine to the cable, while the larger belt base ensures good traction at the end pulleys.

The hardness of the material is also important. At least a 65-shore hardness is recommended. The material should not be sensitive to the lubricant used; neoprene or vinyl are preferred to rubber.

Even with the potential problems described here the caterpillar remains the first choice as a cabler pulling device.

7. Dancer

The dancer is a cable accumulator, the use of which is not compulsory but recommended. Basically, this device is made of a vertically moving sheave on which the cable forms half a turn after coming from the entry sheave and before going out of the exit sheave to the take-up system. The positions of those two sheaves are fixed but the moving sheave is balanced through a counter weight which produces a constant tension on the cable. Its vertical position depends on the amount of cable stored. A larger capacity can be obtained with several cable loops, but the counter weight must be increased accordingly.

The dancer, in addition to providing a constant cable tension, absorbs the cable production variations with the take-up respooling speed changes. We can also use it as a speed sensor to control the take-up command.

8. Take-up System

The take-up system is the end device of a cabling line and it is important that this device does not interfere with the quality of the final product. The respooling of a flat product is not a problem up to the point where the cable reaches the end of a layer just against the spool flange and then changes its angle to begin the next layer.

The minimum radius of the spool core should not be less than 10 in. in order to have a smooth transition. In addition, the triangular void under the next turn should be filled by some kind of support in order to keep the cable flat. This filling could be performed with some kind of automatic injector. The traverse motion could be of two designs:

- Fixed spool in the z, x, plane with a traveling traverse guide in the ± x direction.
- Fixed guide in the z, x, plane with a traveling spool in the ± x direction.

Both designs are used. The traveling spool shows some advantage due to the absence of cable bend in the hard direction except at the layer change point.

9. Design of Cabling Machine for SSC Cables

According to the principles listed in Chapters 3 and 4, the design of a good cabler should obey some simple rules:

- The wire paths from the spool to the turkshead should be of the same length
- The cabling operation should be possible C.W. or C.C.W.
- The wire spool's motion should be obtained through a planetary drive with several reduction ratios available.
- Braking systems for the individual wires should be able to provide a constant tension for each strand from the beginning to the end of the spool.
- A mechanical transmission with no slippage should connect the main barrel drive and the pulling device.
- An emergency brake should be able to stop the machine within two barrel turns.

- The pulling device should be a linear capstan and be able to provide at least 750 lb. of pulling force (a narrow belt type will be preferred).
- A cable tension measuring device should be associated with the caterpillar.
- A differential temperature control between the turkshead frame and the rollers should be installed.
- An electric heater on the turkshead frame triggered by the differential temperature with the rollers will be installed with preferably an adjustable delay.
- A metering micro-pump should pulse a vanishing type oil on the strands just in front of the mandrel. The flow rate of this pump should be adjustable between zero and 100 ml/hr.
- The mandrel support on the z axis of the cabler should be rigid enough to prevent motion of ±0.002 in. during barrel rotation.
- A mandrel temperature control should be installed.
- A broken strand detector should be installed on the wire path between spools and guide plate. This device should be able to trigger the emergency stop within one second of the detection.
- All the wire pulleys or sheaves should be at least 3 in. in diameter.
- All the cable sheaves should be at least 20 in. in diameter.
- Emergency stop buttons should be installed at all the critical components along the cable line: barrel, caterpillar, measuring machine, take-up system.

This list of conditions is not complete, but is given as a starting base for the specifications to be used with an RFQ for a cabling line.

10. Cabling Operation/Recommended Procedure

10.1 Cabler Check-up

We assume that the cabler mechanical maintenance complies with the manufacturer specifications, mainly regarding power, safety, and lubrication.

10.2 Make sure that the wire respooling was performed at a tension at least equal to the specified cabling wire tension (see Chapter 4.1).

10.3 Verify that the mandrel dimensions are in agreement with the specifications (Chapter 5.1.2). Install the mandrel, and check that its symmetry plane coincides with the symmetry plane of the keystoned rollers of the turkshead. The tip should extend at the correct distance of the guide plate.

10.4 Make sure that when rotating the cabler barrel that the mandrel tip does not move more than ±0.002 in. in the x, y directions.

10.5 Turkshead Position

Here, we assume that the turkshead is set in a symmetrical position of rollers as described in Chapter 4.4 and Figure 6.D. We assume also that the rollers were installed according to the manufacturer's specifications. If there is a change in the cable size from a previous operation the position must be adjusted accordingly.

10.6 Methods of Adjustment

For several years, the only method used was a visual alignment performed by an experienced operator, probably a heritage of the "floating mandrel" era.

After proper mandrel installation, the turkshead was moved toward the mandrel and close to its cabling position, as calculated in Chapter 5. This adjustment is delicate due to the various light reflections on the polished roller and mandrel surfaces. An optic fiber endoscope was tried but did not bring much improvement due to the short field depth of the system.

Mandrel at the pinch point:

Bring the turkshead geometric center to a z position close to the pinch point described earlier.

Using a piece of wire to be cabled as a gauge first check the distance between the flat sides of the mandrel and the keystoned rollers. If the mandrel tip is not wedged, perform this control close to the major edge.

Using the same wire gauge, check the distances between the mandrel thin edges and the flat rollers used to limit the cable width.

Verify that the two keystoned rollers are in the same plane and in contact with the flat rollers under no pressure.

Note the exact z position of the turkshead. This position should be the same as described before.

Move the turkshead downstream several inches away from the mandrel tip.

Open the turkshead aperture by moving the adjustable keystoned roller.

Wire the machine with special care about correct strand paths and tension.

Bring back the turkshead at about one wire diameter of the pinch point noted on the z axis.

Close the aperture on the strands bundle, eliminating as many upstream crossovers as possible. Do not compact the bundle at this time.

Start the cabler at slow speed.

Perform the final compaction to the specified thickness progressively.

The cable should start to form. Secure the cable beginning with a clamp to avoid collapsing in front of the caterpillar. Watch for remaining crossovers.

When the cable is secured in the puller, stop the machine, check cable measurements, adjust if needed and begin producing cable.

Adjustment with reference gauge.

In this process, we use a tool that consists of a hardened steel reference gage ground at the same dimensions and keystone angle as the cable. The length should be 5 or 6 in. more than the turkshead thickness.

This keystoned gauge is introduced between the turkshead rollers, close fit but without pressure. The front end is secured perpendicular to a support, which is maintained parallel to the turkshead front plate through three foot screws.

When reference bar extends through the turkshead backplate, the mandrel tip x,y, position can be compared to the reference gauge end and the turkshead position adjusted accordingly.

The z position is obtained as before by calculation and measurement.

The following operations described in the method where the mandrel is at the pinch point have then to be performed the same way.

11. Further Developments

11.1 Cables of Cable

In an earlier technical report (LBL-20129, SSC-MAG-50) July 1985, we had already mentioned the possibility of using small cables instead of strands. The advantage of such a design is to obtain filaments diameter and improved cable flexibility. Some experiments were made with six-around-one wires as initial cable. The following problems were observed:

- Reduction of the cable mechanical stability under tension.
- Larger void fraction, thus less compactness and less critical current.
- Thicker cables: 6 wires diameter.

11.2 Other Solutions:

We are planning to work with small flat cables instead of round ones. The obvious purpose being to correct some of the problems mentioned, and to achieve more mechanical stability (larger elementary wires) improved compacity, and thinner cables: 4 wires diameter.

The cabling of monolithic rectangular conductors will be investigated, but we must remember that any cross section shape different from a circle will introduce twist problem.

11.3 Wider Cables

Recently (October 1990), we have built a new barrel for our experimental cabler. The principle is the same as the previous one but we increased the number of spools from 36 to 48.

There is actually no specific need for a 48-strand cable, but this number is the most flexible for the manufacturing of smaller number of strand cables with a balanced barrel. The production of the classic 36-strand cable for Fermilab Low Beta Quad project or for the SSC external magnet layer 36 strands also is not affected.

So far, few tests were performed with 45 strands of 0.0255 in. diameter. The resulting cable was good but we observed an increased tendency to cable collapsing between the turkshead and the caterpillar and a much greater sensitivity to the settings and tooling parameters than before. Such cable does not forgive a mandrel polishing defect or an excess of strand wrapping around the tip.

The planetary twist and the optimization of cable lay pitch are more important than ever and need a special care to obtain a moderate residual twist in the self locking direction.

Compaction and keystone angle should be also a fine tuning task to avoid filament degradation.

We are planning to perform more tests with different numbers of strands. It will be interesting to find the quality cable limit between a 36-strand cable which was proven very good and the 48-strand cable which is a possible challenge.

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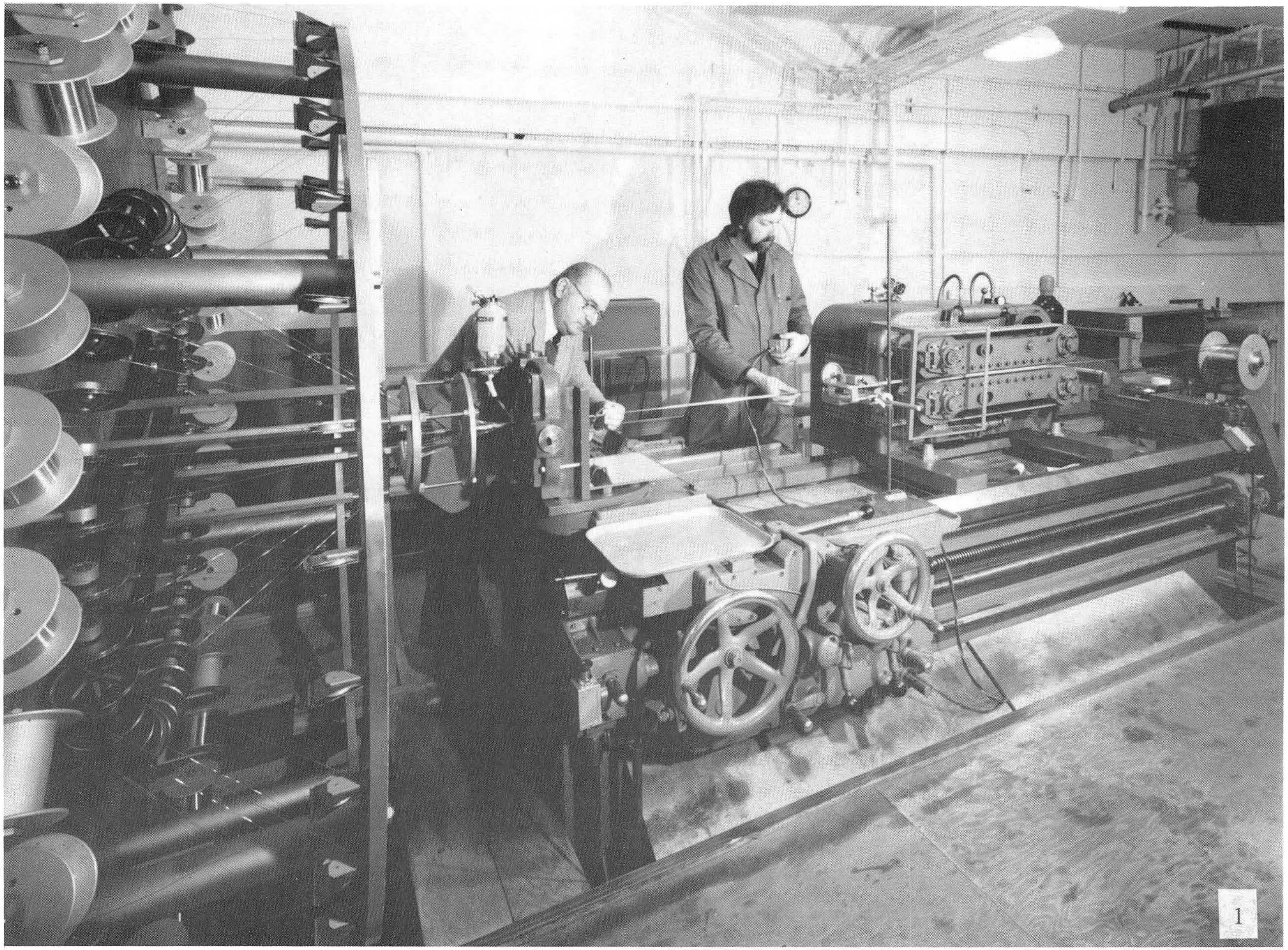
Picture No. 1

Early experimental cabling operation

This picture is an historical one: It shows one of the first cabling operation at LBL on the experimental R&D cabler 1985.



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BBC 851-490

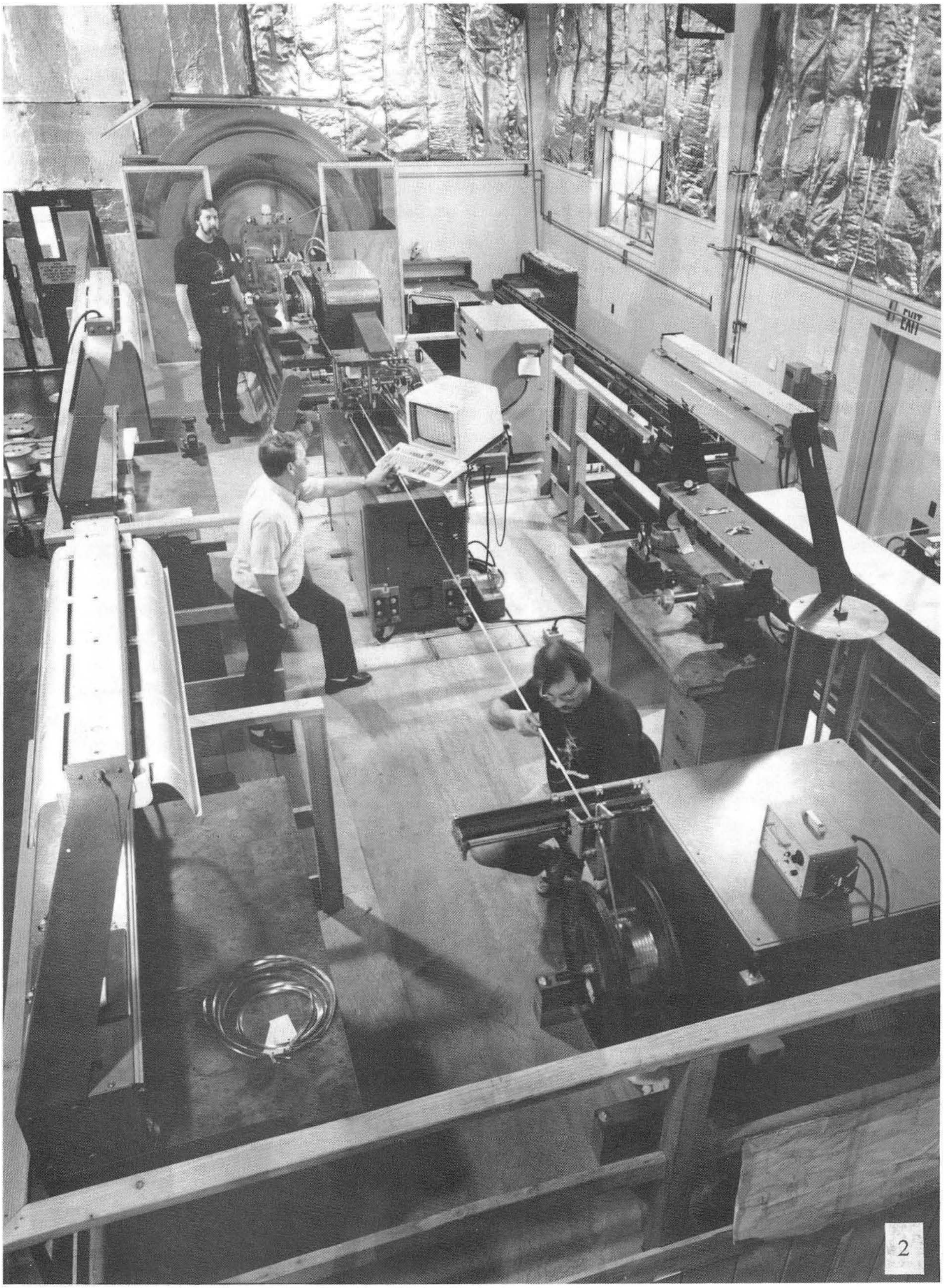
Picture No. 2

Improved LBL cabler

Time is flying! This picture is four years later than Figure 1. The LBL experimental cabler is now fully equipped with magnetic-hysteresis brakes, measuring machine in line and constant torque take up.

Spinning at 50 rpm, 750 ft. of cable are made each hour.

The picture was taken during a 7,000 feet run of a 36 strand cable for the "Low Beta QUAD", project to be installed in Fermi National Laboratory.



BBC 881-317

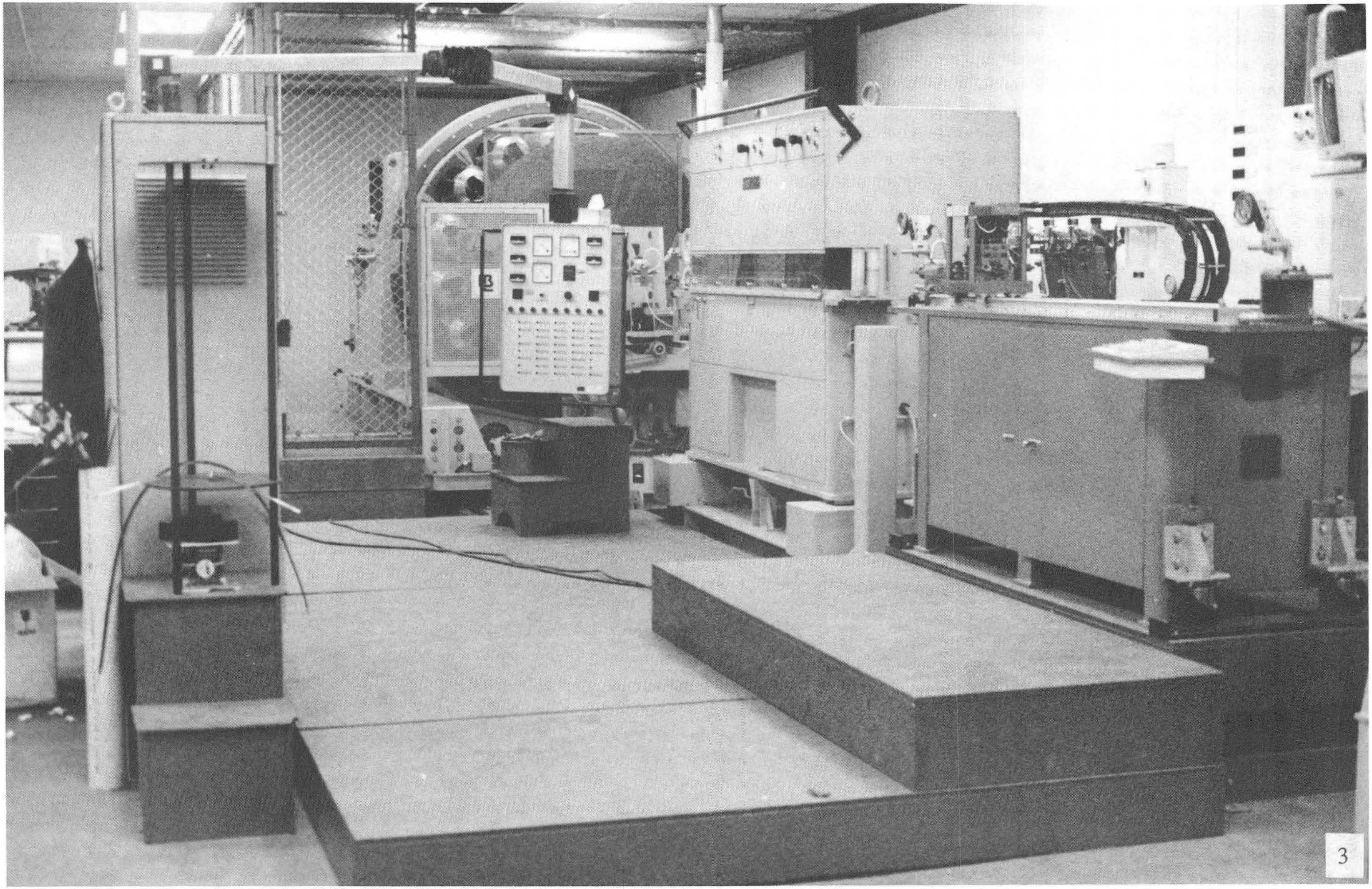
Picture No. 3

Industrial cabler

This picture was taken at New England Electric Wire where the first SSC industrial cabler was installed.

This machine was specified by LBL and manufactured by Dour Metal, SA., an established Belgium company.

The maximum production speed is 30 feet of cable per minute and 15,000 feet per run.



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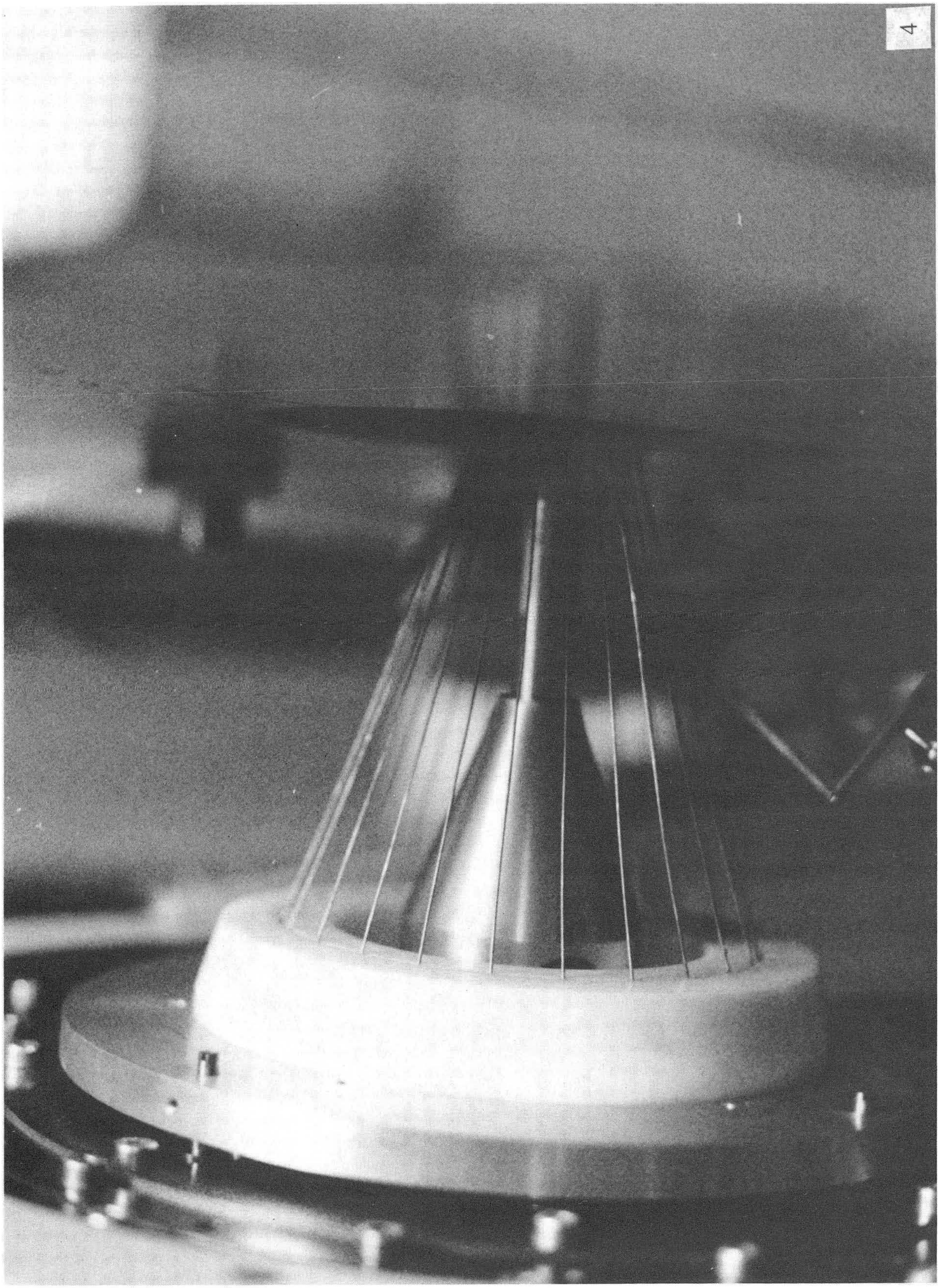
Picture No. 4

Experimental emergency brake on "Dour Cabler"

This picture shows an experimental wire emergency brake on the "Dour" machine.

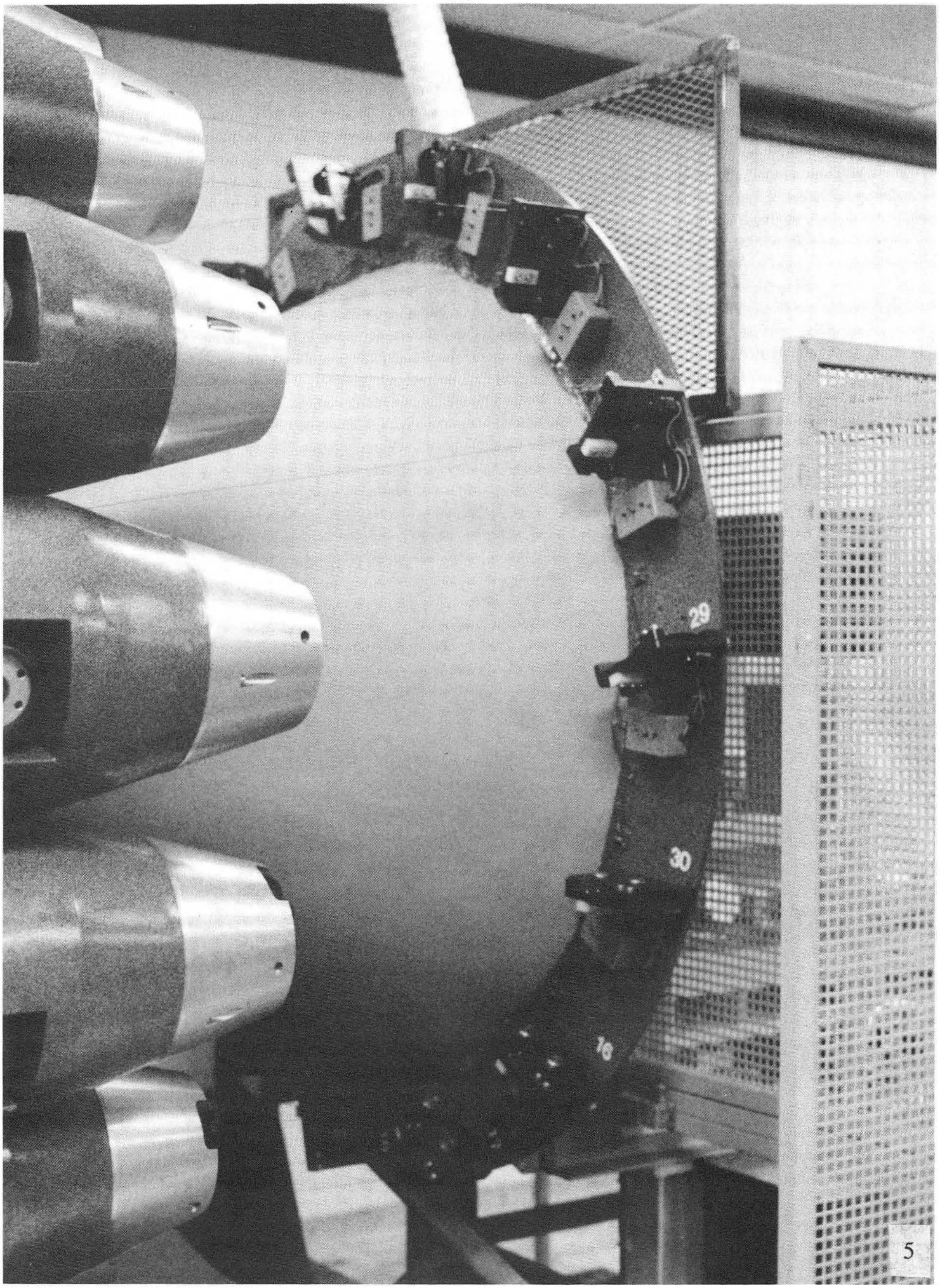


XBC 899-8099

Picture No. 5

Broken-wire detection system on "Dour Cabler"

Partial view of the broken-wire detection system on the "Dour" machine. Two of the wires are missing, and the corresponding red lights are on. Any wire rupture stops the machine immediately.

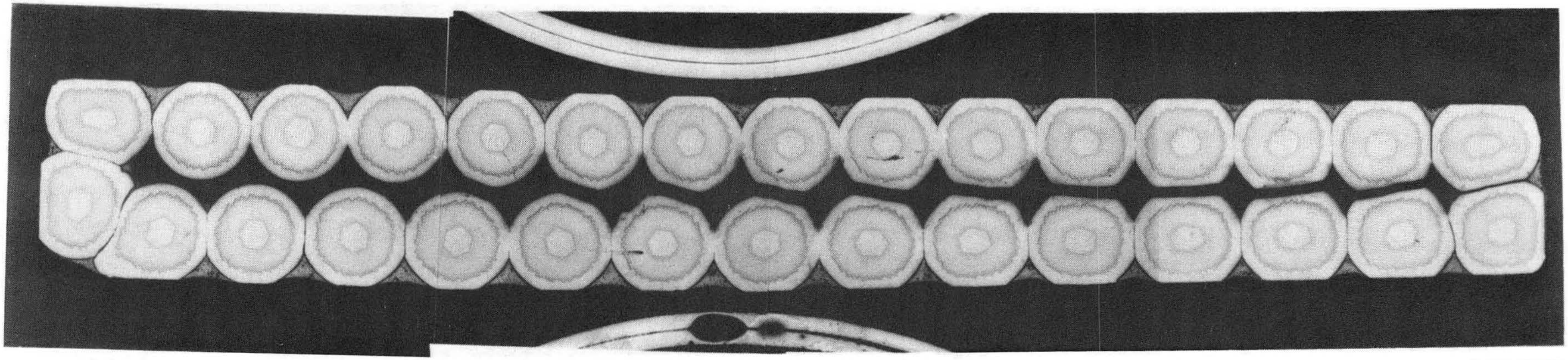


XBC 899-8101

Picture No. 6

Cross section of a 30 strands cable

Cross section of a 30 strand cable made for the external layer of the SSC 40-mm bore dipole magnet.



XBB 8554039

Magnified View (25X) of Outer Cable Cross Section

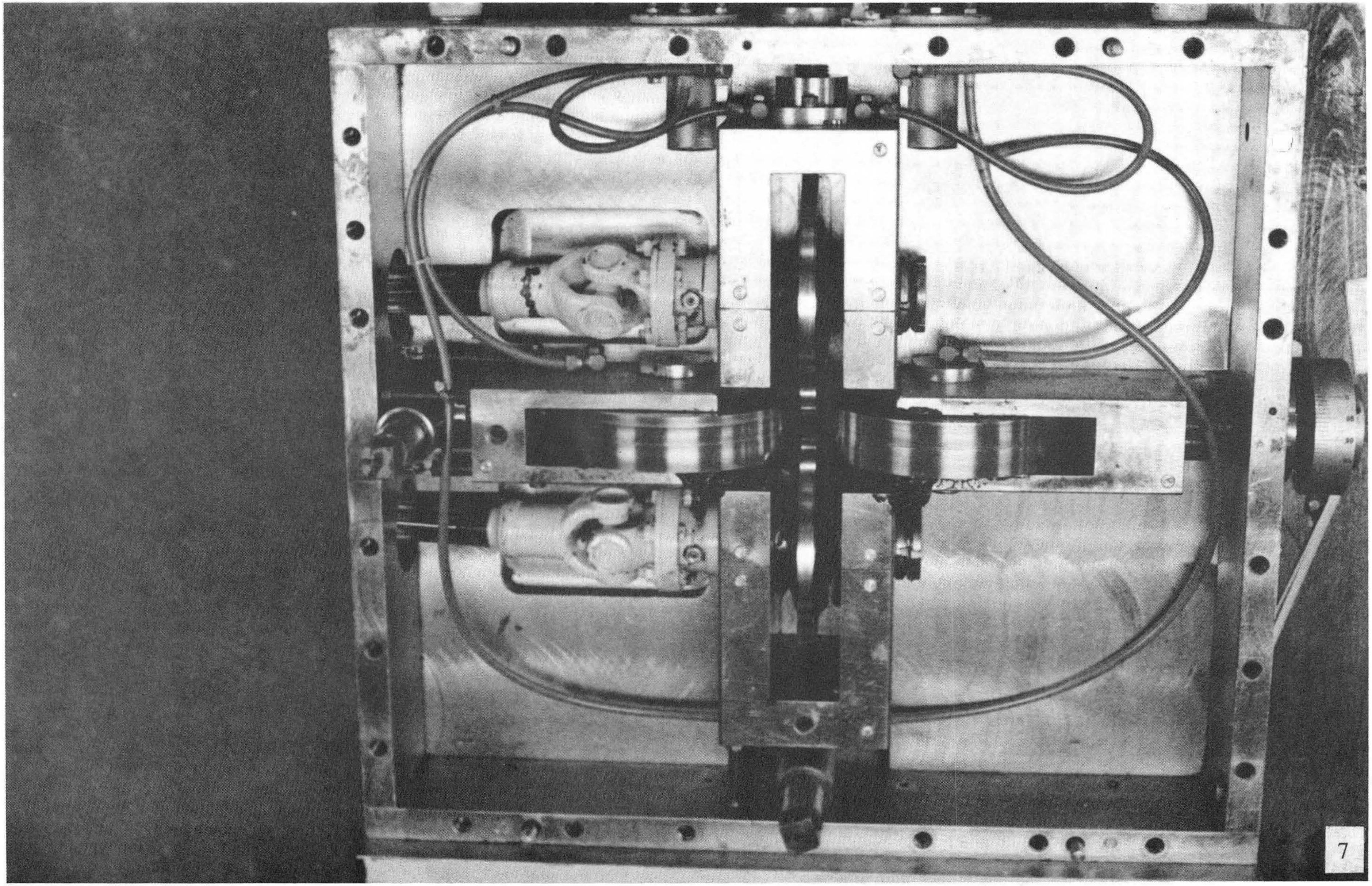
6

Picture No. 7

Motorized Turkshead

View of a motorized turkshead as installed on the "Dour" machine.

In this case, the rollers are in the symmetrical position, according to Sketch 6D Chapter 4.

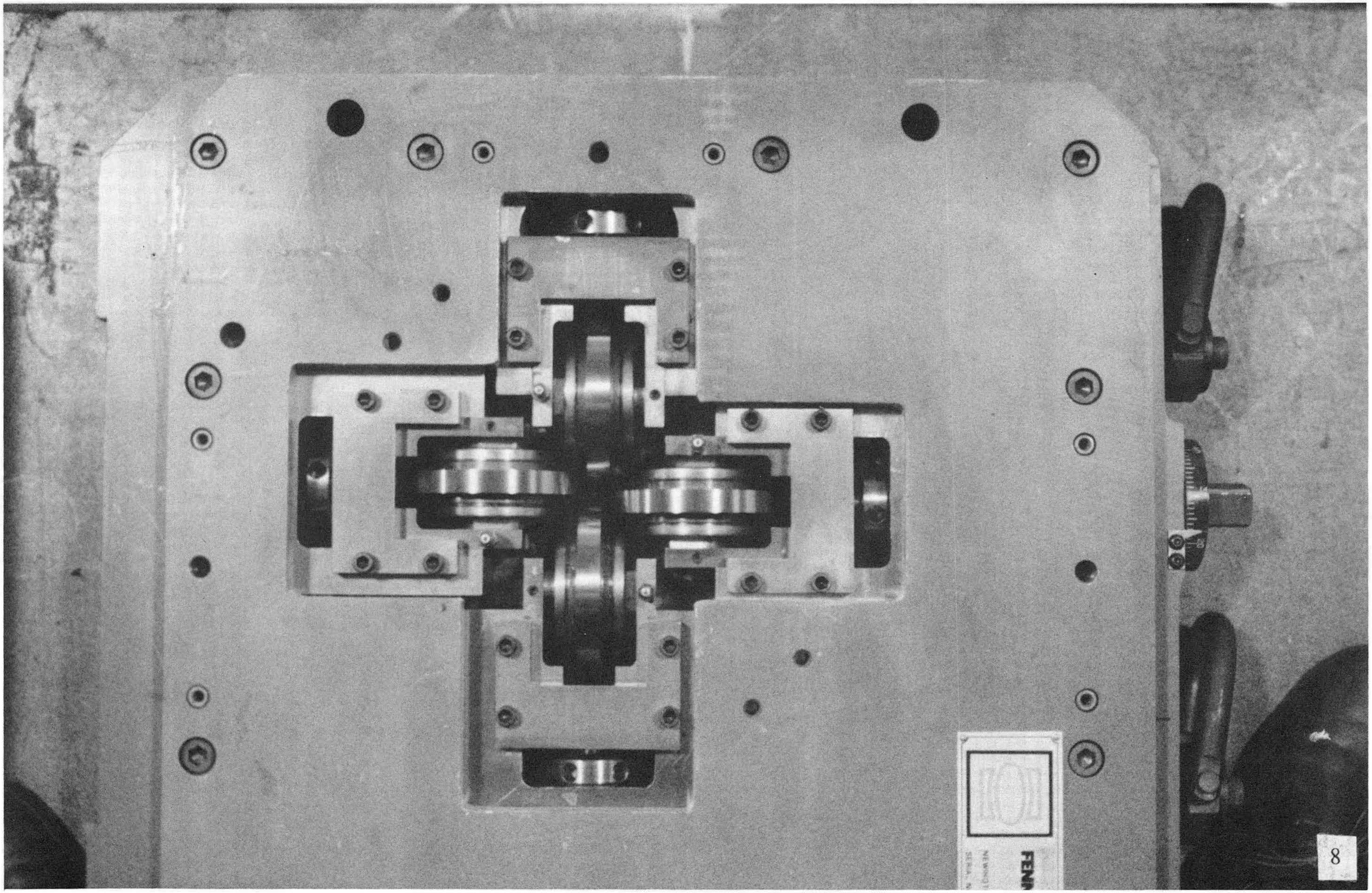


XBC 899-8103

Picture No. 8

Passive Turkshead

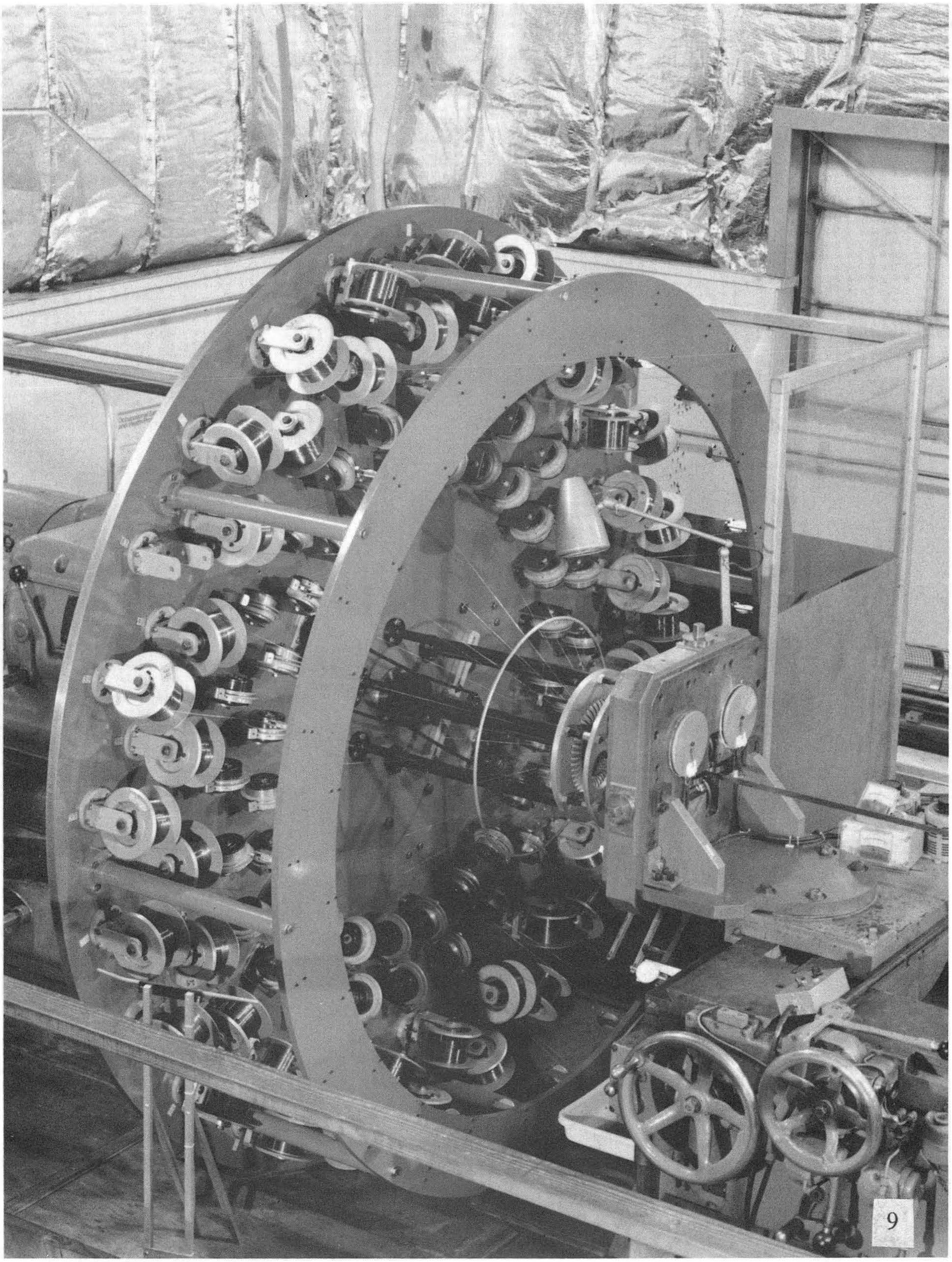
View of a passive turkshead with the rollers disposed in the classic turkshead pattern according to the schematic drawing 6A Chapter 4.



XBC 907-5789

Picture No. 9

The new LBL cabler barrel with 48 spools installed.



BBC 900-8704

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720